

Course 1

Modules 1–6

Fundamentals of Light and Lasers

3rd Edition



OP-TEC *

Optics and Photonics Series

Course 1

Fundamentals of Light and Lasers

3rd Edition

OPTICS AND PHOTONICS SERIES



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PREFACE

The six instructional modules (chapters) contained in this text are designed for use by students and instructors involved in the preparation of technicians in the areas of optics, electro-optics, lasers, and photonics. The materials can be used as an introductory course in AAS programs in laser/electro-optics and photonics at two-year postsecondary community and technical colleges, as supplementary laser/electro-optics courses in related fields such as biomedical equipment, manufacturing, defense and nanotechnology, as well as in programs designed to retrain or update the skills of engineering technicians who are already employed. These materials can also support dual-credit offerings for high school students in STEM career pathways. The modules are designed to be used as a unit or independently, as long as prerequisites have been met.

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Linda J. Vandergriff (Science Applications International Corporation) (Module 1-1)
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FEATURES

Mathematics Videos: Math videos are provided to assist students in performing mathematical operations required in the text. The following is a list of available videos:

1. Scientific Notation
2. Unit Conversion
3. Introductory Algebra
4. Powers and Roots
5. Ratio and Proportion
6. Exponents and Logarithms
7. Graphing in Rectangular Coordinates
8. Geometry
9. Angle measure in Two and Three Dimension
10. Trigonometry
11. Special Graphs

These videos can be accessed at <http://optecvideo.opteccrm.org/> In the Preface of each module, this list of topics is repeated with check marks (✓) by those mathematics topics that will be used in the module. This checklist provides instructors a means of front loading the presentation of material in a module with mathematics instruction. If instructors prefer to provide math instruction using a “just on time delivery” mode, a special icon appears where the mathematics topics presented in these videos are first used within a module.

Laboratory Videos: Laboratories that support, reinforce, and provide a hands-on means of learning presented material are included in each module of the text. To assist students in preparing for these laboratories, the text provides internet accessibility to videos that present safety issues, equipment use, data collection techniques, required calculations, and expected results related to these laboratories. Instructors can use these videos as pre-lab activities to familiarize students with the laboratories, making their laboratory time more efficient and effective. Laboratory procedures are located at the end of each module; the icon identifies those that have videos. Students can access these videos at <http://optecvideo.opteccrm.org/>.

Mini-Tutorial Videos: The text contains some photonics concepts that students often require addition instruction to learn. To assist students with these concepts, mini-tutorial videos are available in the text. These videos present instruction by experienced photonics faculty that give new insights into understanding these difficult concepts and help supplement the instruction students are receiving in their classrooms. Instructors will find these videos valuable in providing out-of-class tutoring assistance to students and also in planning lessons involving these concepts. Each module in the text contains a Mini-Tutorial video which is identified by the icon and these videos are accessible at <http://optecvideo.opteccrm.org/>.

Applets: Some photonics concepts are difficult to visualize. Within each module, applets are referenced that provide students interactive, graphic simulations to improve their understanding of presented concepts. There are over 50 applets distributed throughout the six modules of the text. Applets applicable to certain content within the text are highlighted by a capital **A** with numbers appearing under them. These numbers refer to specific applets that are accessible at <http://optecvideo.opteccrm.org/>.

Real World Connections and Applications: Students are interested in how photonics technicians prepare for their careers, what skills they will need to be successful in future jobs, and what kinds of responsibilities they might be assigned in the workplace. The text has three features that address these questions and bring real world context to its content.

Scenarios: Each module in the text begins the presentation of material with a short essay that depicts the role of photonics technicians in the workplace and provides a link between the material contained in the module and how these technicians apply it.

Meet a Technician: This feature contains a bio of actual technicians with workforce experience in the photonics industry. The bio presents details about how these individuals decided to become technicians, what their experiences were in earning a degree in photonics, what responsibilities they have in the workplace, and how their photonics degree led them to their current jobs. A brief bio from a member of the Photonics Alumni Counsel for Technicians (PACT) is located at the end of each module.

Workplace Scenarios: These problem-based activities allow students to work in groups to generate solutions to tasks that can arise in today's photonics organizations. Students take on technician roles and, within teams, use the material in a module to develop strategies and results for meeting assigned tasks. These activities also provide students an opportunity to enhance their writing skills by requiring reports, in the form of e-mails and memorandums. The scenarios are instructor-friendly with full solutions and instructor notes provided. Teacher Notes and Solutions for the Workplace Scenarios can be obtained by instructors only through OP-TEC at www.op-tec.org/laser.

Glossary of Terms: A glossary of terms for Course 1: Fundamentals of Light and Lasers 3rd Edition.

Index: An index of term for Course 1: Fundamentals of Light and Lasers 3rd Edition.

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- Module 1-1: Nature and Properties of Light
- Module 1-2: Optical Handling and Positioning
- Module 1-3: Light Sources and Laser Safety
- Module 1-4: Basic Geometrical Optics
- Module 1-5: Basic Physical Optics
- Module 1-6: Principles of Lasers
- Glossary of Terms
- Index

Nature and Properties of Light

Module 1-1
of
Course 1, *Fundamentals of Light and Lasers*
3rd Edition

OPTICS AND PHOTONICS SERIES



PREFACE TO MODULE 1-1

This is the first module in *Fundamentals of Light and Lasers*. Following are the titles of all six modules in the course:

1. *Nature and Properties of Light*
2. *Optical Handling and Positioning*
3. *Light Sources and Laser Safety*
4. *Basic Geometrical Optics*
5. *Basic Physical Optics*
6. *Principles of Lasers*

The six modules can be used as a unit or independently, as long as prerequisites have been met.

FEATURES

Mathematics Videos: Math videos are provided to assist students in doing mathematical operations required in this module. The math concepts used in this module are checked ✓ in the following list:

1. Scientific Notation ✓
2. Unit Conversion ✓
3. Introductory Algebra ✓
4. Powers and Roots
5. Ratio and Proportion ✓
6. Exponents and Logarithms
7. Graphing in Rectangular Coordinates ✓
8. Geometry
9. Angle measure in Two and Three Dimension ✓
10. Trigonometry ✓
11. Special Graphs

This checklist provides instructors a means of front-loading the presentation of material in this module with mathematics instruction. If instructors prefer to provide math instruction using a “just on time delivery” mode, a special icon  appears where the checked mathematics topics are first used within this module. All math videos can be accessed at <http://optecvideo.opteccrm.org/>.

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COURSE 1: FUNDAMENTALS OF LIGHT AND LASERS

Module 1-1

Nature and Properties of Light

INTRODUCTION

Photonics is an “Enabling Technology”. What does that mean?

Photonics is a scientific term that refers to phenomena, components and devices like optics, lasers, fiber-optics and electro-optics. Even though most people are unaware of this technology area, it impacts their daily lives and is a vital part of many technical fields—and careers.

What would our lives be like today without photonic devices like lasers? Here are a few well-known laser applications.

Supermarket Checkout Systems—A low-power laser beam is scanned across the “bar codes” that are attached to products we buy. When we check out at the store, we just place the product’s bar code face down on the scanner window. The laser beam sweeps across the bar code and the reflected laser beam is read as a code that identifies the product.

LASIK Eye Surgery—LASIK (laser-assisted in situ keratomileusis) is a surgical procedure that uses a laser to correct nearsightedness, farsightedness, and/or astigmatism. In LASIK, a thin flap in the cornea is created using a pulsed laser. The surgeon folds back the flap and then removes the corneal tissue underneath using an excimer laser. With nearsighted people, the goal of LASIK is to flatten the too steep cornea; with farsighted people, a steeper cornea is desired. LASIK can also correct astigmatism by smoothing an irregular cornea into a more normal shape.

Laser Printers and Copiers—The physical phenomenon at work in a laser printer is static electricity, the same energy that makes clothes in the dryer stick together. A laser printer uses this phenomenon as a sort of “temporary glue” to hold toner on a photoconductive drum. The laser “writes” the print information on the revolving drum, which then transfers it to a sheet of paper. The printed information is then sealed to the paper with heat from a fuser, producing a very high-resolution copy.

Lasers and Fiber Optics in High-Speed Internet and Smart Phones—The properties of laser beams that allow them to be excellent carriers of high-data-rate signals (like high-speed Internet) are that they are extremely high-frequency ($\sim 3 \times 10^8$ Hertz) carriers that have the coherence properties of radio or microwave radiation. These properties allow laser beams to carry many concurrent high-frequency signals. Optical fibers permit the transmission, or “piping,” of laser beams in flexible cables that can be wrapped around corners or laid on the ocean floor. Optical fibers prevent the laser signals from being blocked or scattered by clouds or

other particles in the atmosphere or by electromagnetic interference. This means that laser beams can travel over long distances without significant distortion or attenuation.

Lasers for Burning and Reading CDs and DVDs—A CD is a piece of plastic, about one mm thick. During manufacture of a CD, microscopic bumps are impressed on it generating a single, continuous, extremely long spiral track of data that starts at the center of the disc. The CD player spins the disc while its laser assembly moves outward from the disc's center. The laser and photodetector in the player detect the bumps and flat spaces on the CD. The electronics in the CD player read the output of the photodetector and translate the pattern of bumps and flats into music we hear.

Careers in Optics and Lasers for Photonics Technicians

Many unique, useful laser applications have been developed in medicine, surgery, telecommunication, manufacturing, homeland security, lighting, displays, and nanotechnology, to name a few. Lasers are an enabling technology that provides new solutions to difficult problems, makes our country a safer place, and improves our quality of life. Technician careers in photonics technology provide rewarding opportunities for people who are interested in using their technical knowledge and hands-on skills to solve problems. For instance:

Laser R&D, Design and Production of Devices: Original Equipment Manufacturers (OEMs)

Government, national and corporate labs are conducting research into new and improved lasers, optics and electro-optical devices. Technicians work in laboratories alongside scientists and engineers to discover and develop phenomenon and equipment. Technicians also work with engineers to manufacture laser and electro-optic devices used in fields such as medicine, materials processing and defense. Technicians also work for OEM's as field service technicians to install, maintain and repair the equipment sold by their companies. Technicians working in R&D to design and produce laser equipment must have in-depth knowledge and skills in photonics.

Biomedical Equipment

Lasers and other photonics devices are used extensively in medical diagnostic and therapeutic procedures, such as endoscopy, colonoscopy, various surgeries, cauterization and tattoo removal. Photonics techs work in hospitals and clinics to maintain and repair the equipment. Some are biomedical equipment technicians with specialization in two or three photonics courses.

Manufacturing

Lasers and other electro-optic devices are used in materials processing (welding, cutting, drilling, surface treatment and etching of metals, ceramics, wood, glass, plastics etc.), and are critical in making precision measurements for equipment alignment and quality control. Photonics technicians operate, maintain and repair the photonics equipment. Manufacturing technicians may also receive two or three photonics courses as a specialization.

Energy, Environmental Monitoring and Transportation

Emerging technologies in energy production include solar which relies on photonics devices to collect and transform light into heat and electrical energy. More efficient use of energy in

lighting is achieved through the use of such photonics enabled devices as Light-Emitting Diodes (LEDs). Cleaning the air we breathe and water we drink is enhanced by using photonics devices to detect and monitor pollutants. Photonics is enabling transportation improvement and safety. Intelligent Highway Systems are being equipped with photonics-enabled guidance, collision avoidance and continuous tuning of engines based on driving conditions.

Defense and Homeland Security

Modern military systems are heavily dependent on electro-optic devices that use precision optics systems to see and interpret an enemy's installations or troop/equipment movements. Homeland security depends on careful monitoring of shipments, chemicals and personal equipment, inspections and analyses of materials using optical and photonics devices. High power laser devices are also being used to neutralize enemy weapons and pinpoint damage on targets. Photonics technicians develop and test precision optics, build prototype surveillance and weapon systems and operate/maintain photonics enabled equipment.

Information and Communication Technologies

In the midst of our information age, photonics will remain at the core of communications—gathering, manipulating, storing, routing, and transmitting information. The High Speed Internet is based on laser diode transmitters, photo-optical receivers and fiber-optic cables. Photonics technicians assist in developing the equipment, installing it and maintaining it.

What is this course about? How will you use it?

Course 1, *Fundamentals of Light and Lasers* is the beginning of your career development into the exciting and rewarding careers involving photonics. Whether you will eventually receive in-depth education and training in photonics or you will be adding photonics to your education in another photonics-enabled technology, this course will provide you the fundamental optical and laser concepts, the initial laboratory skills, and the necessary information in laser safety that will support the remainder of your education and career development.

PREREQUISITES

This module requires a basic understanding of high school algebra, geometry, trigonometry, general scientific nomenclature, the scientific process, unit conversions, and basic concepts in elementary physics and chemistry.

OBJECTIVES

When you finish this module you will be able to:

- Describe the wide variety of opportunities available to photonics technicians.
- Define these properties of light:
 - Wavelength
 - Frequency

- Speed
- Period
- Amplitude
- Energy
- Phase
- Coherence
- Polarization
- Describe the dual nature of light—both as a continuous wave and as a discrete particle—and give examples where light exhibits each nature.
- Describe the electromagnetic spectrum and sketch a diagram of its main optical regions.
- Describe the properties of electromagnetic waves.
- Define the terms reflection, refraction, and index of refraction.
- State the law of reflection and Snell's law of refraction.
- Describe diffraction and interference.
- Give a basic explanation of atoms and molecules and their ability to absorb, store, and emit quanta of electromagnetic energy.
- Describe how spectra of light sources are formed.
- Describe line spectra, band spectra, and continuous blackbody radiation.
- Describe how light is scattered, absorbed, and transmitted when passing through optical materials.
- Describe safety procedures to be followed when working in laser/optics laboratories.

SCENARIO

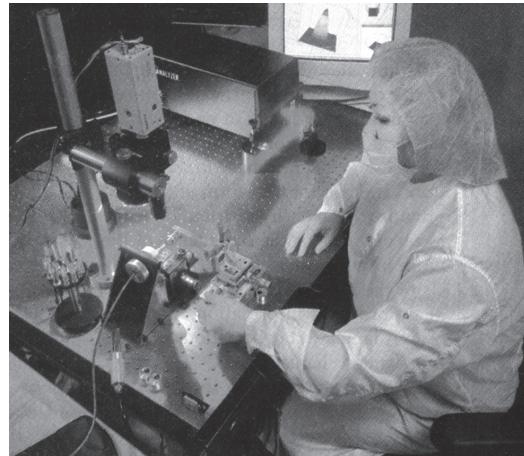
Holly works as a photonics assembly technician. The factory where she is employed creates laser diode assemblies for a variety of commercial uses. As an assembly technician, she creates and aligns laser diode components and ensures that the bonded products meet the tight quality standard she and her company require of all their products.

At the beginning of the shift, Holly gets her assignment for the production run. She prepares for entering the clean room where the work will take place. Then, after entering, she logs on at her assembly station. She selects the correct workspace file for the devices to be manufactured during that shift. The workspace file selection is based on wavelength, other optical properties, and pass/fail criteria set for this particular device.

With the components provided, Holly first sets up the lateral shearing interferometer and the microlens/laser diode product. Then she collimates and directs the laser diode beam into the beam analysis tool for testing.

After that, she reviews the results on the computer monitor and adjusts the alignment until the device is acceptable. Finally, she bonds the microlens and laser diode and stores the final measurements to a log file on the network server. These measurements, along with those of the other devices created during this production run, will serve as a statistical base for evaluation of the production process and the product quality.

Holly will create a batch of microlens/laser diode pairs during her shift. Depending on the order and application, this run may require days or weeks. Then a new product will be designed for production, and Holly and her counterparts on the production floor will create it. This will require an evolving understanding of light and its uses to allow flexibility in the manufacturing process and keep Holly and her company competitive in the growing marketplace.



Photonics technician assembling components¹

¹ Source: *Laser Focus World*, May 1999, 291. Reprinted by permission.

BASIC CONCEPTS

Properties of Light

The preceding section identified many opportunities for technicians working in *photonics*. With this promising prospect before us, we now return to “square one” and begin our study of light and its basic properties.

We begin with a question that has puzzled scientists for centuries—and is still not completely answered. **What is light?** The safest answer we can give at this time is that light seems to have both *wave* and *particle* properties, and that it is basically a form of *electromagnetic energy*.

When it travels through space or passes through small openings, it behaves like a wave, made up of connected electric and magnetic fields, vibrating and traveling together. When it reflects off of mirrors or is absorbed by materials, it seems to take on the properties of particles or packets of energy. We know that the light we see—called visible light—is part of an extensive *electromagnetic spectrum*. This vast spectrum or array of *electromagnetic energy* contains—within its end points—the well-known regions of X-rays, microwaves, radio waves, infrared and ultraviolet light, and gamma rays, as well as that part we know as “visible light.”

We have learned to treat light as a wave when it exhibits a wavelike behavior and as a particle when it acts like discrete clumps of energy—which we call *photons*. Whether we regard light as a wave or as a stream of discrete particles, we use the following properties to describe it:

- Wavelength
- Frequency
- Period
- Amplitude
- Speed
- Phase
- Coherence
- Polarization
- Energy

The wave properties of light Globally change color on numbers and letters introducing concept references

A
5, 8

The numbers below the **A** that appears in several places in this module reference specific applets that demonstrate the concepts being described in the text. These applets are accessible at <http://optecvideo.opteccrm.org/>.

A wave is a disturbance that transmits energy from one point to another. Any periodic disturbance can be represented by waves such as those involved with musical sounds, human speech, the swing of a pendulum, a cork bobbing up and down in the water, and the violent shock from an earthquake. Light, as it travels through space, can be described as a wave phenomenon.

Figure 1-1 illustrates a wave traveling to the right at *one instant of time*. The **displacement** is the vertical distance measured from the equilibrium position at any point along the wave. The **amplitude** is the maximum displacement of the wave. **Wavelength** is defined as “the distance over which the wave repeats itself” and is represented by the Greek letter lambda (λ). For example, Figure 1-1 shows the wavelength from crest to crest and trough to trough.

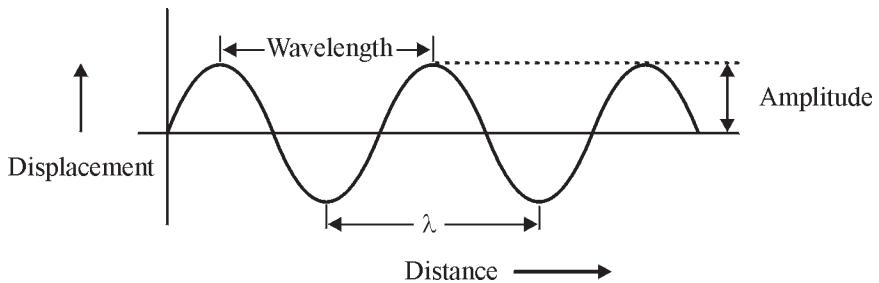


Figure 1-1 Displacement versus distance along a wave at an instant of time

Figure 1-2 illustrates the same wave as a function of time *at a fixed position* along the wave. The **period** is the interval of time over which the wave repeats itself—the time required for one complete cycle of the wave. The **frequency** of the wave is the number of cycles of the wave in one second and is represented by the Greek letter nu (ν).

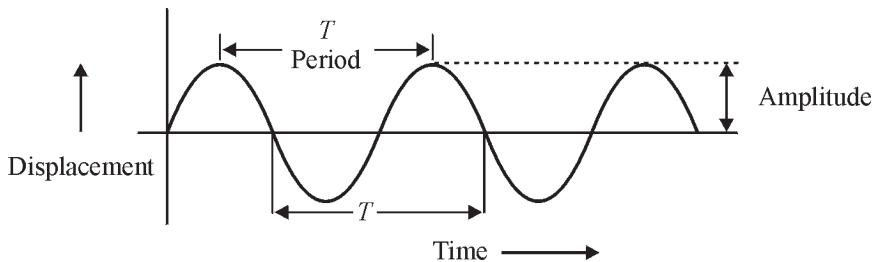


Figure 1-2 Displacement versus time at one position along the wave

Frequency and period are related by Equations 1-1 and 1-2:

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.opteccrm.org/](http://optecvideo.opteccrm.org/).



$$\nu = \frac{1}{T} \quad (1-1)$$

$$T = \frac{1}{\nu} \quad (1-2)$$

where: T = Period in seconds (sec)
 ν = Frequency in hertz (Hz)

The unit of frequency is cycles/second, or hertz, and may be abbreviated as Hz, sec^{-1} , or /sec. Period is measured in seconds and wavelength in meters. Table 1-1 lists prefixes used with these base units and other common units formed. The unit *micrometer* (10^{-6} m) is a widely used unit of length and also is called a “micron.” The micron is represented by either μm or μ , with μm preferred. A common wavelength unit not included in this table is the angstrom (1 Angstrom = 10^{-10} m).

Table 1-1. Prefixes Used to Form Units of Wavelength, Time, and Frequency

Common Use					
Prefix	Symbol	Value	Wavelength (m)	Time (sec)	Frequency (Hz)
Tera	T	10^{12}			THz
Giga	G	10^9			GHz
Mega	M	10^6			MHz
kilo	k	10^3			kHz
milli	m	10^{-3}	mm	ms	
micro	μ	10^{-6}	μm or μ	μs	
nano	n	10^{-9}	nm	ns	
pico	p	10^{-12}		ps	

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Since speed is defined as distance traveled divided by elapsed time, the speed of a wave is the distance traveled in one cycle, (the wavelength) divided by the time required for one cycle (the period). Equations 1-3 and 1-4 are expressions for wave speed V .

$$V = \frac{\lambda}{T} \quad (1-3)$$

$$V = \lambda v \quad (1-4)$$

where: T = Period of the wave

λ = Wavelength

v = Frequency of the wave

V = Speed of the wave

The speed of light traveling through a vacuum is 3×10^8 m/sec and is expressed by the symbol c , which can be substituted for V in Equation 1-4 to give Equations 1-5, 1-6, and 1-7.

$$c = \lambda v \quad (1-5)$$

$$\lambda = \frac{c}{v} \quad (1-6)$$

$$v = \frac{c}{\lambda} \quad (1-7)$$

Examples 1, 2, and 3 illustrate the use of Equations 1 through 7 in the solution of typical problems.

Example 1

Calculation of frequency and period

Given: A radio wave has a wavelength of 30 m.

Find: The frequency and period of the wave

Solution:

$$v = \frac{c}{\lambda} \quad (\text{Eq. 1-7})$$

$$= \frac{3 \times 10^8 \text{ m/sec}}{30 \text{ m}}$$

$$v = 10^7/\text{sec} = 10^7 \text{ Hz} = 10 \text{ MHz}$$

$$T = \frac{1}{v} \quad (\text{Eq. 1-2})$$

$$= \frac{1}{10^7/\text{sec}}$$

$$T = 10^{-7}/\text{sec} = 100 \text{ ns}$$

Need help working with units?
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Example 2

Calculation of wavelength and period

Given: Ordinary household ac current has a frequency of 60 Hz.

Find: The wavelength and period of the wave

Solution:

$$\lambda = \frac{c}{v} \quad (\text{Eq. 1-6})$$

$$= \frac{3 \times 10^8 \text{ m/sec}}{60/\text{sec}}$$

$$\lambda = 5 \times 10^6 \text{ m}$$

$$T = \frac{1}{v} \quad (\text{Eq. 1-2})$$

$$= \frac{1}{60/\text{sec}}$$

$$\lambda = 1.67 \times 10^{-2} \text{ sec} = 16.7 \text{ ms}$$

Example 3

Calculation of frequency and wavelength

Given: The light produced by a HeNe laser has a period of 2.11×10^{-15} sec.

Find: The frequency and wavelength of the wave

Solution:

$$v = \frac{1}{T} \quad (\text{Eq. 1-1})$$

$$= \frac{1}{2.11 \times 10^{-15} \text{ m/sec}}$$

$$v = 4.7 \times 10^{14} \text{ Hz} = 474 \text{ THz}$$

$$\lambda = \frac{c}{v} \quad (\text{Eq. 1-6})$$

$$= \frac{3 \times 10^8 \text{ m/sec}}{4.74 \times 10^{14} / \text{sec}}$$

$$= 6.33 \times 10^{-7} \text{ m}$$

$$\lambda = 633 \text{ nm} = 0.633 \mu\text{m} = 6330 \text{ \AA}$$

A

The nature of electromagnetic waves

7

Light consists of electromagnetic waves moving through space. Figure 1-3 is a representation of connected electric and magnetic fields, moving from left to right, at one instant of time.

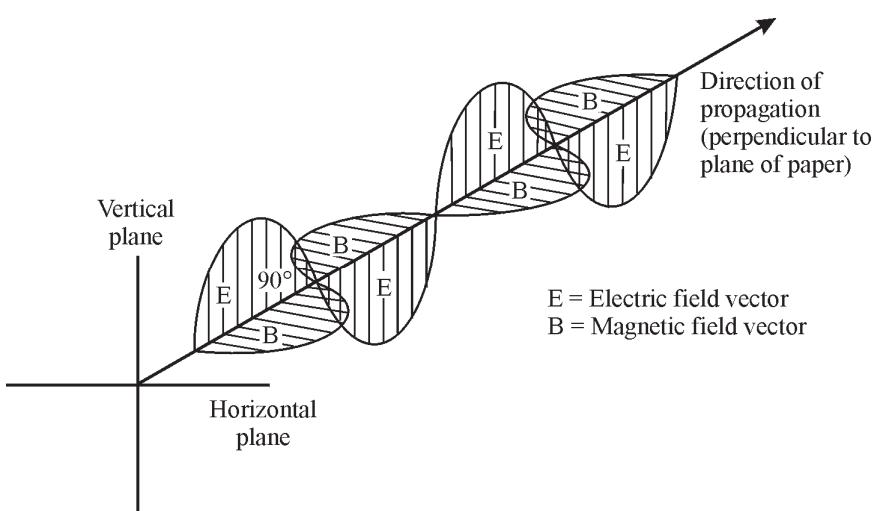


Figure 1-3 Three-dimensional model of an electromagnetic wave

The wave consists of variations in two types of fields in space. In this case, the electric field (E) oscillates vertically to form an electric wave; the magnetic field (B) oscillates horizontally to form a magnetic wave. The two fields are perpendicular to each other, and both are perpendicular to the direction of propagation of the wave. All electromagnetic waves have this same basic composition. They differ only in frequency and wavelength.

The span of frequencies and wavelengths covered by electromagnetic radiation is indicated by Figure 1-4a. Devices that produce or detect electromagnetic waves must be designed to operate at the frequency of the waves they emit or receive. For example, radio AM and FM transmitters and receivers operate at frequencies in the 10^3 to 10^7 Hz range and are designed to emit or respond to these frequencies. X-ray tubes and films are designed for use in the 10^{17} to 10^{19} Hz frequency range. Lasers generally produce laser light in the frequency and wavelength range indicated by Figure 1-4b. This range includes the spectral regions commonly identified as the *infrared*, *visible*, and *ultraviolet* regions. The human eye responds to the narrow visible region shown in Figure 1-4c, spanning a frequency from 4.3×10^{14} Hz to 7.5×10^{14} Hz or, correspondingly, from a wavelength of 0.7×10^{-6} m to 0.4×10^{-6} m.

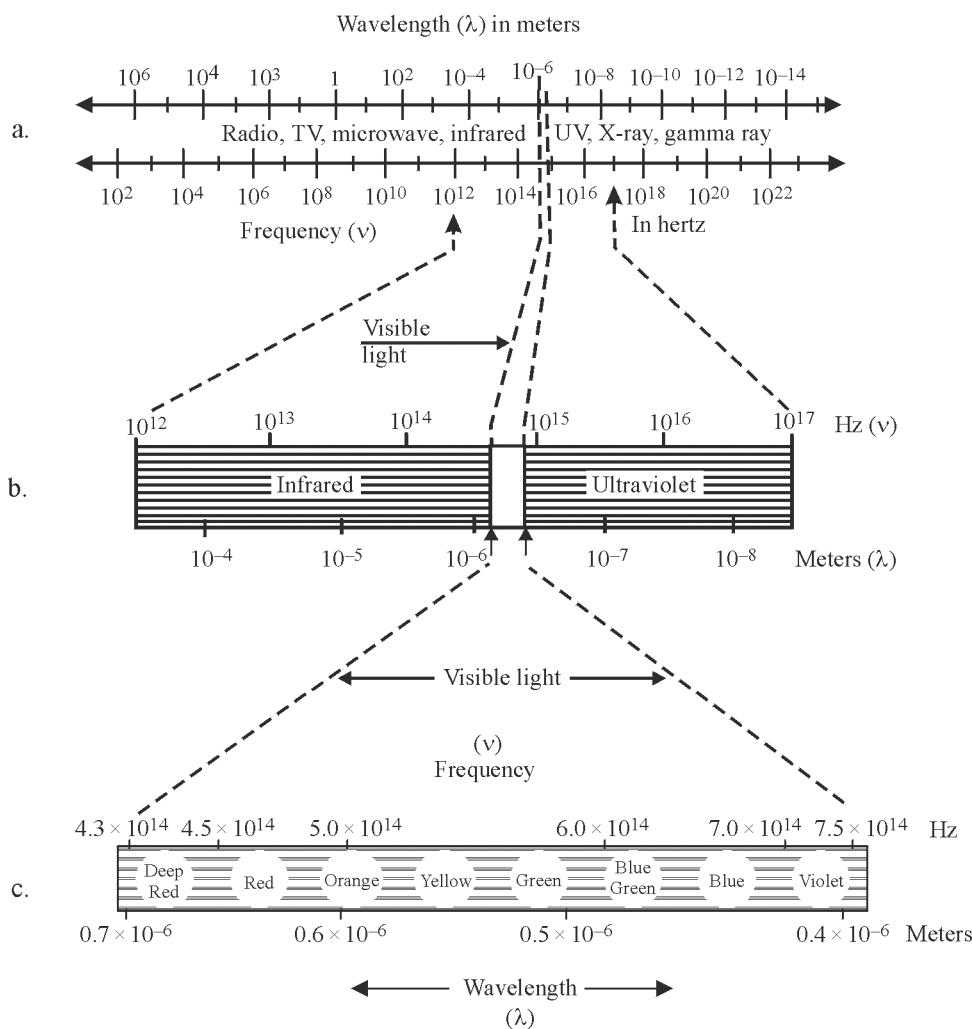


Figure 1-4 The electromagnetic spectrum and its principal regions

Index of refraction

As we have mentioned, all electromagnetic (EM) waves travel through a vacuum at the constant speed of $c = 3 \times 10^8$ m/sec. When these waves travel through a transmitting optical material, however, their speed is reduced. It is as if the interaction of the electrons—always clustered around the atoms in the material—with the electromagnetic wave exerts a “drag” on the EM wave and slows it down. The *index of refraction* of a material is the ratio of the speed of light in a vacuum to its speed in that material and is given by Equation 1-8.

$$n = \frac{c}{V} \quad (1-8)$$

where: n = Index of refraction
 V = Speed of light inside
material
 c = Speed of light in vacuum

Need help with ratios?
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<http://optecvideo.opteccrm.org/>.



The *frequency* of a light wave *does not change* when it enters a material, but its *wavelength* does. It is reduced (Figure 1-5). The index of refraction is also given by the ratio of wavelength of light in vacuum to the wavelength of light in the material (Eq. 1-9).

$$n = \frac{\lambda_o}{\lambda_m} \quad (1-9)$$

where: λ_o = Wavelength in vacuum
 λ_m = Wavelength in material

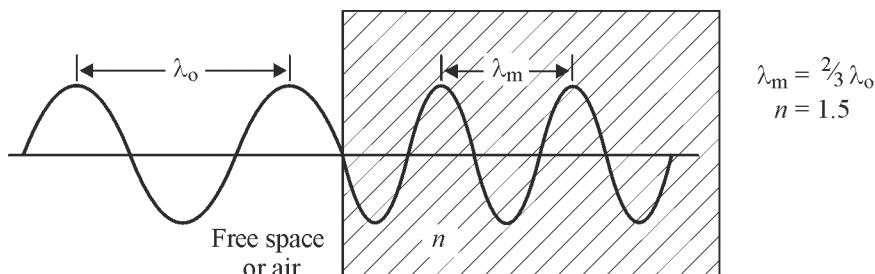


Figure 1-5 Wavelength reduction of light passing through a material of refractive index n

When light leaves a material of index n and enters a vacuum of index $n = 1.0$, it returns to speed c and to wavelength λ_o . The index of refraction of air is about 1.0003 but is assumed to be 1.0 in most applications.

Examples 4 and 5 illustrate the application of Equations 1-8 and 1-9.

Example 4

Index of refraction of ruby

Given: Light travels through a ruby laser rod with a speed of 1.74×10^8 m/sec.

Find: Index of refraction of ruby

Solution:

$$\begin{aligned} n &= \frac{c}{V} \quad (\text{Eq 1-8}) \\ &= \frac{3 \times 10^8 \text{ m/sec}}{1.74 \times 10^8 \text{ m/sec}} \\ n &= 1.72 \end{aligned}$$

Example 5

Speed and wavelength of light in glass

Given: A HeNe laser beam ($\lambda = 633$ nm) travels through a glass window of refractive index of 1.65.

Find: Speed and wavelength inside the glass.

Solution:

$$\begin{aligned} V &= \frac{c}{n} \quad (\text{Eq. 1-8}) \\ &= \frac{3 \times 10^8 \text{ m/sec}}{1.65} \\ V &= 1.82 \times 10^8 \text{ m/sec} \\ \lambda_m &= \frac{\lambda_o}{n} \quad (\text{Eq. 1-9}) \\ &= \frac{633 \text{ nm}}{1.65} \\ \lambda_m &= 384 \text{ nm} \end{aligned}$$

Other wave properties of light

Other important wave properties of light that deserve a brief mention in this introductory module are *phase*, *coherence*, and *polarization*. Let's look at each one in turn.

A Wave phase—Figure 1-6 represents a *sine* wave whose equation is given by

$$Y = A \sin \alpha \quad (1-10)$$

- 5 where: Y = Vertical displacement, positive or negative, above or below midline AB
 A = Amplitude or *maximum* displacement
 α = Phase angle or angular displacement from 0°

Need help with trigonometry?
 Go to
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Need help measuring angles?

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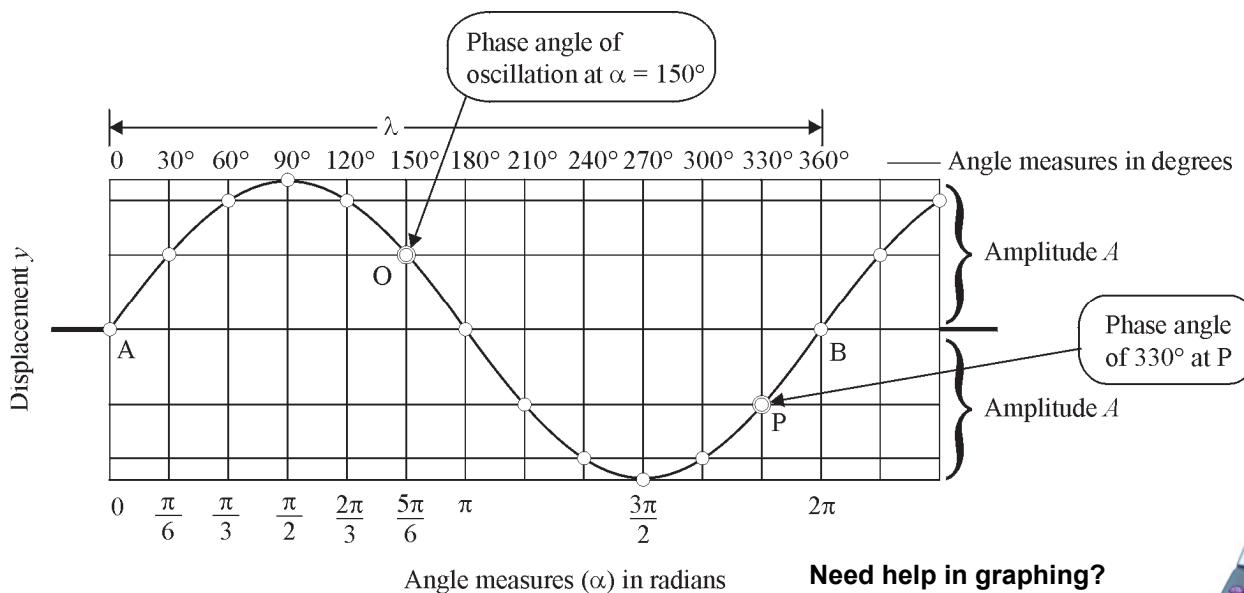


Figure 1-6 Sine wave representation

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The displacement Y is graphed against the phase angle α , expressed in radians along the bottom scale and degrees along the top scale. At point O, the particular phase angle of this oscillation is 150° . At point P, the phase angle is 330° , and so on.

As the phase angle α increases, the displacement Y changes in accordance with the *sine wave* $Y = A \sin \alpha$. One complete wave oscillation (360° or 2π radians) produces one wavelength, or one period, of the wave. Thus, any point along the wave can be specified by its *phase angle* α —such as those at points O and P.

The *phase* of any point on a wave is defined as “the angular displacement” of that point from the last positive zero crossing of the wave. A “positive zero crossing” occurs at those zero displacement points where the new displacement is about to become positive. Points A and B of Figure 1-6 are positive zero crossings of the wave illustrated. At these points, the phase is zero.

The absolute phase of a point on a wave usually is of little interest when one is dealing with light waves, but the *phase difference* between two waves is often of great interest. For example, the phase difference between points O and P on the sine wave in Figure 1-6 is $330^\circ - 150^\circ = 180^\circ$. Figure 1-7 illustrates the idea of “phase difference.”

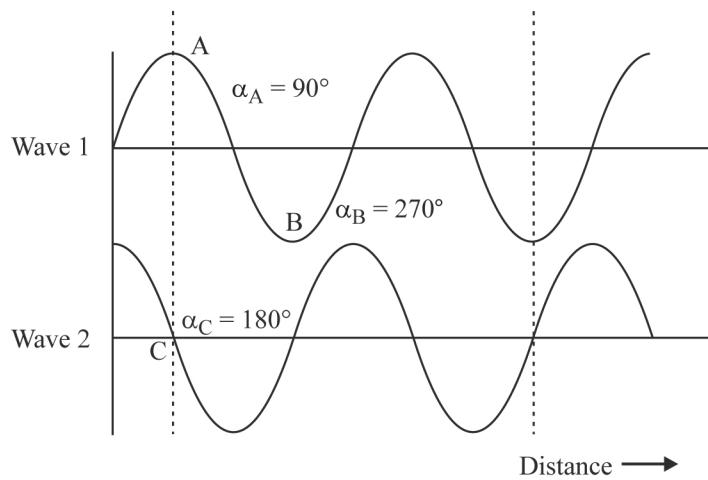


Figure 1-7 Phase difference between several points on two sine waves

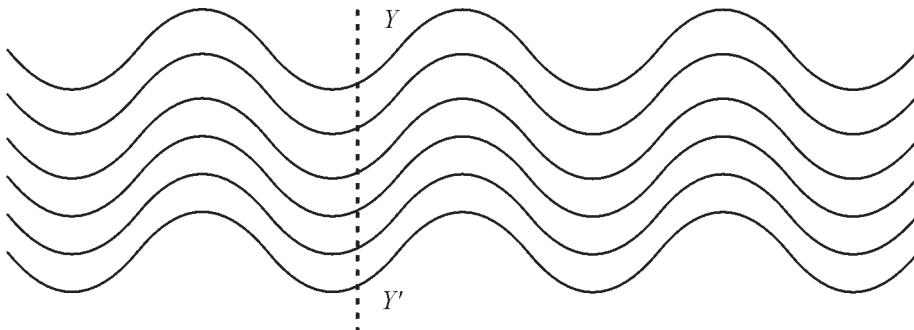
On wave 1, point A has a phase of 90° and point B has a phase of 270° ; therefore, these two points on wave 1 are said to be $(270^\circ - 90^\circ)$ or “ 180° out of phase.”

This same principle is applied at point C on wave 2 to determine the phase difference between waves 1 and 2. The phase angle at point A on wave 1 is 90° . The phase angle at corresponding point C on wave 2 is 180° . Thus the *phase difference* is 90° and the two waves are said to be “out of phase by 90° .”

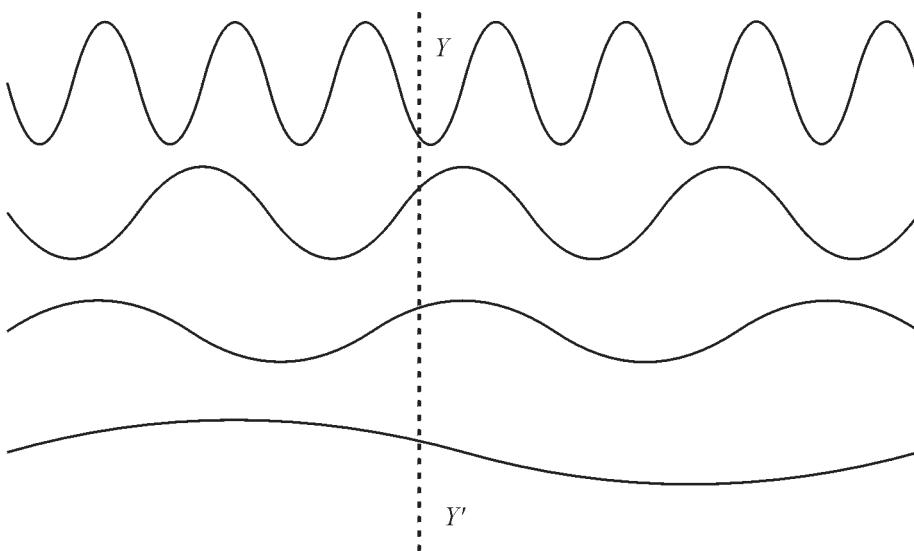
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Wave coherence—Laser light is *coherent light*. Light waves are said to be “coherent” if they are all in phase—or “in step”—with one another. Figure 1-8 illustrates the difference between coherent light and incoherent light. The five waves shown in Figure 1-8a are coherent since each corresponding point on each wave has the same phase angle as the others, all along the length of the waves. You can see, for example, that the crests and troughs (peaks and valleys) for the five waves line up perfectly, and at any arbitrary vertical line YY' , for example, the phase angle α is the same for each wave. In common language, coherent light is made up of waves that are said to be “in step”—each with the *same* wavelength. When added together, coherent waves, produce an overall wave of much greater amplitude—higher peaks and lower valleys.

By contrast, Figure 1-8b illustrates four waves that are *incoherent*. They do not possess identical phase angles along a vertical line such as YY' , and their wavelengths are all different. When added together, they generally produce an overall wave of smaller displacements with varying amplitudes along the curve. Light can be of the same wavelength but incoherent, as well. The condition for being “incoherent” is that the phase angle is random.



(a) Coherent light. Each of the five waves has the **same** phase angle α along the vertical line YY' , and all have the **same** wavelength.



(b) Incoherent light. Each of the four curves has a **different** wavelength and their phases are **different** along any vertical line YY' .

Figure 1-8 Comparing coherent and incoherent light

Incoherent light—such as that from arc lamps, incandescent bulbs, and the sun—is quite common. Coherent light—such as that produced by lasers—is required when producing interference patterns or holograms. It is rather uncommon.

Wave polarization—As shown earlier in Figure 1-3, electromagnetic waves—and thus light waves—are made up of vibrating electric and magnetic fields. The *polarization* of light refers to the orientation or direction of vibration of the electric field as the wave propagates through space.

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The following terms commonly are used in the description of *polarized light*:

- Unpolarized light has no specific orientation of electric field. The direction of the electric field varies randomly at approximately the frequency of light. In Figure 1-9a, this randomness is depicted by the electric field having several different orientations.

- Plane-polarized light is light in which the electric field oscillates in one plane only, as in Figures 1-9b,c.
- In horizontally polarized light (Figure 1-9b), the plane that contains the electric field is horizontal—perpendicular to the plane of the paper—as pictured in the *head-on* view.
- In vertically polarized light (Figure 1-9c), the plane of the electric field is vertical—up and down in the plane of the paper and shown as vertical arrows in the *head-on* view.
- In circularly polarized light, the direction of the electric field is neither random nor confined to a single plane. The direction of the electric field of circularly polarized light sweeps out a circle during each period of the wave.

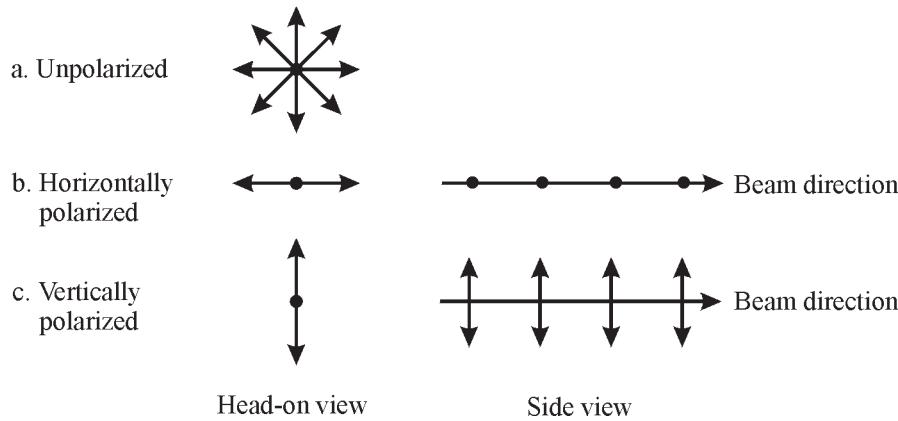


Figure 1-9 Representations of polarized light

Figure 1-10 illustrates the operation of an optical element termed a “linear polarizer.” It consists of a plastic sheet that contains needle-shaped crystals of herapathite (an iodine compound). These crystals strongly absorb the horizontal components depicted in Figure 1-10, but they transmit most of the vertical components. Thus after passing through a linear polarizer, unpolarized light emerges as linearly polarized light, in this instance in the vertical direction.

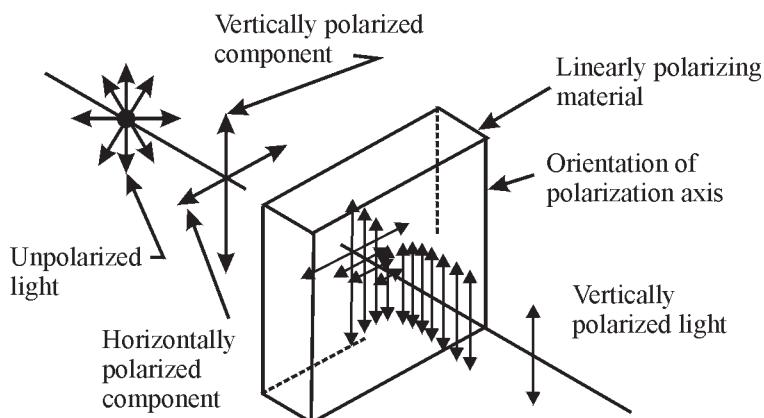


Figure 1-10 Polarization by absorption

Particle properties of light

A 3 So far, we have examined the wave properties of light. We treat light as a wave to describe its propagation from one point to another and to explain its behavior in interference, diffraction, and polarization phenomena. To describe its behavior in ray tracing of reflected and refracted light, or in the emission and absorption of light by atoms, we find it useful to treat light as a “particle”—really a localized wave packet. As we have already mentioned, we refer to this wave packet as a *photon*.

A photon is the smallest division of a light beam that retains the properties of the beam. The characteristics of a photon include its frequency, its wavelength, and its energy. A photon should not be visualized merely as a particle that has physical dimension or a specific location in space. More accurately, a photon is viewed as a “wave packet” that has a specific energy content.

The energy of a photon is directly proportional to the frequency of its wave packet and is given by Equation 1-11.

$$E = h\nu \quad (1-11)$$

where: E = Energy of photon in joules (J)

ν = Frequency in hertz (Hz)

h = Planck's constant = 6.625×10^{-34} joule-seconds. (This famous constant was identified by the German physicist Max Planck in 1900, during his attempt to explain the spectral distribution of black-body radiation. His work introduced the concept of a “quantum of action,” involving the constant h . The “quantum of action” led eventually to the idea of a photon.)

Alternatively, since $\nu = \frac{c}{\lambda}$ (Eq. 1-7), the energy E can be expressed in terms of the wavelength λ and speed c of the photon as in Equation 1-12.

$$E = \frac{hc}{\lambda} \quad (1-12)$$

where: E = Energy of photon in joules

c = Speed of light in a vacuum (m/s)

λ = Wavelength of light in meters

h = Planck's constant = 6.625×10^{-34} joule-seconds

Examples 6, 7, and 8 illustrate the use of these two equations.

Example 6

Calculation of the energy of a photon of given frequency

Given: The frequency of a photon of HeNe laser light is 4.74×10^{14} Hz.

Find: The energy of the photon

Solution:

$$E = h\nu \quad (\text{Eq. 1-11})$$

$$E = (6.625 \times 10^{-34} \text{ J}\cdot\text{sec})(4.74 \times 10^{14}/\text{sec})$$

$$E = 3.14 \times 10^{-19} \text{ J}$$

Example 7

Calculation of the energy of a photon of a given wavelength

Given: The wavelength of a HeNe laser light is 633 nm.

Find: The energy of the photon of this wavelength

Solution:

$$E = \frac{hc}{\lambda} \quad (\text{Eq. 1-12})$$

$$E = \frac{(6.625 \times 10^{-34} \text{ J}\cdot\text{sec})(3 \times 10^8 \text{ m/sec})}{6.33 \times 10^{-7} \text{ m}}$$

$$E = 3.14 \times 10^{-19} \text{ J}—\text{Same as the photon energy calculated in Example 6}$$

Example 8

Calculation of wavelength and frequency of a photon of given energy

Given: A photon has an energy of 1.875×10^{-19} J.

Find: The frequency and the wavelength of the photon

Solution:

From Equation 1-11,

$$\nu = \frac{E}{h}$$
$$= \frac{(1.875 \times 10^{-19} \text{ J})}{(6.625 \times 10^{-34} \text{ J}\cdot\text{sec})}$$

$$\nu = 2.83 \times 10^{14}/\text{sec} = 283 \text{ THz}$$

From Equation 1-12,

$$\begin{aligned}\lambda &= \frac{hc}{E} \\ &= \frac{(6.625 \times 10^{-34} \text{ J} \cdot \text{sec})(3 \times 10^8 \text{ m/sec})}{(1.875 \times 10^{-19} \text{ J})} \\ \lambda &= 1.06 \times 10^{-6} \text{ m} = 1.06 \mu\text{m}\end{aligned}$$

Light Interactions

We see light *reflect* from mirrors and *refract* or bend as it passes from one optical medium to another. We see light *interfere* with itself and *diffract* or spread out as it passes through small openings. And we see light energy be *absorbed* and *scattered* as light passes through optically transparent materials. Each of these interactions helps us understand the behavior of light.

Reflection from plane surfaces

A 9 When a ray of light is incident on a plane, reflecting surface such as a mirror or window pane, all or some of the light is reflected. The part that is reflected obeys the *law of reflection* illustrated in Figure 1-11.

Here the angle the reflected ray makes with the *normal* (line perpendicular to the surface) at the point of incidence is *always equal to the* angle the incident ray makes with the same normal. The incident ray, reflected ray, and normal always lie in the *same* plane surface.

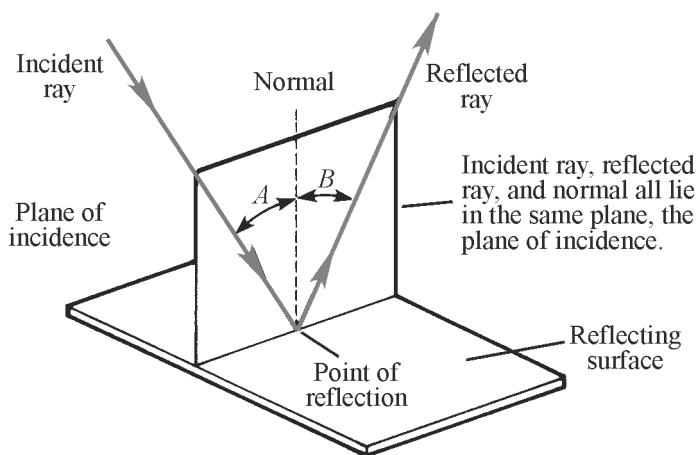
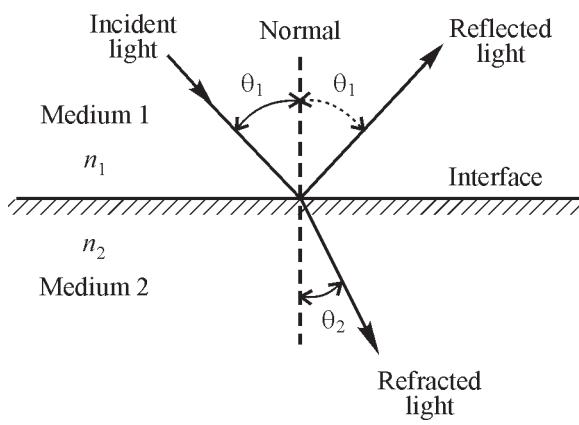


Figure 1-11 Law of reflection: Angle B equals angle A.

The geometry of Figure 1-11 reminds us that reflection of light rays from a plane, smooth surface is like the geometry of pool shots “banked” along the walls of a billiard table.

Refraction at an optical interface

When light is incident on an *interface* between two transparent optical mediums—distinguished from each other by different indexes of refraction, n_1 and n_2 , as shown in Figure 1-12—part of the light is reflected and part is refracted. The reflected part obeys the *law of reflection*. The *refracted part* obeys *Snell's law* (Equation 1-13).



Snell's law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (1-13)$$

where

n_1 = index of refraction of medium 1

n_2 = index of refraction of medium 2

θ_1 = angle of incidence (and reflection)

θ_2 = angle of refraction

For a short lesson about Snell's Law go to
<http://optecvideo.opteccrm.org/>.



Figure 1-12 Refraction of light at an interface

At an interface between two optical media, *Snell's law of refraction* relates the sines of the angles of incidence and refraction to the indexes of refraction of the two media. The law is named after a Dutch astronomer, Willebrord Snell, who formulated the law in the 17th century. Snell's law enables one to calculate the direction of the refracted ray if the refractive indexes of the two media and the direction of the incident ray are known.

As mentioned earlier, the index of refraction for free space (a vacuum) is exactly *one*. For air and most gases, it is very nearly one; so for most calculation it is taken as 1.00. For other materials, it has values greater than one. Table 1-2 lists indexes of refraction for several common materials at $\lambda = 589$ nanometers. (Note: The index of refraction for a given material varies a little with the wavelength; therefore, the index of refraction is always specified at a specific wavelength. This variance gives rise to *dispersion*, which will be covered in Module 1-4, *Basic Geometrical Optics*.)

Table 1-2. Indexes of Refraction for Various Materials at 589 nm

Substance	<i>n</i>	Substance	<i>n</i>
Air	1.0003	Polystyrene	1.49
Diamond	2.42	Quartz (fused)	1.46
Gallium Arsenide (semiconductor)	3.40	Water	1.33
Glass (crown)	1.52	Ice	1.31
Zircon	1.92	Germanium	4.1
Glass (flint)	1.66	Silicon	3.5

Also, much more will be said about the *reflection* and *refraction* of light in Module 1-4, *Basic Geometrical Optics*. Example 9, following, will demonstrate how each is involved in light incident on a glass slide.

Example 9

Light incident on a glass slide

A laser beam near 589 nm is directed onto a microscope glass slide of index of refraction $n = 1.52$. The angle of incidence onto the glass is 60° .

- (a) What is the angle of reflection?
- (b) What is the angle of refraction?

Solution

- (a) From the *law of reflection*, the reflected beam heads off at the *same angle* as the angle of incidence, 60° .
- (b) From *Snell's law*, the refracted angle θ_2 is found as follows:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2, \text{ where } n_1 = 1.00, \theta_1 = 60^\circ, n_2 = 1.52$$

$$\text{Therefore } (1.00)(\sin 60^\circ) = (1.52) \sin \theta_2$$

$$(1.00)(0.87) = 1.52 \sin \theta_2$$

$$\sin \theta_2 = \frac{(1.00)(0.87)}{1.52} = 0.572$$

$$\theta_2 = \sin^{-1} 0.572 = 34.9^\circ$$

The refracted ray must bend toward the normal to the interface as it enters the glass.

Interference and diffraction of light

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The wave nature of light was given great support by Christian Huygens and Thomas Young around the turn of the 18th century. They showed that *in-phase* light waves *of the same wavelength*, coming from two different sources and directed onto a screen, could be made to overlap and *interfere* with each other. Along the screen, located somewhat distant from the two sources, the overlapping light waves would reinforce one another and produce regions of higher light intensities at some points; at other points, in between the bright spots, the light waves would subtract from each other and produce regions of lower light intensities. The series of adjacent bright and dark regions was called *interference fringes*. Their existence could be explained successfully by treating light from the two sources as *waves*.

The classic Young's double-slit experiment—with the formation of fringes—is shown in Figure 1-13 (following).

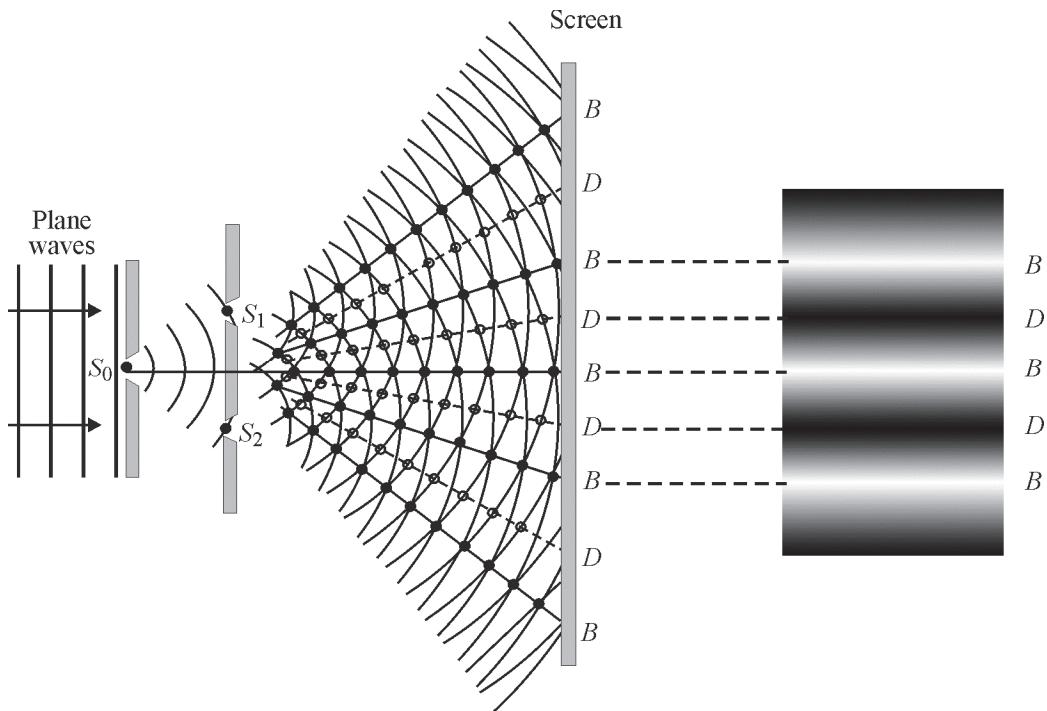


Figure 1-13 Young's famous double-slit experiment

In Figure 1-13, the following is true:

- Light waves emanating from slits S_1 and S_2 are in phase and of the same wavelength.
- The light waves moving outwardly from S_1 and S_2 overlap and reinforce each other along lines with *solid* dots; they cancel each other along lines with *unfilled* dots.
- On the screen, alternate regions of bright (B) and dark (D) make up the interference fringes, as shown roughly in the offset (Figure 1-13b). The dark regions shown are darkest at their centers and fade out gradually into the white regions. Similar fading occurs as the white regions blend into the dark region.

When light passes through small openings or by sharp boundaries such as a razor-blade edge, interference of light waves produces *diffraction* patterns. These diffraction patterns exhibit fringes and extend into the regions of geometrical shadow, where light, treated as a beam of particles, could not go.

Figure 1-14 shows the beautiful diffraction patterns obtained when light is passed through a circular pinhole (1-14a), through a narrow-slit (1-14b), and by a sharp edge (1-14c).

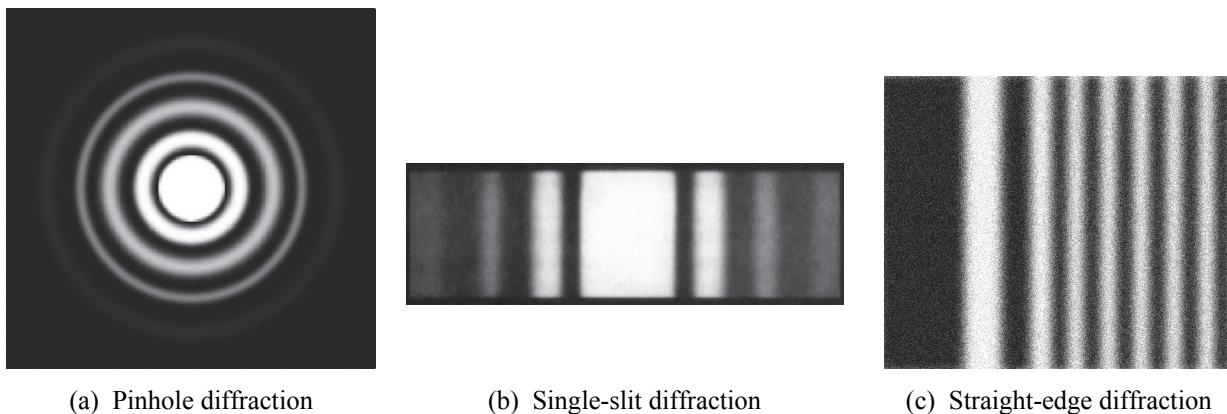


Figure 1-14 Sketches of several common diffraction patterns

It is not possible to explain the occurrence of these patterns with light considered as streams of particles. Only the wave theory of light and the concept of interference of overlapping light waves accounts for the details in these fringe patterns. Much more will be said about interference and diffraction in Module 1-5, *Basic Physical Optics*.

Absorption and scattering of light

A **3** When a light beam passes through an optical medium, some of the light is *reflected* at the two interfaces, some is *absorbed* inside the medium, some is *scattered* outside of the beam while in the medium, and what is left is *transmitted*. This is shown schematically in the sketch in Figure 1-15. In this figure, the width of the light beam depicts the energy contained within it. As the beam passes through a medium, its physical width stays constant, but as illustrated in the figure its energy content decreases as photons leave it through reflection, absorption, and scattering interactions.

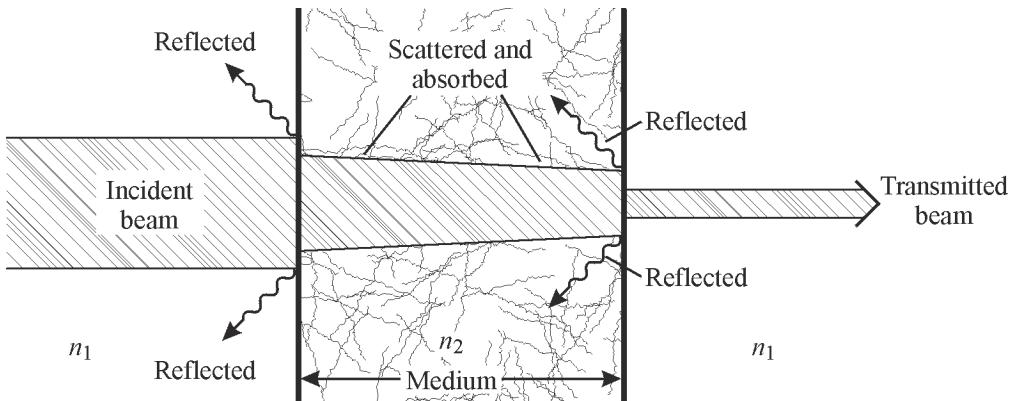


Figure 1-15 Losses in light energy passing through an optical medium

The intersection of light with matter is best understood by treating light made up of photons—more like wave packets or particles than the pure waves of Huygens and Young. The details of the interaction involve atoms, energy levels in atoms, and photons of electromagnetic energy.

All matter is made up of atoms. An atom is the smallest unit that retains the characteristics of a chemical element. It consists of a positive nucleus surrounded by negative electrons arranged in distinct energy shells designated K through O, as shown in Figure 1-16. The notation K(2) indicates that the K-shell is complete when it has 2 electrons. Similarly, L(8) indicates that 8 electrons complete the L-shell, and M(18) indicates that 18 electrons complete the M-shell.

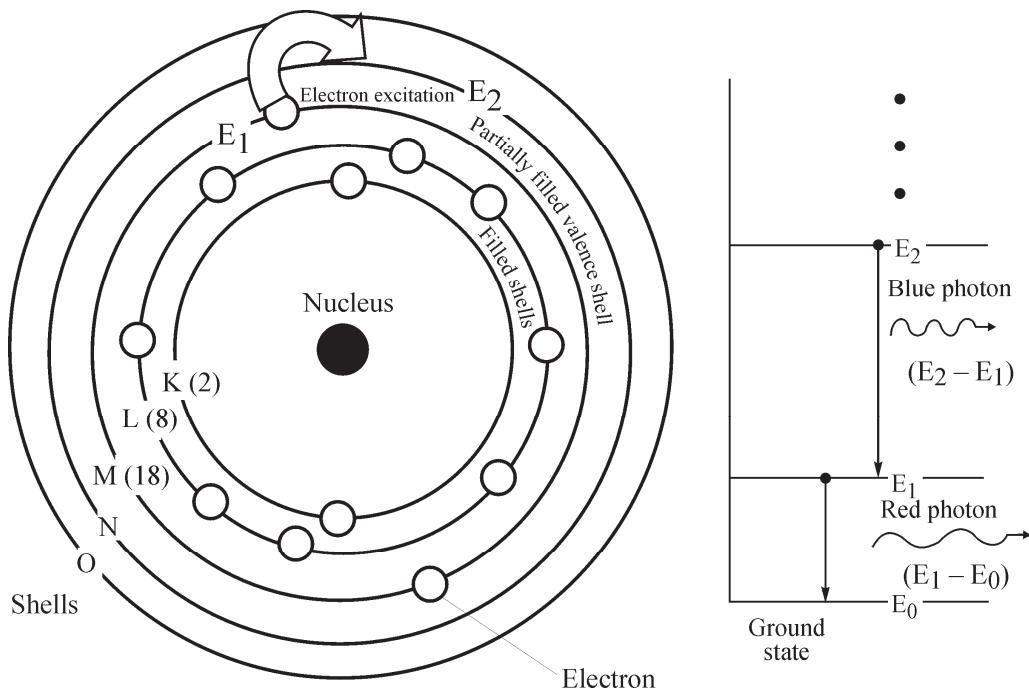


Figure 1-16 *Atomic model*

We model the energy of an atom with the positions of its electrons. When all the electrons are in an unexcited, or ground, state, the atom is assumed to be at its lowest energy level. When the atom absorbs energy, electrons can be “excited” and moved into higher-energy shells. As electrons move from one shell to another, unique amounts, or quanta, of energy are absorbed or emitted. A photon is such a quantum of energy. This is how an atom can absorb or emit light.

An atomic energy-level diagram shows the unique electron energies available in a given atom. An energy-level diagram for hydrogen is shown in Figure 1-17. Hydrogen has only one electron, and it can exist in only one of the available energy levels shown at a time. The lowest level, E_1 , is the *ground state*. Energy must be added to the atom for the electron to move to a higher level. Note that energy levels range from a value of -13.6 eV (electron volts) for the lowest energy level ($n = 1$) to a value of 0 eV for the very highest energy level ($n = \infty$)—when the electron breaks free from the atom.

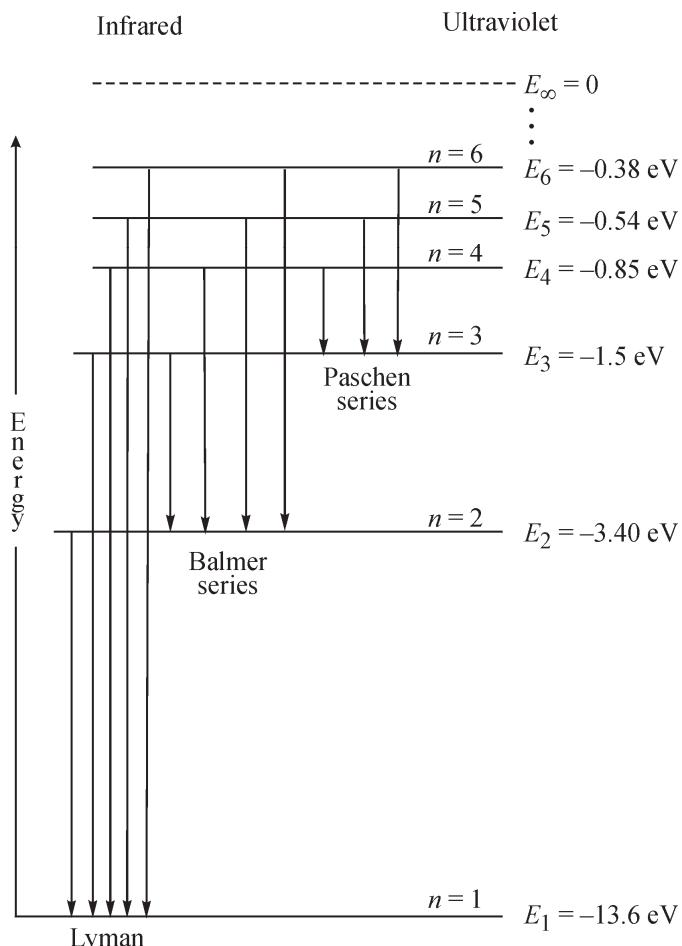


Figure 1-17 Energy-level diagram for a hydrogen atom

Suppose a hydrogen atom is in an excited state, say, the $n = 3$ level. The atom can make a transition to the ground state by *emitting a photon*. The energy of the emitted photon equals the decrease in energy of the atom, as illustrated below.

$$\begin{aligned}E_{photon} &= E_3 - E_1 \\&= -1.51 \text{ eV} - (-13.6 \text{ eV}) \\&\equiv 12.09 \text{ eV}\end{aligned}$$

The atom can also *absorb photons*. This happens when the energy of a photon exactly matches the difference between two electron energy levels. For example, a hydrogen atom in the ground state can absorb a photon whose energy is 12.09 eV. The electron in the atom will then move from energy level E_1 to energy level E_3 .

Spectra of light sources

The sources of electromagnetic radiation are many. Usually sources are divided into two categories, natural and man-made. Examples of natural sources of radiation include the sun, observable stars, radio stars, lightning, and, in fact, any living body. Some of the man-made sources of radiation are incandescent and fluorescent lights, heaters, lasers, masers, radio and television antennas, radars, and X-ray tubes.

Two types of spectra are important in photonics: *emission* and *absorption* spectra. An emission spectrum is formed by light emitted from a source. An absorption spectrum is formed when light that passes through an optical medium is partially absorbed.

All materials with temperatures above absolute zero emit electromagnetic radiation. Every atom and molecule has its own characteristic set of spectral lines. The specific wavelengths and energies that produce a spectral “fingerprint” depend on the atomic and molecular structure of the material. The *line spectra* observed early in the scientific age led to a significant understanding of the structure of atoms and eventually to the development of modern quantum theory. This theory holds that light emitted by an atom or molecule has a discrete wavelength, corresponding to a specific energy-level change within the atom or molecule.

To observe a *line* or *band* spectrum, light is passed through a slit. The image of this slit is then refracted by a prism or diffracted by a grating and recorded on film or a spectrograph. The slit is imaged on the film at a different position and at a different intensity for each different wavelength of the light, thereby forming a “fingerprint” of that particular light. Spectroscopy is the science that analyzes line spectra and identifies the different chemical elements that make up the material.

Emission spectra—Figure 1-18 represents the typical *emission spectrum* of a monatomic gas, such as helium or neon. This type of spectrum is produced by an electrical discharge passed through a gas sample contained at low pressure. Each of the lines in the emission spectrum is produced by a single atomic transition, from one energy level to the other, and the *intensity* of each line produced is dependent on the probability of atoms making that particular transition. Stronger lines are the result of more probable transitions from energy states having short atomic lifetimes. Weaker lines are the result of less probable transitions from states that have longer atomic lifetimes.

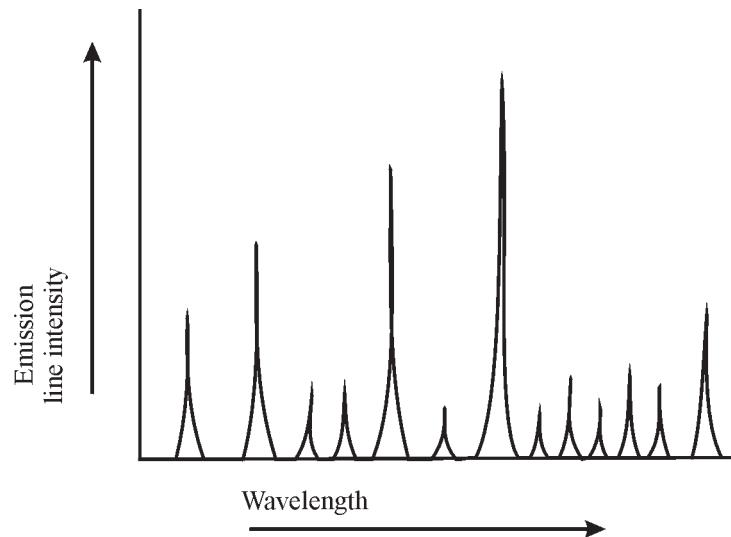


Figure 1-18 Line spectrum of a monatomic element

Absorption spectra—Absorption is the transfer of energy from an electromagnetic wave to the atoms or molecules in a material. Energy transferred to an atom, for example, excites electrons to higher energy states. Thus absorption depends very much on the energy level structure of particular elements or compounds. The wavelength/intensity spectrum of light that passes through the material appears to have certain wavelengths removed (those of the absorbed light) and is called the absorption spectrum. *Selective absorption* explains why different objects that we see have different colors. For example, a red apple is “red” because the skin of the apple absorbs all colors (wavelengths) incident on it except red, which it reflects to us to see as red light.

Figure 1-19 represents a typical absorption spectrum for a solid material. Unlike the comparatively narrow spikes of a gaseous spectrum seen in Figure 1-18, this spectrum consists of broad, irregularly spiked regions called *absorption bands*.

Areas containing a closely spaced group of strong lines appear as an absorption band. In crystalline solids such as Nd:YAG (Neodymium atoms in yttrium aluminum garnet), these absorption bands consist of groups of closely spaced, sharp-edged lines. In solids such as Nd:glass that lack an ordered crystal structure, the bands are broader and less distinct. The wavelength characteristics of these absorption bands are important in determining the type of electromagnetic radiation we should use to excite solid-state lasers.

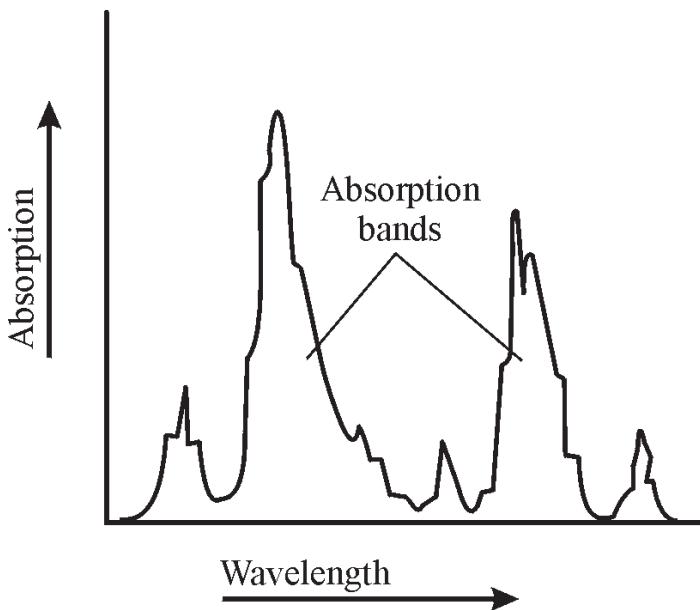


Figure 1-19 Absorption spectrum of a solid

Blackbody radiation—The spectrum of electromagnetic radiation emitted by an object at some absolute temperature T —generally referred to as *thermal radiation* or blackbody radiation—is shown in Figure 1-20. Three thermal radiation—or *blackbody radiation*—curves are shown, at absolute temperatures of 1600°K, 2400°K, and 3200°K. Note that as the temperature rises, the amount of light (area under the curve) increases and the *peak* radiant power, $P(\lambda)$, shifts towards shorter wavelengths. (It was precisely in the challenge of accounting for the detailed shapes of these curves that Max Planck hypothesized the need for quanta of light (photons) and gave birth to the field of quantum physics.)

The shift in wavelength of the emitted radiation of a thermal source, as it is heated, is familiar to most of us. We see an object become “red-hot” as the temperature increases. That’s because a larger amount of the radiation is being emitted in the red part of the spectrum. If we continue to increase the temperature, we move toward the “white-hot” level.

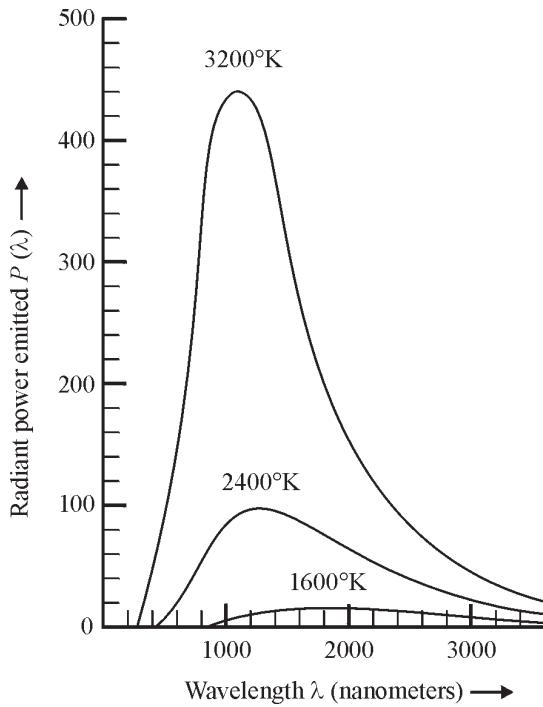


Figure 1-20 Spectral distribution of blackbody radiation

The shift of peak wavelength as a function of the absolute temperature is given by the so-called *Wien displacement law* (Equation 1-14):

$$\lambda_{\max} T = 2.898 \times 10^{-3} \text{ m} \cdot \text{K} \quad (1-14)$$

where λ_{\max} is the wavelength at which the $P(\lambda)$ has a maximum value in meters
 T is the absolute temperature in degrees Kelvin.

Example 10

Peak wavelength maximum of blackbody radiation at room temperature

Assuming that a body is at room temperature ($68^{\circ}\text{F} = 20^{\circ}\text{C} = 293\text{K}$), what is the peak wavelength of the thermal radiation given off by this body?

Solution: Treating the body as a blackbody and making use of Equation 1-14,

$$\begin{aligned} \lambda_{\max} T &= 2.898 \times 10^{-3} \text{ m} \\ \lambda_{\max} &= \frac{2.898 \times 10^{-3} \text{ m}}{293} = 9.89 \times 10^{-6} \text{ m} = 9.89 \mu\text{m} \end{aligned}$$

Thus the peak wavelength is near 10 micrometers, deep into the infrared region of the EM spectrum. This explains why we do not “see” the radiation emitted by room-temperature bodies. Our eyes

cannot “see” infrared radiation. But so-called “snooper scopes” do and thus can see warm bodies moving around in the dark.

Scattering of light

Scattering is the redirection of light caused by its interaction with matter. The scattered light may have the same or longer wavelength (lower energy) compared with the incident radiation, and it may have a different electric field polarization.

If the dimensions of the scatterer are much smaller than the wavelength of light, like a molecule, for example, the scatterer can absorb the incident light and quickly reemit the light in a different direction. See Figure 1-21. If the reemitted light has the same wavelength as the incident light, the process is called *Rayleigh scattering*. If the reemitted light has a longer wavelength, the molecule is left in an excited state, and the process is called *Raman scattering*. In Raman scattering, secondary photons of longer wavelength are emitted as the molecule returns to the ground state.

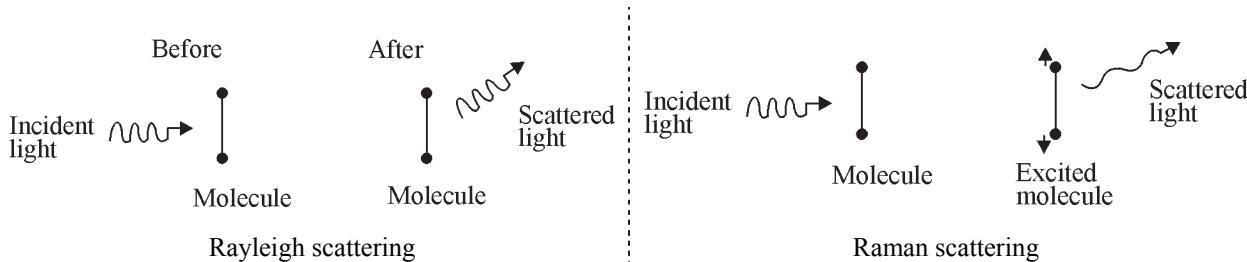


Figure 1-21 Rayleigh and Raman scattering

Air molecules (O_2 and N_2) are Rayleigh scatterers of visible light and are more effective at scattering shorter wavelengths (blue and violet). Can you use this information to explain why, on a clear day, the sky looks blue?

If the scatterer is similar in size to—or is much larger than—the wavelength of light, the existence of matching energy levels is not important. All wavelengths are equally scattered. This process is called *Mie scattering*. Water droplets effectively scatter all wavelengths of visible light in all directions. Can you use this information to explain the color of a cloud?

Fundamentals of Laboratory Safety

Before we examine the nature and properties of light with the help of several laboratory experiments, where we will be using lasers to provide us with intense, visible light beams, we need to review general laboratory safety practices—especially with lasers.

The HeNe gas laser is by far one of the most common types of lasers and is of historical importance, since it, along with the ruby laser, was one of the first to be built. HeNe lasers in the 0.5-mW to 5.0-mW range are common tools for alignment and science laboratories (1 milliwatt = 10^{-3} watt). Although these devices are safe if handled properly, they can cause injury if used improperly. The following procedures will ensure the safe operation of a HeNe laser.

- **DO NOT LOOK DIRECTLY INTO THE LASER BEAM.**

The low-power HeNe laser is little more than a coherent, monochromatic light bulb. The common laboratory HeNe laser described here is not capable of burning or drilling holes in most materials; and accidental, momentary eye exposure will not normally cause eye damage. Nevertheless, the highly directional, intense beam of light should be treated with caution, care, and respect. Common sense dictates that one **must not look** directly into any bright light source such as the sun, carbon arc, or an arc lamp projector, and particularly a laser beam. The lens of the eye can focus the beam from even a low-powered (1–5 mW) HeNe laser to a small spot on the retina and cause thermal damage to retinal tissue.

- **DO NOT LOOK AT SPECULAR REFLECTIONS OF THE LASER BEAM.**

Specular reflections are those from mirrors, watch crystals, polished metal surfaces (painted and unpainted), or any other highly reflective surface. Specular reflections of a laser beam are considered secondary laser sources and, as such, are treated with the same caution as one does the direct laser beam.

- **TAKE CARE WHEN MOVING THE LASER OR WHEN MOVING OBJECTS IN THE BEAM PATH OF THE LASER.**

Most low-power HeNe lasers are small enough to be moved about easily. If the laser must be moved during its operation, care must be taken to direct the beam carefully in order that it will not shine into anyone's eyes. For the reasons outlined above, caution also must be taken not to direct the beam upon a specular reflector when the laser is moved.

If an object must be moved into the beam of a laser, movement should be deliberate, with due consideration given to where the reflections will be directed. Usually, a laser should be turned off before it is moved.

- **BEWARE OF HIGH VOLTAGE, ESPECIALLY WHEN THE CASE OR ENCLOSURE OF AN OPERATING LASER IS OPEN.**

The HeNe laser described here contains a high-voltage power supply. This unit should not be disassembled, demonstrated, or serviced by anyone unfamiliar with such devices. Most lasers contain either high-voltage or high-current power supplies that should be treated with caution. Each year more people in the laser industry are injured by electrical hazards than by exposure to laser beams.

- **OPERATE THE LASER IN AN AREA DESIGNED FOR LASER OPERATION**

If possible, the laser should be operated with the beam horizontal and below eye level to prevent eye damage. All potential specular reflectors should be removed from the beam area. Adequate provision for all support equipment should be made prior to the operation of the laser. The number of persons working around the laser should be kept to a minimum, and the area in which the laser is being operated should be illuminated as much as possible. Access to the operation area should be limited and appropriate warning signs exhibited.

Most low-power HeNe lasers are designed to operate with 110/120 volts, single phase, 50-60 Hz AC power. Some may operate with 220/240 volts, single- or three-phase 50-60 Hz AC power. Prior to the operation of any laser, the correct power requirements for that laser should be determined from the laser specification. The power cord attached to the laser should be examined. For most low-power HeNe lasers, the unit is equipped with a power cord consisting of a three-wire, grounded plug. The third-wire, grounded terminal must not be bypassed.

- **DO NOT INTENTIONALLY OR INADVERTENTLY TRACK VEHICLES OR AIRCRAFT WITH THE LASER BEAM.**
Federal laws prohibit the tracking of vehicles or aircraft with laser beams. Such actions could cause considerable property damage, loss of eyesight, or even loss of lives.
- **DO NOT LEAVE AN OPERATING LASER UNATTENDED. ALWAYS TURN THE POWER TO IT OFF WHEN IT IS NOT BEING USED.**
When not in use, the laser should be turned off to prevent accidental exposure to the beam by unqualified persons.



LABORATORIES

Purpose

Examine basic properties of light such as the following:

- speed
- wavelength
- color spectrum of visible light
- polarization

Laboratory 1-1A Finding the Speed of Red Light in Optical-Grade Plastic

Go to
<http://optecvideo.opteccrm.org/>
for an introduction to this
activity.



Theory

The speed of light in a vacuum, c , is exactly 299,792,485 m/s. Current physical theory asserts that nothing in our universe can have a speed greater than c . When light, or any electromagnetic wave, moves in any other medium it will have a speed less than c . In general, the speed of light through a medium depends upon both the medium and the wavelength of the light. The object of this experiment is to use the definition of index of refraction and Snell's law to determine the speed of red light in optical plastic.

Key definitions and relationships

1. The index of refraction for any medium, n , is defined as: $n_i = \frac{c}{v_i}$ where v_i is the speed of light in medium, i .
2. Snell's law $\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1}$
3. The speed of light in vacuum and air is the same to an accuracy of six significant figures, so we will use $n_{air} = 1.00000$.

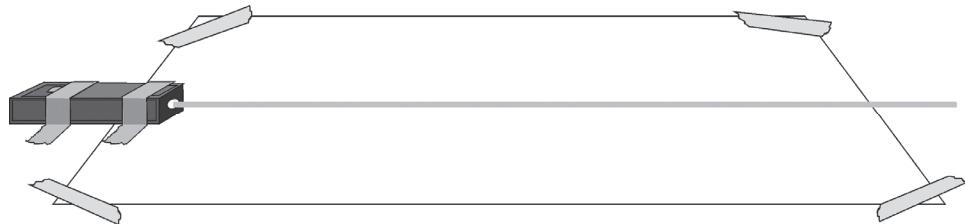
Equipment

1. Laser, either a red laser pointer or a Class I or II HeNe laser
2. Laboratory stand and clamps to hold laser and gratings
3. Plastic optical block, approximately 8 cm \times 6 cm \times 2 cm

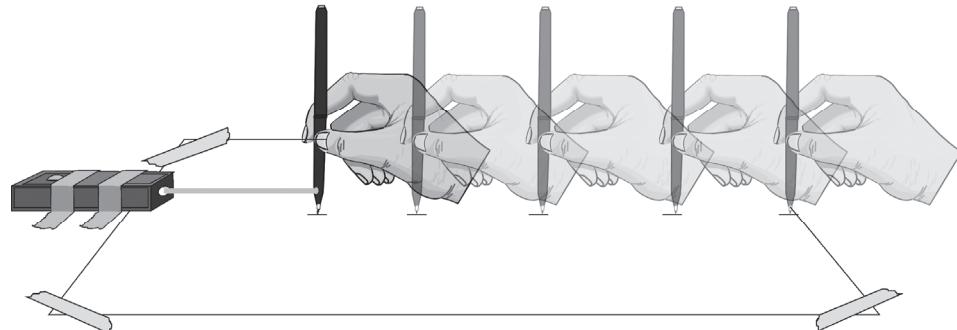
4. 8½" × 14" white paper
5. Masking tape
6. Meterstick
7. Protractor

Procedure

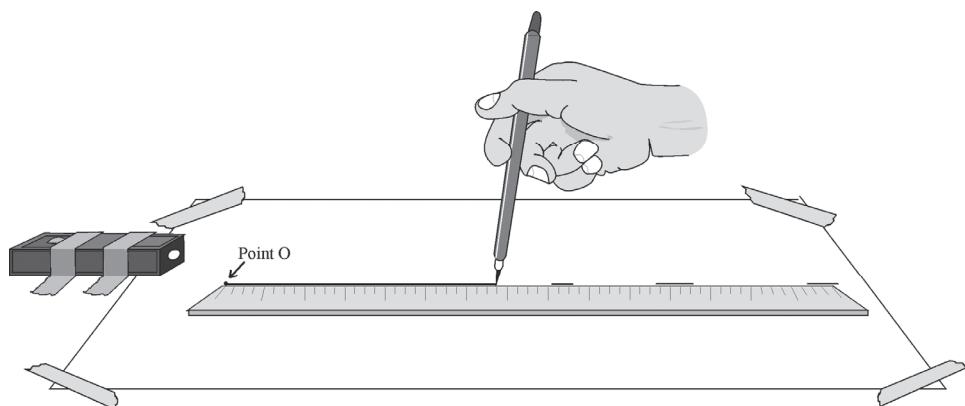
1. Tape a legal-size sheet of blank white paper to the tabletop. Tape a laser pointer on the left side so the beam is directed left to right across the paper.



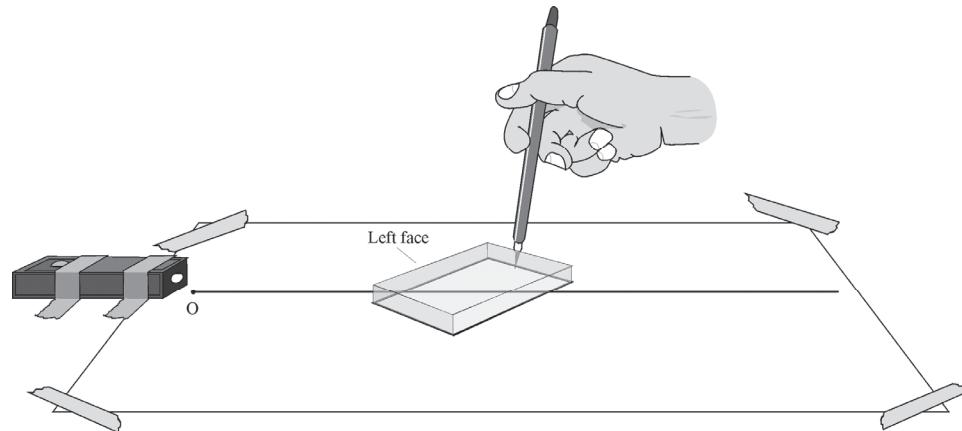
2. Turn on the laser. Hold a pencil in a vertical position at the right edge of the paper where the laser beam hits the center of the pencil. Mark the paper with a small dot or dash. See sketch.



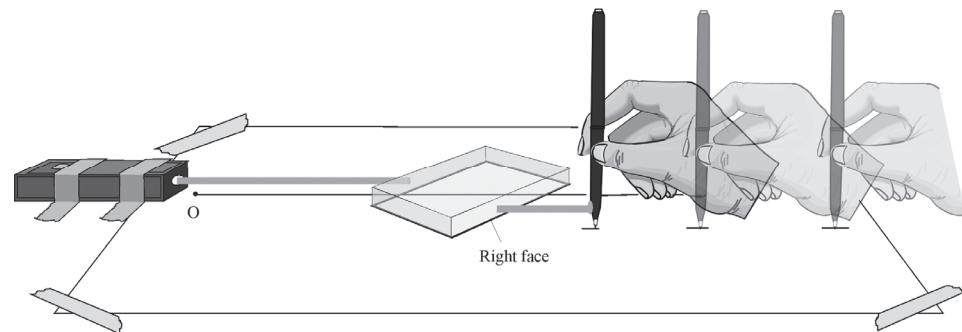
Move the pencil directly left one or two inches and repeat. Continue until you have five or six marks extending left to right across the paper. Draw a “best-fit” straight line through the marks. Label the point at the left end of this line point O. See sketch.



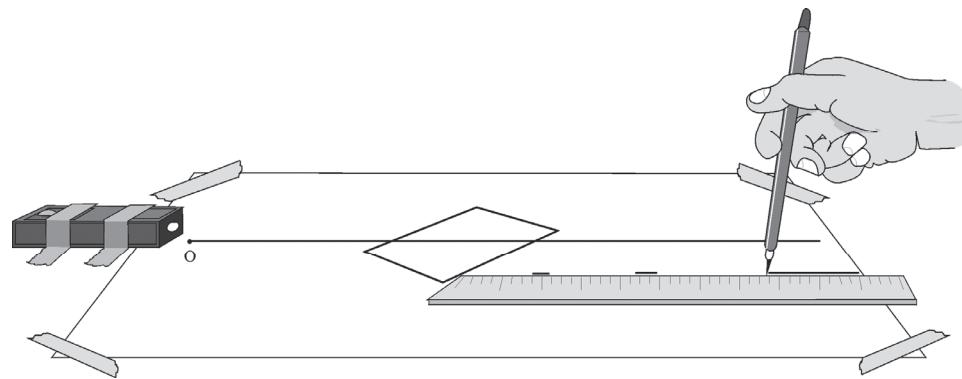
3. Place the plastic block with the large surface down. The left face of the block should intersect the line on the paper at a 40- to 50-degree angle, and the laser beam should hit the left face about 1 cm from its lower left corner. Hold the block firmly in place and draw an outline of the block on the paper. See sketch.



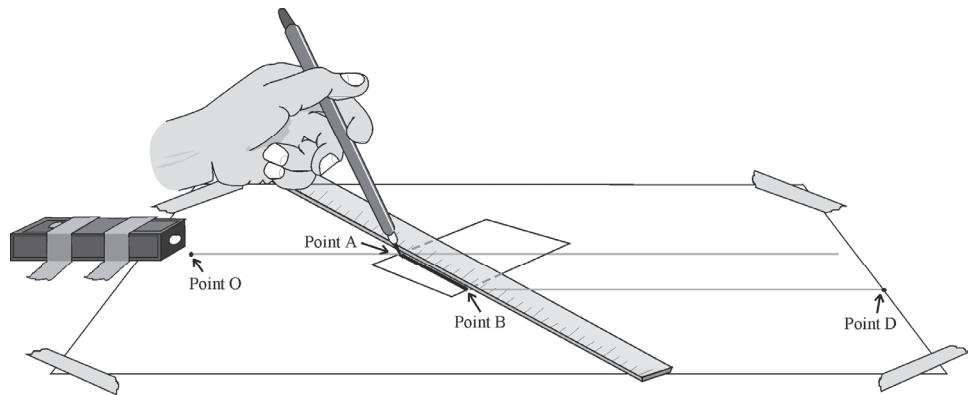
4. Turn on the laser. The beam is refracted by the block and should exit the block through the right face. Move your pencil along the right edge of the paper until you find the beam. Mark the location of this exit beam at five or six places on the paper just as you did for the straight beam in step 2. See sketch.



5. Remove the plastic block. Draw a best-fit straight line through the marks along the exit beam path. See sketch.

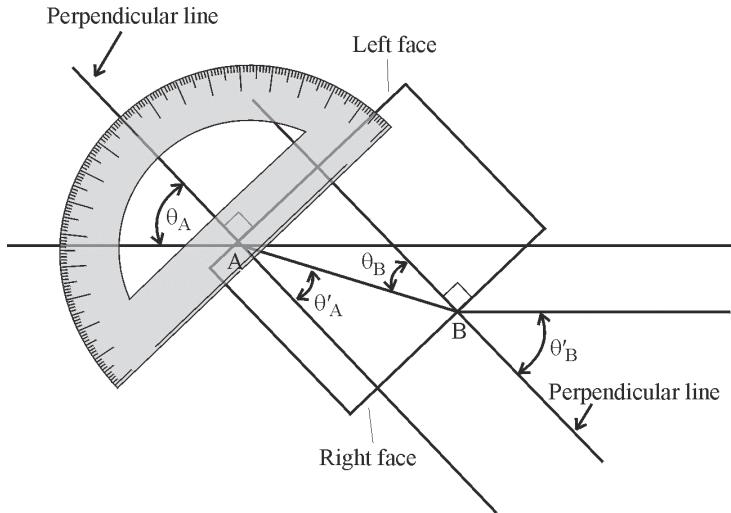


Mark the right end of the line as point D. Extend this line to the left until it intersects the line marking the lower edge of the plastic block. This is the point where the beam left the block. Mark this point as point B. Mark the point where the incident beam hit the left face of the block as point A. Connect points A and B with the line segment AB. See sketch.



Note: The line segment OA describes the path of the laser beam that is incident on the block. The line segment AB describes the path of the refracted beam through the block. The segment BD describes the beam's path after it exits the block.

6. Use the protractor to draw a line through point A that is perpendicular to the left face of the block. Draw another line through point B that is perpendicular to the right face of the block. See sketch.



7. Measure and record the angle θ_A between the incident beam and the normal line at the left face of the block (point A). Do the same for the refracted beam at this face. This is angle θ'_A . See sketch.
8. Measure the angle between the normal line and the incident and refracted (exit) beams at the right face of the block (point B). Label these as θ_B and θ_B' . See sketch.
9. Using θ_A and θ_A' , use Snell's law to find the ratio $\frac{n_{\text{air}}}{n_{\text{plastic}}}$ at the left interface between air and plastic.

- Using θ_B and θ_B' , use Snell's law to find the ratio $\frac{n_{\text{plastic}}}{n_{\text{air}}}$ at the right interface between plastic and air.
- The index of refraction of air, n_{air} , has a value of 1.00000. Use this and the results of steps 9 and 10 to find the numerical value of n_{plastic} from your measurements at A and at B. Average the two values to determine your final estimate of n_{plastic} .
- Use the definition of index of refraction and the known value of speed c in a vacuum to calculate the speed of light in the plastic block.

Laboratory 1-1B

Determining the Wavelength of Red Light

Go to
<http://optecvideo.opteccrm.org/>
 for an introduction to this activity.



Theory

When a beam of light is incident on a diffraction grating, part of the light will pass straight through. Part of the light is diffracted to paths that diverge at different angles on both sides of the original path. The angle θ at which the light diverges is related to the wavelength and spacing of the lines on the grating. The relationship is described by

$m\lambda = d \sin\theta_m$ where λ is the wavelength of the incident light in meters, d is the spacing between lines on the grating in meters, m is an integer that takes on the values 0, 1, 2, ..., and θ_m is the diffraction angle for a particular diffraction order m .

If the diffraction angle θ_m can be measured for a particular order m and the grating spacing d is known, the wavelength of the light can be calculated.

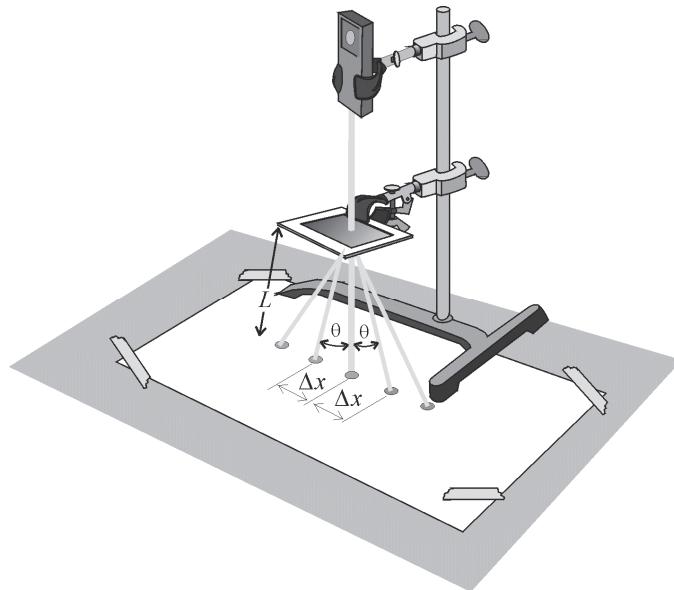
Equipment

- Laser, either a red laser pointer or a Class I or II HeNe laser
- Laboratory stand and clamps to hold laser and gratings
- Transmission grating with 300 to 800 lines/mm
- $8\frac{1}{2}'' \times 14''$ white paper
- Masking tape
- Meterstick

Procedure

1. Position the laser so the beam goes straight down through the grating—perpendicular to the grating surface—and onto the white paper. There it produces a center spot with diffracted spots on both sides as shown in the sketch.
2. Measure the vertical distance from the grating to the paper. Record this as L .
3. Measure the distances from the central spot to the center of the first diffracted spots on both sides. Average these two distances and record the average as Δx . For these nearest diffracted spots, $m = 1$.
4. Calculate the diffraction angle using $\theta_1 = \tan^{-1}\left(\frac{\Delta x}{L}\right)$
5. Calculate the wavelength of the red laser light using this first-order diffraction angle, θ_1 where $m = 1$. The equation is then

$$\lambda = \frac{d \sin \theta_1}{1}$$



Laboratory 1-1C The Spectrum of Colored Light

Go to
<http://optecvideo.optecrrm.org/>
for an introduction to this activity.



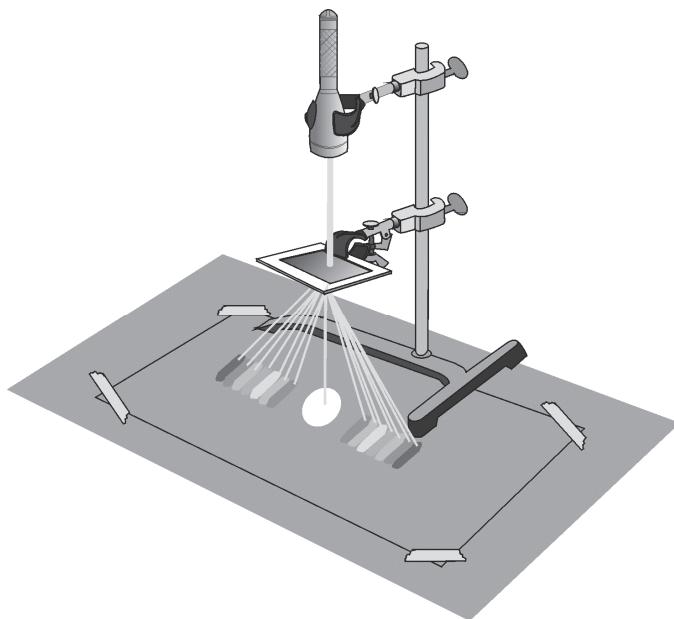
Equipment

1. Flashlight with focusing capability, similar to the Mini-Maglight series
2. Laboratory stand and clamps to hold laser or flashlight and grating
3. Transmission grating with 300 to 800 lines/mm
4. Red, green, blue, purple, yellow, and orange filters
5. 8½" × 14" white paper
6. Masking tape

Procedure

Part 1. The spectrum of white light

1. Mount the flashlight in a clamp on the stand with the beam projected straight down onto a sheet of white paper.
2. Mount the diffraction grating in another clamp and position it four or five inches below the flashlight. Focus the light perpendicularly onto the grating surface. See sketch.
3. Move the grating, and flashlight if necessary, up or down until you see clearly both the light transmitted straight down through the grating, forming a white spot on the paper, and the first order spectrum of colors. See sketch.
4. Draw lines through each color you can identify in the spectrum, and label each line with its color.



Part 2. The components of different colors of light

5. Hold a red transmission filter between the flashlight and the grating. What is the color of the center spot where light is transmitted straight through the grating? List all the colors that you can clearly identify in the diffracted spectrum on either side of the center spot.
6. Replace the red filter with the other filters in this order: green, blue, purple, yellow, and orange. For each filter list all the colors you can identify in the diffracted spectrum of the light formed on either side of the center spot.
7. Answer the following questions with complete sentences.
 - (a) Why are red, green, and blue primary colors?
 - (b) What colors of light must be combined to make purple light?
 - (c) What colors of light must be combined to make yellow light?
 - (d) How can a color TV produce any color it needs when it has only red, green, and blue color guns?

Laboratory 1-1D

The Polarization of Light

Go to
<http://optecvideo.opteccrm.org/>
for an introduction to this activity.



Equipment

1. Flashlight with focusing capability, similar to the Mini-Maglight series
2. Laboratory stand and clamps to hold laser or flashlight and grating
3. Two polarizing filters
4. Microscope slide or similar thin, flat glass plate
5. 8½" × 14" white paper
6. Masking tape

Procedure

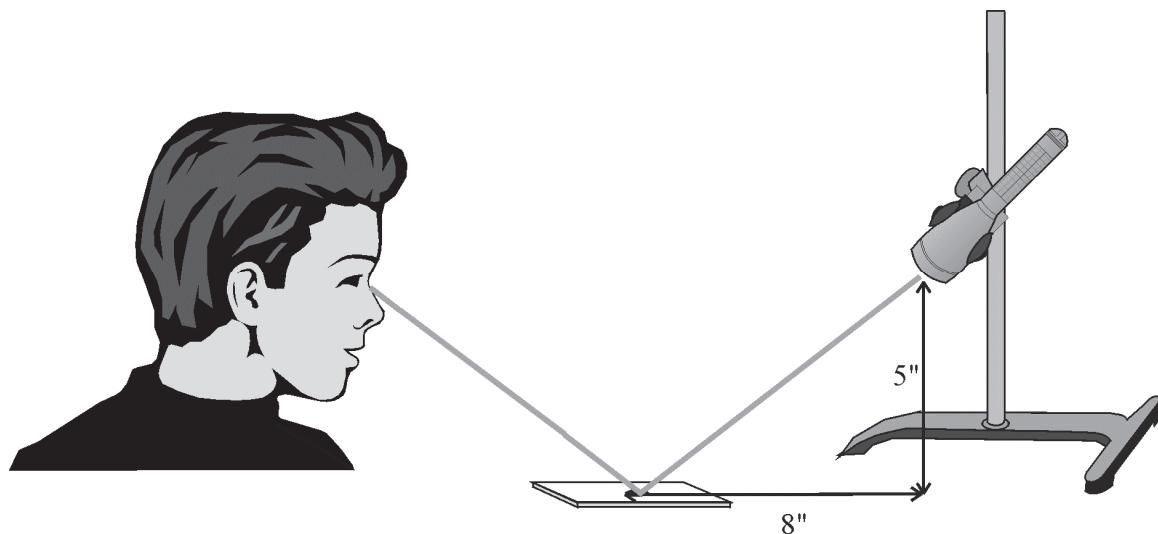
Part 1. Polarizers and analyzers

1. Clamp a flashlight with the beam projected horizontally about five feet above the floor. It should be arranged so that it is easy to look directly into the light when you are five or six feet from the flashlight.
Hold one polarizer at arm's length in front of you and look at the light through the polarizer. The light you see is now polarized in the preferred direction of the filter.
2. Hold a second polarizing filter (analyzer) with your other hand. Place it between you and the first filter. Rotate the second filter about the axis of the light beam. Notice the change in brightness of the light passing through both filters and reaching you.
3. What can you say about the relation between the polarizing direction of the two filters when the light transmitted has its maximum brightness?
4. What can you say about the relation between the polarizing direction of the two filters when the light transmitted has its minimum brightness?

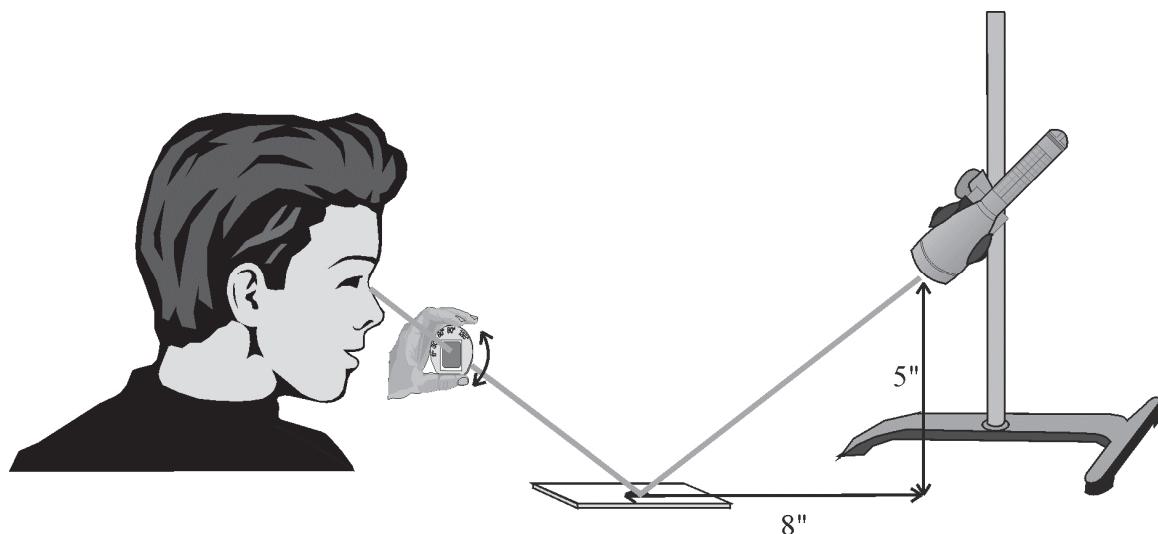
Part 2. Polarization by reflection

5. Clamp the flashlight so the center of the lens is five inches above the table and the light beam is focused on a spot eight inches horizontally from the flashlight. Place a microscope slide on the table at the position of the focused spot. See sketch.

6. Position yourself in line with the microscope slide and the flashlight. Move until you can see the reflection of the flashlight from the slide. See sketch.



7. Hold a polarizing filter so you can see the reflection through the filter. Rotate the filter about the axis of the reflected beam. See sketch. What do you observe about the brightness of the reflection as you rotate the filter?



8. How does the reflection from the glass affect the properties of the reflected light?

WORKPLACE SCENARIO

Here is your opportunity to use the concepts learned in this module to solve an actual problem that could arise in a photonics company. Your instructor will provide directions for developing a solution.

Testing Sunglasses for UV Protection

Scenario

You are a photonics technician working for a consumer product testing laboratory. The laboratory has decided to perform a “UV Protection” safety test on several brands of commercial sunglasses. You have worked with your manager and the engineering team to design the test. Your team used an ANSI (American National Standards Institute) standard to develop the test and determined from this standard that sunglass lenses should have a UVA (385 nm) transmittance equal to or less than five percent.

Data Collection

At your company’s photonics test lab, there is a 385 nm light source and photometer. With knowledge gained from your photonics coursework, a copy of the ANSI standard, including test methods, and currently available research on this topic, you are ready to collect data.

You purchase ten different sunglass models, and then proceed to test them. Your test consists of reading the power of the 385 nm source without the sunglasses, and reading the power of the 385 nm source with the sunglasses inserted between the source and the photometer detector. Your test efforts produce the data recorded in Table I.

Sunglass Model	385 nm Source Power without Sunglasses	385 nm Source Power with Sunglasses
Raybond Wrap	5.4 mW	0.15 mW
Raybond Flat	5.4 mW	0.17 mW
Clearday Men's	5.6 mW	0.32 mW
Clearday Women's	5.3 mW	0.18 mW
Eyewear Cheap	5.4 mW	1.12 mW
Eyewear Medium	5.6 mW	0.85 mW
Eyewear Expensive	5.5 mW	2.4 mW
Shades Men's	5.6 mW	0.21 mW
Shades Children	5.6 mW	1.14 mW
Shades Women's	5.3 mW	0.19 mW

Table I - Sunglass Test Data

Problem and Tasking

After testing the sunglasses and recording your data, your manager asks you to:

- Calculate the effectiveness of each sunglass model in blocking UV Radiation (Percent Transmittance at 385 nm).

- Record your data and results in a Table.
- Highlight any sunglass models that do not meet specification .
- Search the internet and determine three brands of sunglasses that meet the ANSI standards. Record the effectiveness of each brand in blocking UV radiation.
- Write a laboratory report to document your test, including your data and findings, and internet search results. In the document, your manager wants you to include an explanation of UVA, UVB, and UVC radiation and to document the damage these bands of UV radiation cause to the eye if proper protection is not provided by sunglasses.

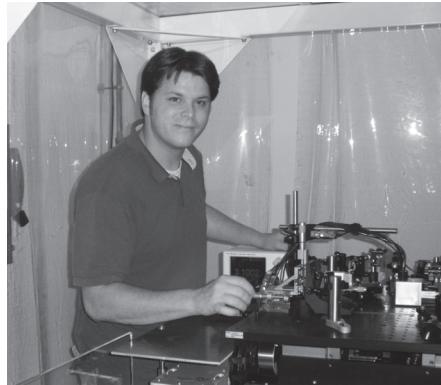
PROBLEM EXERCISES AND QUESTIONS

1. Ordinary helium-neon laser light has a wavelength of 632.8 nanometers.
 - a. What is its speed in air in m/s?
 - b. What is its frequency in Hertz?
 - c. What is its energy in joules?
2. Sketch a picture of a sine wave showing wave displacement versus distance *at a given time*. On the sketch:
 - a. Show a wavelength.
 - b. Show a positive and negative wave displacement.
 - c. Show the wave amplitude.
3. Sketch a picture of a sine wave showing wave displacement versus time *at a given position*. On this sketch:
 - a. Show a wave period.
 - b. Show the wave amplitude.
 - c. Relate the period and frequency with a simple equation.
4. A Nd-YAG laser has a wavelength of 1.064 μm . What is its equivalent wavelength in:
 - a. Angstroms
 - b. Nanometers
 - c. Meters
5. From a diagram of the electromagnetic spectrum:
 - a. Determine the wavelength spread (in nanometers) and frequency spread (in Hz) for visible light.
 - b. Identify the type of EM radiation that has wavelengths around 10^{-12} meters and frequencies around 10^{21} Hz.
 - c. Identify the type of EM radiation with a wavelength around 1 meter and frequency near 10^8 Hz.
6. A beam of light in air is incident on an air-diamond interface along a normal to the interface.
 - a. As the light enters the diamond, does the beam bend toward the normal, bend away from the normal, or remain along the normal?
 - b. Does the light speed up or slow down in the diamond crystal?
 - c. If diamond has an index of refraction of 2.42, what is the speed of light in diamond?

7. A beam of HeNe laser light at 632.8 nm is incident on a smooth, flat germanium crystal at an angle of 60° with the normal. The index of refraction of germanium at this wavelength is near 4.1 .
 - a. What angle does the reflected beam make with the normal?
 - b. What angle does the refracted beam make with the normal?
 - c. What is the speed of light in germanium?
 - d. Draw a sketch showing the incident ray, reflected ray, refracted ray, normal, and air-germanium interface.
8. One thousand photons in a beam are incident on a semi-transparent glass slide at an angle of 10° . One hundred photons are reflected back and lost at the front air-glass interface as well as at the rear glass-air interface. Fifty photons are scattered out of the beam by impurities in the glass while the beam is passing through, and 150 are absorbed by the glass material.
 - a. How many photons are in the transmitted beam?
 - b. Compared with the number of photons in the incident beam, what is the percent transmission of this beam through the slide?
9. A hydrogen atom in excited energy state $E_3 = -2.4 \times 10^{-19}\text{ joules}$ drops down to the ground state at energy level $E_1 = -21.76 \times 10^{-19}\text{ joules}$, giving off a photon.
 - a. What is the energy of the emitted photon in joules?
 - b. What is its wavelength in meters?
 - c. Based on the EM spectrum, what type of electromagnetic radiation is this?
10. A normal body temperature for a healthy person is 98.6°F . This is equivalent to 37°C or 310 K .
 - a. Based on Wien's displacement law, what is the maximum wavelength in micrometers emitted by a normal body at this temperature?
 - b. What type of detector is needed to "see" this radiation?

MEET A TECHNICIAN

Michael Bass



Michael Bass received Associate in Applied Science degrees in Electronics Engineering Technology and Laser and Photonics technology from Central Carolina Community College. He works for BrightView Technologies, a start-up company that manufactures optical films for the management of light distribution.

“These optical films consist of billions of microstructures or microlenses that manage light, making them more aesthetically pleasing by adjusting the viewing angle for light distribution.” Michael started as a technician three years ago for BrightView’s main technology platform, called E-lamps.

“Today, I am responsible for the well-being of this whole system: everything from the optics alignment and calibrations of the system, all the way to manufacturing, logistics, and process controls. It’s very interesting; I’m in a world between research/development and manufacturing. Most photonics jobs are on the cutting edge of technology. That’s one of the things I find most interesting, working with technology and taking it from the research and development stage to a practical application stage, whether it is manufacturing, medical, or telecommunications. The applications of photonics are almost endless, which means the opportunities that can be opened for you are very broad.”

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Optical Handling and Positioning

Module 1-2
of
**Course 1, *Fundamentals of Light and Lasers*
3rd Edition**

OPTICS AND PHOTONICS SERIES



PREFACE TO MODULE 1-2

This is the second module in Course 1 (*Fundamentals of Light and Lasers*) of the STEP curriculum. Following are the titles of all six modules in the course:

1. *Nature and Properties of Light*
2. *Optical Handling and Positioning*
3. *Light Sources and Laser Safety*
4. *Basic Geometrical Optics*
5. *Basic Physical Optics*
6. *Principles of Lasers*

The six modules can be used as a unit or independently, as long as prerequisites have been met.

FEATURES

Mathematics Videos: Math videos are provided to assist students in doing mathematical operations required in this module. The math concepts used in this module are checked ✓ in the following list:

1. Scientific Notation ✓
2. Unit Conversion
3. Introductory Algebra ✓
4. Powers and Roots ✓
5. Ratio and Proportion
6. Exponents and Logarithms ✓
7. Graphing in Rectangular Coordinates ✓
8. Geometry
9. Angle Measures in Two and Three Dimensions ✓
10. Trigonometry ✓
11. Special Graphs

This checklist provides instructors a means of front-loading the presentation of material in this module with mathematics instruction. If instructors prefer to provide math instruction using a “just on time delivery” mode, a special icon  appears where the checked mathematics topics are first used within this module. All math videos can be accessed at <http://optecvideo.opteccrm.org/>.

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COURSE 1: FUNDAMENTALS OF LIGHT AND LASERS

Module 1-2

Optical Handling and Positioning

INTRODUCTION

There are a variety of optical components and optical systems in a photonics laboratory. Typical optical systems contain lenses, filters, polarizers, beam splitters, positioners, mounts and optical tables. The number of optical sources that are used vary from white light sources to lasers of almost all wavelengths between ultraviolet and the far infrared. An understanding of the variety of materials used at different wavelengths is essential. A wide range of materials including crystals, amorphous substances such as glass, quartz and metals are involved in the family of optical components. In addition to a knowledge of the components, a student should understand their thermal, mechanical, and chemical properties. Some optical components are coated—either to preferentially transmit or reflect a set of wavelengths.

To maintain the integrity of optical elements, proper cleaning, inspection and proper storage must be followed. Each type of optical component needs a special type of mounting and alignment procedure so that integrated optical systems function efficiently. Individual mounting systems and combinations of them and their mounting techniques are important. Single and multi-dimensional stages and their applications have to be understood.

There are an enormous number of mountings, materials and systems. It is beyond the scope of this introductory module to deal with all of them. Most of the important components and systems are explained with examples. References for further study are provided at the end. A list of companies (vendors) who can supply these components is given at the end of the module.

PREREQUISITES

To understand this module, the student must have studied Module 1.1—*Nature and Properties of Light*. A clear understanding of the electromagnetic spectrum and the different interactions of light with materials is essential to an understanding of this module. A basic knowledge of high school algebra, trigonometry, scientific nomenclature and units of conversion are necessary.

OBJECTIVES

After studying this module, the student will be able to understand:

- The nature of optical materials and their transmission and reflection characteristics as a function of wavelength.
- The thermal, mechanical, and chemical properties of optical materials used in making optical components.
- How materials are chosen for specific uses in the visible, ultraviolet, and infrared regions.
- How single and multiple antireflection coatings and filters are made and used.
- The construction and use of different mountings for lenses, mirrors, and other optical components.
- How single and multi-dimensional translational and rotational stages work.
- How to set up optical systems involving components, optical benches and vibration-free tables.
- How to inspect surfaces of optical elements for scratches, chips, or digs.
- How to inspect optical elements for thermal and mechanical defects.
- How to handle, clean, and store optical elements.
- How to contact specific vendors and determine the cost of different optical materials and components.

SCENARIO

Jamie is a photonics technician at the Precision Optics Corporation. In this position, Jamie works closely with optical engineers at her company to test new prototype designs of optical systems used on laser-guided weapons. These weapons “paint” a target with a laser beam and then use the reflected part of this beam to guide them to the target’s location.

Jamie is well qualified to test her company’s prototype designs. Having earned her AAS degree in Photonics, she has the knowledge and skills to assemble optical systems, align them, and collect data to check their performance. To prepare for a test, Jamie first reviews the engineer’s schematic drawing of the prototype to determine the specific components being used and their position in the optical system. Next, she gathers the required components for the test and inspects each one to ensure they meet the scratch, dig, and chip criteria established by the engineers and also do not have any mechanical or thermal defects that could corrupt the test results. Once the needed components are collected, she cleans them and then carefully places each one, using the engineer’s drawing, on a vibration-free table. To do this placement, she has to put these components in special mounts that allow her to accurately position and precisely align them. When Jamie has set-up and aligned a prototype system, she then conducts her test, collects data, and generates a report for the engineers. In the report, she is expected to include any observations that may help the engineers improve the prototype’s performance and maintainability.

In Module 1-2 of the *Fundamentals of Light and Lasers* text, you will learn about the inspection, cleaning, handling and placement techniques that Jamie uses and have an opportunity in the module’s laboratories to practice these skills.

BASIC CONCEPTS

Bulk Optical Materials and Their Properties

This section deals with different types of materials that are used in optical components. A large variety of materials—both transparent and non-transparent—are used in a photonics laboratory.

Properties of Materials

A transparent optical medium such as a window, prism, or a lens requires:

1. Low absorption of light while passing through it
2. Low reflection loss of light incident on its interfaces (surfaces)
3. Low refraction of the transmitted light (smaller refractive index)
4. Minimum distortion of light while passing through—due to imperfections in the material or the surface finish
5. A high damage threshold to laser radiation
6. Minimal optical degradation due to temperature, water vapor or other “hostile” environmental conditions

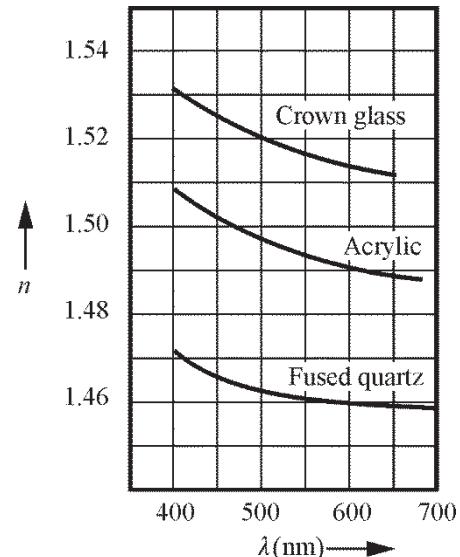
Refractive index

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The numbers below the **A** that appears in several places in this module reference specific applets that demonstrate the concepts being described in the text. These applets are accessible at <http://optecvideo.opteccrm.org/>.

Refractive index is an important property of an optical material. It is defined as the ratio of the speed of light in a vacuum to the speed of light in a particular medium. The speed of light in a vacuum has a constant value of very nearly 3×10^8 m/sec. It reduces slightly when passing through an optical medium.

Refractive index is a unitless quantity and is always greater than one. The larger the refractive index of the medium, the larger will be its variation with changes in wavelength. In general, the refractive index of an optical medium decreases with increase of wavelength. The refractive index of several important optical materials as a function of wavelength is shown in Figure 2-1. The variation in index of refraction is given for the visible region, i.e., for λ from 400 nm to 700 nm.



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Figure 2-1 Refractive index of several optical materials as a function of wavelength

A simple equation can be written which relates the refractive index (n) to the wavelength of light in a vacuum (λ_0) and the wavelength of light in a medium (λ_m):

$$n = \frac{\lambda_0}{\lambda_m} \quad (2-1)$$

As shown in Module 1-1, *Nature and Properties of Light*, an alternate equation for the index of refraction of a material is given by $n = \frac{c}{v}$, where c is the speed in a vacuum and v is the speed in the medium.



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Absorption and transmission

A beam of light incident on a flat, optically transparent medium is partly reflected, partly absorbed, partly scattered, with the rest transmitted. The amount of absorption depends on the thickness of the material, the nature of the material, and the wavelength. A simple equation for optical absorption in a given absorber is given by Equation 2-2.

$$E = E_0 e^{-\alpha x} \quad (2-2)$$

where E_0 is the incident irradiance (power per unit area)

E is the transmitted irradiance

α is the absorption coefficient in units of *reciprocal length*

x is the absorber thickness in the *same* units of length used for α

The geometry is shown in Figure 2-2.



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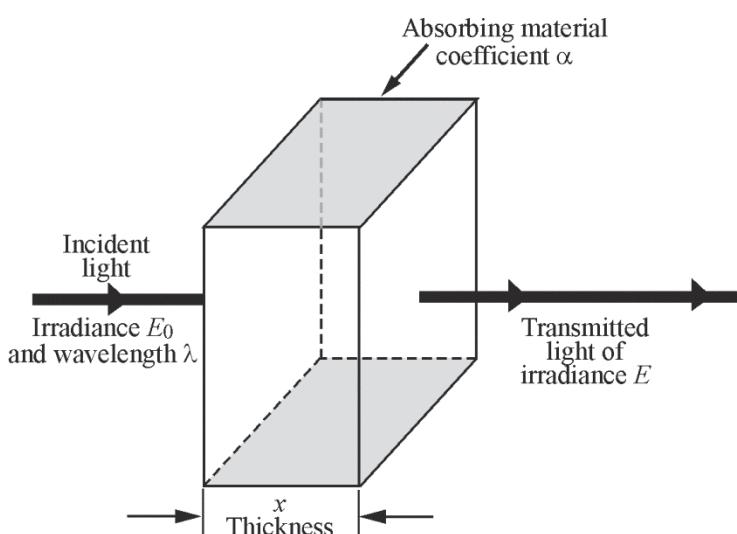


Figure 2-2 Absorption of light passing through a transparent medium of thickness x

The transmittance T is often used in describing the percentage of light passing through an absorber. It is given by Equation 2-3.

$$T = \frac{E}{E_0} \times 100\% \quad (2-3)$$

where T is the transmittance (a percentage),
 E_0 is the incident irradiance, and
 E is the transmitted irradiance.

The transmittance ($T = \frac{E}{E_0} \times 100\%$) decreases with an increase of either or both, α and x ,

since $E = E_0 e^{-\alpha x}$ decreases as α and x increase. The absorption coefficient α depends on the nature of the material and the wavelength of the light. Most of the optical glass materials transmit nearly 100% of visible light—from the near ultraviolet to the near infrared. However, transmittance generally decreases beyond these regions. The following example shows how to use Equations 2-2 and 2-3 in calculating the transmittance T .

Example 1

The absorption coefficient of a material is 4.0 cm^{-1} . If the material has a thickness of 0.1 cm , calculate the transmittance T .

Solution: Applying Equation 2-2 to find the irradiance E after transmission, we obtain

$$\begin{aligned} E &= E_0 e^{-\alpha x} \\ E &= E_0 e^{-(4 \text{ cm}^{-1})(0.1 \text{ cm})} && \text{(Note that the length units "cm" cancel in the exponent.)} \\ \text{so } E &= E_0 e^{-0.4} = 0.67 E_0 \end{aligned}$$

Now use Equation 2-3 to find the transmittance T :

$$\begin{aligned} T &= \frac{E}{E_0} \times 100\%, \text{ where } E = 0.67 E_0 \\ T &= \frac{0.67 \cancel{E_0}}{67\% \cancel{E_0}} \times 100\% && \text{(Note that the transmittance does not depend on the incident irradiance.)} \end{aligned}$$

Transmission characteristics of several optical glasses are shown in Figure 2-3.

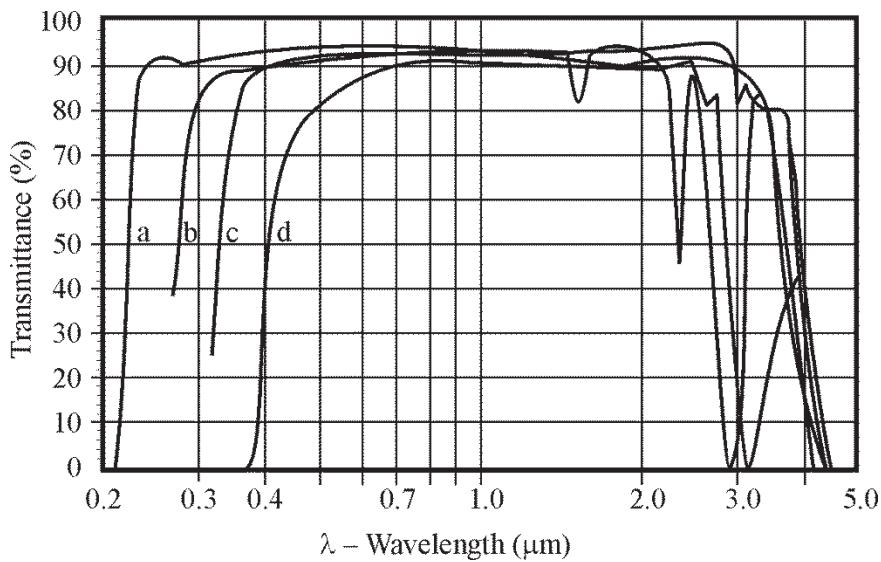


Figure 2-3 Transmission characteristics of several optical materials: (a) fused silica, (b) fused quartz, (c) Pyrex, and (d) Zerodur (Source: www.escopproducts.com)

Figure 2-3 shows that fused silica and fused quartz can be used in the ultraviolet region from 0.2 to 0.4 μm . Practically all glasses have reduced transmission beyond 3.4 microns in the infrared region. A study of this figure helps one choose a suitable optical material for a given transmission region.

For far infrared transmission, semiconductor materials such as germanium (1.8–25 μm), cadmium telluride (0.9–33 μm) and sodium chloride (0.5–26 μm) can be used. However, sodium chloride is hygroscopic (absorbs water) and will be fogged when exposed to the atmosphere. Transmission characteristics and properties of some of the infrared materials are given in Table 2-1.

Table 2-1. Characteristics of Some Infrared Transmitting Materials

Material	Wavelength range (μm)	Refractive index @ 2 μm	Comments
Sodium chloride (NaCl)	0.25 to 16	1.52	Low cost; hygroscopic; high mechanical and thermal shock resistance
Potassium bromide (KBr)	0.25 to 25	1.53	Far infrared; soft; hygroscopic; good thermal shock resistance
Calcium fluoride (CaF ₂)	0.15 to 8	1.42	Insoluble in water; acid resistant; strong material
Barium fluoride (BaF ₂)	0.13 to 13.5	1.46	Insoluble in water; cleaves easily; low thermal and mechanical shock resistance
Germanium (Ge)	0.4 to 35	2.31	Low absorption coefficient at 10.6 μ ; suitable for low power CO ₂ laser mirrors; can be hard-coated with dielectric layers
Gallium arsenide (GaAs)	1.0 to 11.0	3.12	Low absorption coefficient at 10.6 μ ; can be hard-coated with dielectric layers; useful for high-power CO ₂ laser windows
Zinc selenide (ZnSe)	0.5 to 22.0	2.40	Lower absorption coefficient than GaAs; useful for high-power IR laser applications; expensive
Cadmium telluride (CdTe)	2.0 to 25.0	2.80	Low absorption coefficient; useful for high-power IR laser windows; expensive

Surface reflection of ordinary light

A Reflection takes place at an interface between two media due to the difference in refractive indices. An equation for the percentage of reflection R when light is *incident perpendicular to the interface* is given by Equation 2-4:

$$R(\%) = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \times 100 \quad (2-4)$$

where n_1 and n_2 are refractive indices of the two materials. Since the ratio in brackets is *squared*, it does not matter which medium we label n_1 and which n_2 . Either arrangement gives the same result for $R(\%)$. Further, this means that the reflection at the interface is the *same* whether light strikes the interface going from medium n_1 to medium n_2 or from n_2 to n_1 .

A simple calculation with $n_1 = 1$ (air) and $n_2 = 1.5$ (glass) shows that for *perpendicular incidence* at the interface from air-to-glass, about 4% of the light will be reflected back into the air. Figure 2-4 shows the reflection and transmission at an interface.

If light is incident on a window of thickness t and refractive index n_2 and the window is situated in a medium of refractive index n_1 (usually air with $n_1 = 1.0$), multiple reflections take place at the front and rear interfaces. In that case, the total light energy reflected is greater than that given by Equation 2-4. The correct result for $R(\%)$, taking into account all of the multiple internal reflections, is given by Equation 2-5. Here it is assumed that absorption and scattering inside the window is small.

$$R_{\text{tot}} = 1 - \frac{2n_r}{n_r^2 + 1}, \quad (2-5)$$

Where R_{tot} is the **total** reflection, $n_r = \frac{n_w}{n_{\text{med}}}$, n_w is the refractive index for the window, and n_{med} is the refractive index for the medium surrounding the window. For any optical window, neglecting absorption and scattering, $T_{\text{tot}} + R_{\text{tot}} = 1$. Example 2 shows how to calculate the total reflection for a window of index $n = 1.6$ situated in air, $n = 1.0$.

Example 2

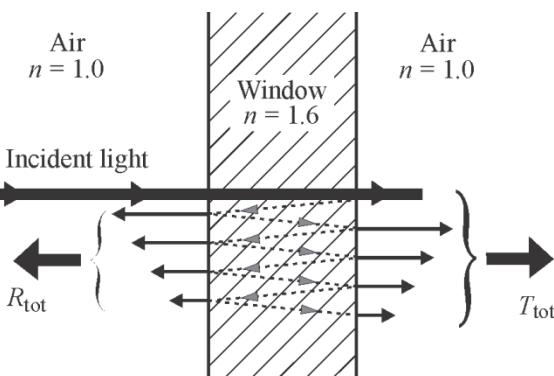
An optical window of index 1.6 is located in air, as shown. Light is incident on the window at an angle of incidence equal to 90° . Find R_{tot} .

Solution: According to Equation 2-5,

$$R_{\text{tot}} = 1 - \frac{2n_r}{n_r^2 + 1}$$

where $n_r = \frac{n_w}{n_{\text{med}}} = \frac{1.6}{1} = 1.6$

$$R_{\text{tot}} = 1 - \frac{2 \times 1.6}{(1.6)^2 + 1} = 0.10 = 10\%$$



When light is incident on an interface between two optical media at some angle less than 90° , the amount of light reflected changes with angle of incidence. (The exact amount is given in texts on optics under a discussion titled “Fresnel Reflection.”)

Surface reflections of polarized light

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Let us now say a few words about how differently the two perpendicular components of polarized light are reflected at an optical surface. A general understanding of the difference helps us understand the action of Brewster windows.

Consider *unpolarized light* to be incident on an interface with *equal amounts* of E_{TE} and E_{TM} . (Refer to Module 1-1, *Nature and Properties of Light*, for a quick review of the properties of polarized light, if necessary.) The electric field vibration E_{TE} —represented by a dot (•)—is oriented in a direction totally *perpendicular* to the plane of incidence and the light ray. The electric field vibration E_{TM} —represented by a double-headed arrow (↑)—is also totally perpendicular to the direction of the light ray but lies **in** the plane of incidence.

Fresnel showed that the reflected light will have more of the E -field vibration E_{TE} than E_{TM} . And the transmitted light will have more of the E -field vibration E_{TM} than E_{TE} . At a specific angle of incidence called the **Brewster angle**, the reflected light will have **only** the E -field vibration E_{TE} (dots). See Figure 2-5. The refracted beam will have all of the E_{TM} vibration (arrows), but less of the E_{TE} vibration since some has gone off in the reflected beam. Thus, the light in the reflected beam (around 15% of the incident light on an air-glass interface) is completely polarized with the E_{TE} vibration (dots).



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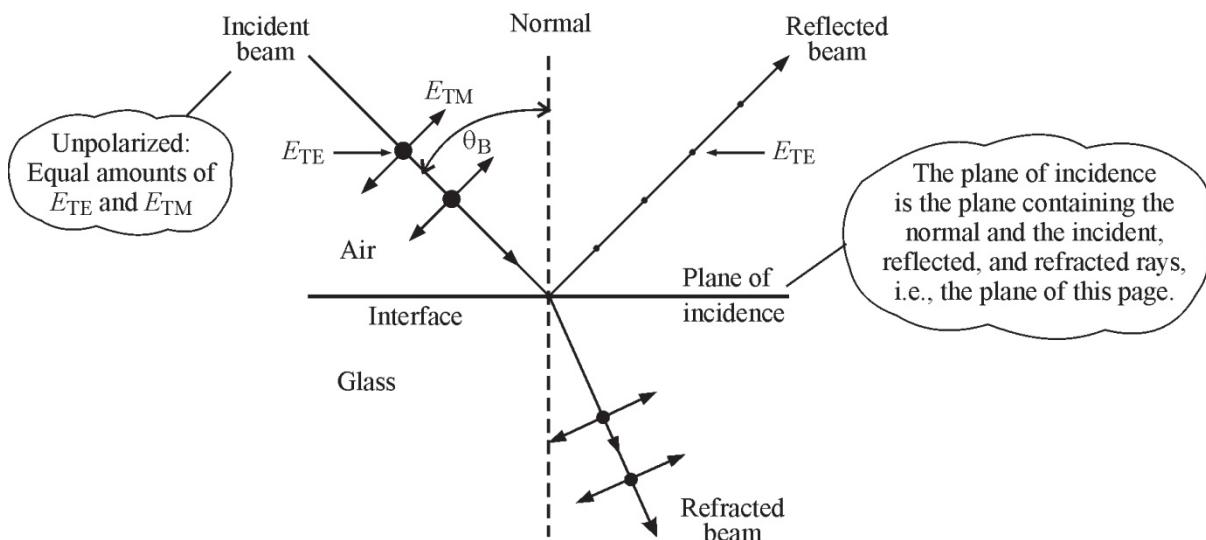


Figure 2-5 Reflection and refraction of initially unpolarized light containing equal amounts of E_{TE} and E_{TM} .

Figure 2-6 shows a beam of polarized light (totally E_{TM}) incident on a *Brewster window* at Brewster’s angle θ_B . Since the E -field vibration is all E_{TM} , there can be **NO** reflected light. If there were, the vibration would have to be *longitudinal*, that is, only the direction of the

reflected ray. But light, an electromagnetic wave, contains only *transverse* vibrations, that is, vibrations perpendicular to the ray direction. Thus at Brewster's angle, there is no reflected light, only refracted light. And the refracted light is totally of the polarization E_{TM} .

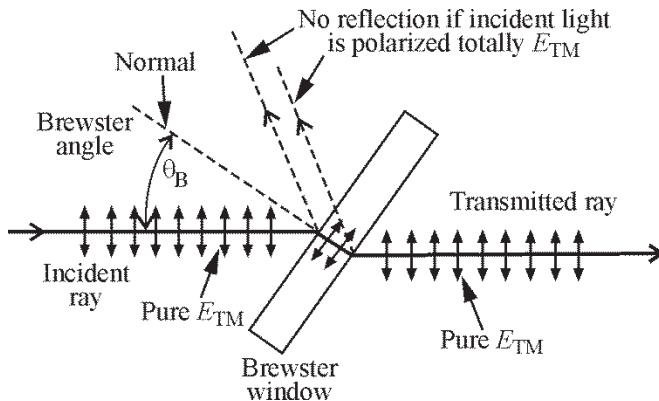


Figure 2-6 Absence of reflected light at a Brewster angle of incidence when incident light is totally polarized as E_{TM}

The value for the Brewster angle θ_B can be calculated from a simple formula, Equation 2-6.

$$\theta_B = \tan^{-1} \left(\frac{n_2}{n_1} \right) \quad (2-6)$$

where θ_B = Brewster angle

n_1 = index of refraction of the *incident* medium

n_2 = index of refraction of the *refracting* medium

Example 3 shows the calculation for a Brewster window at the air-glass interface when the glass has an index of 1.6.

Example 3

Calculate the Brewster's angle θ_B for light incident on an air-glass interface and on a glass-air interface if the glass has an index of 1.5.

Solution

Air-to-glass: $\theta_B = \tan^{-1} \left(\frac{n_2}{n_1} \right) = \tan^{-1} \left(\frac{1.5}{1.0} \right) = 56.3^\circ$

Glass-to-air: $\theta_B = \tan^{-1} \left(\frac{n_2}{n_1} \right) = \tan^{-1} \left(\frac{1.0}{1.5} \right) = 33.7^\circ$



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Note that the two angles are complementary, that is, their sum equals 90° .

If a window tilted at Brewster's angle is introduced in a laser cavity between the two mirrors, the initially unpolarized light can become polarized of the form E_{TM} after many cavity round trips. How does this happen? The back and forth light in the laser cavity passes through the cavity many times (300,000,000 times a second for a one-meter cavity). Each time the beam strikes either the front or rear surface of the window, around 15% of the E_{TE} vibration is reflected (removed from the beam). It does not take many passes for the back and forth beam to lose all of its E_{TE} components and be left with **only** E_{TM} polarized light.

Thermal properties

Extreme heat or cold and rapid changes in temperature can cause temporary or permanent changes in the physical characteristics of an optical element. Since the element is mounted on a metallic mount, variations in temperature can cause unwanted changes in the dimensions of the mount. Minimal changes in the physical properties of both the optics and the mounts are important for maintaining the integrity of the system. Some of the important parameters are *melting point* and *coefficient of thermal expansion*. These properties of some glasses and metals are shown in Table 2-2. The difference between the thermal expansion of the optical element and the metallic mount can produce stress on the optical element that can be serious if the temperature is very large or small. Further, if a lens is held in a metallic mount, and the combination is subjected to a high temperature, the primary heat loss experienced by the lens will be through its edges and onto the mount. This will make the window hotter at the center and cooler at the edges. This condition can create a distortion in the optical properties of the lens.

Table 2-2. Thermal properties of some materials

Material	Melting point °C	Thermal conductivity J s - m - °C	Linear coefficient of thermal expansion α $(\times 10^{-6})$ $(^{\circ}\text{C})^{-1}$
Metals			
Copper	1083	238	17
Silver	961	427	24
Steel	1535	79.5	11
Crystals and Glasses			
Glass (Flint)	1425	0.8	9
Glass (Pyrex)	1450	0.7	3.2
Fused Quartz	1600	0.6	0.5
CdTe	1045	0.015	4.5
Si	1693	0.0013	0.07

Mechanical properties

A non-uniform stress on an optical component can result in distortion in the bulk medium and therefore its surface. This distortion is unacceptable in many applications. A relationship between the maximum stress P (Pascals) and the geometry of a window is given by Equation 2-7.

$$t = D(1.06) \left(\frac{\Delta P}{F_a} \right)^{\frac{1}{2}} \quad (2-7)$$

where t = window thickness

D = unsupported diameter for a circular window

ΔP = pressure difference between sides of window (Pascals)

F_a = elastic limit of material (Newtons/m²)

A simplified calculation of the required window thickness to prevent distortion, for a vacuum chamber with a large pressure difference between the inside and outside, is shown below.

Example 4

A vacuum chamber is designed with one atmosphere of pressure outside (1×10^5 Pa) and 1×10^{-8} Torr pressure (1.33×10^{-6} Pa) inside. A circular window of diameter 0.25 m made out of NaCl ($F_a = 2.4 \times 10^6$ Pa) is used. The window is mounted on the chamber with a neoprene o-ring. Calculate the minimum thickness of the window if significant optical distortion is to be prevented.

Solution: For a circular window with a neoprene o-ring, using Equation 2-7,

$$t = D(1.06) \left(\frac{\Delta P}{F_a} \right)^{\frac{1}{2}}$$



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Substituting the values:

$$\begin{aligned} t &= 0.25 \times 1.06 \left(\frac{1 \times 10^5 - 1.33 \times 10^{-6}}{2.4 \times 10^6} \right)^{\frac{1}{2}} \\ &= 0.17 \text{ m} \end{aligned}$$

So the window must be at least 17 cm thick to avoid distortion!!

Elastic limits F_a of some window materials are given in Table 2-3.

Table 2-3. Elastic Limits F_a for Some Window Materials

Material	F_a (Psi)	F_a (Pa) $\times 10^6$
CaF ₂	5300	36
Polytran(CaF ₂)	8000	55
BaF ₂	3900	26
KRS-5	3800	25
LiF	1580	10.8
NaCl	350	2.4
Polytran (NaCl)	1400	9.6
KCl	330	2.4
Polytran (KCl)	1600	10.8
KBr	160	1.1
CsI	810	5.6
MgF ₂	7200	49.6

Chemical properties

Chemical damage to optical elements is caused mainly by the chemical's ability to etch or dissolve the window material. Examples of such damage can be seen in the effect of acetone on plastics as well as on the effects of water vapor on ionic crystal windows such as NaCl and NaBr. Glasses are not soluble in water. Solubilities in water of some of the crystalline and amorphous materials are shown in Table 2-4 in terms of the ratio of (grams of material dissolved) per (100 grams of water).

Table 2-4. Solubilities of Some Optical Materials

Material	Solubility $\left(\frac{\text{gms dissolved}}{100 \text{ gms of H}_2\text{O}} \right)$
ADP	22.7
Al ₂ O ₃	Insoluble
CaF ₂	0.001
CdS	Insoluble
GaAs	Insoluble
KBr	53.5
KCl	34.7
LiF	0.27
MgO	Insoluble
Quartz	Insoluble

Cost

Cost of optical components depends on many factors. Glass and fused quartz optics are comparatively expensive because these materials have to be ground and polished, and then tested and maintained for correct flatness or curvature. Plastic optics are much cheaper since they can be molded. Once a mold is prepared, many thousands of optical elements can be produced with minimum cost. Optical elements made out of crystals are expensive since these crystals have to be grown in large size with expensive equipment. Many surface and bulk faults occur in these crystals and most of the time only a small portion of a grown crystal can be used to make an optical element. Some crystals are also hygroscopic (absorb water) and have to be used in either a vacuum or inert gas atmosphere, such as helium or argon. Applying anti-reflection or anti-transmission coatings increases the cost of these elements considerably. In summary, the manufacturing cost of an optical element depends on factors such as:

- i. Size
- ii. Material
- iii. Surface curvatures of the element
- iv. Accuracy of the flatness or curvature
- v. Wavelength of light to be transmitted
- vi. Type of coating on surface
- vii. Correction of aberrations

A list of some vendors of optical components and systems is given at the end of the module.

Optical Coatings and Methods of Coating Deposition

Optical coatings deal with the deposition of materials of specific thickness and composition on surfaces of optical components to control the amount of light passing through them. These components include front surface mirrors, filters, lenses, and prisms, to name a few. There are many ways in which the coatings can be applied. In most of the optical coatings, the material is deposited in a vacuum chamber with pressures of the order of 10^{-8} Torr (2×10^{-8} psi). The optical element on which the material is deposited is called a “substrate.” A typical vacuum deposition chamber is shown in Figure 2-7. A detailed account of all the methods of applying optical coatings is beyond the scope of this module. However, a brief description of several different methods of coatings and their applications will be discussed here.

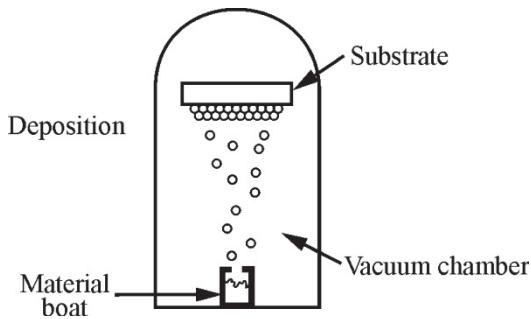


Figure 2-7 Schematic diagram of a typical vacuum deposition chamber

Evaporation

In this process, material in solid form is converted into vapor either by thermal vaporization or by electron beam bombardment. In *thermal vaporization*, the coating material is heated in a tungsten, molybdenum, or platinum “boat” by passing high current through the boat. The substrate is positioned above the boat so that the rising vapor of the material will deposit itself on the substrate as shown in Figure 2-7.

In the case of *electron beam deposition*, the coating material is evaporated by direct electron bombardment. A high-energy electron beam is concentrated in a very small movable spot in multi-pocketed, water-cooled crucibles. Different evaporating materials can be contained in the multi-pockets. This method avoids contamination that may result from interaction between the coating material and the boat when heated by high electric currents.

Sputtering

This is a technique useful for large size substrates. The substrate and target of the material to be deposited are held close together in a vacuum chamber. The substrate is cooled. When high voltage is applied, heavy ions from the plasma formed between the target and the substrate bombard the target and knock out small particles of target material. These particles then condense on the cooled substrate. Sputtering produces uniform coatings over large areas.

There are a number of variations to the sputtering process. One is *radio-frequency (r.f.) sputtering*. In this process, an alternating voltage at a very high frequency (13.56 MHz) is used. This increases the ion current density. In this process, electrons in the plasma pick up additional energy from oscillations, which results in higher ion current and larger deposition rates. Another type of process is *magnetron sputtering*. This uses the principle that ionized particles in a properly oriented magnetic field follow a curved path. This allows electrons to pass through a longer path and create more ionization, which in turn results in larger and more uniform deposition rates. Sputtering is mostly used for deposition of insulating materials such as silicon dioxide, titanium dioxide, and aluminum dioxide.

Thickness control of coatings

For optical coatings, control of coating thickness is very important. There are two ways to monitor the thickness of a thin film while it is still in the chamber. The first method is to use a *crystal oscillator*. A quartz crystal plate is placed in the same plane as the substrate to be coated. The resonant frequency of the quartz crystal depends on the mass of the crystal. When additional material is deposited on it, its increased mass will change and hence the resonant frequency will change. Observing this change can be used as a technique to monitor the thickness of the deposition. This type of monitor can be used to measure the thickness of a few layers of metal or dielectric coatings. However, as the number of layers increases, the sensitivity of the crystal to coating thickness decreases, and hence, it becomes increasingly unreliable.

In the second type, *interference effects* observed in a transmitted or reflected optical beam are monitored. In the transmission mode, monochromatic light passes through a transparent substrate being coated and its transmittance is monitored. As one expects, the transmittance decreases as the thickness of the coating layer builds up. If the refractive index of the material to be deposited is higher than that of the substrate, the decrease in transmission momentarily stops when the thickness of the deposit is $\frac{1}{4}$ of the wavelength of the monochromatic light used. If the evaporation is continued beyond $\frac{1}{4}$ wave thickness, the transmittance increases to the original value and then again momentarily stops when the thickness is equal to $\frac{1}{2}$ the wavelength of the monochromatic light.

This process can be repeated many times using layers of different indices. As the number of layers increases, each additional layer produces a smaller change in transmittance or reflectance. After many layers of deposition, this method also becomes less sensitive as the signal-to-noise ratio decreases. This technique is used mostly for materials with well-defined refractive indices such as semiconductors and dielectrics.

Antireflection coatings

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Antireflection coating that greatly reduces reflection is achieved with one or more layers of coatings on a glass or other suitable surface. It is possible to achieve nearly zero percent reflection or nearly 100% transmission. In the section headed “Surface reflection of ordinary light” (following Table 2-1), it was shown that when light is incident at 90° to the surface—i.e., at normal incidence—the percent reflectivity is given by:

$$R(\%) = \left(\frac{n_1 - n_2}{n_2 + n_1} \right)^2 \times 100 \quad (2-8)$$

Using this equation for an air-glass interface (where $n_{\text{glass}} = 1.5$), we found that 4% of the light would be lost for each reflection. For a given optical element with two surfaces, such as a window or lens, nearly 8% will be lost on one pass through. For a multi-lens device such as a camera, this loss will be increased with reflection at each surface. This loss can be prevented by applying antireflection coatings. It was also seen that as the angle of incidence changes, or the degree of polarization changes, the reflectivity changes.

Single-layer antireflection coatings

Consider a dielectric material with refractive index n_2 that is to be coated on a substrate surface whose refractive index is n_3 . It is assumed here that $n_3 > n_2 > n_1$. There will be a reflection from the air-dielectric boundary as well as from the dielectric-substrate boundary, as shown in Figure 2-8.

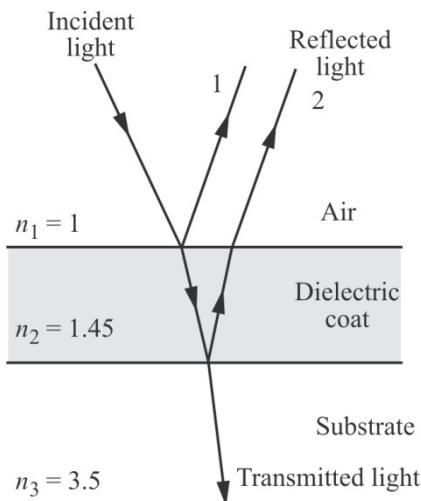


Figure 2-8 Reflection at multiple interfaces with different refractive indices

The two reflections will occur at the two faces of the dielectric coat. A useful quantity when dealing with coatings is defined as the **optical thickness**. The optical thickness of a medium is defined as the product of its refractive index and thickness, nt . The two reflections will be out of phase (180°) with each other if the optical thickness of the dielectric coat is an odd multiple of $\frac{1}{4}$ of the incident wavelength, that is, $nt = \frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}$, and so on. Such an optical thickness

causes destructive interference between the light reflected from the top and bottom surface of the dielectric coat and the reflected intensity approaches zero. If the optical thickness (nt) is an odd multiple of $\frac{\lambda}{2}$, that is, $\frac{\lambda}{2}, \frac{3\lambda}{2}, \frac{5\lambda}{2}$, and so on, the two reflecting waves will be in phase

and constructive interference takes place. The case for destructive interference where $n_2t = \frac{\lambda}{4}$ is

shown in Figure 2-9. Applying coatings of different optical thicknesses leads to constructive or destructive interference and can be extended to several layers to produce light of high or low reflectivity in an optical element.

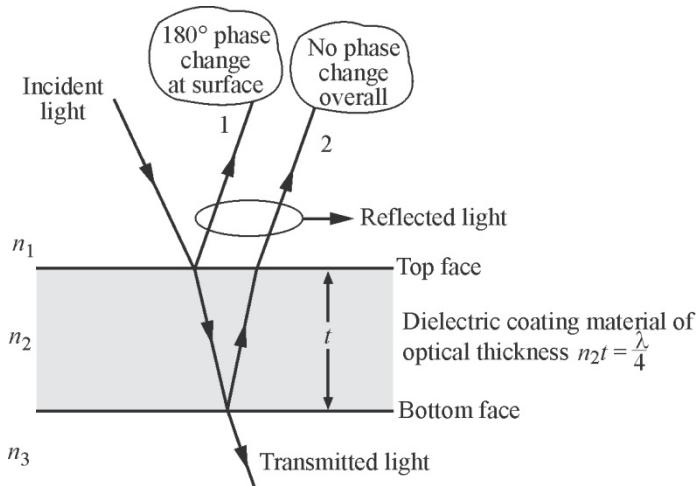


Figure 2-9 Reflection at top and bottom interfaces of coating material. Reflected rays 1 and 2 are 180° out of phase, leading to destructive interference and little or no reflected light.

The *minimum* thickness t of the coating shown in Figure 2-9 that causes a low reflectivity (high transmittance) is obtained from Equation 2-9.

$$t = \frac{\lambda}{4n} \quad (\text{antireflecting condition}) \quad (2-9)$$

where t = thickness of coat

n = refractive index of coat

λ = wavelength of light incident on the coat

For a wavelength of 550 nm and refractive index of 1.4, Equation 2-9 yields for the minimum thickness t ,

$$t = \frac{550 \times 10^{-9} \text{ m}}{4 \times 1.4} = 98.2 \text{ nm}$$

The thickness of the optical coating is also dependent on the angle of incidence of the light, and as the angle changes, the wavelength peak of the reflectance changes. The equation for off-normal incidence is complicated and depends on the degree of polarization present in the incident light. An angle of incidence measured from the surface normal of up to 25° shifts the reflectance peak to slightly shorter wavelengths.

Multiple-layer antireflection coatings

As explained earlier, by using multiple layers, the efficiency of the antireflection coating can be increased. For alternative layers of dielectric coats, materials of different refractive index are used. Their thickness can be calculated using Equation 2-9. In multi-layer, anti-reflection coatings, materials such as zirconium dioxide ($n = 2.1$), zinc sulfide ($n = 2.32$), or titanium dioxide ($n = 2.4$) are used.

Alternately, a single dielectric coat applied in layers of different thicknesses can be applied in layers of different thicknesses. An *ideal anti-reflection* coating will be completely transmitting with zero reflection losses, be wavelength independent, angle of incidence independent and polarization-state independent. Also, it will have a high power density threshold and be resistant to chemical damage. However, such coatings do not exist. Most often, a computer optimized, ten-layer antireflection coating is more than adequate for a photonics optical element. Computer software for determining such optimization is available.

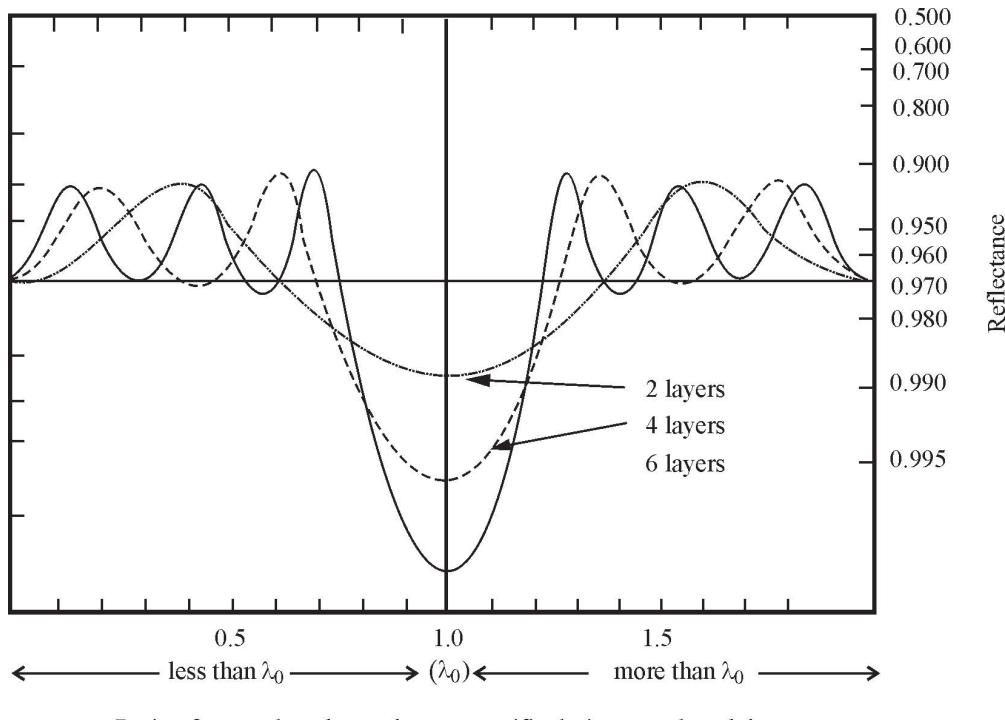
High-reflection coatings

Reducing the reflectivity of a surface has been discussed in the section headed “Surface reflection of ordinary light” (following Table 2-1). Coating the surface of an optical element with single or multiple layers of the desired optical thickness can also **increase** the surface reflectance. This is particularly important for laser mirrors where one mirror is desired with a nearly 100% reflectivity, the other mirror around 95%.

Single-layer high-reflection coatings—Surface reflectance of an optical element can be increased by applying either dielectric coatings or metallic coatings. Reflectivity due to dielectric coating depends upon both the coating as well as on the substrate. Coatings can be designed either for very high reflectance or partial reflectance. Partial reflectors can be used in the preparation of filters. However, the wavelength range of dielectric coatings is limited.

Multi-layer coatings are always preferable since with them it is possible to increase the reflectivity by many orders. The process for coating multi-layer high-reflecting elements is exactly the same as the one for anti-reflection coating—except that now the refractive indices and the thickness will be adjusted to give *constructive interference* between the reflected rays.

Alternate layers of higher and lower refractive index materials are coated to achieve as high as 99% reflectivity. Such high reflectivities can be achieved only in a narrow wavelength region and the reflectivity is also dependent on the angle of incidence. Increase in reflectivity of multiple layers of dielectric coatings is shown in Figure 2-10. Observe in Figure 2-10 how the reflectance increases from around 0.98 for 2 layers to a value higher than 0.995 for 6 layers. The coatings can also be adjusted to produce mirrors with full or partial reflections, interference filters, and polarizers.



Ratio of a wavelength near λ_0 to a specific design wavelength λ_0

Ratio of a wavelength near λ_0 to a specific design wavelength λ_0

Figure 2-10 Increase of reflectivity at a specific wavelength λ after reflection at multiple layers of coating

Metallic coatings—Metallic coatings can produce highly reflective, broadband, specular reflectors. Metallic films can be deposited on polished substrates. Some substances like aluminum can be directly coated on glass. For substances like gold, an intermediate layer such as chrome has to be used. It is better not to use very thick coatings since they tend to scatter light more.

Metallic coatings, however, tarnish very quickly by contact with the atmosphere and form metallic oxides. Coating the metal films with a dielectric film can prevent this. Typical reflection curves for some metals are shown in Figure 2-11.

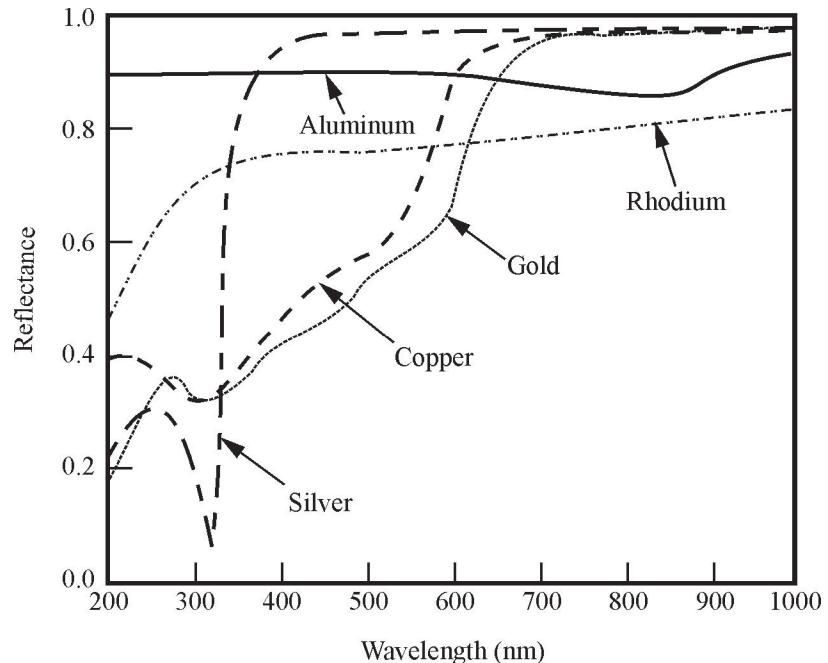


Figure 2-11 Reflectance of some metals as a function of wavelength

Some of the optical thin film materials and their properties are given in Table 2-5. Physical properties of some optical materials are given in Table 2-6.

Table 2-5. Some Optical Thin Film Materials and Their Properties

Material	Chemical formula	Transparent region (μm)	Refractive index	Density g/cc	Remarks
Aluminum oxide	Al_2O_3	0.2–9	1.65–1.60	3.6	Used in UV and mirror protection
Chromium oxide	Cr_2O_3	0.6–5	2.2	5.2	Very hard; resistant to acids
Hafnium dioxide	HfO_2	0.25–11	2.09–1.95	9.7	UV multilayers; high damage threshold
Indium oxide	In_2O_3	0.4–9	2.05	7.2	Hard, used for mirror protection
Silicon monoxide	SiO	0.45–7	1.9–1.83	2.0	Protection for Al and Ag mirrors
Titanium dioxide	TiO_2	0.45–11	2.5–2.25	4.7	Durable, multi-layer protection coatings, high tensile strength
Zirconium dioxide	ZrO_2	0.3–11	2.3–2.0	5	Visible multilayer coatings; hard film
Aluminum fluoride	AlF_3	0.2–12	1.36–1.30	2.9	AR coatings in UV to IR range
Cerium fluoride	CeF_3	0.2–14	1.35	2.6	Water resistant
Magnesium fluoride	MgF_2	0.15–6	1.42–1.36	301	AR coatings
Yttrium fluoride	YF_3	0.25–11	1.45–1.3	8.0	IR multilayer coatings; high damage threshold
Cadmium telluride	CdTe	0.9–25	2.65	6.0	soft IR multilayer coatings
Lead telluride	PbTe	3.5–80	5–10	8.1	Far IR multilayer coatings
Zinc selenide	ZnSe	0.6–16	2.6–2.35	5.2	IR multiplayer coatings
Zinc sulfide	ZnS	0.4–14	2.5–2.15	3.8	IR multilayer

Table 2-6. Properties of Some Optical Materials in the Visible Region

Material	Refraction index	Transmittance range (μm)	Density (g/cm^3)	Specific heat ($\text{J g}^{-1} \text{K}^{-1}$)	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	Softening point ($^\circ\text{C}$)	Hardness (kg/mm^2)	Thermal expansion (10^{-6} m K^{-1})
Fused silica	1.67–1.42	0.2–4	2.2	0.743	1.38	1585	530	0.5
Flint glass (SF 10)	1.77–1.703	0.38–2.3	4.28	0.47	0.8	595	276	7.9
		0.35–2.3	4.22	0.42	0.71	576	340	8.2
Flint glass (SF 8)	1.75–1.66	0.35–2.3	4.22	0.858	0.71	576	340	8.2
BK7 glass	1.54–1.49	0.315–2.35	2.51	0.86	1.114	719	520	7.1
Crown glass	1.53–1.52	0.32–2.3	2.55	0.77	1.11	708	542	9.5
Crown glass (Pyrex)	1.48–1.47	0.36–2.3	2.23	0.76	1.13	821	481	3.25
Calcium fluoride	1.44–1.32	0.15–8.0	3.19	0.85	9.71	1360	158	18.9
Sodium chloride	1.85–1.44	0.25–16	2.16	0.2	6.5	1074	18	41
Sapphire	1.83–1.59	0.15–5.0	3.97	0.76	22.2	2040	1370	8.4

Source: *Photonics Design and Applications Handbook 2003* (published by *Photonics Spectra*)

Filters

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Optical filters are devices that transmit and attenuate a certain portion of the electromagnetic spectrum—either in terms of wavelength or intensity. There are a large variety of filters useful for different applications. In this section, fundamentals of filters and their applications will be discussed.

Filters are divided into a number of categories depending on their function and use. These are (a) broadband filters (b) narrow-band filters (c) neutral-density filters (d) step filters (e) radiometric filters (f) photometric filters (g) polarizing filters and (h) special application filters. We shall consider each one in turn.

Broadband filters—These filters transmit a certain band of wavelengths of light and block the light outside of this band. Inexpensive colored plastic or glass filters, all dielectric interference filters, and metallic band-pass filters belong to this category. The more expensive filters permit active transmission of up to 95% in the desired region and attenuate the other wavelengths to less than 10%. A schematic diagram of a band-pass filter is shown in Figure 2-12. Some important characteristics of a band-pass filter are:

1. Peak transmission (T_{\max}) occurs at the desired wavelengths.
2. Full width at half maximum (FWHM) is the wavelength span between two points whose transmission is at half the value of T_{\max} .
3. Pass-band is the wavelength span between two points on the curve where the transmission is 5% of peak value.
4. Rejection ratio is more applicable to narrow-band filters and is the ratio of the T_{\max} and the transmittance outside the band.

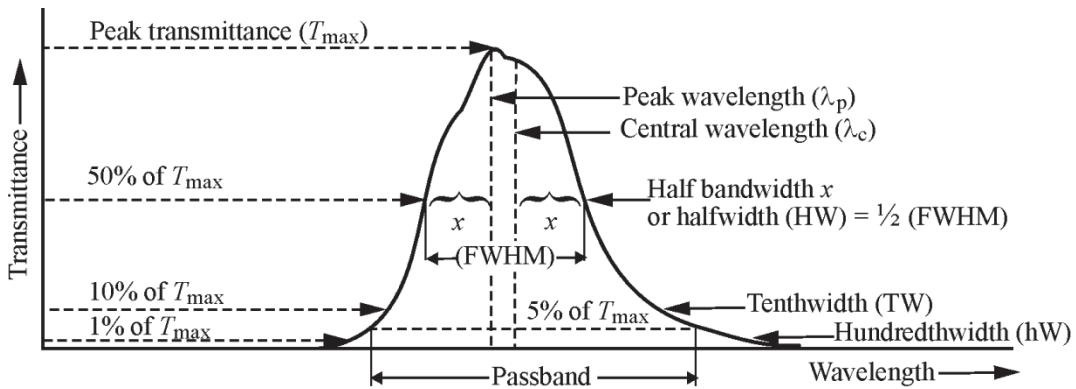


Figure 2-12 Properties of a band pass filter

Any filter will reduce the intensity of light, even in the band of wavelengths that it transmits. Hence, a filter correction factor has to be applied. In the section headed “Absorption and transmission,” the transmittance was given in terms of the thickness and the absorption coefficient. For band pass filters, intensity will be further reduced due to reflection at its two surfaces. Hence, Equation 2.2 is rewritten as Equation 2-10.

$$T = t_1 t_2 e^{-\alpha_\lambda x} \quad (2-10)$$

where T is the transmittance

$(t_1 t_2)$ is the filter correction factor for the transmittance at each surface

α_λ is the wavelength dependent absorption coefficient

x is the filter thickness

Cut-off filters—Cut-off filters allow radiation up to a specific wavelength to pass through and abruptly cut off the remaining wavelengths. There are two types of these filters: (a) the short-wave pass filters and (b) the long-wave pass filter. A long-wave pass filter is shown in Figure 2-13. The cut-off wavelength is not exactly “abrupt” and somewhat slopes down. The wavelength at 37% of T_{max} is generally considered as the *cut-off wavelength*. The sharpness of the “cut off” is the wavelength difference between the 5% and 70% transmission points.

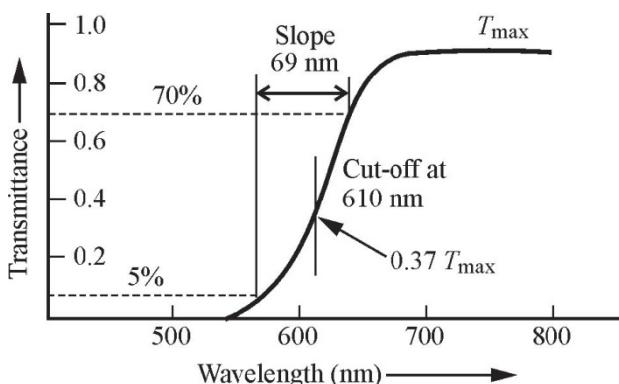


Figure 2-13 Properties of a high pass cut-off filter

These filters can be made with a combination of dichroic (colored glass) filters. This type of filter is particularly useful when harmful radiation of a higher or lower wavelength has to be cut off. For example, a frequency-doubled YAG laser has a green output at 532 nm. However, a certain amount of 1.06 μm radiation (twice 532 nm) is also transmitted. A low pass filter can eliminate this higher wavelength.

Neutral-density filters—These filters are not wavelength sensitive. They are intensity sensitive. Part of the radiation incident on these filters is either absorbed or reflected, and the remaining radiation is transmitted. The *optical density* (OD) of such a filter is involved in Equation 2-11:

$$T = 10^{-\text{OD}} \quad (2-11)$$

where T is the transmission and OD is the optical density. The optical density is a pure number which indicates the level of light transmitted as given by Equation 2-11.

Got to
[http://optecvideo.
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 for a short lesson
 about Optical
 Density



Example 5

A neutral-density filter used in a laser laboratory has an optical density of 0.7. Find the percent transmission of the filter.

Solution: $T = 10^{-\text{OD}} = 10^{-0.7} = 0.2 = 20\%$

Thus the neutral-density filter attenuates the incident light by 80%, essentially at all wavelengths, so that only 20% of the incident light is transmitted.

Neutral-density filters come in two different forms. Individual filters with a specific transmission and circular filters (filter wheels) with various portions having different transmissions. A schematic diagram of the transmission of several neutral-density filters is shown in Figure 2-14.

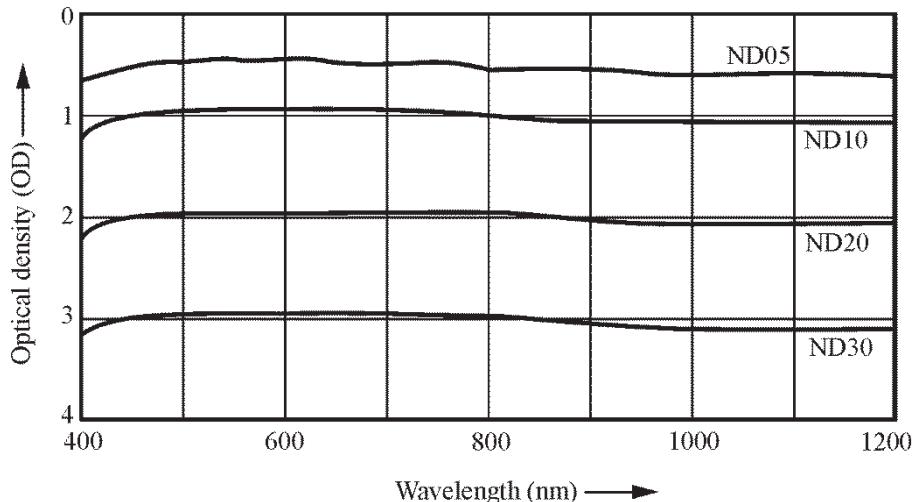


Figure 2-14 Optical densities of some neutral-density filters

Narrow-band filters—These are usually interference filters where many layers are coated on a suitable substrate so that only a specific wavelength is transmitted; the rest are reflected. A narrow-band filter that transmits a wavelength near 500 nm is shown in Figure 2-15.

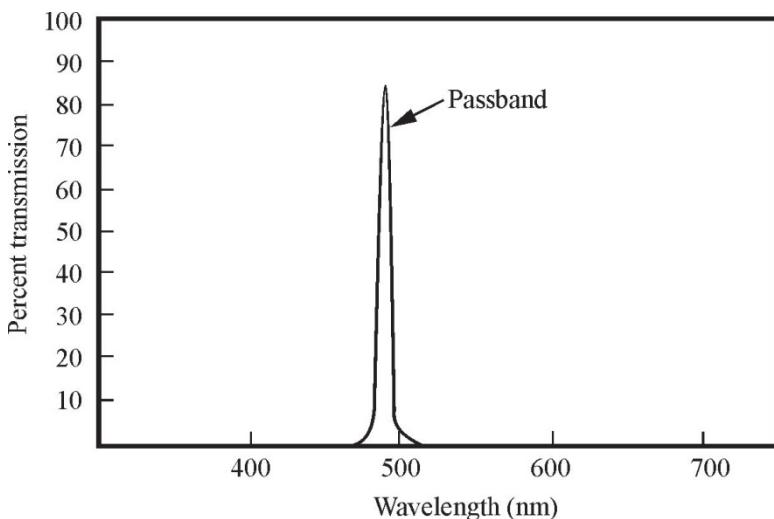


Figure 2-15 Percentage of transmission of a specific narrow-band filter

Such filters can be combined with absorption filters that further absorb wavelengths outside of the specific transmission wavelength. These types of filters are called combination filters.

Radiometric filters—Light detectors often do not have a flat response to all wavelengths of light. Hence, their response to lasers of different wavelengths will not be the same. A filter that transmits light equally at all wavelengths is called a *radiometric filter*. A transmission curve for such a filter attached to a detector is shown in Figure 2-16.

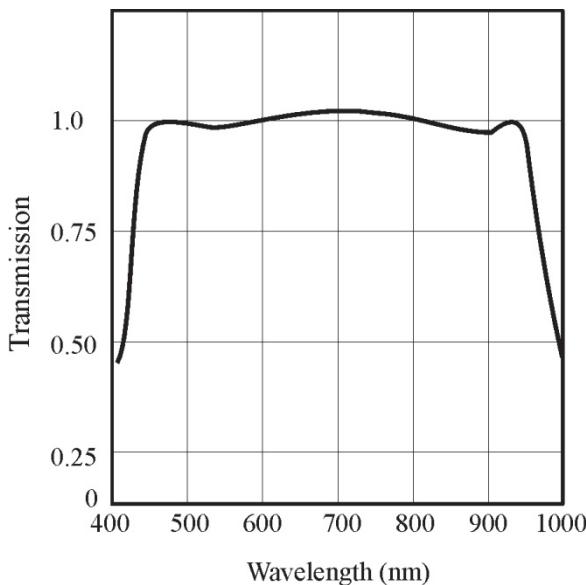


Figure 2-16 Transmission characteristics of a radiometric filter showing a nearly uniform transmission between 400 nm and 1000 nm

Photometric filters—Sometimes it is necessary for a detector to respond to light in the same way the human eye does. A photometric filter is one that transmits maximum light at 550 nm and falls off steeply on either side. This response is similar to the response of the eye. A photometric filter response is shown in Figure 2-17. The solid line represents the response of the human eye and the dotted line represents the photodetector with a photometric filter attached to it. Note the close agreement between the response of the eye and a photodetector fitted with a photometric filter.

Eye protection wear—Laser safety is a very important factor in a laser laboratory. Among various organs of the body, the eye is the most vulnerable to laser radiation. A reflected laser beam focused on the retina by the eye's optical system can result in severe and irreparable damage. Several types of goggles are available to protect the eye from such laser beams.

Impact resistant polymer goggles use different types of absorbing material that protect the eyes against scattered or reflected radiation. The absorbers are uniformly applied on the goggle surface and are not affected by scratches on the surface. Different filter materials are used in the goggles to protect the wearer from incident laser radiation of different wavelengths. Goggles for different laser intensities and wavelengths are available from most of the well-known photonics suppliers.

Transmission characteristics of a goggle used to protect the wearer from CO₂ laser light are shown in Figure 2-18. As you approach the wavelength of 10,600 nm for CO₂ lasers, the transmission will be near 0. More details concerning laser safety are discussed in Module 1-3, *Light Sources and Laser Safety*.

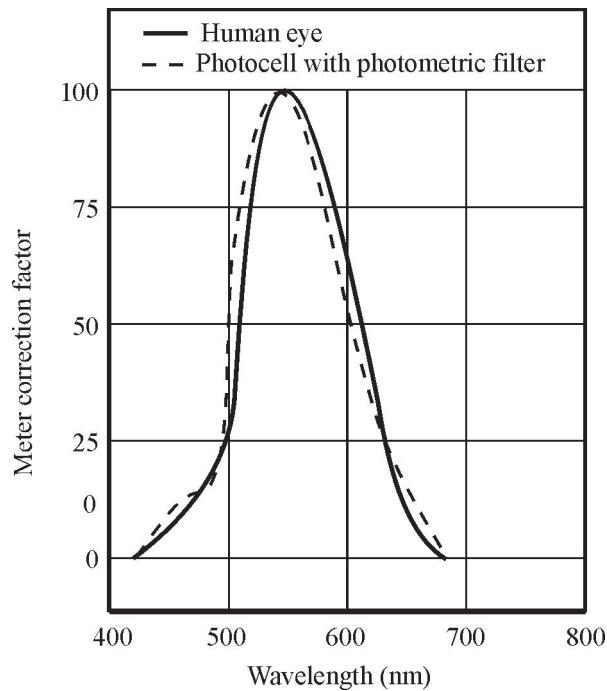


Figure 2-17 Transmission characteristics of a photometric filter

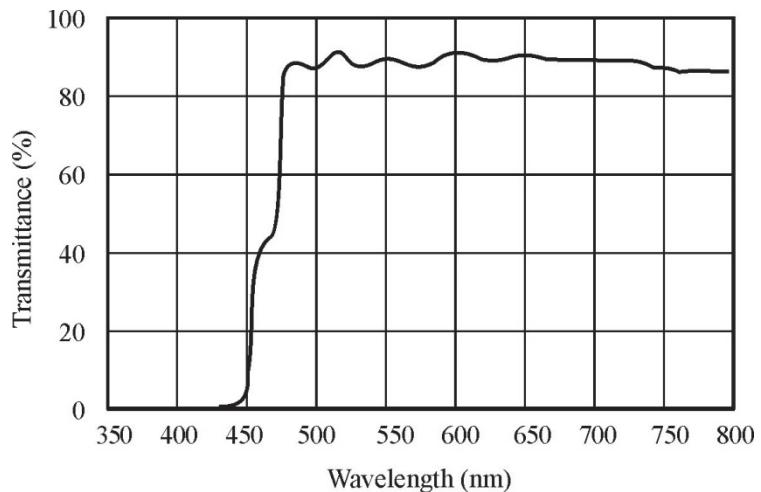


Figure 2-18 Transmission characteristics of a safety goggle suitable for protection from CO₂ laser beams

Laboratory Mountings

This section examines those mountings for optical components most often found in laser and optics laboratories.

Optical benches

An optical bench or optical rail is a long stable base on which optical components can be mounted. This rail can have different cross-sectional shapes so that mounts with a reverse geometrical configuration can be positioned and moved along the rail. Optical components such as lenses, mirrors, filters and detectors can be mounted on movable carriages. Component supports are attached to rods with adjustable heights. A cross-sectional view of such an optical bench set-up is shown in Figure 2-19.

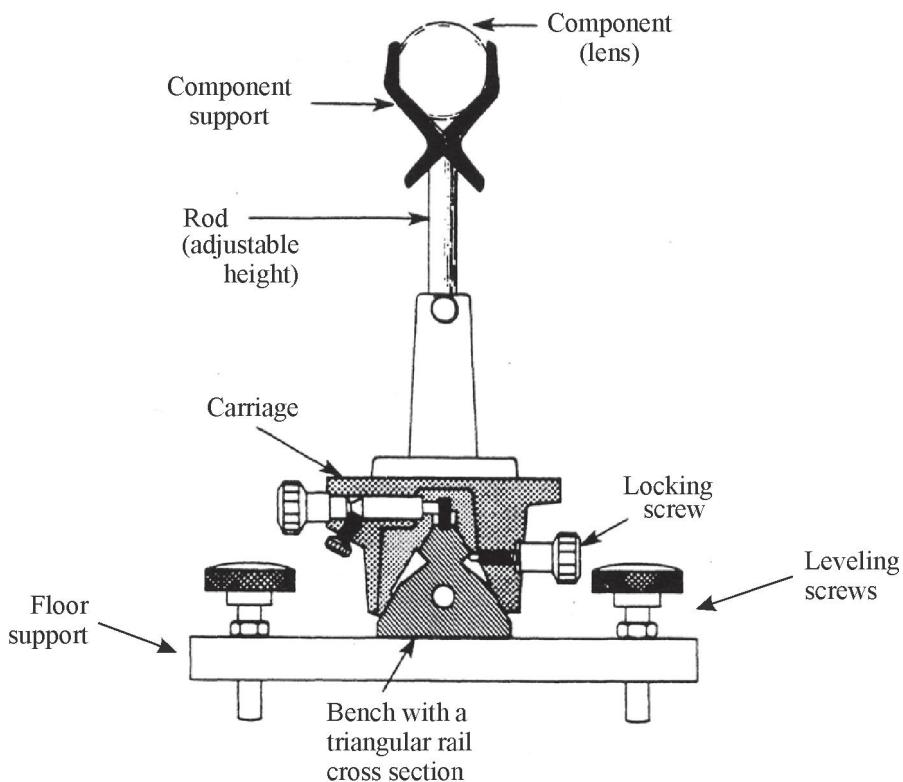


Figure 2-19 Cross-sectional view of a triangular optical rail with carriage, adjustable rod, lens support and lens

The cross-section of an optical rail can be (a) double rectangular rail, (b) triangular rail, or (c) flat bed.

Triangular rail—The rail has the cross-section of an equilateral triangle as shown in Figure 2-19 and is usually made of aluminum, cast iron, or steel. Two grooves on either side of the rail are used to guide the carriages and secure them on the side with a locking screw. On either end of the rail, there are flat supports whose height and tilt can be adjusted with vertical screws. This allows the optical bench to be leveled horizontally. A number of uprights can be positioned

along the rail and components mounted on them. A typical arrangement of an optical system on a triangular rail is pictured in Figure 2-19.

Double rectangular rail—Double rectangular rails are generally made of aluminum. There will be two rails parallel to each other with a fixed spacing between them. Their length can be between 15 centimeters and 2 meters. They have slotted mounting holes, which allows bolts to be attached to a flat table. The carriages have slots, which allow the components to move along the rail and be fixed at any point with a side screw. Sometimes a linear scale running along the length of the rail is used to locate the position of the component. The carriages allow different types of mounts to be placed in a line. An arrangement of double rectangular rails is shown in Figure 2-20.

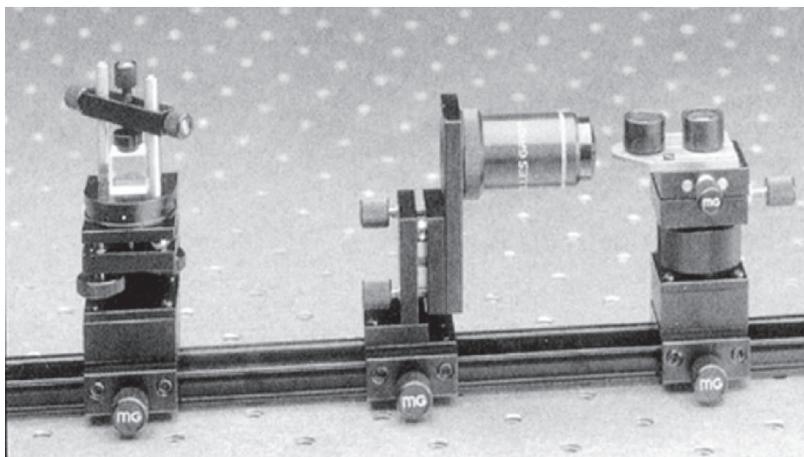


Figure 2-20 Double rectangular optical rail (Courtesy: Newport Corporation)

Flat-bed optical bench—A flat-bed bench is used when maximum stability is required for the optical system. Flat beds are made either out of high-grade stainless steel or granite. The rail has a dovetail cross-section along which carriers can be moved and fixed at desired positions. This type of bench is quite heavy and very stable. A typical flat bed bench is shown in Figure 2-21.

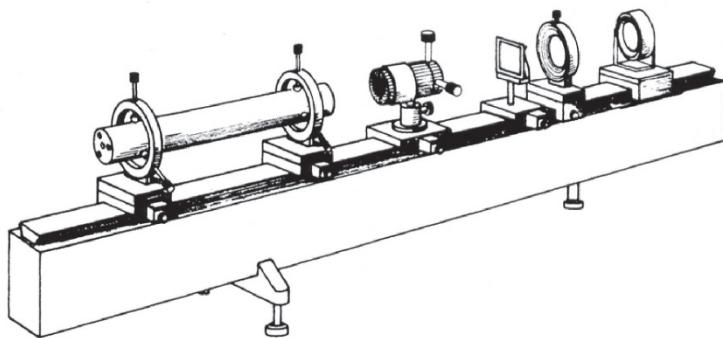


Figure 2-21 Flat-bed bench for optical mounting

Optical tables

Optical tables are used instead of bench rails when optical elements must be aligned along more than one axis and when vibration isolation is required. A typical example where such an optical table is used is in a holographic set-up. Optical tables of different sizes, both with and without legs, are available. Most of the optical tables come with drilled and threaded holes, equidistant from each other, so that optical mounts can be directly screwed into them. The optical tables are made out of ferromagnetic stainless steel tops.

They are filled with honeycomb-cores and provide flat, rigid support for optical elements.

When external vibrations need to be completely eliminated, optical tables with pneumatic isolation legs are used. Vibrations that reach the optical table are generally of a low frequency (<30 Hz) and are due to the motion of the laboratory floor—generally from people walking nearby. The pneumatic legs are designed to have a vibration frequency far less than 30 Hz so that no vibrations are transferred to the table. A typical isolation table with pneumatic legs is shown in Figure 2-22.

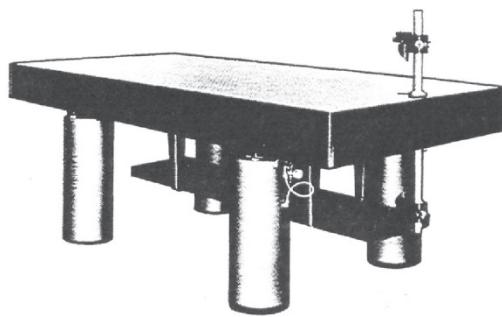


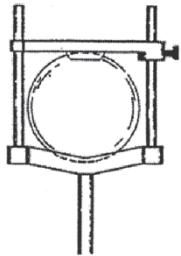
Figure 2-22 Isolation table with pneumatic legs

Component supports

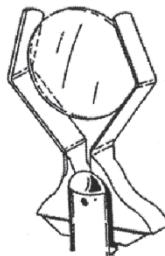
A variety of component supports are available for holding optical elements. Some of the optical elements are lenses, mirrors, optical flats, light detectors, and lasers.

The most important component support is the lens mount. Figure 2-23 shows five different ways of holding a lens: (a) sliding-grip holder, (b) spring grip holder, (c) a swing arm holder, (d) a threaded holder, and (e) a self-centering holder.

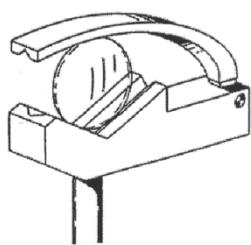
The *sliding-grip* lens holder has a V-groove in which the lens can rest and the movable horizontal bar can be fixed with a side screw. Thus ,a lens can be held between the V-groove and the horizontal bar. This support is mounted on a cylindrical rod that can be moved vertically to fix the lens at any height. In the *spring grip* lens holder, the lens is held in the jaws of a double “V” spring. The lens is positioned between the two jaws. This mount is inexpensive and simple, but not very stable. A slight variation of the double “V” spring is a single swing spring that can move vertically up and down. A lens is firmly held in a metal “V” groove at the bottom and the lens is held in position by the spring above. This holder also is simple but unstable.



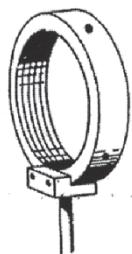
(a) Sliding grip



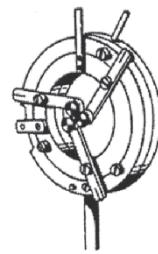
(b) Spring grip



(c) Swing arm



(d) Threaded ring

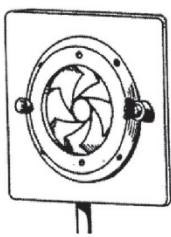


(e) Self-centering

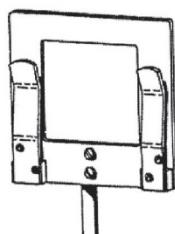
Figure 2-23 *Different types of lens/mirror mounts*

A semi-permanent mounting is the *threaded lens* holder. This holder has to be made specifically for a lens of particular diameter. The cylindrical holder has threads inside and a retaining collar at the end. Once the lens is inserted in the cylinder, a threaded retaining screw can be used to hold the lens. This holder is sturdy and can be used when lenses need not be changed often. The *self-centering* holder helps in moving the position of the lens in a vertical axis. In this holder, three arms that can hold the lens in position are held by springs. These arms have grooves to hold a small portion of the lens at three points along the edge of the lens. This holds the lens securely in position but allows the lens to move along vertical and horizontal axes. This type of mount allows alignment of the lens with other components of the system. It is not usually recommended for permanent type set-up. Other than lenses and mirrors, many other optical elements have to be positioned in an optical system. Such holders are shown in Figure 2-24.

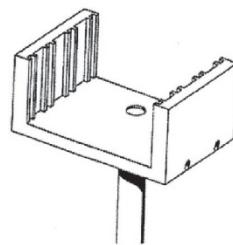
An iris diaphragm (Figure 2-24a) is one that permits a change in the aperture size. This has several metal leaves which, when moved by a knob on the side, increases or decreases the size of the aperture. Slide holders can hold a filter or multiple filters as shown in Figures 2-24b and c. In the first case, a rectangular frame holds the filter by means of two spring clips. In the second case, a number of grooves along vertical sides can hold several slides aligned in a row. An adjustable clamp will allow a prism to be positioned in a desirable direction (Figure 2-24d). The prism is held on a circular base with an adjustable clamp on top. A slight modification of the sliding grip lens holder can be used to hold a laser. The base of this holder has a "V" groove and there are two horizontal bars on the top. The two top bars and the "V" groove can hold a cylindrical object firmly (Figure 2-24e). Most of these mounts can be combined with one-, two-, and three-dimensional movable positioners for finer adjustment of the optical element.



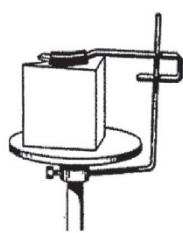
(a) Iris diaphragm



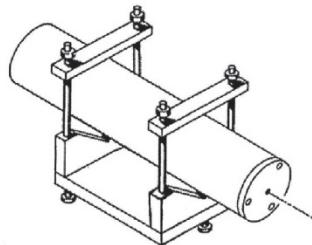
(b) Filter holder



(c) Filter holder



(d) Prism holder



(e) Laser holder

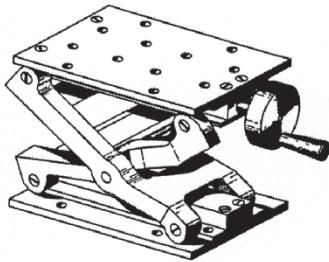
Figure 2-24 Other types of holders for optical elements

Positioning Equipment

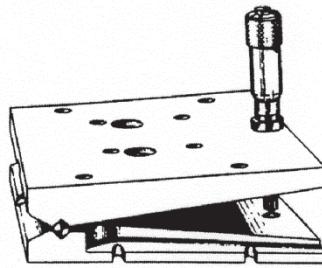
Along with laboratory mounts for holding various optical elements, one generally needs a variety of positioners to move and position optical elements. These are described below.

Lab jacks

Lab jacks are platforms that can be raised up and down or tilted at an angle. They help in adjusting the heights of different optical components. The most common lab jack is the *scissors jack*. It has two heavy metal plates connected by two pairs of cross bars hinged at the center. By turning a knob located on the side, the upper plate can be raised or lowered (Figure 2-25a). The second type is the *sine table*. This also has two heavy plates, one above the other. The upper plate is attached to the lower plate on one side by a hinge. The other side has a screwing mechanism that causes it to move it up and down. This allows the optical component located on the top plate to tilt to a desired angle. This table is shown in Figure 2-25b.



(a) Scissors jack

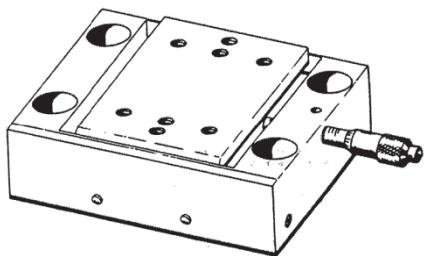


(b) Sine table

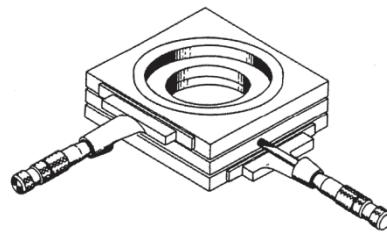
Figure 2-25 Schematic diagram of a scissors jack and “sine table”

Translation tables

Translation tables provide adjustable motion in one or two dimensions. These can be combined with other devices to produce either a three-dimensional motion or a combination of linear and rotational motions. The simplest of them is a linear translator (Figure 2-26a).



(a) Linear translator



(b) Two-dimensional translator

Figure 2-26 Schematic diagrams of one-dimensional and two-dimensional translators

By turning a micrometer screw, the top table moves linearly with respect to the bottom part. This is accomplished by the shaft of the micrometer pushing a ball bearing-supported spring-loaded table. This micrometer can be attached to a slow motion motor to provide smooth and slow linear motion. Motion in two axes can also be accomplished by stacking two linear translators above and perpendicular to each other. These two can be permanently attached to each other, as shown in Figure 2-26b.

Rotation stages

Rotational motion about an axis is achieved with rotary stages. The rotary stage is controlled by a worm gear on the knob shaft that drives a circular ring gear through a full 360° . Such a rotational device can be mounted on a vertical shaft to provide rotational motion to an optical component such as a circular sheet of Polaroid. Pictures of these rotational stages are shown in Figure 2-27.

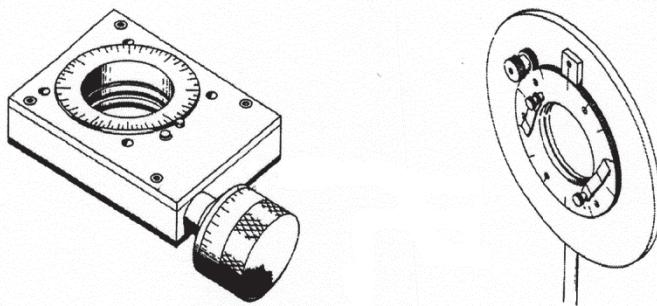


Figure 2-27 Picture of a simple rotational stage and a rotational stage designed to hold Polaroid sheets

Combination and special supports

It is possible to combine a translation and a rotation of an optical element in a single device to locate a desired position for the element. Such a device can first center an object along the optic axis by using a translation stage and then rotate it to the required angle by using the rotational table. Such a device is shown in Figure 2-28.

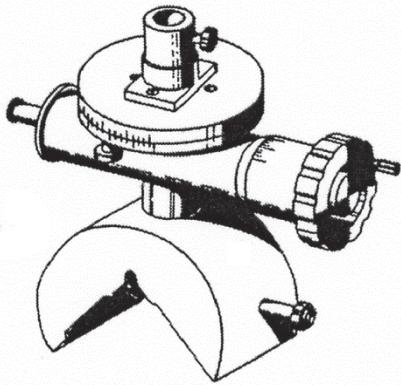
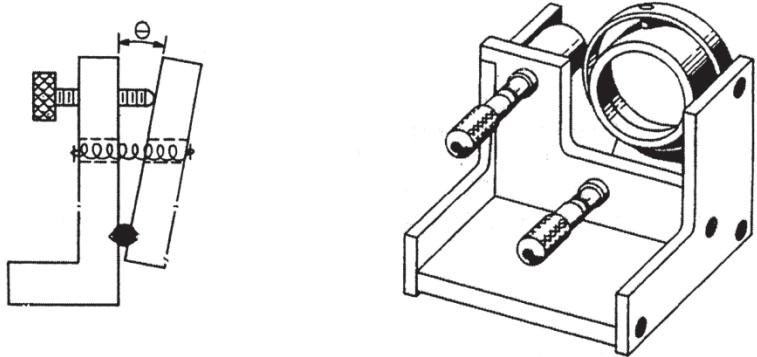


Figure 2-28 Combined rotational and translational stage

Angular motion

Sometimes an optical component may have to be tilted either in one or two perpendicular directions. For example, such a device is critical in adjusting the position of a laser cavity mirror. Two such devices, one permitting tilting around one axis and the other permitting tilting around two axes are shown in Figure 2-29.



(a) Single-angle tilt

(b) Double-angle tilt

Figure 2-29 One and two-dimensional tilting stages

A *goniometer* is a device that can rotate an object about a point such that the rotation point is unobstructed by the goniometer itself. Two such goniometers can be stacked one above the other to produce orthogonal motion about a common point in space. A commercial version of a goniometer is shown in Figure 2-30.

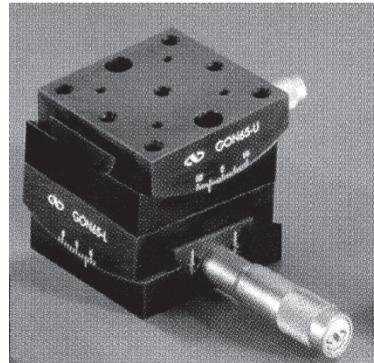


Figure 2-30 A commercial goniometer
(Courtesy: Newport Corporation)

Nanopositioning stages

These are devices that produce linear and circular positioning, or their combination, with extreme precision and in very small motions. These kinds of minute motions are obtained by using a piezoelectric device. They can produce a linear travel of 3 mm with steps as small as 50 μm . Rotational devices with a rotation of 360° with a resolution less than one arc-second are available. These types of devices are most useful in the positioning of fibers.

Surface Quality of Optical Components

Over time and usage, most optical components develop some defects either on the surface or inside the bulk material. Surface defects include *scratches*, *digs*, *chips*, and *fractures*. An internal defect is called an *inclusion*. In addition, there can be defects on cemented surfaces in multiple lenses. They can be caused by mishandling and mechanical or thermal stress.

Surface abrasion

Abrasion of a surface includes scratches on the surface due to other harder materials coming into contact with the surface or even by improper cleaning procedures. Unintentional rubbing of particles from the air such as sand, grit, or dust can also cause surface damage.

Scratches—Scratches are markings on the optical surface. *Scratch number* is the width of the scratch in terms of thousandths of a millimeter. For example, an 80 scratch is equivalent to an 80 μm scratch. However, this number is mostly a rough estimate. Most of the visible scratches are 60 or more.

Digs—These are small pits or craters on the optical surface. They are defined by their widths in hundredths of a millimeter. For example, the diameter of an irregularly shaped 40 dig is 0.4 millimeters. No more than two digs of size more than 20 dig should exist on a surface if it is to be considered a good optical surface.

Edge chips—These are small portions of the material chipped away at the edges of the optical element such as a lens. These become important only when they extend into the usable aperture of the lens. Chips smaller than 0.5 mm can be ignored.

Cemented surfaces—When two or more lenses are cemented together, the interface and its quality become important in the functioning of the system. Edge separation at a cemented interface cannot extend into the element by more than 1.0 mm. The cement that binds the lenses must be uniform and without any translucent areas.

The vulnerability of the surface of an optical element to such abrasions depends on the hardness of the material. If the surface has dielectric coatings on it, the abrasion depends on the nature of the coatings. If they are soft coatings, they are easily susceptible to abrasion.

Extreme heat and cold or rapid changes in temperature can cause temporary or permanent damage to the optical surface. Material characteristics such as softening point and thermal expansion coefficient, and its anisotropy, are thus important. (Anisotropy is the non-equivalence of a property in different directions.)

Some chemicals are capable of dissolving window surface materials. Examples of these are found in the effect of acetone on plastic optical surfaces and of water vapor on salt windows made from alkali halide crystals such as NaCl. Fungus also can attack the dielectric coatings on the surface and damage the lens surface. In such cases, the lens will have pockmarks on it. Pollution in the atmosphere can also contaminate optical surfaces. High intensity laser beams can easily damage laser mirrors, since long exposure to high intensity laser beams can evaporate the coatings on the mirrors and reduce their reflectivity.

Internal damage

Mechanical or thermal stress can cause internal damage to an optical component. Sometimes even a manufacturing process can introduce *inclusions*. These are trapped particles inside optical materials and internal inhomogeneities such as bubbles. Minute cracks and dislocations can occur in crystalline optical materials due to their growth processes. Both of these are problems if they are subjected to high power laser applications. Inhomogeneities are variations of refractive index across the aperture of the optical component. On rare occasions, localized visible variations of refractive index appear in the form of thin threads. These are called *striae*. Some optical materials will fluoresce, that is, they emit light when exposed to ultraviolet light. For example, fused quartz fluoresces as a strong blue color when exposed to strong ultraviolet light.

Inspection Methods and Procedures

It is important to know how to inspect various surfaces defects and decide whether or not to use the component in the system. One defective optical element in a system can degrade the entire system.

Surface imperfection measurements

The simplest method of observing and measuring a surface defect is to observe the surface under a microscope. The surface is first cleaned by an approved method and then placed on a stage of a microscope. A lamp using a condensing lens illuminates the test piece. This arrangement is shown in Figure 2-31. The scratches, digs, and other surface defects can be observed through the microscope. Using the magnification of the microscope, the size of the scratches and digs can be measured. A usable optical element should have no scratches on the center of the lens or within the usable aperture of the lens.

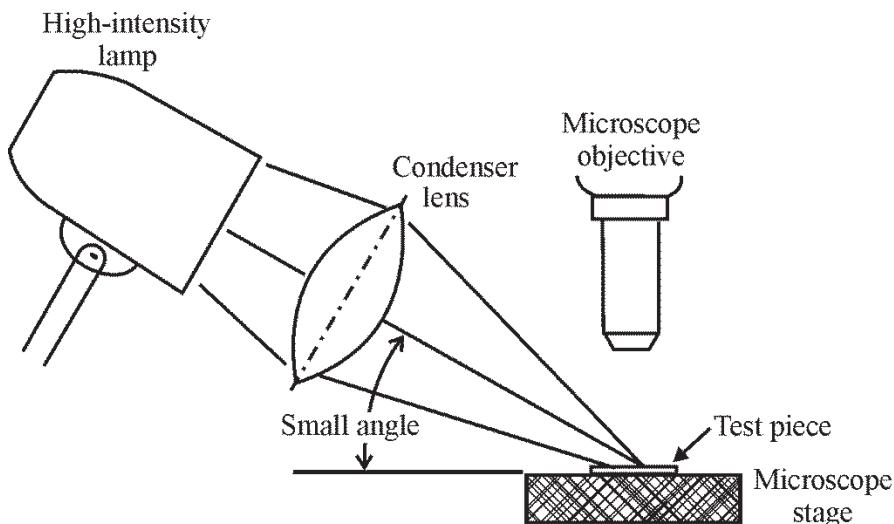


Figure 2-31 Schematic diagram for observing surface imperfections on an optical element

Internal defects in the optical element

Figure 2-32 shows the technique for observing the internal defects of an optical element. A laser beam is passed through a test piece and the output beam is diverged by a negative lens and focused on a screen. The projected image is carefully inspected for any local variation of brightness. To ensure that the observed variations are not due to the properties of the laser or the diverging lens, the test object is removed and the image is again observed. By moving the test piece in two dimensions perpendicular to the laser beam, different portions of the test piece can be examined.

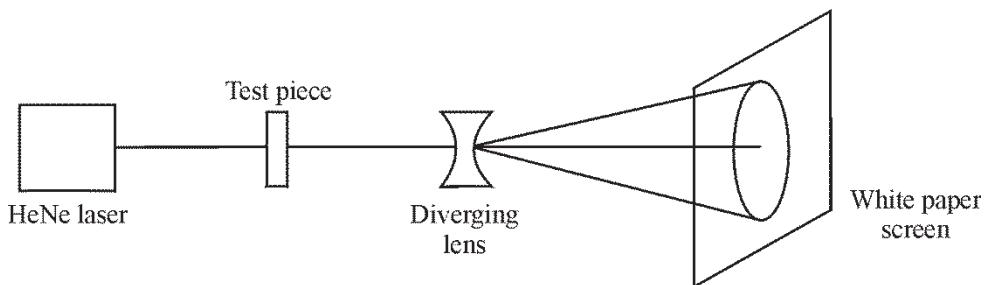


Figure 2-32 Schematic diagram of an optical setup used to observe internal defects in an optical element

Flatness testing for an optical element with a plane surface

The flatness of a plane surface such as an optical window can be measured with the help of an *optical flat*. When the test plate is placed on the optical flat and viewed in monochromatic light, a number of fringes (dark and bright bands) appear due to the interference of light reflected from the top surface of the test piece and the interface between the test piece and the optical flat. The flatness of the test plate is defined in terms of a fraction of the wavelength. The smaller the value, the greater is the flatness of the test piece.

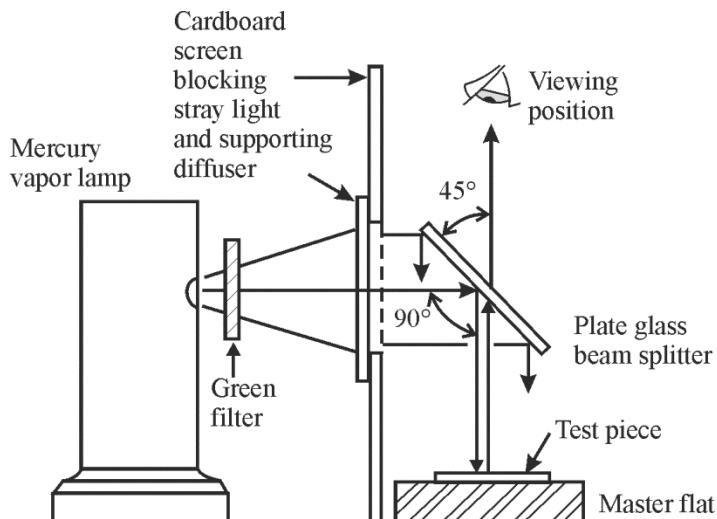


Figure 2-33 Experimental setup designed to observe interference fringes on a flat optical element

For example, a $\frac{\lambda}{10}$ surface is flatter than a $\frac{\lambda}{4}$ surface. The spacing between two successive dark (or two bright) bands is equal to one half of a wavelength of the illuminating light. This implies that the larger the number of fringes seen on the flat, the less flat the surface is. Further, if the fringes are straight lines, then the test piece is flat along the direction of the fringe. Technically speaking, if both the test plate and the master optical flat are perfectly flat, there should be no

fringes at all! This, of course, is impossible. If the fringes are crooked, then the test piece is non-uniform on the side touching the optical flat. The experimental setup to observe the fringes and typical fringe patterns of a window on an optical flat are shown in Figures 2-33 and 2-34. It is important that both the master flat and the test piece be clean and that no dust particles or air bubbles exist between the flats.

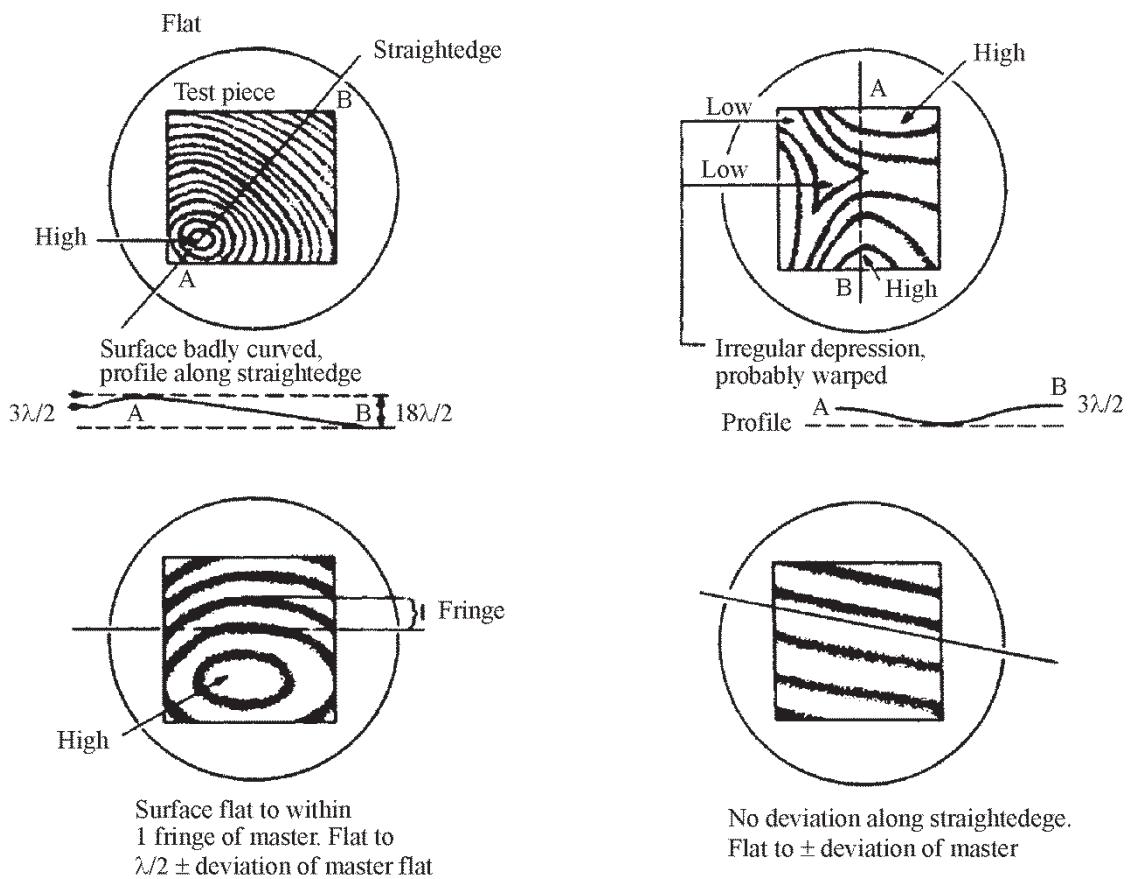


Figure 2-34 Typical interference patterns observed on flat optical test plates of different flatness

Spectral qualities of mirrors

Front-surface mirrors are made with coatings of one or more layers of aluminum on the surface and are covered either by a dielectric coating to prevent the aluminum from oxidizing or by multilayer dielectric coatings to give higher reflectivity. The reflectivity of a metal depends on wavelength, surface preparation, and the angle of incidence. Spectral characteristics of some metals were given in Figure 2-11. This figure shows that aluminum coatings can be used in the ultraviolet region while silver coatings are preferable in the visible region. Magnesium fluoride and silicon monoxide are used as protective surfaces on silver and aluminum coatings, even though this may slightly reduce the reflectivity. Multilayer dielectric coatings can increase reflectivity at a specific wavelength, as was shown in Figure 2-10.

Care and Cleaning of Optics

It is very important to have clean optics in a photonics laboratory. *Dust, grime, grease, scratches, and fingerprints* are most undesirable items on surfaces of optical components. Before cleaning and storing an optical component, a few important facts must be understood. The first is to know whether the component has multilayer coatings on it. This can be easily seen in reflected sunlight. If there are coatings on the surface, a multi-color reflection will be seen. In such cases, one needs to know whether they are soft coatings or hard coatings. When in doubt, it is not advisable to “contact” clean it. The best and only way is to **blow dry** clean air on it and remove the dust particles. Otherwise, it must be sent to a professional company. Secondly, an optical assembly should never be taken apart to clean it unless the person knows exactly what is being done. Most often, optical assemblies like eyepieces are assembled in a clean room and they do not need internal cleaning.

Preparation for cleaning an optical component

The first thing that is required before cleaning an optical component is a clean environment. A dust-free room and a clean table are essential for cleaning an optical component. The object must first be inspected for dirt and grime. While the optical surface is being inspected, it should never be touched by a bare hand; a latex glove must be used. Fingerprints can permanently damage an optic surface. Lenses, mirrors, and flats should only be held by the edges and never on the front and back sides.

Materials required

Some of the materials required for cleaning are:

- (a) Reagent-grade methanol or 2-propanol in a drop dispensable bottle (commercial lens cleaners also can be used).
- (b) Long fiber, low ash content lens tissues with no additives or chemicals.
- (c) Clean air duster—such as a camera cleaning brush/ air blower or any of the “dust-off” spray cans.
- (d) Q-tips.
- (e) Clean, dust-free rubber gloves.

Cleaning procedures

First, the dust and grime must be removed from the surface. For this, air has to be blown along the surface using the air duster. Observing the surface in a bright light will show whether dust particles are still there. The surface is not to be blown on by mouth since saliva can deposit itself on the surface. Rubber gloves must be worn on the hands and cleaned in water to remove any powder on the glove. A dryer must then be used to dry the gloved hand. With a Q-tip wetted by a small amount of cleansing liquid, the surface must be gently cleaned using a circular motion from outside towards the center. Only light pressure should be applied. A clean lens tissue or a clean Q-tip must be used to wipe out the excess cleaning liquid and let the surface dry. The process must be repeated until the surface is clean.

Mirrors usually require only a dust-off and not a cleaning. If they do not have some greasy impurities sticking to the surface, they can be given a “bath.” The mirror must be removed from its casing and then put under gently running water. A small amount of detergent liquid is applied to the surface and once again put under running water. Finally, the surface must be cleaned with distilled water and allowed to dry. A hot air dryer should never be used to dry the surface. After the surface is dry, an air blower can be used to blow away any other particles sticking to the surface.

Precautions to be taken in cleaning an optical component

- (a) Water and soap solutions make hands slippery. Care must be taken to see that the object does not slip from the hands. A good idea is to keep the hands ‘on’ the table so that the height of a fall will be small!
- (b) Lens tissue, cotton swabs, or fingers should never be inserted in methanol.
- (c) Dry lens tissues can scratch the surface. Hence, a drop of cleaning liquid should always be used.
- (d) Optical components must always be held by their edges.

Storage of optical components

The proper storage of optical components is important. A well-stored component will last longer and will be very effective in an optical system.

- (a) Clean optical components must always be kept covered so airborne particles do not again settle on them.
- (b) Optical components must be stored in a clean, covered area.
- (c) They must be in a cool area with minimum temperature fluctuation.
- (d) When the component is not in use, it should be stored in a covered place and not left on the table.
- (e) From time to time, optical components must be inspected for defects and scratches. Defective optics should not be used in a system since they will negatively affect overall system performance.

LABORATORIES

Laboratory 1-2A: Familiarization with Optical Equipment and Components

**Go to
<http://optecvideo.opteccrm.org/>
for an introduction to this
activity.**



In this laboratory, you will complete the following tasks:

- Familiarize yourself with the optical equipment and components found in a typical photonics lab.
 - Prepare a purchase requisition for a new set of parts.

Equipment

All the parts of Newport Kit: OEK-STD

Procedure

Identify all the parts of the Newport OEK-STD kit and complete the following purchase requisition. Please obtain prices from the website of the supplier at <http://www.newport.com/>.

Laboratory 1-2B: Care and Cleaning of High Grade Optical Components

Go to
<http://optecvideo.opteccrm.org/>
for an introduction to this
activity.



In this laboratory, you will complete the following tasks:

- Practice the “drop and drag” technique.
- Practice the “forceps and pad” method
- Demonstrate the proper procedure for cleaning a mirror.
- Research other methods for cleaning optical components.

Equipment

Newport Kit: OEK-STD

Optics Tissue

Optics Brush

Forceps

Lens Cleaner

Lens Cots

Procedure

1. Practice the “drop and drag” technique for loose optics, as demonstrated by your instructor, using the Beam splitter from the Newport Kit. Repeat until you are comfortable with this method.
2. Next, check all of the lenses in the Newport kit. For any lenses that need cleaning, practice the “forceps and pad” method for mounted optics. Repeat until you are comfortable with this method.
3. When ready, demonstrate competency to your instructor by cleaning a mirror from the Newport Kit using the “drop and drag” and the “forceps and pad” method.
4. Research other cleaning methods. Document your findings. Practice your researched method and demonstrate your proficiency to the instructor.

Laboratory 1-2C: Building an Inexpensive Spectrometer

Go to
<http://optecvideo.opteccrm.org/>
for an introduction to this activity.



In this laboratory, you will complete the following tasks:

- Observe the light spectrum of a fluorescent and incandescent light.
- Determine the energy of the photons in the observed spectral bands, lines, and/or continuum.

Equipment

Spectroscope (Hand Held – Edmund Scientific Spectrometer – Item # 3052521)

Fluorescent Light Source (e.g. ambient, room lighting)

Incandescent Light Source (e.g. ambient, room lighting)

Procedure

1. Observe light spectra for the following sources. Draw a rough sketch of each spectrum using colored pencils in the space provided. Identify each spectrum as line, band, or continuous.
 - a. Fluorescent Light
 - b. Incandescent light

2. Complete the table below based on your observations and estimations. Use the equations below to determine the photon energy of each of the estimated wavelengths. Enter your results in Table 2-7.

Table 2-7

	Color	Estimated Wavelength	Energy (eV)	Energy (Joules)
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				

Energy of a Photon (ϵ) in $eV = h\nu = hc/\lambda$

where $h = 4.14 \times 10^{-15} \text{ eV}\cdot\text{s}$ and

$$c = 3 \times 10^8 \text{ m/s}$$

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ Joules (J)}$$

WORKPLACE SCENARIO

Here is your opportunity to use the concepts learned in this module to solve an actual problem that could arise in a photonics company. Your instructor will provide directions for developing a solution.

Developing Optics Cleaning Procedures

Scenario

Since graduating with a two year associate photonics technology degree, you have been working as a technician with a field service organization, which specializes in providing preventive maintenance and repair on lasers. Since you are recognized as one of the most knowledgeable technicians on the team, you have been assigned a new employee to train. The new employee just graduated with a similar associate degree, but, as is typical with new graduates, has little “on the job” experience.

During the work day, your supervisor assigns you a service order involving a laser system. The service order states that this system’s output power has dropped below its normal operating range. As a training exercise, you ask the new employee to examine the laser and diagnose what is causing this problem. The laser system has an output window mounted in a plastic enclosure. When your trainee examines the window, she notices that the window appears dirty. You inspect the window and agree. When asked how this window can be cleaned, your trainee suggests that as dirty and smudged as the window is the best way would be to start with a cotton swab saturated with a strong cleaning solution like acetone. Also, to save time, she suggests cleaning the window in the housing versus removing it. Your first thought is to have the trainee check for an equipment service manual. An internet search shows that the manual is not available. Next, you have the trainee call the manufacturer. She learns that due to the age of the laser system, the manufacturer no longer provides technical support for it. As a last resort, you have the trainee check company records to see if an optical layout diagram exists for the laser system. From the engineering records kept by your company, your trainee is able to find this diagram and notices it identifies the window manufacturer as Melles Griot, and the part number of the window as W2-PW1-5010M-C-HE-415-700.

Problem and Tasking

With no service manual or technical support, you must devise a procedure for cleaning the laser system’s window that will not damage it or its housing. To accomplish this task, you will have to search the internet to determine the material compositions and recommended cleaning procedures for the window, its coating, and the window housing and then, using this information, develop a cleaning process. When the process is developed, you will then need to document it in an intra-office memo to your trainee so she can perform this cleaning operation and have a record of it for future use.

PROBLEM EXERCISES AND QUESTIONS

1. Define the term *refractive index*. Why does it vary with wavelength? If the wavelength of light incident perpendicular to an interface in air is 650 nm and its wavelength changes to 644 nm in the medium, what is the refractive index of the medium?
2. What are the factors that determine the transmission of light through a medium? The absorption coefficient of a material is 4.5 cm^{-1} . If the thickness of the material is 12 mm, find the percentage of light transmission.
3. Name some of the materials that can be used as a window in the ultraviolet, visible, and infrared regions, respectively. What are the important criteria in choosing a window material? Why is germanium more suitable as a window material for a CO₂ laser than NaCl?
4. If two optical materials on either side of an interface have refractive indices of 1.35 and 1.45 respectively, what is the total reflection at the interface?
5. Explain what Brewster's angle is and where is it useful? A thin glass plate has a refractive index of 1.65. Calculate the Brewster's angle for this glass plate in air.
6. How does a change in temperature affect the optical properties of a material? What are the important thermal properties that have to be considered when selecting a material for an optical component?
7. How does mechanical stress affect the optical properties of a window material? The following are the parameters that have to be considered in designing a circular window for a vacuum chamber. What is the minimum thickness required for the window if no optical distortion should take place? $P_{\text{outside}} = 1 \times 10^5 \text{ Pa}$, $P_{\text{inside}} = 1.48 \times 10^{-6} \text{ Pa}$, $D = 0.36 \text{ m}$, and $F_a = 0.34 \times 10^6 \text{ Pa}$
8. Explain briefly, how optical coatings are deposited on a substrate. How can the thickness of the coating be controlled and measured?
9. Explain how an anti-reflection coating is made. How is the thickness of the coating determined? Calculate the minimum thickness of a coating required for incident light of wavelength 560 nm if the refractive index of the coated medium is 2.1.
10. Describe the following type of filters and state what they are used for:
 - a. Neutral density
 - b. Short wavelength pass filter
 - c. Band pass
 - d. Multiple layer
11. Name five different types of lens and filter holders. Explain their advantages and disadvantages.
12. What are the types of surface defects that can occur on an optical surface? How can they be observed?
13. Name three types of optical benches. State one advantage and one disadvantage of each.

14. Explain the experimental procedure for determining the flatness of an optical element.
15. What are the precautions to be taken in cleaning an optical element such as a lens or a mirror? What are the materials that are required to clean a lens?
16. What are the precautions to be taken for storing optical components?

MEET A TECHNICIAN

Colt Jesse



Colt Jesse earned an Associate's of Applied Sciences degree in Electronics Engineering Technology, with a specialty in Photonics, from Indian River State College. Colt's education took an unusual route. For him, the "cart came before the horse." He got a job in photonics, realized how much photonics interested him, and then pursued the education that would assure him of a rewarding, advancing career.

Colt works as a photonics technician at Infrared Associates, which manufactures detectors that are mainly used for measuring temperatures and spectroscopy in scientific and medical equipment.

"If you've ever seen the television show Mythbusters, they use a touchless thermometer to point at something and measure its temperature. Our detector is in that thermometer."

Colt's work consists of several activities, dealing with many different stages in the creation of infrared light detectors.

"I start by growing the material we use to make the detectors. It's a crystal matrix that's actually grown from mercury, cadmium, and tellurium. It usually takes one whole day to grow and cool the crystals, so I begin by mixing the appropriate metals and putting them into the furnace to let them do their thing. Then I assemble detectors into final units, or I perform spectroscopic analyses on the materials I'd grown the day before to determine the cut-off wave lengths of their response. Sometimes I dice up the detectors into their final chips or design new arrays for new products we're making."

Colt loves his job. And he's eager to show others the potential of the photonics field.

"If you're science-minded, and looking for a field that's new and interesting, that is always advancing, always changing, then look into photonics. You can do all sorts of weird and interesting things with light. You can change it into electrical energy and change it back into light energy. (With infrared devices), you can see things you couldn't normally see."

REFERENCES

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Light Sources and Laser Safety

Module 1-3
of
Course 1, *Fundamentals of Light and Lasers*
3rd Edition

OPTICS AND PHOTONICS SERIES



PREFACE TO MODULE 1-3

This is the third module in *Fundamentals of Light and Lasers*. Following are the titles of all six modules in the course:

1. *Nature and Properties of Light*
2. *Optical Handling and Positioning*
3. *Light Sources and Laser Safety*
4. *Basic Geometrical Optics*
5. *Basic Physical Optics*
6. *Principles of Lasers*

The six modules can be used as a unit or independently, as long as prerequisites have been met.

FEATURES

Mathematics Videos: Math videos are provided to assist students in doing mathematical operations required in this module. The math concepts used in this module are checked ✓ in the following list:

1. Scientific Notation ✓
2. Unit Conversion ✓
3. Introductory Algebra ✓
4. Powers and Roots
5. Ratio and Proportion
6. Exponents and Logarithms ✓
7. Graphing in Rectangular Coordinates
8. Geometry
9. Angle Measure in Two and Three Dimension
10. Trigonometry
11. Special Graphs

This checklist provides instructors a means of front-loading the presentation of material in this module with mathematics instruction. If instructors prefer to provide math instruction using a “just on time delivery” mode, a special icon  appears where the checked mathematics topics are first used within this module. All math videos can be accessed at <http://optecvideo.opteccrm.org/>.

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COURSE 1: FUNDAMENTALS OF LIGHT AND LASERS

Module 1-3

Light Sources and Laser Safety

INTRODUCTION

This module addresses various nonlaser light sources, such as incandescent lamps, fluorescent discharge lamps, high-intensity discharge lamps, flashlamps, arc lamps, and LEDs. It also discusses in detail aspects of laser safety including the human eye, laser hazards, laser safety controls, maximum permissible exposure, laser safety glasses, and laser accidents. The laboratory experience at the end of the module will help one understand the dangers associated with lasers, with small and large beam diameters, and with constant power levels.

PREREQUISITES

Before you work through this module, you should have completed Module 1-1, *Nature and Properties of Light*. You should also have a working knowledge of intermediate algebra.

OBJECTIVES

Upon completion of this module, you should be able to:

1. Define the following properties of laser light:
 - a. Monochromaticity
 - b. Directionality
 - c. Coherence
2. Distinguish between the different types of nonlaser light sources and identify their characteristics.
3. Recognize and avoid various nonbeam hazards such as electrical and chemical hazards.
4. Label a diagram of the human eye, showing its principal parts. State the function of each principal part.
5. Match the parts of the eye with the spectral regions to which they are most vulnerable.
6. Given the basic information required, calculate retinal spot size and retinal irradiance.

7. Describe the following laser classifications, based upon the potential hazards:
 - a. Class 1 laser
 - b. Class 2 laser
 - c. Class 3a laser
 - d. Class 3b laser
 - e. Class 4 laser
8. Define maximum permissible exposure (MPE). Why is MPE important?
9. Describe three general types of laser hazard controls.
10. Describe laser-hazard warning signs.
11. Describe the most frequent causes of laser accidents.
12. List five laser safety precautions that are applicable to all types of lasers.

SCENARIO

Joan recently graduated from a two-year photonics program at her local community college. She accepted a job at City Hospital in Philadelphia as a laser technician.

City Hospital uses CO₂, argon, and Nd:YAG lasers for its surgical procedures. Joan soon discovered that her responsibilities would also include being the laser safety officer (LSO). Joan recalled the discussions she had in school about laser safety and the laser safety concepts she learned. Because being a laser safety officer is a major responsibility and critical to the well-being of both the staff and the patients, the hospital and Joan realized more training would be necessary. The hospital sponsored Joan's attendance at a five-day course on medical laser safety given by the Laser Institute of America in Orlando, Florida. At this course, the duties of a laser safety officer were discussed, including topics such as safety education, laser hazards and controls, personal protection, medical surveillance, and more. As Joan begins her duties as LSO, she realizes how important laser safety is for all in the medical working environment. Good luck, Joan, as a photonics technician and laser safety officer.

BASIC CONCEPTS

Important Properties of Nonlaser and Laser Light Sources

As discussed in Module 1-1, *Nature and Properties of Light*, light can be understood as consisting of waves traveling through space. Light occurs in different wavelengths, just as waves on the ocean vary in length. Wavelength is the distance between peaks on a light wave, as represented in Figure 3-1. The color of light depends on its wavelength. Violet light has the shortest wavelength of all visible colors, and red light has the longest, as seen in Figure 3-2a. White light is a combination of all visible colors or wavelengths.

Laser light, unlike ordinary light, is unique in that it usually consists of only a single color of light. The wavelengths that make up this single color, while not perfectly equal in length, occur within a very narrow range of wavelengths. **Monochromaticity** is the laser light's property of containing only one pure color and a narrow range of wavelengths.

The light from an ordinary source like a light bulb radiates away from the source in all directions, as shown in Figure 3-2b. This spreading or divergence of ordinary light is what makes it so useful for lighting homes and workplaces.

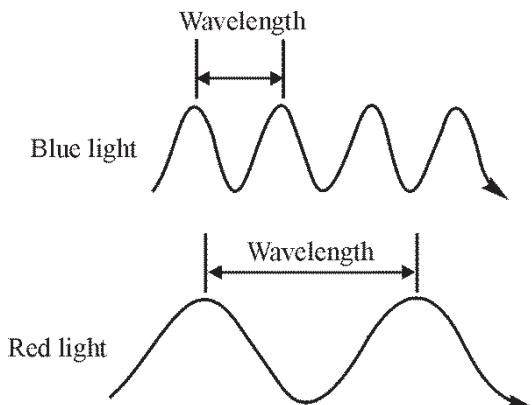


Figure 3-1 Light waves

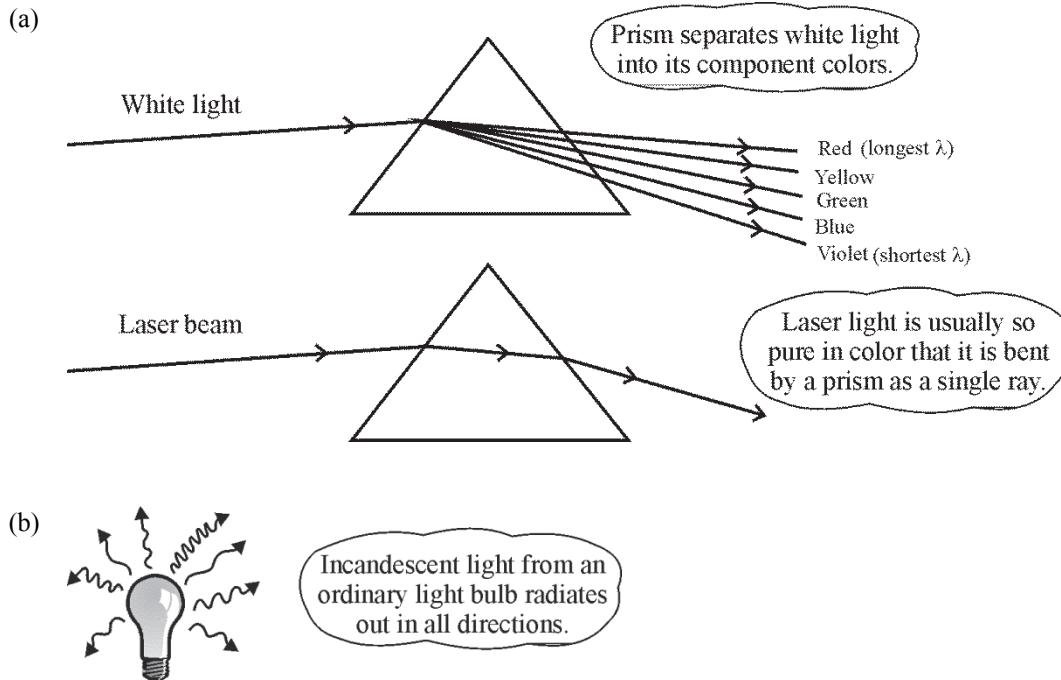


Figure 3-2 White light, laser light, and light emitted by an incandescent bulb

Laser light, however, is very **directional**. By comparison, the light emitted by a laser diverges very little, as shown in Figure 3-3.

Noncoherent light waves *produced by* ordinary sources don't form an orderly pattern. Their amplitudes combine in a random fashion and produce a resultant wave

that is no larger than any of the multiple single waves, as seen in Figure 3-4a. Such light is said to be *incoherent*. By contrast, the waves produced by a laser travel through space in step with one another. They're said to be "in phase" or **coherent**. Since all the separate waves in the beam remain in step with one another, as shown in Figure 3-4b, the resultant wave is much stronger than that of any single wave. A very intense, coherent beam is generated.

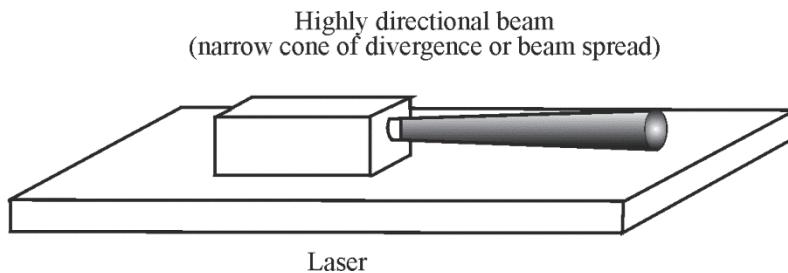
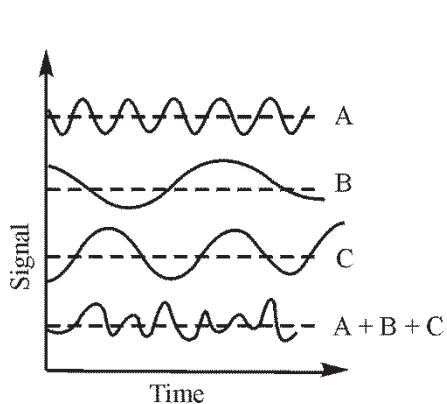


Figure 3-3 Concentrated directionality of laser light

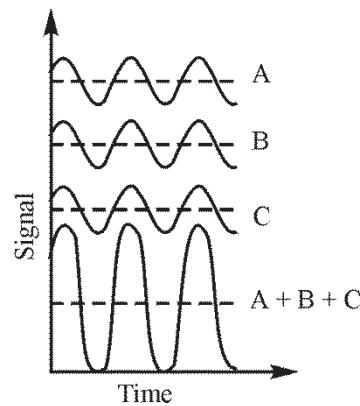
The numbers below the **A** that appears in several places in this module reference specific applets that demonstrate the concepts being described in the text. These applets are accessible at <http://optecvideo.opteccrm.org/>.

A

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(a) Incoherent light



(b) Coherent light

Figure 3-4 Adding coherent and incoherent light waves

Nonlaser Light Sources

The following *nonlaser light sources* will be discussed in turn:

1. Incandescent sources
2. Fluorescent-low pressure discharge lamps
3. High-intensity and -pressure discharge lamps (HID)
4. Flashlamps and arc lamps
5. Light-emitting diodes (LED)

Incandescent sources

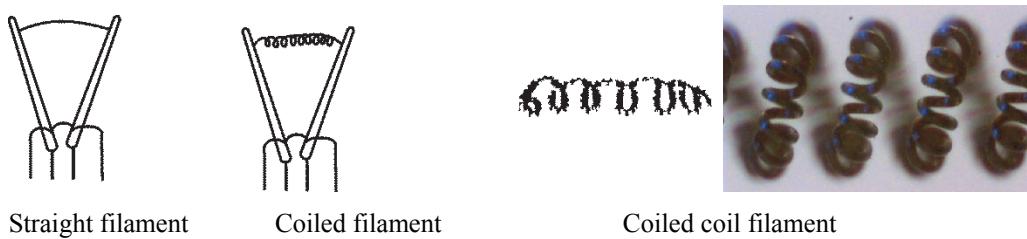
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Incandescent sources are similar to but not exactly as intense as blackbody radiators. A blackbody radiator is considered to be an almost perfect emitter. The first incandescent lamps in the nineteenth century were carbon-, iron-, osmium-, or tantalum-filament lamps. However, in spite of its low ductility, tungsten has replaced all these filament materials because of its low vapor pressure, high melting point (3655 K), and strength. Today tungsten is typically alloyed with metals such as thorium and rhenium.

Most modern incandescent lamps are filled with gas to increase the lifetime of the filament. These fill gases are generally mixtures of argon and nitrogen, with high percentages of argon for low-voltage lamps and very high percentages of nitrogen for high-voltage projection lamps. Occasionally krypton is added for still greater lifetime. None of these gases appreciably influences the spectral quality of the incandescent source. However, the tungsten-halogen-type lamp has become increasingly common. Tungsten-halogen lamps contain a small amount of a halogen, such as bromine, chlorine, or iodine. The halogen teams with the tungsten to create a regenerative cycle—particles of tungsten thrown off by the filament combine with the halogen to form a gas that is attracted to the hot filament and attaches to the filament. However, the lost particles of tungsten do not redeposit in exactly the same place, so the filament is modified, spotting and eventually failing as before. The important feature of the tungsten-halogen lamp is that the particles of tungsten collected by the filament are prevented from depositing on the glass. Thus, the lamps do not form a black coating on the inner surface.

Halogen lamps are hot, and they must run hot to keep the regenerating cycle going—nothing less than 500 degrees F will do. For comparison, a 100-watt household lamp is never hotter than about 450 degrees, meaning that this temperature is too low for a halogen lamp. Ordinary glass does not stand the higher temperature needed, so all halogen lamps are made of special heat-resistant glass or of quartz. In fact, the halogen lamp is now perhaps better known as a quartz lamp.

Lamp filaments made of tungsten wire are sometimes used in a straight length but more often formed into a coil, or a coiled coil, Figure 3-5. This drawing shows the various common filament styles. The better (and more expensive) filaments have close-spaced coils to secure a bright, uniform light. Less expensive are the wide-spaced filaments, and these are entirely practical for many applications, such as slide projectors.



Straight filament

Coiled filament

Coiled coil filament

Figure 3-5 *Types of incandescent filaments. Filaments are arranged upon support structures within the bulb in a variety of ways. The filament itself may be either, straight, coiled, or coiled coil.*

A high-intensity lamp uses a low-voltage automotive 6- or 12-volt bulb. Low-voltage lamps can be used on standard household current by using a small and inexpensive transformer to reduce the usual 110 volts to the required level. With the transformer concealed, the end product is useful for spotlighting.

Fluorescent light sources

Fluorescent light sources are low-pressure discharge lamps with a fluorescent phosphor. Most fluorescent lights consist of mercury discharge lamps that emit 90% of their energy at a wavelength of 253.7 nm. These ultraviolet photons can excite a number of phosphors, producing a range of wavelengths from infrared to ultraviolet. Visible wavelengths are characterized as white, warm white, cool white, etc. Fluorescent lamps can have either cold or hot cathode electrodes. Cold electrodes are used when a rapid start is necessary. Hot cathode electrodes give greater *luminous efficiency* and because of this most lamps today use hot cathode electrodes. (Luminous efficiency is a ratio of the *visible* light energy produced by a light source (measured in lumens) to the *electrical* energy (in watts) needed to power the light source.) The luminous efficiency of a fluorescent lamp increases with its length. For example, an 80-inch lamp is 40% more efficient than a 15-inch lamp. The output of a fluorescent lamp is also a function of the type of ballast used. The two common types of ballast are the *rapid-start* and the *preheat* ballast. Most of today's lamps operate with rapid-start ballasts. However, research has suggested that the preheat ballast may yield up to 20% higher light output as compared to the rapid-start type. Lamp life could also be significantly affected by the choice of ballast.

High-intensity discharge lamps (HID)

High-intensity discharge (HID) lamps (Figure 3-6) can be made of mercury, sodium, or metal halides. The gas pressures inside the lamps are usually 2–4 atmospheres.

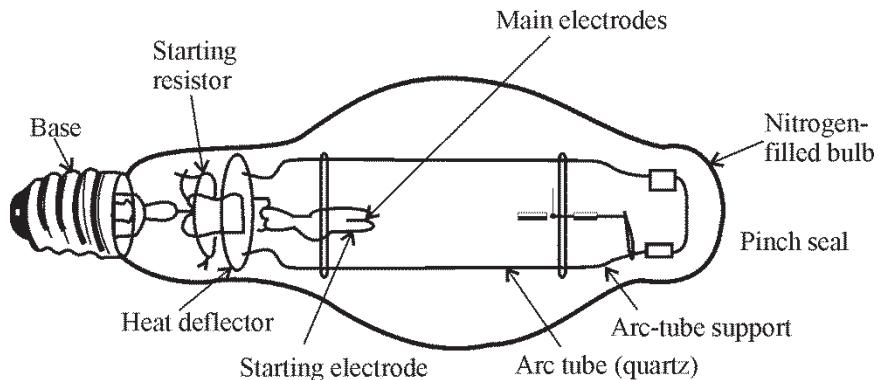


Figure 3-6 Mercury HID lamp. This cutaway drawing shows the construction of an Hg-HID lamp. The inner envelope is of quartz; the outer envelope of borosilicate glass (adapted from Kaufman and Christensen, 1972).

HID lamps—specifically those containing mercury—have two envelopes: the inner quartz discharge tube and an outer glass jacket. The outer jacket absorbs the UV radiation generated by the internal operation of the bulb. In places like gymnasiums, high-bay industrial areas, and public buildings, these lamps are often not enclosed in protective fixtures. The outer jacket can be broken in some instances by flying projectiles without damaging the inner discharge tube. If the lamp does not extinguish, substantial levels of UV radiation will be emitted to the outside. An HID lamp *can cause serious skin burn and eye inflammation* from shortwave ultraviolet radiation if the outer envelope of the lamp is broken or punctured. Lamps that will automatically extinguish when the outer envelopes are broken or punctured are commercially available.

Flashlamps and arc lamps

Flashlamp and arc lamps are high-intensity discharge devices commonly used in photography and laser technology. They usually contain gases such as xenon and krypton. The flash or arc is initiated by a high voltage placed across the discharge tube. This action in turn ionizes the gas and produces a high-intensity light with output peaks in both the visible and infrared regions of the electromagnetic spectrum. See Figure 3-7.

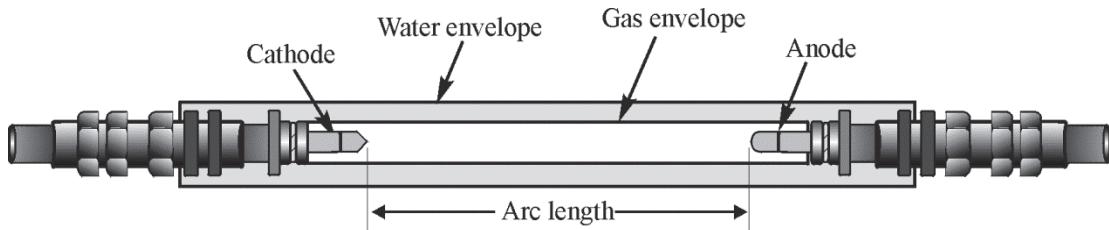
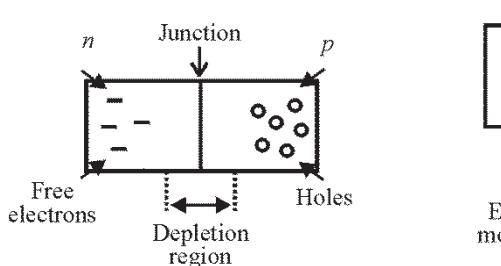
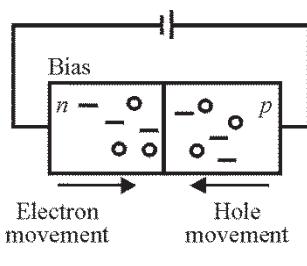


Figure 3-7 Diagram of a gas arc lamp with water jacket for cooling

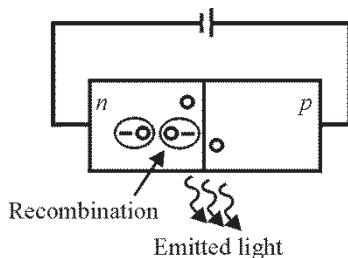
The quartz tube is usually 1.5 mm in thickness with a metal electrode at each end. Water jackets are provided for cooling purposes.

Light-emitting diodes (LED)

Light-emitting diodes are semiconductor devices that are directly modulated by varying input current. They are usually made of aluminum-gallium-arsenide (AlGaAs). However, other dopants may be added to vary wavelength. LEDs are common in fiber-optic communication, pocket calculators, and other visual displays. These devices can emit light in both the visible and infrared regions of the spectrum. Unlike a semiconductor laser (a laser pointer for example), a light-emitting diode emits light in all directions and has a low irradiance. Power from LEDs generally is in the microwatt range up to maybe a few milliwatts. LEDs are small in size, low temperature, rugged, and inexpensive devices. They operate with *pn* junctions (see Figures 3-8a and 3-8b). In a *pn* junction, two slabs of different semiconducting materials are put together with the *n* material having an excess of electrons and the *p* material having a deficiency of electrons—that is an excess of holes. Each time an electron falls into a hole (recombination), a photon of light is emitted (see Figure 3-8c). The emitted photons produce an incoherent beam of light. When current flows across a *pn* junction, free electrons from the *n*-type material are forced to combine with holes in the *p*-type material and release energy. The entire device is no larger than a grain of sand.

(a) *pn* junction

(b) Movement across junction



(c) Photon generation

Figure 3-8 Simplified theory of LED operation

Concepts of Laser Safety

The use of lasers by industry and by the academic community continues to increase. Many educational institutions are using a wide variety of lasers in many different ways. Traditional disciplines in universities, colleges and high schools, such as biology, chemistry, and physics, now recognize the laser as an essential teaching element. Unique environments associated with educational institutions (such as civil engineering, earth and planetary sciences, and biomedical research) have also incorporated lasers into their educational processes. The objective of this

section is to provide *reasonable and adequate guidance* for the safe use of lasers by evaluating and minimizing hazards associated with laser radiation in educational and workplace environments. The hazard evaluation procedure used is based on the ability of the laser beam to cause biological damage to the eye or skin during intended use, and is related to the classification of the laser or laser system from Class 1, considered to be nonhazardous, to Class 4, very hazardous. Lasers or laser systems are certified by the manufacturer for the specific hazard class in accordance with the Federal Laser Product Performance Standard.

A Eye hazards

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The eye is the part of the body most vulnerable to laser hazards. Damage to the eye can occur at much lower laser power levels than damage to the skin. And, injuries to the eye are generally far more serious than injuries to the skin.

The human eye is a complex optical system. It is designed to receive, focus, and detect light. The normal human eye is roughly the shape of a slightly elongated sphere. It's about the size of a quarter (25 mm, or about 1 inch) in diameter. The outer white layer of the eye is called the **sclera**. The sclera—with the aid of the internal fluids (vitreous humor and aqueous humor)—helps to maintain the shape of the eye.

Light passes into the front portion of the eye through the **cornea**. The light that enters is focused to a spot on the back of the eye, the **retina**. There it forms an image on cells especially designed for light detection. Sensitive nerve cells relay the optical image—in the form of electrical signals—to the brain for interpretation. Figure 3-9 shows the essential parts of the human eye. The light irradiance (in units of watts/m²) of the image formed on the retina is 100,000 times greater than the light irradiance at the front of the eye. It is this considerable *optical gain* that creates an eye hazard when stray laser beams enter the eye.

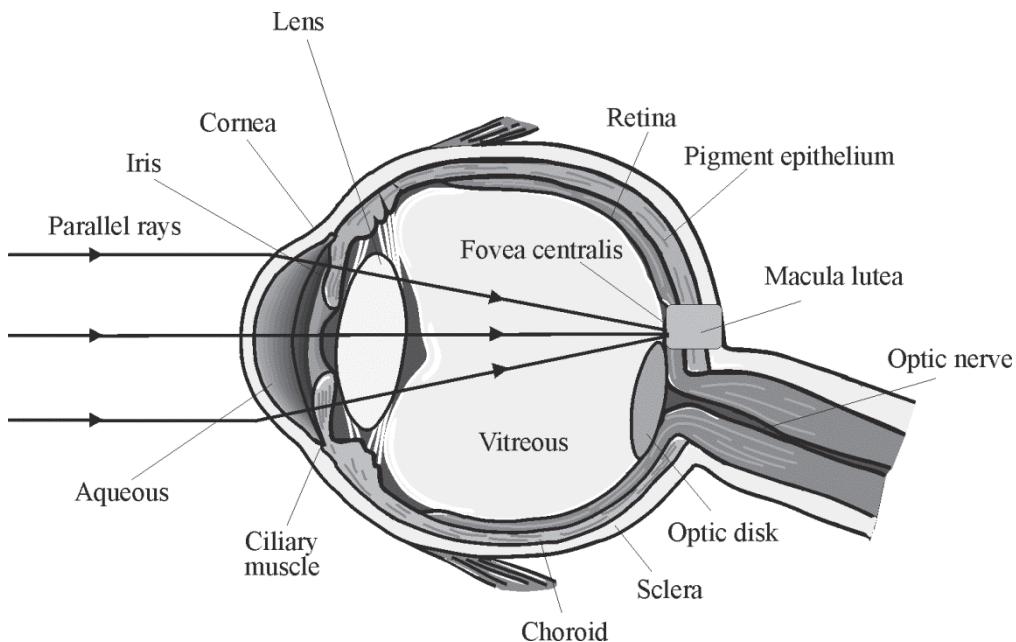


Figure 3-9 Schematic diagram of the eye

The **cornea** is the outermost, transparent layer. It covers the front of the eye. The cornea can withstand dust, sand, and other assaults from the environment. That's partly because corneal cells replace themselves in about 48 hours. Thus, mild injuries to the cornea are healed quickly.

The **aqueous humor** is a liquid (mostly water) between the cornea and the lens. The water in the aqueous humor absorbs heat, so it protects the internal portion of the eye from thermal (heat) radiation. The index of refraction is approximately 1.33, same as water.

The **lens** of the eye is a flexible tissue that changes shape. In conjunction with the cornea, the lens focuses light on the back of the eye. When the lens changes shape, its focal length also changes. This enables the eye to focus on both near and far objects.

The **iris** controls the amount of light that enters the eye. The iris is the pigmented or colored part of the eye. It responds to light intensity by adjusting its size. The change in iris size adjusts pupil size and controls the amount of light admitted to the eye.

The **pupil** is the opening in the center of the iris through which light passes. The size of a pupil changes from about 2 mm to 7 mm, according to the brightness of light in the environment. The darker the environment, the larger the pupil will be. A fully dilated pupil (expanded to admit the greatest amount of light) is considered to be about 7 mm.

The **vitreous humor** is a colorless gel that fills the large area at the center of the eyeball. The vitreous humor helps to maintain the shape of the eye.

The **retina** is the light-sensitive layer located at the back of the eye. Think of it as a sort of viewing screen on which the cornea and lens focus an image. The retina contains two types of photoreceptor (light-receiving) cells: rods and cones. These cells convert the optical image produced by the lens into electrical signals. The signals then are transmitted to the brain. The **fovea** is the most sensitive, central part of the retina. It's the area responsible for the most detailed vision. A foveal lesion caused by laser radiation is a worst-case scenario for vision. The **optic nerve** carries electrical impulses from the retina to the brain.

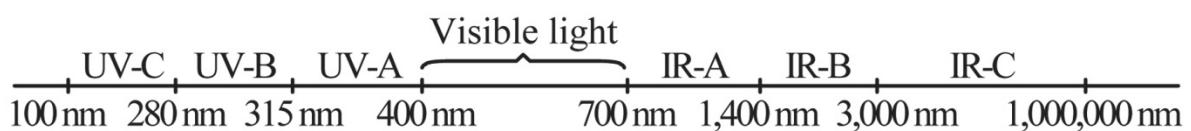
Absorption of radiation by the eye

Certain areas of the eye absorb more light in one spectral region than in other regions. Absorption of laser radiation above a certain level leads to tissue injury. Figure 3-10 shows some absorption characteristics of the eye for different electromagnetic radiation wavelengths. Shorter wavelengths of ultraviolet (UV-C and most UV-B), which range from 315 nm to 280 nm for UV-B and 280 nm to 100 nm for UV-C, are absorbed primarily in the cornea (see Figure 3-10a). Longer wavelengths of ultraviolet light (UV-A), which range from 315 nm to 400 nm, are absorbed principally in the lens of the eye (see Figure 3-10b).

Radiation in the visible and IR-A (400 nm to 1400 nm—Figure 3-10c) is the most hazardous and is transmitted by the optical components of the eye. It eventually reaches the retina, where most of the radiation is absorbed in the retinal pigment epithelium and in the choroid, a dark brown layer with exceptionally large blood vessels and high blood flow rate. Some infrared radiation in the IR-A, which ranges from 700 nm to 1400 nm, and IR-B, which ranges from 1400 nm to 3000 nm, is absorbed by the lens. Far-infrared radiation, which ranges from 3000 nm to 1 mm, is absorbed primarily by the cornea. Table 3-1 identifies different wavelength regions coded by symbols from IR to UV. The scale below the table indicates the relative position of these regions based on wavelength.

Table 3-1

Laser Wavelength Regions	
IR-C	= 1 mm to 1400 nm
IR-B	= 3000 nm to 1400 nm
IR-A	= 1400 nm to 700 nm
Visible light	= 700 nm to 400 nm
UV-A	= 400 nm to 315 nm
UV-B	= 315 nm to 280 nm
UV-C	= 280 nm to 100 nm



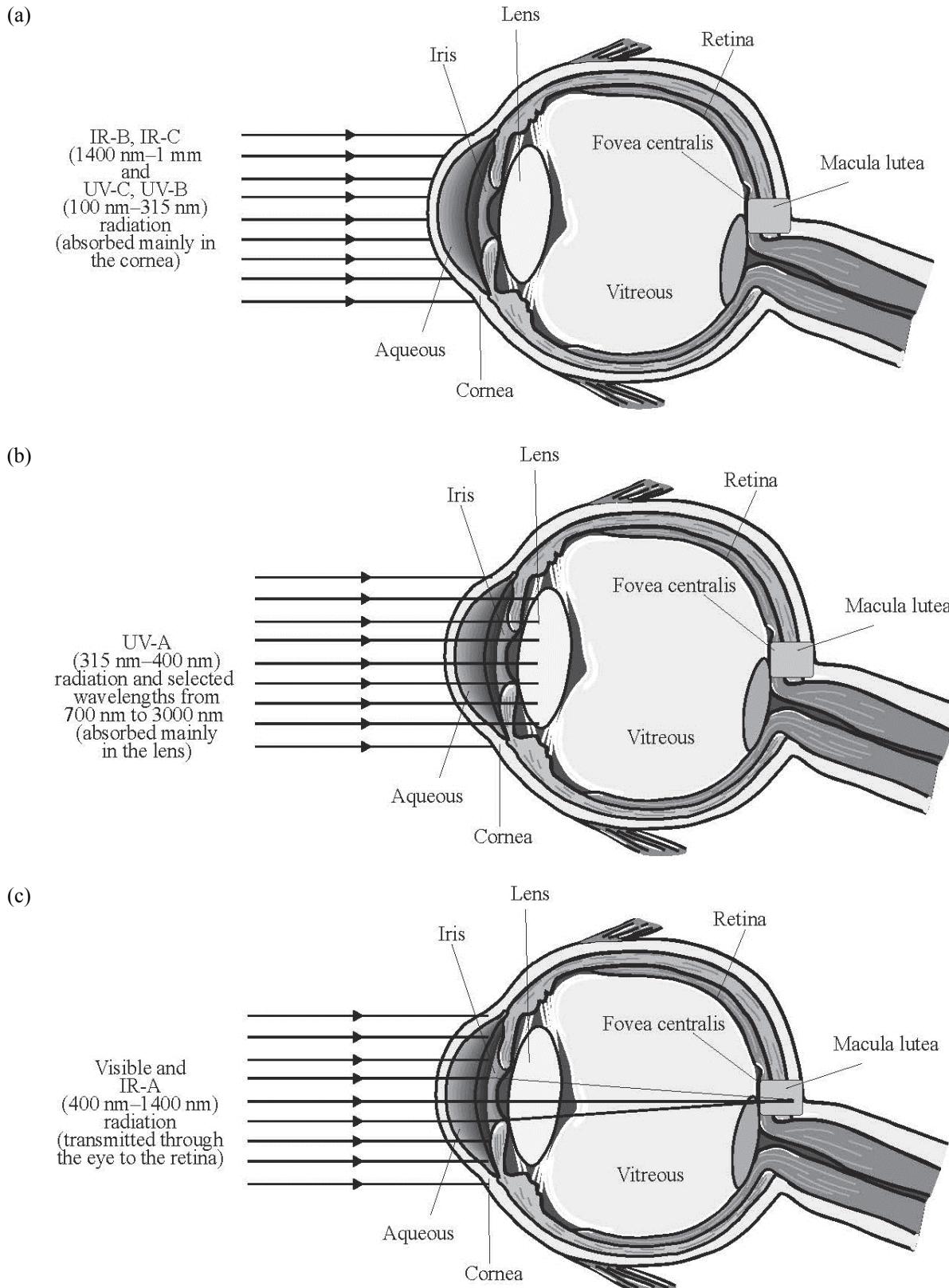


Figure 3-10 Absorption characteristics of the eye for different wavelengths

Figure 3-11 gives a representation of the electromagnetic spectrum somewhat different from the one presented in Module 1-1, *The Nature and Properties of Light*. This drawing indicates the position of IR, visible, and UV as related to other wavelengths, but without detail on wavelength and frequency values for each region.

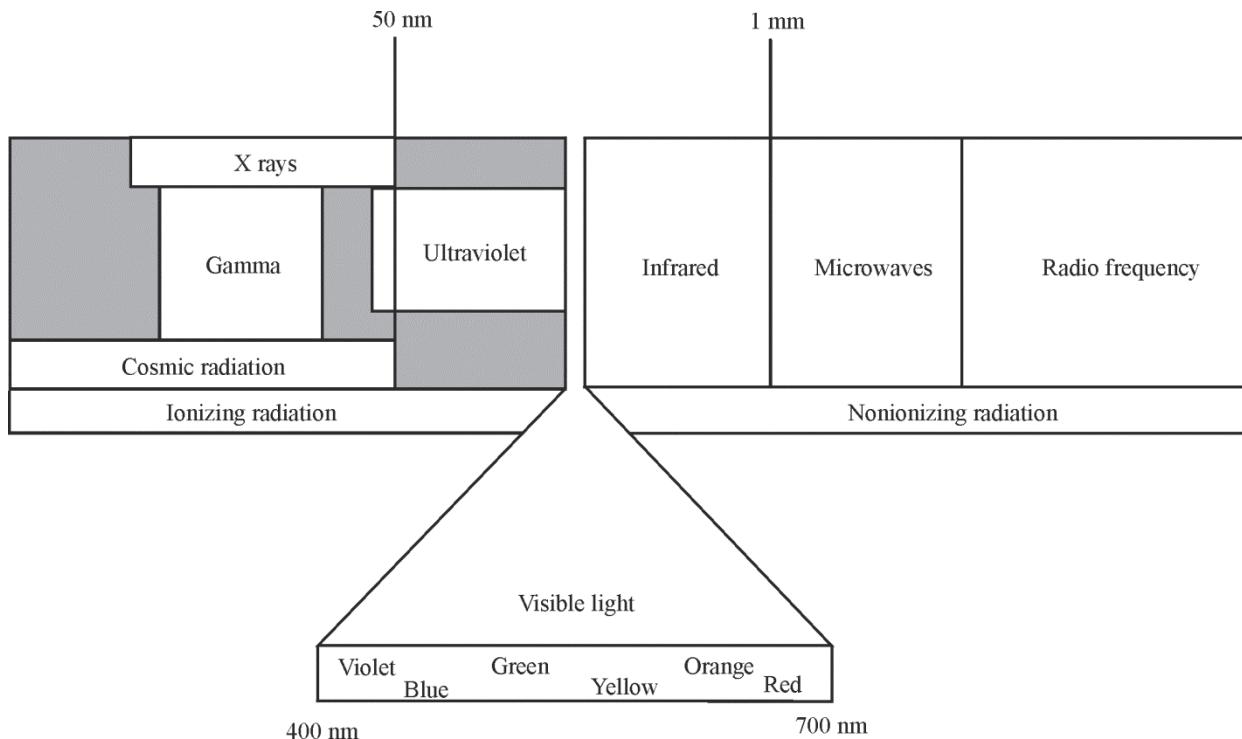


Figure 3-11 Important regions of the electromagnetic spectrum

An important quantity of measure related to laser damage to the eye is retinal irradiance (E), defined as power per unit area, usually expressed in W/cm^2 or mW/cm^2 .

$$E = \frac{\text{power (W)}}{\text{area (cm}^2\text{)}} \quad \text{or} \quad E = \frac{\text{power (mW)}}{\text{area (cm}^2\text{)}} \quad 3-1$$

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Irradiance is much higher at the retina than at the cornea or lens. That's because the laser light is focused by the cornea and a strong converging lens to a small area on the retina, as shown in Figure 3-12. This focusing accounts for the optical gain discussed earlier.



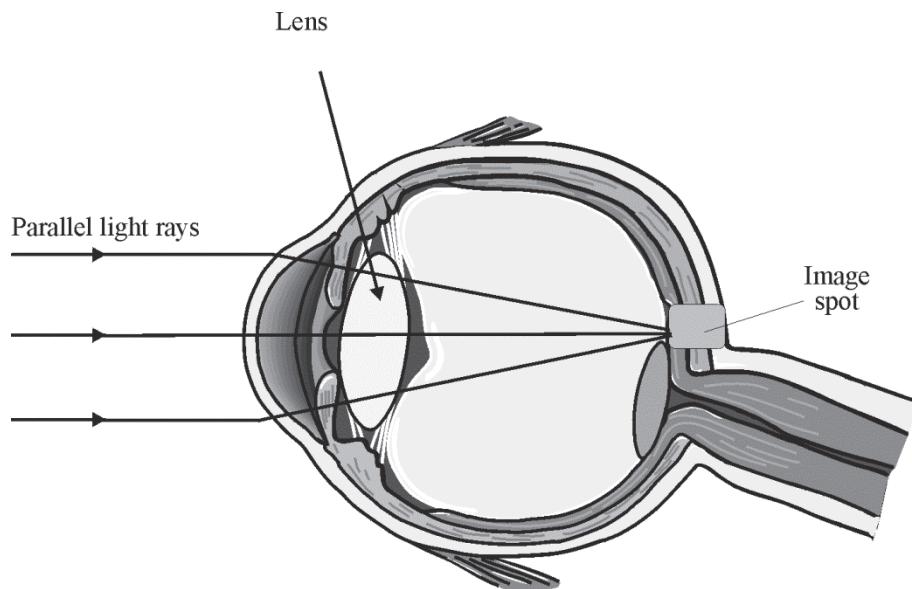


Figure 3-12 Focusing of parallel light rays from a distant source or laser beam to a small spot on the retina

The reduced size of the irradiated area means higher values of irradiance. In the condition called **intrabeam viewing**, shown in Figure 3-13, the focusing of the incident beam causes a tremendous increase of irradiance. Example 1 takes you through the calculation of the irradiance at the retina.

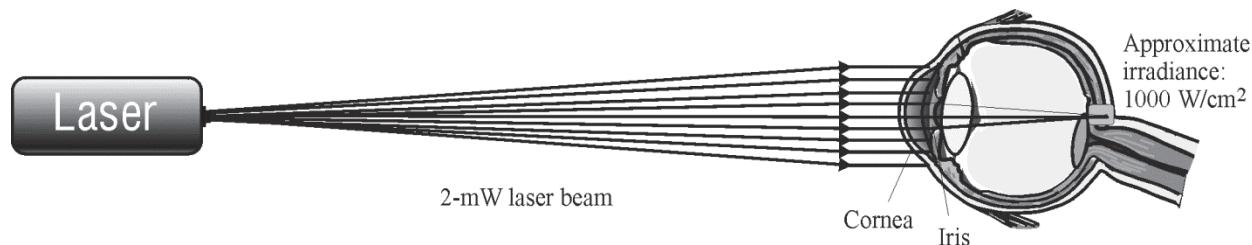


Figure 3-13 Intrabeam viewing conditions with eye intercepting a laser beam

Example 1

Irradiance of a Focused Laser Pointer Beam on the Retina

A laser pointer produces a 2-mW beam. The total beam cross section enters the eye and is focused by the cornea and lens to a spot on the retina of $16 \mu\text{m}$ in diameter.

Given: Power $P = 2 \text{ mW}$

Retinal spot diameter $d = 16 \mu\text{m} = 16 \times 10^{-6} \text{ m} = 1.6 \times 10^{-5} \text{ cm}$

Find: The irradiance on the retina, assuming that all of the 2 mW of power is focused on the retina.

Solution: Area of spot A :

$$A = \frac{\pi d^2}{4}$$

$$A = \frac{(3.14)(1.6 \times 10^{-3} \text{ cm})^2}{4}$$

$$A \cong 2 \times 10^{-6} \text{ cm}^2$$

Irradiance E :

$$E = \frac{P}{A}$$

$$E = \frac{2 \times 10^{-3} \text{ W}}{2 \times 10^{-6} \text{ cm}^2}$$

$$E = 1000 \text{ W/cm}^2$$

Example 2

A 1-mW HeNe laser beam with a divergence of 0.5 mrad enters the eye. Find the irradiance on the retina if the focal length of the eye, from cornea to retina, is equal to $f = 1.7 \text{ cm}$.

Given: Power $P = 1 \text{ mW}$

Full-angle divergence (beam spread) $\theta = 0.5 \text{ mrad}$

$f = \text{focal length of eye focusing system } (1.7 \text{ cm})$

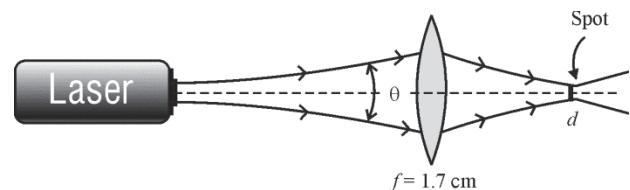
Solution: The solution to this problem requires three steps:

1. Calculate focal spot diameter. (Note: Laser propagation theory shows that, when a laser beam of divergence θ is focused by a lens of focal length f to a spot of diameter d , the spot diameter d is given by $d = f\theta$.)
- Therefore,

$$d = f\theta$$

$$d = (1.7 \text{ cm})(0.5 \times 10^{-3} \text{ rad})$$

$$d = 8.5 \times 10^{-4} \text{ cm}$$



2. Calculate the area of the spot.

$$A = \frac{\pi d^2}{4}$$

$$A = \frac{\pi(8.5 \times 10^{-4} \text{ cm})^2}{4}$$

$$A = 5.7 \times 10^{-7} \text{ cm}^2$$

3. Calculate the retinal irradiance.

$$E_{\text{Ret}} = \frac{\text{Power in beam focused on retina}}{\text{Area of focused spot}}$$

$$E_{\text{Ret}} = \frac{1 \times 10^{-3} \text{ W}}{5.7 \times 10^{-7} \text{ cm}^2}$$

$$E_{\text{Ret}} = 1.75 \times 10^3 \text{ W/cm}^2$$

The skin

The risk of skin injury by lasers might seem to be greater than the risk of eye damage because we have so much more skin tissue than eye tissue. In fact, potential risks to the skin are considered secondary to risks to the eyes. This is because skin injuries don't often have the dire consequences (such as partial loss of vision) that eye injuries do. Skin injuries may affect only the external dead layer of the skin cells. And even a more penetrating damage usually will heal eventually. Large-area exposures that can lead to serious skin infections and other complications are not commonly associated with laser use because the beam is relatively small.

Laser radiation can affect the skin thermally or photochemically. To understand the effects of optical radiation on the skin, some knowledge of the anatomy of the skin is helpful.

Skin consists of two main layers: the **epidermis** (surface layer) and the **dermis** (the underlying layer). The layers are shown in the greatly enlarged diagram in Figure 3-14.

The outermost layer of the epidermis is the **stratum corneum**. It consists mainly of dead cells. The stratum corneum gives protection against water loss, abrasion, dust, air, and radiant energy. This layer of dead cells is about 8 μm to 20 μm thick.

In the layer of the epidermis just below the stratum corneum, there are specialized cells that produce melanin pigment granules. Once produced, these granules migrate throughout the epidermis. They help to protect the dermis against harmful ultraviolet radiation. As they absorb radiation, they darken. So they're responsible for the skin's color change during suntanning. The entire epidermis averages about 0.1 mm in thickness.

The **dermis** is the site of many specialized cells and glands. It contains mostly connective tissue that gives elasticity and support to the skin. The dermis also has numerous blood vessels, nerve cells, sweat glands, and hair follicles. Sweat glands have an essential role in regulating body temperature. Sweat allows for evaporative cooling of the body and, in this way, gets rid of excess heat. Nerve cells include heat sensors, cold sensors, pain sensors, and tactile (touch) sensors. Blood vessels allow for the maintenance of healthy tissue and play an important role in heat regulation.

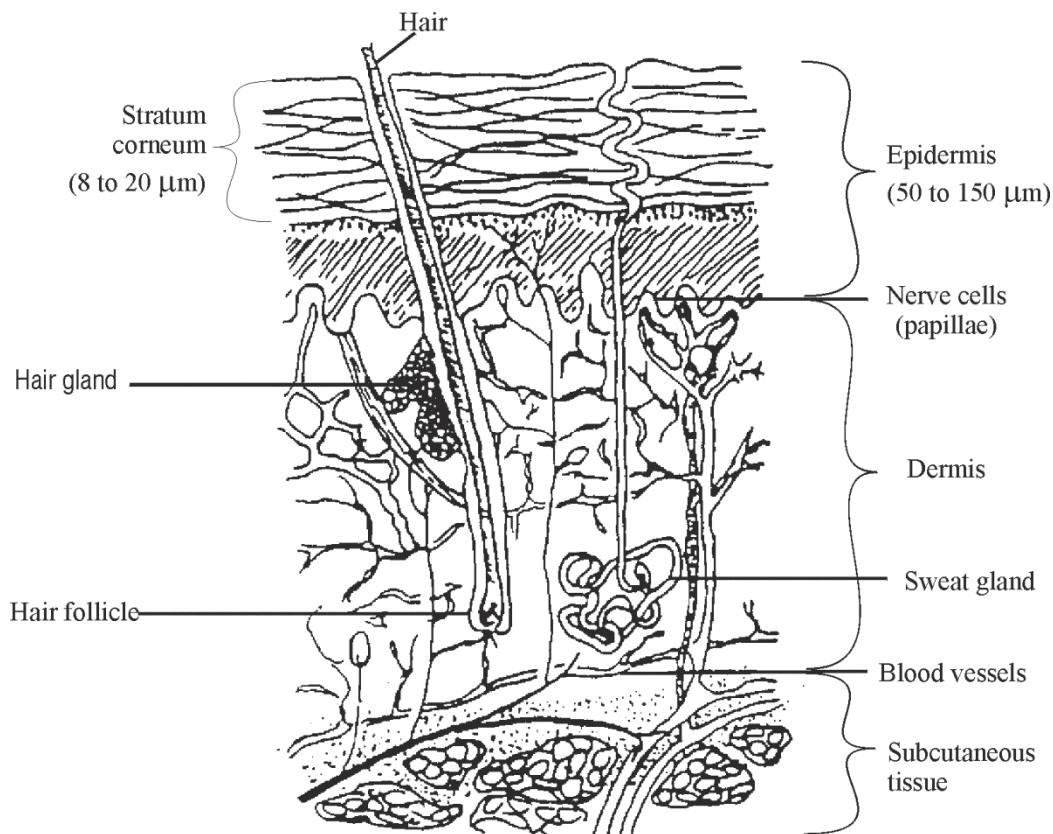


Figure 3-14 Anatomy of the skin

The skin reflects most visible and IR-A (near-infrared) radiation. The epidermis is highly absorbing at UV-B and UV-C wavelengths and at IR-B and IR-C wavelengths. The skin is less sensitive to UV-A than to UV-B or UV-C. The melanin granules of the epidermis absorb much of the ultraviolet radiation incident upon the skin and, as mentioned, thus protect the dermis from harmful UV. However, with enough power and duration, the incident radiation of any wavelength in the optical spectrum can penetrate the protective filter of the epidermis and cause deep internal injury.

Ultraviolet radiation in the UV-B and UV-C regions causes reddening (sunburn) and eventual tanning—known as erythema—of the skin. Erythema is a photochemical occurrence. Chronic exposures to UV are known to accelerate aging of the skin. They increase the risk of skin cancer. We don't know the precise wavelength range that may lead to the occurrence of cancer, but UV-B has been implicated by some studies.

Laser-induced thermal change to the skin is most pronounced at far-infrared wavelengths such as are produced by CO₂ lasers. Thermal damage also can be caused by visible and near-infrared wavelengths, but at higher irradiance values than for far-infrared laser beams.

The pain from thermal injury to the skin by most lasers is enough to alert the user to move out of the beam path. However, a number of high-power visible and IR lasers now are used. They are capable of producing significant burns to the skin in much less than one second. Users may not be able to move out of the beam path before serious injury occurs.

Laser Safety Standards and Safety Classifications

The primary laser safety standard in use today is the ANSI (American National Standards Institute) Z-136.1. A new laser safety standard for educational institutions ANSI A-136.5 was made available in 2000. Both standards can be obtained from the Laser Institute of America in Orlando, Florida. ANSI is a nonprofit organization for which expert volunteers participate on committees to set standards in various fields. In 1969, ANSI addressed the issue of laser safety at the request of the U.S. Department of Labor. The resulting standard (ANSI Z-136), issued in October 1973, was directed primarily to users: operators, technicians, laser safety officers, safety engineers, and research personnel. The standard has been revised five times since 1980 with the latest revision completed in 2007. It provides guidance for the safe use of lasers and laser systems by defining control measures for each of the four broad laser classifications. However, technical information on measurements, calculations, and biological effects also are provided for those who want to carry out their own measurements and calculations.

Laser hazard classifications

The most important criterion you will use in applying laser safety control measures is the hazard classification designated by manufacturers on the equipment labels. Certain controls are required for each class. Below you will find both the 2000 and 2007 ANSI Z-136.1 Laser Classifications. Both are provided because many laser systems before and even after 2007 use the old classification system.

2000 ANSI Z-136.1 Laser Classifications

Class 1 (exempt lasers) cannot, under normal operating conditions, emit a hazardous level of optical radiation. Included in this category is laboratory equipment using lasers with all beam paths and reflections enclosed.

Class 2, or a low-power visible laser device of 1 milliwatt, does not have enough output power to injure a person accidentally, but may injure the eye when stared at for a long period. A “caution” label must be on the device. Many HeNe lasers are Class 2 but not all. These lasers are used for alignment procedures and optical experiments.

Class 3a lasers—rated in power from 1 milliwatt to 5 milliwatts—cannot injure a normal person when viewed with the unaided eye but may cause injury when the energy is collected and put into the eye as with binoculars. Most *laser pointers* fall into this category. A danger or caution sign must label the device, depending on its irradiance.

Class 3b lasers from 5 milliwatts to 500 milliwatts can produce eye injury when viewed without eye protection. This class of laser requires a danger label and could have dangerous specular reflections. *Eye protection is required.*

Class 4 lasers above 500 milliwatts in power can injure you by directly viewing either the specular or diffuse reflections of the beam. A danger sign will label this laser. These lasers can also present a fire hazard. *Eye and skin protection is required.*

2007 ANSI Z -136.1 Laser Classifications

Class 1 lasers or laser systems may produce visible or invisible laser radiation. Under all normal conditions of operations, Class 1 lasers are considered to be incapable of causing injury from directly viewing the beam.

Class 1M lasers may produce visible or invisible laser radiation. A Class 1M laser or laser system is considered to be incapable of producing hazardous exposure conditions during normal operation unless the beam is viewed with an optical instrument such as an eye-loupe (diverging beam) or a telescope (collimated beam). Such viewing is prohibited by this standard.

Class 2 lasers produce low-power visible laser radiation. The output power of a Class 2 laser does not exceed 1 mW and eye protection is normally afforded by the natural aversion response (blink reflex) time (0.25 s). Direct viewing of Class 2 laser radiation is prohibited.

Class 2M lasers or laser systems emit visible laser radiation and eye protection is normally afforded by the natural blink reflex time (0.25 s). However, direct viewing of Class 2M laser radiation with certain optical aids is potentially hazardous and is prohibited.

Class 3R lasers produce moderate levels of visible or invisible laser radiation and require more stringent controls than Class 2 lasers. The CW output power of a Class 3R visible laser is between 1 to 5 mW and the normal aversion response is generally sufficient to prevent injury from inadvertently viewing the output with the unaided eye. Eye exposure to Class 3R lasers that produce ultraviolet light or infrared emissions may not be perceived by the eye at the end of injury. For such lasers, the Class 3R accessible emission limit does not rely upon the normal aversion response, but rather on the fact that the eye does not fixate on the beam long enough to cause injury. However, the use of collecting optics, e.g., binoculars, can produce retinal irradiances that are considered capable of causing injury. Optically aided eye exposure to Class 3R lasers that produce ultraviolet or infrared emissions may not be perceived by the eye.

Class 3B lasers may produce visible or invisible emissions. The output power of the CW visible and infrared Class 3B lasers range from 5 to 500 mW. They are considered medium power lasers and are capable of producing eye injury when viewed directly or with optics, even if viewed momentarily. For visible Class 3B lasers, the normal aversion response (0.25 s) does not prevent injury. Class 3B lasers do not usually produce a hazardous diffuse reflection or fire hazard. At the upper end of the Class 3B range, skin burns may be possible.

Class 4 lasers are visible or invisible lasers emitting radiation capable of causing injury to the eye and skin as well as producing dangerous specular and diffuse reflections. They can also produce a fire hazard.

Z136.1 (2000)	Z136.1 (2007)
Class 1	Class 1 Class 1M
Class 2	Class 2 Class 2M
Class 3	Class 3R
Class 3b	Class 3B
Class 4	Class 4

Types of controls: Engineering, administrative, personal protective

The hazards posed by Class 3b, Class 3B, and Class 4 lasers require systematically applied controls to prevent skin and eye injuries. First, we will examine the types of controls available. Control measures may be broken down into three main types: engineering controls, administrative controls, and personal protective equipment.

Engineering controls involve design features or devices applied to the laser, laser beam, or laser environment that restrict exposure or reduce irradiance. Such controls include beam shutters, beam attenuators, remote firing and monitoring systems, and the protective housing placed entirely around some laser systems.

Administrative control measures involve procedures and information rather than devices or mechanical systems. Some important administrative controls are posting of warning signs and labels, establishment of standard operating procedures (SOP), and safety training.

Personal protective equipment is worn by personnel using the laser or being in the vicinity of the laser. This control includes protective eyewear, gloves, and special clothing. Table 3-2 lists some of the more commonly used control measures for Class 3b, Class 3B, and Class 4 lasers and laser systems.

Table 3-2. Control Measures for Class 3b, Class 3B, and Class 4 Lasers

Engineering Controls	Administrative and Procedural Controls	Personal Protective Equipment
Protective housing and service panel	Laser safety officer (LSO)	Eyewear
Interlocks on the protective housing	Standard operating procedures	Clothing
Door interlocks and remote-control connector	Limitations on use by class	Gloves
Beam attenuators and beam shutters	Entry limitations for visitors	
Key switch or padlock	Education and training	
Filtered viewing optics and windows	Maintenance and service manuals	
Emission delay	Marking of protective devices	
Warning lights, emission indicators	Warning signs and labels	
Beam enclosure		
Controlled beam path		
Laser controlled area		
Beamstops		
Remote firing and/or monitoring		

* David Sliney and Myron Wolbarsht, *Safety with Lasers and Other Optical Sources: A Comprehensive Handbook* (New York: Plenum Press, 1980), p. 512.

Maximum permissible exposure (MPE)

How much exposure to laser light is hazardous? To answer this question, you have to take into account the output characteristics of the laser. Those characteristics include wavelength, output energy and power, size of the irradiated area, and duration of exposure. If you're using a pulsed laser, you also must consider the pulse repetition rate.

Sensitivity to a given wavelength varies significantly from person to person. **Maximum permissible exposure (MPE)** limits indicate the greatest exposure that most individuals can tolerate without sustaining injury. The MPE involves both an incident *irradiance* level **and** an *exposure* time. Thus, an MPE is usually expressed in terms of the allowable exposure time (in seconds) for a given irradiance (in watts/cm²) at a particular wavelength. Table 3-3 gives the maximum permissible exposure for the eye for a variety of lasers operating at different irradiance levels. For example, Table 3-3 indicates that, for an argon laser operating at 0.514 μm, the MPE is 2.5×10^{-3} W/cm² for an exposure time of 0.25 seconds and 1×10^{-3} W/cm² for an exposure time of 3×10^4 seconds. MPEs are useful for determining optical densities for eyewear or windows.

Table 3-3. Point Source MPEs for the Eye for Commonly Used Lasers
(Reference: ANSI Z136.5 2009)

Laser Type	Wavelength (μm)	MPE (watts/cm ²)		
		Exposure time in seconds		
		t=0.25 s	t=10 s	t=3 × 10 ⁴ s
CO ₂	10.6	—	0.1	0.1
Nd:YAG (CW) ^a	1.33	—	40×10^{-3}	40×10^{-3}
Nd:YAG (CW)	1.064	—	5.0×10^{-3}	5.0×10^{-3}
Nd:YAG Q-switched ^b	1.064	—	17×10^{-6}	17×10^{-6}
Nd:YAG (freq doubled)	0.532	2.5×10^{-3}	—	1.0×10^{-3}
GaAs (diode)	0.840	—	1.9×10^{-3}	1.9×10^{-3}
InGdAlP (diode)	0.670	2.5×10^{-3}	—	1.0×10^{-3}
HeNe	0.633	2.5×10^{-3}	—	1.0×10^{-3}
Krypton	0.647	2.5×10^{-3}	—	1.0×10^{-3}
	0.568	2.5×10^{-3}	—	1.0×10^{-3}
	0.530	2.5×10^{-3}	—	1.0×10^{-3}
Argon	0.514	2.5×10^{-3}	—	1.0×10^{-3}
XeF ^c	0.351	—	—	33.3×10^{-6}
XeCl ^c	0.308	—	—	1.3×10^{-6}

a A less commonly used wavelength

b Operating in repetitive pulse duration mode at 11 Hz, 12-ns pulse, 20 mJ/pulse

c When repeated exposure levels on successive days are anticipated to approach the MPE, the MPE must be reduced by a factor of 2.5.

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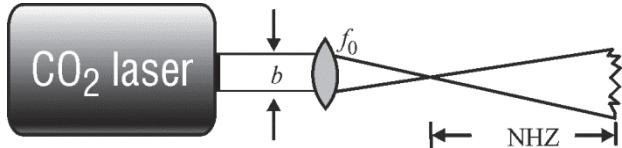


Another quantity of interest in laser safety is called the **Nominal Optical Hazard Distance (NOHD) also known as the Nominal Hazard Zone (NHZ)**. These terms are used interchangeably in this text. This zone describes the region within which the level of direct, reflected, or scattered (diffuse) laser radiation is above the allowable MPE. Example 3 shows how to calculate an NHZ for a given laser and given MPE. Table 3-4 lists nominal hazard zones for three common lasers. The data used in the NHZ calculations for the three lasers listed in Table 3-4 are given in Table 3-5.

Example 3

Nominal Hazard Zone Calculation

A CO₂ laser with a power P of 500 W and exit beam diameter b out of the laser of 3 cm is focused by a convex lens of focal length $f_0 = 20$ cm. Determine the nominal hazard zone (NHZ) measured from the focal point of lens. (Note: From laser safety theory, it is shown that the NHZ for a laser of given power and exit beam diameter b is given by the formula $\text{NHZ} = \frac{f_0}{b} \left(\frac{4P}{\pi(\text{MPE})} \right)^{\frac{1}{2}}$.



Given:

- $P = 500$ W (power)
- $f_0 = 20$ cm (focal length of lens)
- $b = 3$ cm (beam diameter at exit port of laser)
- MPE = 0.1 W/cm² at either 10 seconds or 3×10^4 seconds (Refer to Table 3-3 or Table 3-5.)

$$\text{NHZ} = \frac{f_0}{b} \sqrt{\frac{4P}{\pi \text{ MPE}}}$$

$$\text{NHZ} = \frac{20}{3} \sqrt{\frac{4 \cdot 500}{3.14 \cdot (0.1)}}$$

$$\text{NHZ} = (6.67)(79.8) = 532 \text{ cm}$$

$$\text{NHZ} = 5.32 \text{ m}$$

Note that this value agrees with the entry in Table 3-4 for a CO₂ laser with an exposure duration of either 3×10^4 s (8 h) or 10 s, with a lens-on-laser.

Table 3-4. NOHD or NHZ for Various Lasers and Exposure Criteria

Laser Type	Exposure Criteria	NOHD or NHZ (m)		
		Diffuse	Lens-on-Laser	Direct
Nd:YAG	8 hr	0.56	16.9	376
	10 s	0.56	16.9	376
CO ₂	8 hr	0.40	5.3	390
	10 s	0.40	5.3	390
Argon	8 hr	0.52	70	1000
	0.25 s	0.25	33.6	490

Notes: See Table 3-5 for laser criteria.

The information in Table 3-5 is required for calculating the extent of the NOHD or NHZ and should be obtained from the manufacturer of the laser or laser system.

Table 3-5. Criteria Used for the Calculations in Table 3-4

Laser Parameter	Nd:YAG	CO ₂	Argon
Wavelength (μm)	1.064	10.6	0.488
Beam power (W)	50.0	500.0	5.0
Beam divergence (mrad)	3.0	2.0	1.0
Beam size at aperture (mm)	3.0	20.0	2.0
Beam size at lens (mm)	5.0	30.0	3.0
Lens focal length (mm)	75.0	200.0	200.0
MPE: 8 hours (mW/cm^2)	5.0	100	5.8×10^{-3}
MPE: 10 s (mW/cm^2)	5.0	100	—
MPE: 0.25 s (mW/cm^2)	—	—	2.5

Absorption, Lambert's law, and optical density

A
84,
106

In general, when a light beam is transmitted through a transparent material, some of the light energy is *absorbed* and, at times, *scattered*, and the beam intensity decreases continuously. Here let us concentrate on absorption. The absorption may be minimal, as in air, or considerable, as in a dark piece of glass. In each case, the absorption process removes energy from the beam and converts it to thermal energy of the transparent medium—by increasing the kinetic energy of the atoms and molecules.

If a beam of irradiance E_0 watts/cm² is incident on a slab of optical material as shown in Figure 3-15, the beam irradiance decreases to a value E_x watts/cm² after passing through a thickness x of the optical material. The value of irradiance E_x at position x is given by *Lambert's law*.

$$E_x = E_0 e^{-\alpha_\lambda x} \quad 3-2$$

where E_x is the irradiance after traveling through a thickness x of the absorbing material

E_0 is the irradiance incident on the absorbing material

α_λ is the absorption coefficient

x is the absorbing thickness of the absorbing material

e is the Naperian logarithmic base

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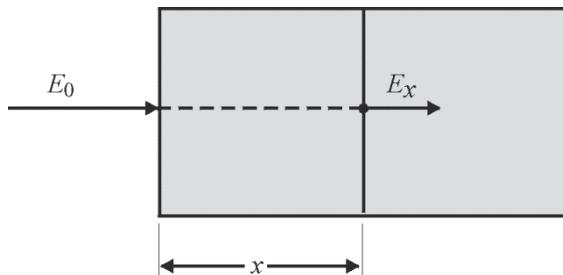


Figure 3-15 Absorption of light in transparent materials

The absorption coefficient α_λ is a property of the absorbing material and the wavelength of the light. For eye filters (used in laser safety goggles) where the absorption coefficient for the filter is known and the filter thickness is predetermined, the product $\alpha_\lambda x$ is replaced by a quantity called the *optical density*, described by the symbol OD. In that case, with the base 10 replacing the base e , Lambert's law takes the form

$$E_x = E_0 10^{-OD} \quad 3-3$$

And since the transmission of light through an absorber is defined as the ratio of E_x/E_0 , we can rewrite Equation 3-3 in a form used commonly with optical filters

$$T = 10^{-OD} \quad 3-4$$

where $OD = \text{optical density}$

$T = \text{transmission}$

Note that, since $OD = \alpha_\lambda x$, the optical density itself is a wavelength-dependent quantity. Optical density is usually labeled on the temple of the goggles or on the filter itself. Thus, if the OD of a filter is known, the transmission through the filter can be calculated from Equation 3-4. For example, laser safety eyewear with an $OD = 3$ has a transmission T of 10^{-3} or 0.1%. Table 3-6 below gives transmission values for a range of OD values.

Table 3-6. Transmission at Various OD Values

OD	Transmission	%Transmission
0	1	1.0
1	10^{-1}	10%
2	10^{-2}	1%
3	10^{-3}	0.1%
4	10^{-4}	0.01%
5	10^{-5}	0.001%
6	10^{-6}	0.0001%
7	10^{-7}	0.00001%

Suppose the maximum permissible exposure (MPE) for a given laser beam of exit irradiance E_0 is known. Then a filter must be used to reduce the incident irradiance (in W/cm²) to the permissible irradiance (in W/cm²). See Figure 3-16.

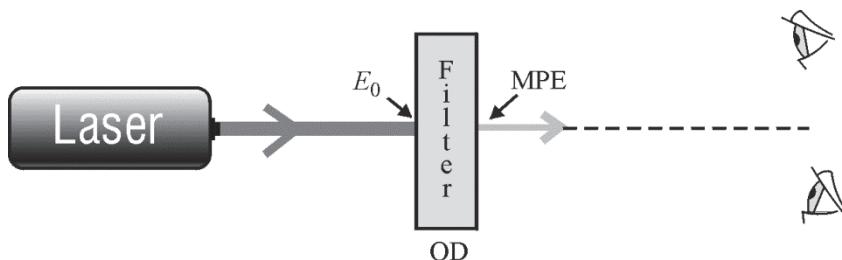


Figure 3-16 Using an optical filter to reduce beam irradiance

If we replace E_x in Equation 3-3 with MPE, we get

MPE = $E_0 10^{-OD}$ or, equivalently, $10^{+OD} = E_0 / \text{MPE}$. Solving the last expression for OD gives another useful equation.

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$$OD = \log_{10} \left(\frac{E_0}{\text{MPE}} \right)$$

3-5

Example 4 involves a sample calculation for the minimum optical density (OD) required for a specified laser power and recommended MPE.

Example 4

An Nd:YAG laser with a power of 40 watts is projected onto a fully dilated technician's eye pupil of 7-mm diameter. The eye is exposed for a duration of 10 seconds. Calculate the minimum optical density OD of a laser safety goggle needed to protect the eye from damage. Refer to Table 3-3 for the appropriate maximum permissible exposure (MPE).

Given

- Nd:YAG laser
- $\lambda = 1064 \text{ nm}$

- $t = 10$ s of exposure
- $d = \text{eye pupil diameter} = 7$ mm, when fully dilated
- $\text{MPE} = 0.0051 \text{ W/cm}^2$ (See Table 3-3 for Nd:YAG, 1.064 μm , 10-second exposure.)
- $P = 40$ W of laser power
- $A = \text{area of pupil} = \frac{\pi d^2}{4} = \frac{(3.14)(0.7 \text{ cm})^2}{4} = 0.38 \text{ cm}^2$

Solution

Using Equation 3-5, where $\text{OD} = \log_{10}\left[\frac{E_0}{\text{MPE}}\right]$ and $E_0 = P/A$, we get:

$$\text{OD} = \log_{10}\left[\frac{40 \text{ W} / 0.38 \text{ cm}^2}{0.0051 \text{ W} / \text{cm}^2}\right]$$

$$\text{OD} = \log_{10}[20,640]$$

$$\text{OD} = 4.3$$

The required optical density for the laser safety goggles would be 4.3 or larger.

Laser safety eyewear is required for Class 3b and Class 4 lasers and laser systems. Eyewear should be comfortable and in good condition, not scratched or discolored. Some filters may be clear and others tinted, depending on the wavelength of the incident laser light.

Laser safety signs

The most common signs used for lasers and laser systems are the DANGER, CAUTION, and NOTICE signs. Figure 3-17 shows samples of the signs used in laser environments prior to the year 2000. Figure 3-18 shows the new signs approved in the year-2000-revised general standard, ANSI 136.1, and the new ANSI 136.5 standard approved for educational institutions. It should be noted that those shown in Figure 3-17 may still be seen in laser-use areas since it may take years for the new signs to replace the older ones.

Caution signs are used for a Class 2 laser and some Class 3a lasers, depending on their irradiance. **Danger** signs are used on some Class 3a, Class 3b, and Class 4 lasers and laser systems. **Notice** signs are used in a temporary laser controlled area while service or repair is being done.

The top part of Figure 3-18 shows samples of the structure (lettering, symbols, and colors) of the new DANGER, CAUTION, and NOTICE warning signs. The lower part of the figure shows samples of warning signs for various levels of laser power.

The eight DANGER signs involve three (4S-1, 4S-2, and 4S-3) for Class 4 lasers; three (3BS-1, 3BS-2, and 3BS-3) for Class 3b lasers; one (3AS-1) for a Class 3a laser; and one (BDS-1) with just a “DANGER” sign. Each of the eight signs appears in white letters and symbols on a bright red background.

The three CAUTION signs—yellow background with black lettering and symbols—labeled 3AS-2, 2S-1, and BCS-1 are to be used in Class 3a and Class 2 laser environments. The single

NOTICE sign—in blue, white, and red colors—labeled TCA-1 is to be used in areas where laser repair is in progress.

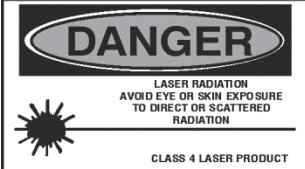
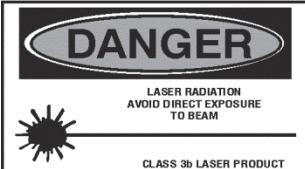
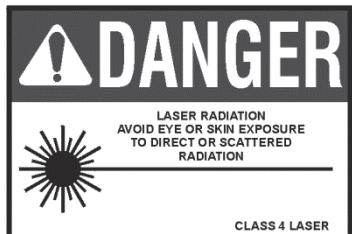
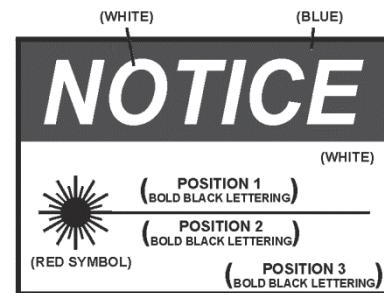
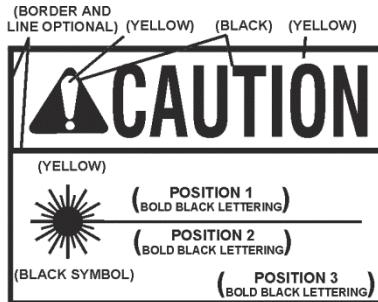
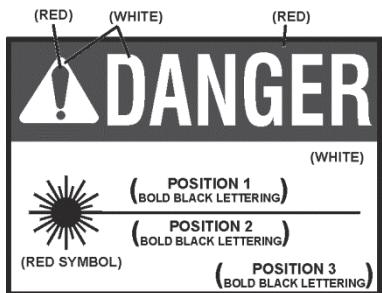
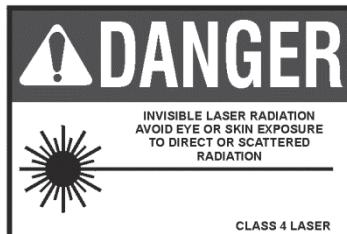
 <p>DANGER LASER RADIATION AVOID EYE OR SKIN EXPOSURE TO DIRECT OR SCATTERED RADIATION CLASS 4 LASER PRODUCT</p>	<p>Laser Area Signs are used to mark the area designated a laser hazard zone. The signs vary according to the classification of the laser or laser system. The signal word “CAUTION” is used on all signs associated with Class 2 lasers and laser systems and Class 3a lasers and laser systems that do not exceed the appropriate MPE for irradiance.</p>
 <p>DANGER LASER RADIATION AVOID DIRECT EXPOSURE TO BEAM CLASS 3b LASER PRODUCT</p>	<p>The signal word “DANGER” is used with all signs associated with all other Class 3a, and all Class 3b and Class 4 lasers and laser systems.</p>
 <p>DANGER LASER RADIATION AVOID DIRECT EYE EXPOSURE CLASS 3a LASER PRODUCT</p>	<p>Temporary Laser Controlled Area Signs are posted outside a temporary laser controlled area when the laser system is being serviced. The signal word “NOTICE” is used for this type of sign. The area outside the temporary area remains Class 1, while the area within is either Class 3b or Class 4.</p>
 <p>NOTICE LASER REPAIR IN PROGRESS DO NOT ENTER EYE PROTECTION REQUIRED</p>	<p>All signs and labels shall be conspicuously displayed in locations where they will best serve to warn onlookers.</p>
 <p>CAUTION LASER RADIATION DO NOT STARE INTO BEAM CLASS 2 LASER PRODUCT</p>	

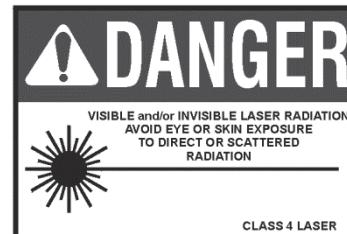
Figure 3-17 Laser area warning signs for lasers approved prior to 2000. Some may still be in use in laser environments.



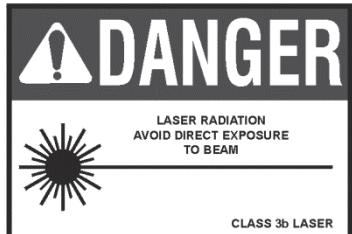
4S-1



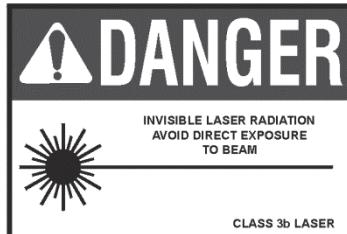
4S-2



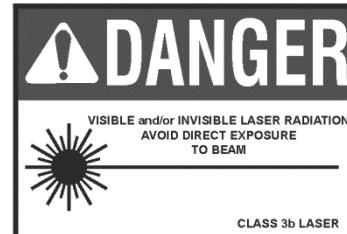
4S-3



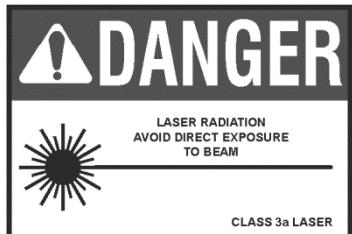
3BS-1



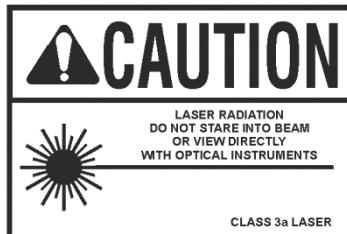
3BS-2



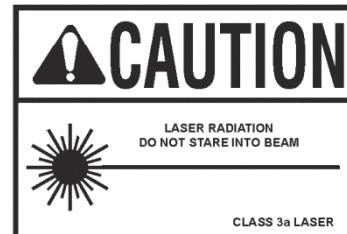
3BS-3



3AS-1



3AS-2



2S-1



TCA-1



BDS-1



BCS-1

Figure 3-18 General structure (top) and samples (bottom) of the new DANGER, CAUTION, and NOTICE warning signs adopted in the year 2000 (Note: The actual signs are in color, as described in the text. The colors do not show up on the black-and-white versions shown here.)

Laser accidents

Most laser accidents occur because adequate control measures are not in place: for example, doing alignment procedures without laser safety eyewear or wearing the wrong eyewear for the laser used. Below is a chart that summarizes the causes of most accidents using lasers. See Figure 3-19.

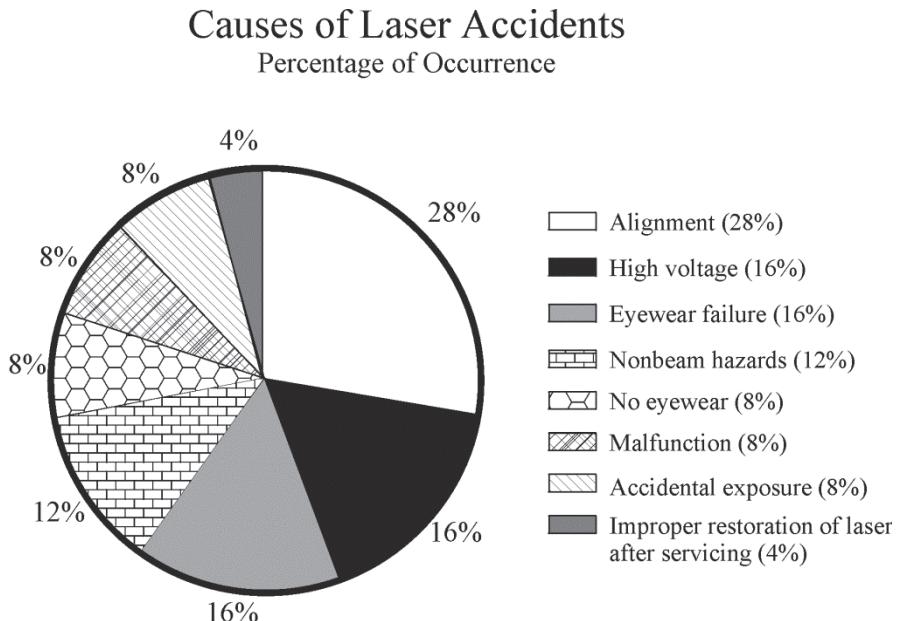


Figure 3-19 Causes of most laser accidents

As in all aspects of laboratory, field, classroom, or industrial safety, the best measures are a positive attitude and common sense.

The following list of precautions is not all-inclusive for every application, although it does represent a comprehensive collection of thoughts from a number of people who are experienced in the safe use of lasers.

Go to
<http://optecvideo.opteccrm.org/>
for a short lesson about laser safety.



Safety rules for all lasers, regardless of output power level

1. Avoid looking directly into any laser beam or at its reflection.
2. Remove all unnecessary specular (shiny) reflecting surfaces from the work area.
3. Operate lasers in well-defined areas to which access can be controlled. The area should be posted with appropriate signs to alert persons passing by the area that a potential hazard exists.
4. The laser system should be operated only by or under the direct supervision of a person knowledgeable of the hazards and control methods for both beam and nonbeam conditions. This individual is usually the laser safety officer (LSO) who is designated by the administration of the company, hospital, or educational institution. The LSO shall have the authority and the responsibility to effect monitoring and enforce the control of laser hazards and to achieve the knowledgeable control of laser hazards.
5. Any accident should be reported immediately to the responsible medical authority. If there is an accidental exposure to the eye, the services of an ophthalmologist should be sought.

Nonbeam hazards

There are four well-known nonbeam potential hazards associated with the use of lasers and laser systems.

1. Fire hazard
2. Explosion hazard
3. Electrical hazard
4. Chemical hazard

Fire hazard—Class 4 laser systems represent a fire hazard. Enclosure of Class 4 laser beams can result in potential fire hazards if enclosure materials are likely to be exposed to irradiances exceeding 10 W/cm^2 or beam powers exceeding 0.5 W. The use of flame-retardant materials is advisable and necessary.

Explosion hazard—High-pressure arc lamps, filament lamps, and capacitor banks in laser equipment shall be enclosed in housings that can withstand the maximum explosive pressure resulting from component disintegration. The laser target and elements of the optical train that may shatter during laser operation shall also be enclosed or equivalently protected to prevent injury to operators and observers. Explosive reactions of chemical laser reactants or other laser gases may be a concern in some cases.

Electrical hazard—The use of lasers or laser systems can present an electric shock hazard. This may occur from contact with exposed utility power use, device control, and power-supply conductors operating at potentials of 50 volts and above. These exposures can occur during laser setup or installation, maintenance, and service, where equipment protective covers are often removed to allow access to active components as required for those activities. Those exposed can be equipment installers, users, technicians, and uninformed members of the public, such as passersby.

The following potential problems have frequently been identified during laser facility audits.

- Uncovered electrical terminals
- Improperly insulated electrical terminals
- Hidden “power-up” warning lights
- Lack of personnel trained in current cardiopulmonary resuscitation practices, or lack of refresher training
- “Buddy system” not being practiced during maintenance and service
- Non earth-grounded or improperly grounded laser equipment
- Non-adherence to the OSHA lock-out standard (29 CFR 1910.147)
- Excessive wires and cables on floor that create fall or slip hazards

Chemical hazards—Dye lasers use a complex fluorescent organic compound that, when in solution with certain solvents, forms a lasing medium for dye lasers. Certain dyes are highly toxic or carcinogenic. Since these dyes have to be frequently changed; therefore, special care must be taken when handling, preparing solutions, and operating dye lasers.

The use of dimethylsulfoxide (DMSO) as a solvent for cyanine dyes in dye lasers should be discontinued if possible. DMSO aids in the transport of dyes into the skin. If another solvent cannot be found, low-permeability gloves should be worn by personnel any time a situation arises where contact with the solvent may occur.

LABORATORIES

Laboratory 1-3A: Irradiance

As discussed in the text, irradiance is defined as power per unit area and one of the most important concepts in regard to laser safety.

Go to
<http://optecvideo.opteccrm.org/>
for an
introduction to this activity.



Equipment

The following equipment is needed to complete this laboratory:

HeNe laser (Class 2 or 1 mW)

Photoelectric power meter

Diverging lens

Neutral-density filter, OD = 2.0 (1% transmission)

A sheet of graph paper with millimeter divisions or a metric ruler. A calibrated aperture can also be used to determine beam diameter. This aperture could be a simple hole in an aluminum sheet in the range of 2-6 mm.

Procedure

In this laboratory exercise, you will use an optical power meter to determine the power and irradiance of laser light. The power and area of a HeNe laser beam will be expanded with a diverging lens, and the irradiance will be determined at several distances. You will prepare a graph of irradiance-versus-distance from the lens.

A. Power and irradiance of a HeNe laser beam

1. Observing laser safety procedures, turn on HeNe Class 2 laser.
2. Position the sensor head of the photoelectric power meter about 10 cm from the output aperture of the laser. Turn on the power meter to a full-scale range. Measure the laser beam power and record in Table 3-7.
3. Place a neutral-density (ND) filter in the beam path to reduce its intensity.
Note: Do not handle the ND filter with your fingers since its surface is delicate. Use lens tissue and handle it only by its edges!
4. To the right of the ND filter, position a piece of graph paper (10 cm from output aperture of laser) so that the laser beam is incident upon it. Or, place a nonreflecting meter ruler there as vertical as possible. If you use an aperture, you may place that aperture 10–20 cm from the laser.

5. Calculate and record the area of the beam and the irradiance of the beam in Table 3-7.

Table 3-7. Power and Irradiance of a HeNe Laser Beam

Laser power using photoelectric power meter:

$$P = \underline{\hspace{2cm}} \text{ mW}$$

Beam diameter: $d = \underline{\hspace{2cm}}$ mm = $\underline{\hspace{2cm}}$ cm

Beam area: $A = \frac{\pi d^2}{4}$

$$A = \underline{\hspace{2cm}} \text{ cm}^2$$

Irradiance: $E = \frac{P}{A}$

$$E = \underline{\hspace{2cm}} \text{ mW/cm}^2$$

B. Irradiance of a diverging beam

1. Observing all safety precautions, turn on the laser.
2. Place a diverging lens in the laser beam about 10 cm from the laser output aperture, as illustrated in Figure 3-20. Be careful of reflections off the lens when inserting the lens in the beam. Be sure that neither reflections nor the expanded laser beam enters the eye directly.

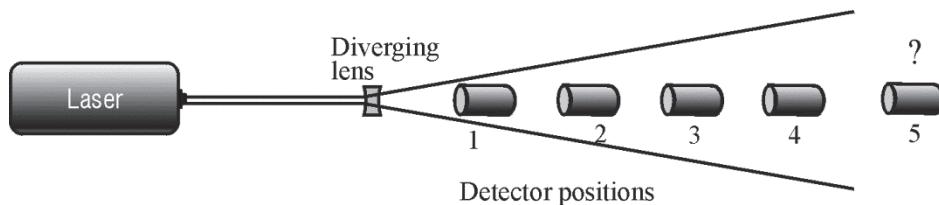


Figure 3-20

3. Measure the power of the expanded beam at four distances from the diverging lens, as indicated in Figure L-1. The beam should be larger than the detector at the nearest point, and all measurements should be made on the center of the beam. Record distances and corresponding powers in Table 3-8.
4. Calculate the irradiance at each point by dividing the power detected by the receiving area on the detector—or the area of the opening of an ambient light shade if one is used.
5. Draw a graph of irradiance-versus-distance from the diverging lens.
6. Select a fifth distance beyond the fourth measurement. Use your graph to predict the irradiance of the expanded beam distance. Measure the power at the fifth distance, calculate the irradiance, and compare the calculated value with your predicted value.

7. Describe the effect a diverging lens has on the irradiance of a laser beam.

Table 3-8. Data Table: Irradiance of a Diverging Beam

Detector area: $A = \underline{\hspace{2cm}}$ cm²

Position	Distance (cm)	Power (mW)	Irradiance (mW/cm ²)
1			
2			
3			
4			

Laboratory 1-3B: Laser Eye Protection Equipment

In this laboratory, you will complete the following tasks:

Determine the optical density of the eye protection needed to safely use a specified laser.

Find suppliers that provide this eye protection at least expensive price.

Go to
[http://optecvideo.
opteccrm.org/](http://optecvideo.opteccrm.org/)
 for an
 introduction to
 this activity.



Equipment

Laser selected by your instructor, e.g., He-Ne laser in Newport Kit: OEK-STD

Procedure

1. Ask your instructor for the power and wavelength of the laser you will be using in your lab.
 $\text{Power} = \underline{\hspace{2cm}}, \text{Wavelength} = \underline{\hspace{2cm}}$
2. Using the formulas of module 3, determine the minimum optical density of the eye protection you need.
3. Search the Internet for best prices from at least two different suppliers.

Laboratory 1-3C: Windows and Mirrors

In this laboratory, you will complete the following tasks in two separate laboratories:

Observe Fresnel reflection in an optical window. (Laboratory 3-3A)

Measure reflection and transmission coefficients of an optical window (Laboratory 3-3A)

Measure and compare reflection and transmission coefficients of front and rear surface mirrors (Laboratory 3-3B)

Go to
[http://optecvideo.
opteccrm.org/](http://optecvideo.opteccrm.org/)
 for an
 introduction to
 this activity.



Laboratory 1-3C.1

Equipment

Acrylic Block

He-Ne Laser

Optical Power Meter

Two lab jacks

Beam Stop (a book or similar object)

Note on accuracy: The results of this lab are HIGHLY sensitive to the condition of the optical surfaces. Make sure that any optical surfaces the laser strikes are very clean. Any oils from your fingers will drastically affect your results. In addition, scratches will affect your results, so choose surfaces that are as smooth as possible.

Procedure—Acrylic Block

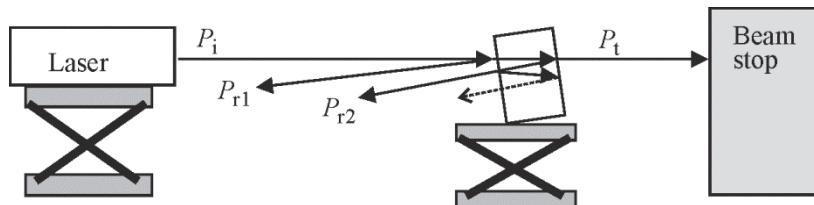


Figure 3-21

1. Place the acrylic block ($n = 1.49$) at less than 1 meter from the laser beam output. Position the acrylic block such that the two reflected beams are just barely resolved.
2. See the figure above. Measure each of the following values.
Remember that $R = [(n - 1)^2/(n+1)^2]$

$$P_i = \underline{\hspace{2cm}} \quad P_{r1} = \underline{\hspace{2cm}} \quad P_{r2} = \underline{\hspace{2cm}} \quad P_t = \underline{\hspace{2cm}}$$

3. Determine the approximate power absorbed by the acrylic block (P_a).
Formula: $P_a = P_i - P_t - P_{r1} - P_{r2}$

4. Determine the predicted value for P_{r1} .
Formula: $P_{r1} = P_i * R$

5. Determine the predicted value for P_{r2} .
Formula: $P_{r2} = (P_i - P_{r1(\text{predicted})} - P_a) * R * (1 - R)$

- Determine the predicted value for P_t .

Formula: $P_t = P_i - P_{r1(\text{predicted})} - P_a - P_{r2(\text{predicted})}$

- Determine the % error for your measured values of P_{r1} , P_{r2} , and P_t .

- Determine the “Absorption Coefficient” (a) of the material.

Formula: $E = E_0 (e^{-ax})$

Laboratory 1-3C.2

Equipment

He-Ne Laser

Optical Power Meter

Front Surface Mirror

Rear Surface Mirror

Two lab jacks

Note on accuracy: The results of this lab are HIGHLY sensitive to the condition of the optical surfaces. Make sure that any optical surfaces the laser strikes are very clean. Any oils from your fingers will drastically affect your results. In addition, scratches will affect your results, so choose surfaces that are as smooth as possible.

Procedure—Front and Rear Surface Mirrors

- Most mirrors on the walls of bathrooms are rear surface mirrors. Using the mirror obtained in the lab, identify the front (coated) surface. Orient the mirror such that the coated surface is facing the laser. Direct a He-Ne laser beam at the front surface of the mirror. You should orient the mirror in a similar way that you did with the acrylic block in Procedure A. Make the incident angle as small as possible.
- Measure P_i and P_{r1} and determine the reflectivity of the mirror coating.

Formula: $R_{\text{coating}} = P_{r1}/P_i$

$$P_i = \underline{\hspace{2cm}} \quad P_{r1} = \underline{\hspace{2cm}}$$

$$R_{\text{coating}} = \underline{\hspace{2cm}}$$

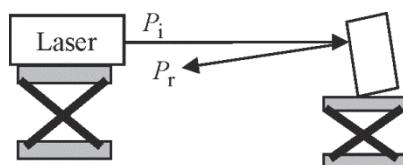


Figure 3-22

- Keep in mind that this mirror is made with a crown glass ($n = 1.52$). Your next task will be to turn the mirror around and measure the properties of a rear surface mirror. We will assume that no power is absorbed by the glass for purposes of these measurements (just to simplify calculations).
- See the figure above. Measure each of the following values.
Remember that $R = [(n - 1)^2/(n + 1)^2]$ and $R_{coating}$ is the result obtained above.

$P_i = \underline{\hspace{2cm}}$ $P_{r1} = \underline{\hspace{2cm}}$

$P_{r2} = \underline{\hspace{2cm}}$ $P_t = \underline{\hspace{2cm}}$

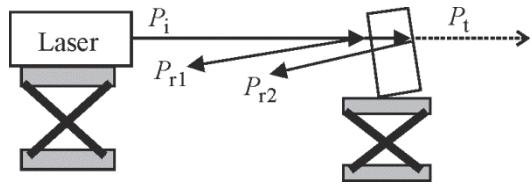


Figure 3-23

- Determine the predicted value for P_{r1} .

Formula: $P_{r1} = P_i * R$

- Determine the predicted value for P_{r2} .

Formula: $P_{r2} = (P_i - P_{r1(\text{predicted})}) * R_{coating} (1 - R)$

- Determine the predicted value for P_t .

Formula: $P_t = P_i - P_{r1(\text{predicted})} - P_{r2(\text{predicted})}$

- Determine the % error for your measured values of P_{r1} , P_{r2} , and P_t .

- Based on your measurements, what is one advantage and one disadvantage that a rear surface mirror has over a front surface mirror. Describe an application in which a rear surface mirror would be the best choice. Describe an application in which a front surface mirror would be the best choice.

Laboratory 1-3D: Optical Filters

In this laboratory, you will complete the following tasks:

Measure the power incident on and power transmitted through four different color filters

Measure the power incident on and power transmitted through three filter sets.

Calculate the transmission through these various filters.

Calculate the optical density and absorption coefficient of these various filters.

Go to
[http://optecvideo.
opteccrm.org/](http://optecvideo.opteccrm.org/)
for an
introduction to
this activity.



Definition of Terms and Required Formulas

Terms

T_{meas} = Transmission through a filter (measured)

T_{corr} = Transmission corrected for reflection

T_{tot} = Transmission of multiple filters

OD_{tot} = Optical Density of multiple filters

P_{in} = Power into filter

P_{out} = Power out of filter

x = filter thickness (in cm)

OD = Optical density

α = absorption coefficient

Formulas

$$T_{\text{meas}} = P_{\text{out}}/P_{\text{in}}$$

$$T_{\text{corr}} = P_{\text{out}}/[(1 - R)^2 * P_{\text{in}}]$$

$$T_{\text{corr}} = e^{-\alpha x}$$

$$\alpha = -\ln(T_{\text{corr}})/x$$

$$OD = -\log_{10}(T_{\text{meas}})$$

$$T_{\text{meas}} = 10^{-OD}$$

$$T_{\text{tot}} = T_1 * T_2 * \dots * T_n$$

$$OD_{\text{tot}} = OD_1 + OD_2 + \dots + OD_n$$

$$R = [(n - 1)/(n + 1)]^2$$

Equipment

He-Ne Laser

Optical Power Meter

Blue Filter

Yellow Filter

Red Filter

Green Filter

Clothespins (or Filter Holder)

Newport Kit: OEK-STD

Procedure

1. Set up a filter holder in front of a He-Ne laser such that the filters can be easily replaced.
2. Measure P_{in} and P_{out} for He-Ne light and record this data in Table 3-9 and Table 3-11. Also calculate the T_{meas} and OD of each filter for the following and record in data Table 3-9. Make sure to control the ambient room light in order to get consistent measurements.

Table 3-9. Measurements of Filters at 632.8 nm

Filter Color	P_{in} (mW)	P_{out} (mW)	$\frac{T_{\text{meas}}}{P_{\text{out}}/P_{\text{in}}}$	OD $-\log_{10}(T_{\text{meas}})$
Blue				
Yellow				
Green				
Red				

3. Next, prepare to measure three filter sets
 - Set 1: green and yellow
 - Set 2: green and red
 - Set 3: green, red, and yellow
4. Calculate the transmission of each combination (see formula for T_{tot} above). Record in the column labeled “ $T_{\text{predicted}}$ ” in Table 3-10.
5. Measure P_{in} and P_{out} for each filter set and determine $T_{\text{meas}} = P_{\text{out}}/P_{\text{in}}$. Compare your results by determining the % Error. Record your data in Table 3-10.

Table 3-10. Combination Filter Sets

Filter Set	P_{in} (mW)	P_{out} (mW)	$\frac{T_{\text{meas}}}{P_{\text{out}}/P_{\text{in}}}$	$T_{\text{predicted}}$ $T_1 * T_2 * \dots * T_n$	% Error
Green + Yellow					
Green + Red					
Green + Red + Yellow					

6. Use a micrometer to measure the thickness of the filter. Make sure to convert your thickness to CENTIMETERS before recording it in the data table.
7. In order to find the absorption coefficient of the filter, you'll need to find T_{corr} (to take into account the Fresnel reflection).

Table 3-11. Absorption Coefficient at 632.8 nm ($n = 1.499$)

Filter Color	P_{in} (mW)	P_{out} (mW)	T_{corr} $P_{\text{out}}/[(1-R)^2 * P_{\text{in}}]$	x(cm)	$\alpha(\text{cm}^{-1})$ $-\ln(T_{\text{corr}})/x$
Blue					
Yellow					
Green					
Red					

Laboratory 1-3E: Optical Photometer Use and Stability

In these laboratories, you will complete the following tasks:

Become familiar with an optical photometer.

Learn how to determine the specifications of an optical photometer.

Learn how to properly use an optical photometer.

Go to
[http://optecvideo.
opteccrm.org/](http://optecvideo.opteccrm.org/)
for an
introduction to
this activity.



Laboratory 1-3E.1

Equipment

HeNe Laser

Industrial Fiber Optics Digital Photometer

Manual for the Industrial Fiber Optics Digital Photometer

Procedure

Read the Manual for the Industrial Fiber Optics Digital Photometer

Questions

Use the Manual to answer the following questions:

1. What kind of power supply is used? Describe what voltage?
2. Describe the detector.
3. Over what range of wavelengths will the photometer work?

4. Is the photometer calibrated for all wavelengths? If not, at what wavelength is the photometer calibrated? What would you have to do for other wavelengths?
5. What is the accuracy?
6. What is the operating temperature range?
7. How large is the detector active area?
8. What is the maximum optical input?
9. What would happen if you exceed the maximum optical input by a small amount?
10. What might happen if you exceed the maximum optical input by an excessive, large amount?
11. What does it mean to “zero” the meter?
12. Describe how to zero the meter.
13. When should you zero the meter?
14. What would you need to calibrate the photometer?
15. What should you do when you finish using the photometer? What will happen if you don’t?
16. What is the purpose of the “+V” and “-V” jacks?

17. What is the digital resolution of the LCD?

18. What is the purpose of the detector housing?

Laboratory 1-3E.2

SAFETY NOTE: Never look directly into the beam of any laser. Use an index card to determine the position of the laser beam at any given time. Also, keep in mind that some laser light is reflected when it strikes the dish. This reflected light is not powerful enough to be considered hazardous if a laser pointer is used.

Equipment

HeNe Laser

Industrial Fiber Optics Digital Photometer

Manual for the Industrial Fiber Optics Digital Photometer

Procedure

1. Follow the operating procedures of the manual to take measurements of the sun and a HeNe Laser.
2. Record in Table 3-12 and compare the two readings.
3. Discuss the difference in readings. Is this what you expected?

Table 3-12

Sun Power Reading	HeNe Power Reading	% Difference

Laboratory 1-3E.3

Equipment

HeNe Laser

Industrial Fiber Optics Digital Photometer

Manual for the Industrial Fiber Optics Digital Photometer

Procedure

1. Allow the photometer to cool down for 15 to 20 minutes.
2. Take and record readings, in Table 3-13, of the HeNe beam starting at $t = 0$ (first initialization of the laser beam) and continue at five second intervals for the first minute, and then one minute intervals for 15 to 20 minutes, or until you think that the readings have reached stability.

3. Calculate the % change in the readings.
4. Explain what are some possible reasons for any instability in the readings?

Table 3-13

$t =$	Time Elapsed	Reading	% Change
0	0		
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			

RESOURCES

The Laser Institute of America located in Orlando, Florida, provides many resources on laser safety. These resources include laser hazard software packages, laser safety guides for eyewear protection, all of the ANSI (American National Standards Institute) safety standards, and laser safety reference guides for all environments in which lasers are used. (www.lia.org)

WORKPLACE SCENARIO

Here is your opportunity to use the concepts learned in this module to solve an actual problem that could arise in a photonics company. Your instructor will provide directions for developing a solution.

Developing Specifications for Laser Safety Glasses

Scenario

You are employed by a company as a laser technician. Your company does turn-key manufacturing of complete high-end complex printed circuit (PC) boards that includes design, PC layout, bare board manufacture, board component population, and test. Customers include several medical device research companies that do not have enough prototype volumes to support doing this work themselves, so they sub-contract it to your company. Because of the precision necessary with some PC board designs, a laser is used for micro-machining. There are two laser micro-machining departments. You are responsible for setting-up and maintaining the lasers in one of these departments. There is another laser technician responsible for the other department.

Your manager is head of the engineering department within your company. The people in this department are mainly electronics engineers and, with the exception of you and the other laser technician, have little expertise in laser systems.

During your normal workday, you receive an email from your manager. The email informs you that a new laser has just arrived to replace one that is currently being used. In the email, the manager says that the new laser is a Cobolt Rumba Diode Pumped Solid State Laser PSS CW Laser (Part Number 1064-05-01-2000-500) and that it will replace the CW 1W 1064 nm arc-lamp pumped Nd:YAG laser now on the manufacturing floor. The manager ends the email with a few questions:

1. Since the laser beam is exposed during operations, are safety glasses required?
2. If safety glasses are required,
 - a. Can the safety glasses we use for the old laser be used for the new one?
 - b. If not, what is the specification for the safety glasses required by the new laser and how did you verify this specification?
 - c. Based on this specification what brand, and model/part number would you recommend and what is the estimated unit cost of these glasses?
3. What should be done with the scratched safety glasses we are currently using with other lasers on the manufacturing floor? I have received some complaints that they are difficult to see through.

Problem and Tasking

Your task is to answer the manager's questions and develop a reply to his email that includes attachments documenting any calculations you perform.

Additional Information

To accomplish this task, you need to know that the old safety glasses have an OD = 3 @ 1064nm. Since safety is such an important aspect of any industrial process, you should check any OD calculations at the Laser Institute of America (LIA) website and use their OD calculator at <https://www.lia.org/evaluator/od.php>.

Finally, the following is a list of websites you might find useful in answering the manager's questions:

http://en.wikipedia.org/wiki/Diode-pumped_solid-state_laser

<http://www.cobolt.se/Filer/dokument/Manuals/Owners-Manual-model-05-Gen-5-rev-1.09.pdf>

http://en.wikipedia.org/wiki/Laser_safety#cite_note-iec-2060825-1-3

<https://www.lia.org/evaluator/od.php>

http://www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=762&gclid=CObPp52j-6wCFQdN4AodqHogTA

PROBLEM EXERCISES AND QUESTIONS

1. Explain the difference between incandescent and fluorescent light sources.
2. Define coherence and monochromaticity.
3. Calculate the irradiance of a laser beam in watts/cm² if the power of the laser beam is 500 milliwatts and the diameter of laser beam is 2 mm.
4. Identify the laser wavelengths that are hazardous for the following:
 - a. cornea of the eye
 - b. retina of the eye
5. Give the power levels for Classes 2, 3a, 3b, and 4 laser safety classifications.
6. Explain when to use a:
 - a. caution sign
 - b. danger sign
 - c. notice sign
7. Calculate the transmission through filters with the following optical densities:
 - a. OD = 2
 - b. OD = 5
 - c. OD = 6
 - d. OD = 8
8. Explain the difference between engineering controls, administrative controls, and personal protective equipment in regard to control measures.
9. Explain the role of the laser safety officer (LSO) in an industrial environment.
10. Identify the maximum intrabeam permissible exposure (MPE) for the eye:
 - a. CO₂ laser for 10 seconds
 - b. HeNe laser for 0.25 second
 - c. Argon laser for 600 seconds
 - d. XeCl laser for 30,000 seconds
11. Calculate the minimum optical density for protective eyewear using an argon laser of wavelength 0.514 μm, for a given exposure time of 0.25 second, a power of 5 watts, and a worst-case scenario of a dilated eye of 7-mm pupil diameter
12. List the three major causes of laser accidents.
13. Discuss the nonbeam hazards described in this module and suggest procedures and controls to reduce or eliminate them.

14. An argon laser with a power of 15 W and a beam diameter out of the laser of 4 mm is focused for 10 minutes by a converging lens of focal length 15 cm. Determine the NHZ measured from the focal point of the lens.

15. A laser delivers an irradiance of 105 W/cm^2 in a certain target area. If you are working in this area and the MPE for this laser is given by Table 3-3 to be 0.005 W/cm^2 , what is the minimum OD for the laser goggles you should be wearing?

MEET A TECHNICIAN

Lee L'Esperance



Lee received his Associate of Applied Science in Laser Electro-Optic Technology from Camden County College (CCC), his Bachelor of Science in Electrical Engineering from Drexel University and his Master of Science in Systems Engineering from Rensselaer Polytechnic Institute.

Lee started on what is now a 32-year career with the same company. His first job, after graduating from CCC was with the engineering research center at Western Electric in fiber optics measurement within the engineering research center for Western Electric now called Alcatel-Lucent.

Although Lee has been with the same company for 32 years, he is quick to point out that he hasn't done the same job all that time.

"Photonics was what got me in the door, but there are other things you can branch out into as you move forward in your career and as technology changes."

After his work in performance enhancement of fiber optics, Lee got involved in the production of undersea optical communications repeaters.

"There are undersea cables that go from the United States to Europe and they're all fiber optics-based. They have repeaters at certain intervals and inside those repeaters are lasers."

Lee's career began with photonics and progressed in many unexpected ways, but it has always been exactly what he wanted to do. The job Lee L'Esperance enjoys most is connecting people to the future. He started by getting information to people through fiber optics.

"After a while, I decided I wanted to have opportunities to be a little bit closer to the customer."

Now he works to bridge the gap between future technology and today's consumers.

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Basic Geometrical Optics

Module 1-4
of
Course 1, *Fundamentals of Light and Lasers*
3rd Edition

OPTICS AND PHOTONICS SERIES



PREFACE TO MODULE 1-4

This is the fourth module in *Fundamentals of Light and Lasers*. Following are the titles of all six modules in the course:

1. *Nature and Properties of Light*
2. *Optical Handling and Positioning*
3. *Light Sources and Laser Safety*
4. *Basic Geometrical Optics*
5. *Basic Physical Optics*
6. *Principles of Lasers*

The six modules can be used as a unit or independently, as long as prerequisites have been met.

FEATURES

Mathematics Videos: Math videos are provided to assist students in doing mathematical operations required in this module. The math concepts used in this module are checked ✓ in the following list:

1. Scientific Notation
2. Unit Conversion
3. Introductory Algebra ✓
4. Powers and Roots ✓
5. Ratio and Proportion
6. Exponents and Logarithms
7. Graphing in Rectangular Coordinates ✓
8. Geometry
9. Angle Measure in Two and Three Dimension ✓
10. Trigonometry ✓
11. Special Graphs

This checklist provides instructors a means of front-loading the presentation of material in this module with mathematics instruction. If instructors prefer to provide math instruction using a “just on time delivery” mode, a special icon  appears where the checked mathematics topics are first used within this module. All math videos can be accessed at <http://optecvideo.opteccrm.org/>.

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COURSE 1: FUNDAMENTALS OF LIGHT AND LASERS

Module 1-4

Basic Geometrical Optics

INTRODUCTION

Optics is the cornerstone of photonics systems and applications. In this module, you will learn about one of the two main divisions of basic optics—*geometrical (ray) optics*. In the next module, you will learn about the other—*physical (wave) optics*. *Geometrical optics* will help you understand the basics of light reflection and refraction and the use of simple optical elements such as mirrors, prisms, lenses, and fibers. *Physical optics* will help you understand the phenomena of light waves, light wave interference, diffraction, and polarization, the use of thin film coatings on mirrors to enhance or suppress reflection, and the operation of such devices as gratings and quarter-wave plates.

PREREQUISITES

Before you work through this module, you should have completed Module 1-1, *Nature and Properties of Light*; Module 1-2, *Optical Handling and Positioning*; and Module 1-3, *Light Sources and Laser Safety*. In addition, you should be able to manipulate and use algebraic formulas, deal with units, understand the geometry of circles and triangles, and use the basic trigonometric functions (sin, cos, tan) as they apply to the relationships of sides and angles in right triangles.

OBJECTIVES

When you finish this module, you will be able to:

- Distinguish between *light rays* and *light waves*.
- State the *law of reflection* and show with appropriate drawings how it applies to light rays at plane and spherical surfaces.
- State *Snell's law of refraction* and show with appropriate drawings how it applies to light rays at plane and spherical interfaces between different optical media.
- Define *index of refraction* and give typical values for glass, water, and air.
- Calculate the *critical angle* of incidence for the interface between two optical media and describe the process of *total internal reflection*.

- Describe how total internal reflection can be used to redirect light in prisms and trap light in fibers.
- Describe *dispersion* of light and show how a prism disperses white light.
- Calculate the *minimum angle of deviation* for a prism and show how this angle can be used to determine the refractive index of a transparent material shaped into a prism.
- Describe what is meant by *Gaussian* or *paraxial* optics.
- Describe the relationship between *collimated light* and the *focal points* of convex and concave *mirrors*.
- Use *ray-tracing techniques* to locate the images formed by plane and spherical mirrors.
- Use the *mirror equations* to determine location, size, orientation, and nature of images formed with spherical mirrors.
- Distinguish between a *thin lens* and a *thick lens*.
- Describe the shapes of three typical *converging (positive)* thin lenses and three typical *diverging (negative)* thin lenses.
- Describe the *f-number* and *numerical aperture* for a lens and explain how they control image brightness.
- Use *ray-tracing techniques* to locate images formed by *thin lenses*.
- Describe the relationship between *collimated light* and the *focal points* of a *thin lens*.
- Use the *lensmaker's equation* to determine the focal length of a thin lens.
- Use the *thin-lens equations* to determine location, size, orientation, and nature of the images formed by simple lenses.

SCENARIO

Manuel Martinez is a photonics technician hired recently to work for a large optical company that manufactures optical components such as mirrors, lenses, prisms, beam splitters, fibers, and Brewster windows—all to customer specifications. While in school, Manuel studied light imaging with mirrors and lenses, ray tracing, and calculations with simple formulas. After two months on the job, he discovered that he uses those same ideas day in and day out. To be sure, things are much more “high tech” in his company, for now Manuel has access to powerful computers and computer programs that trace rays through complicated optical systems, often containing elements with nonspherical surfaces, something Manuel never had a chance to do at school. He enjoys the challenge of using state-of-the-art lab equipment he’s never seen before, including autocollimators, spectrophotometers, and surface profilers. All in all, he’s really satisfied because all of the optics he had in his “Geo” course back at school really prepared him for his laboratory work here. This month, Manuel is learning how to “grind and polish optical surfaces to spec,” and how to apply the principles of geometrical optics to determine when the surfaces are “near tolerance.” Manuel finds his work fascinating and can hardly wait to get to work each morning. “Geo” was never so much fun.

BASIC CONCEPTS

The Laws of Reflection and Refraction

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The numbers below the **A** that appears in several places in this module reference specific applets that demonstrate the concepts being described in the text. These applets are accessible at <http://optecvideo.opteccrm.org/>.

We begin our study of *basic geometrical optics* by examining how light reflects and refracts at smooth, *plane* interfaces. Figure 4-1a shows ordinary *reflection* of light at a plane surface, and Figure 4-1b shows *refraction* of light at two successive plane surfaces. In each instance, light is pictured simply in terms of straight lines, which we refer to as *light rays*.

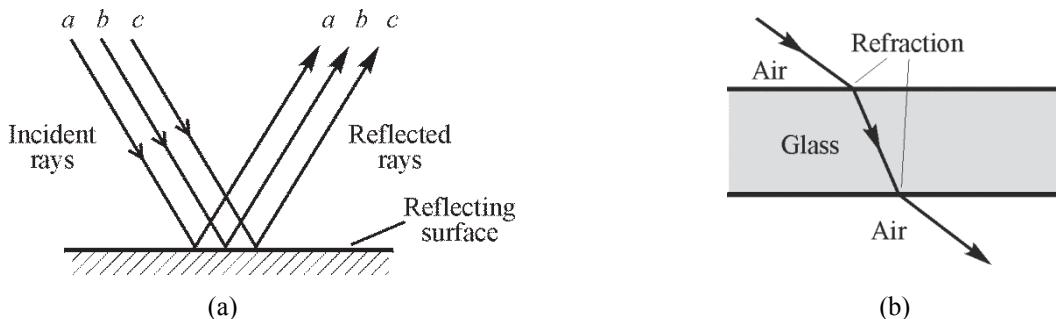


Figure 4-1 Light rays undergoing reflection and refraction at plane surfaces

After a study of how light reflects and refracts at plane surfaces, we extend our analysis to smooth, curved surfaces, thereby setting the stage for light interaction with mirrors and lenses—the basic elements in many optical systems.

In this module, the analysis of how light interacts with plane and a curved surface is carried out with *light rays*. A light ray is nothing more than an imaginary line directed along the path that light energy follows. It is helpful to think of a light ray as a thin pencil of light, very much like a narrow, well-defined laser beam. For example, if you observe the passage of a laser beam in a fish tank filled with milky water and visually trace the path of the beam from entrance into and exit from the tank, you are, in effect, looking at a “light ray” representation of light energy passing through the tank. We all use light rays to explain how shadows are formed.

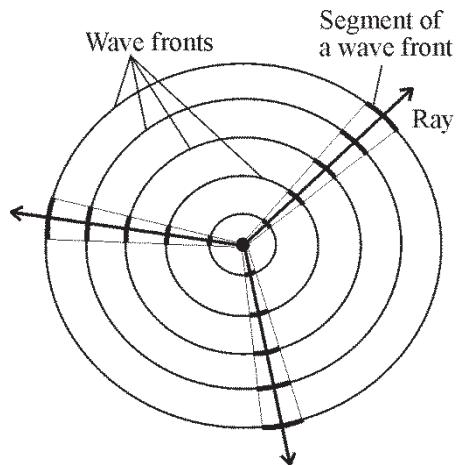
Light rays and light waves

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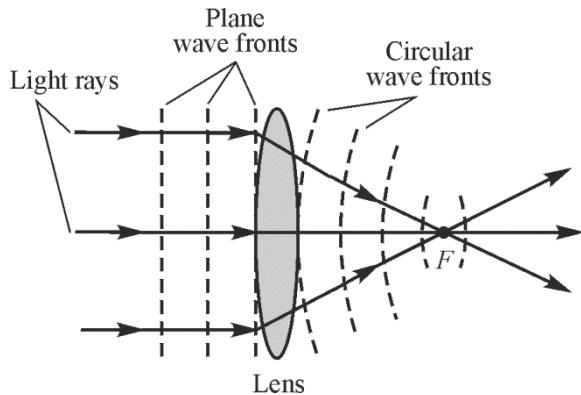
Before we look more closely at the use of *light rays*, we need to say a brief word about *light waves* and the connection between light rays and light waves. For most of us, *wave motion* is easily visualized in terms of water waves—such as those created on a quiet pond by a bobbing cork. See Figure 4-2a. The successive high points (crests) and low points (troughs) on the water surface occur as a train of circular waves moves radially outward from the bobbing cork. Each of the circular waves represents a *wave front*. A wave front is defined here as a series of adjacent points that connect identical wave displacements—that is, points that connect identical positions above or below the normal surface of the quiet pond.



(a) Radiating circular waves from a bobbing cork



(b) Light rays and circular wave fronts



(c) Bending of light rays and changing shapes of wave fronts by a thin lens

Figure 4-2 Waves and rays

In Figure 4-2b, circular wave fronts are shown with radial lines drawn perpendicularly to them along several directions. Each of the rays describes the motion of a *restricted part or segment* of the wave front along a particular direction. Geometrically, then, a *ray* is a line perpendicular to a series of successive *wave fronts*. The direction of the ray specifies the *direction of energy flow* in the wave.

Figure 4-2c shows a cross section of plane wave fronts of light bent by a lens into circular wave fronts that then converge onto a focal point F . The same diagram shows three particular *light rays* perpendicular to these wave fronts, undergoing bending by the lens as they head for the focal point F . Figure 4-2c shows the geometrical connection between actual waves and the rays used to represent them. In the study of *geometrical optics*, we find it useful to represent the interaction of light waves with plane and spherical surfaces—such as those found in mirrors and lenses—in terms of the bending of *light rays*.

With the useful geometrical idea of a simple light ray, we can illustrate propagation, reflection, and refraction of light in clear, uncomplicated drawings. For example, in Figure 4-3a, the propagation of light from a “point source” is represented by equally spaced light rays radiating outwardly from the source. Each ray indicates the geometrical path along which light energy moves as it leaves the source. Figure 4-3b shows the reflection of several light rays at a curved mirror surface, and Figure 4-3c shows the refraction (bending) of a single light ray passing through a prism, that is, as it passes from air, through the prism material, and again into air.

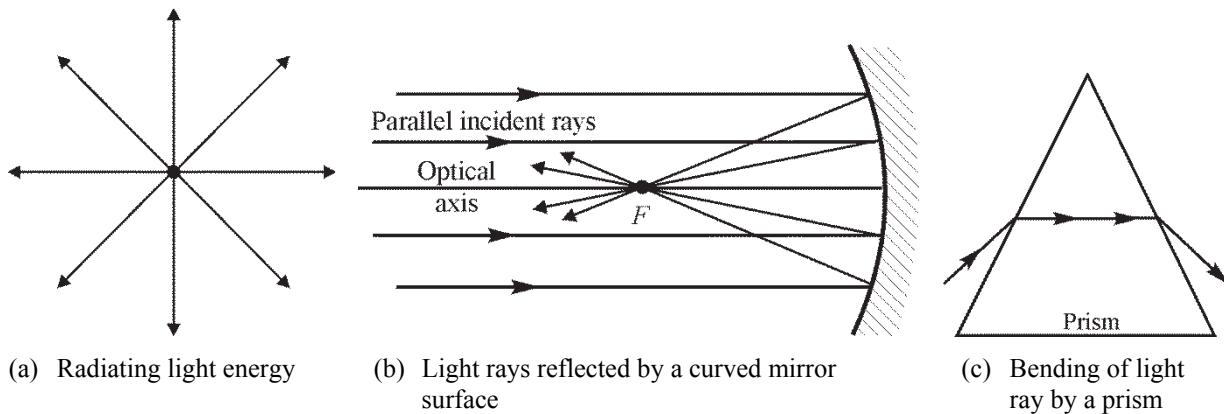


Figure 4-3 Typical light rays in (a) propagation, (b) reflection, and (c) refraction

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Reflection of light from optical surfaces

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When light is incident on an *interface* between two transparent optical media—such as at the surface between air and glass or between water and glass—four things can happen to the incident light.

- It can be partly or totally reflected at the interface.
- It can be scattered in random directions at the interface.
- It can be partly transmitted via refraction at the interface and enter the second medium.
- It can be partly absorbed in either medium.

In our introductory study of geometrical optics, we shall consider only smooth surfaces that give rise to *specular* (regular, geometric) reflections as shown in Figure 4-4a. We shall ignore ragged, uneven surfaces that give rise to *diffuse* (irregular) reflections as shown in Figure 4-4b.

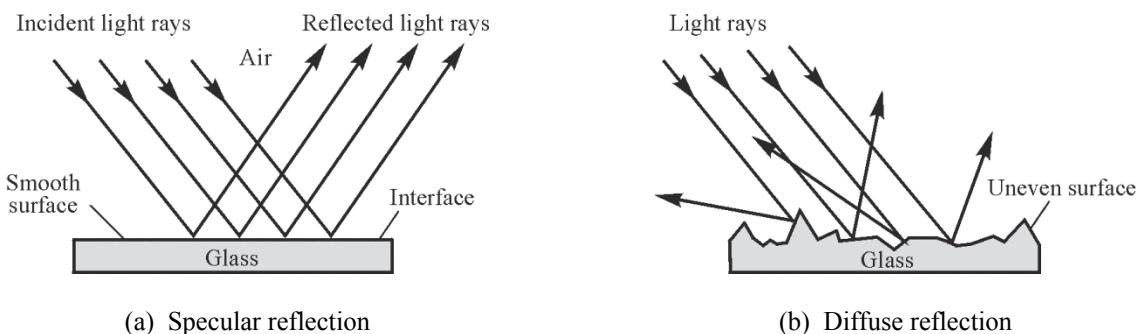


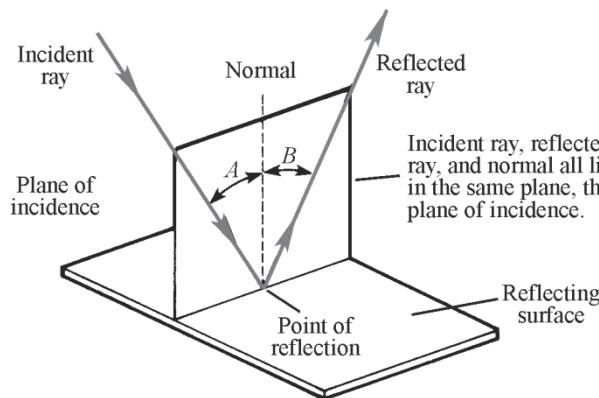
Figure 4-4 Specular and diffuse reflection

In addition, for simplicity, we shall ignore the *absorption* of light energy that most always occurs along a path of travel. But, keep in mind that absorption is an important consideration when the amount of light energy transmitted from source to receiver is a factor of concern, as, for instance, when we want as much light energy as possible to pass through an optical system such as a microscope.

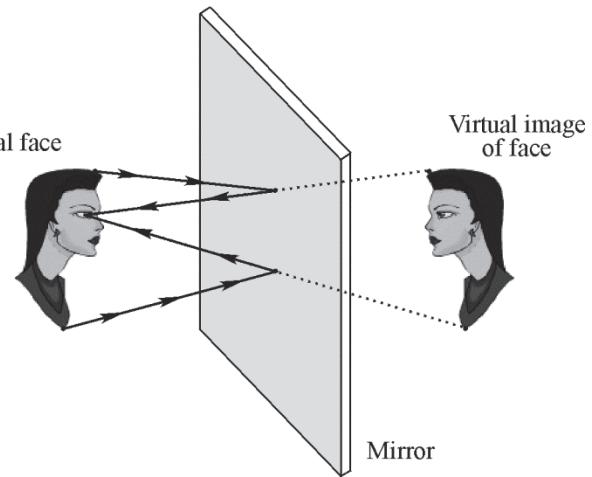
The law of reflection: plane surface—When light reflects from a plane surface, as shown in Figure 4-5a, the angle (B) formed by the *reflected ray* and the *normal* (line perpendicular to the surface) at the point of incidence is always equal to the angle (A) formed by the *incident ray* and the same normal. Note carefully that the incident ray, reflected ray, and normal always lie in the *same plane*.



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angles?
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optecrcm.org/](http://optecvideo.optecrcm.org/).



(a) Law of reflection: Angle B equals angle A



(b) Image formation in a plane mirror

Figure 4-5 Reflection from a plane surface and a mirror

The geometry of Figure 4-5a reminds us that reflection of light rays from a plane, smooth surface is like the geometry of pool shots “banked” off the walls of a billiard table.

With the *law of reflection* in mind, we can see that, for the specular reflection shown earlier in Figure 4-4a, each of the incident, parallel rays reflects off the surface at the same angle, thereby remaining parallel in reflection as a group. In Figure 4-4b, where the surface is made up of many small, randomly oriented plane surfaces, each ray reflects in a direction different from its neighbor, even though each ray does obey the *law of reflection* at its own small surface segment.

The image of your face that you see in a mirror each morning is formed by light rays obeying the *law of reflection*. Light rays leave each point on your face, travel to the mirror, and reflect back to your eyes, as shown in Figure 4-5b. The extension of these rays behind the mirror forms a *virtual* image of your face. The image is called “virtual” because it’s **not** formed behind the mirror, even though you “see” it there.

Reflection from a curved surface—With spherical mirrors, reflection of light occurs along a curved surface. The *law of reflection* holds, since at each point on the curved surface one can draw a *surface tangent* (a plane surface) and erect a *normal* to a point *P* on the surface where the light is incident, as shown in Figure 4-6. One then applies the *law of reflection* at point *P* just as was illustrated in Figure 4-5, with the incident and reflected rays making the same angles (*A* and *B*) with the normal to the surface at *P*. Note that successive surface tangents along the curved mirror surface in Figure 4-6 are *ordered* (not random) sections of “plane mirrors” and serve—when connected—as a spherical surface mirror, capable of forming distinct images.

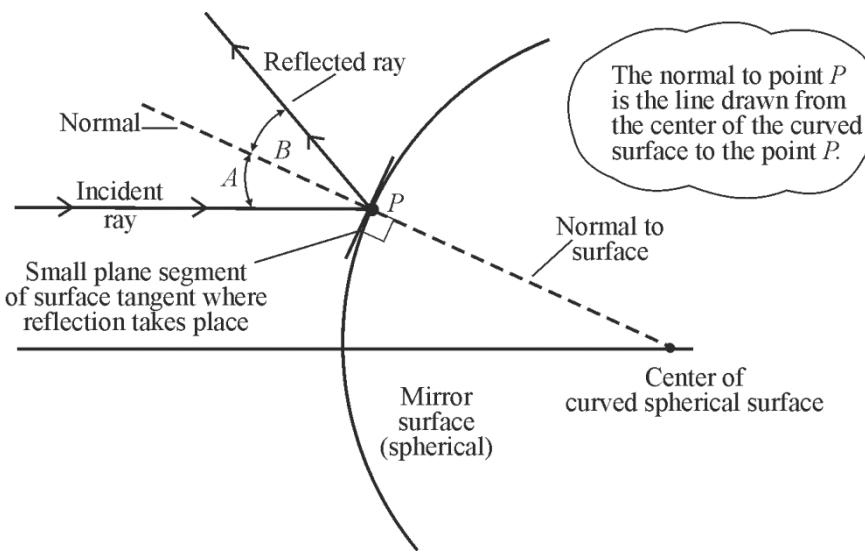
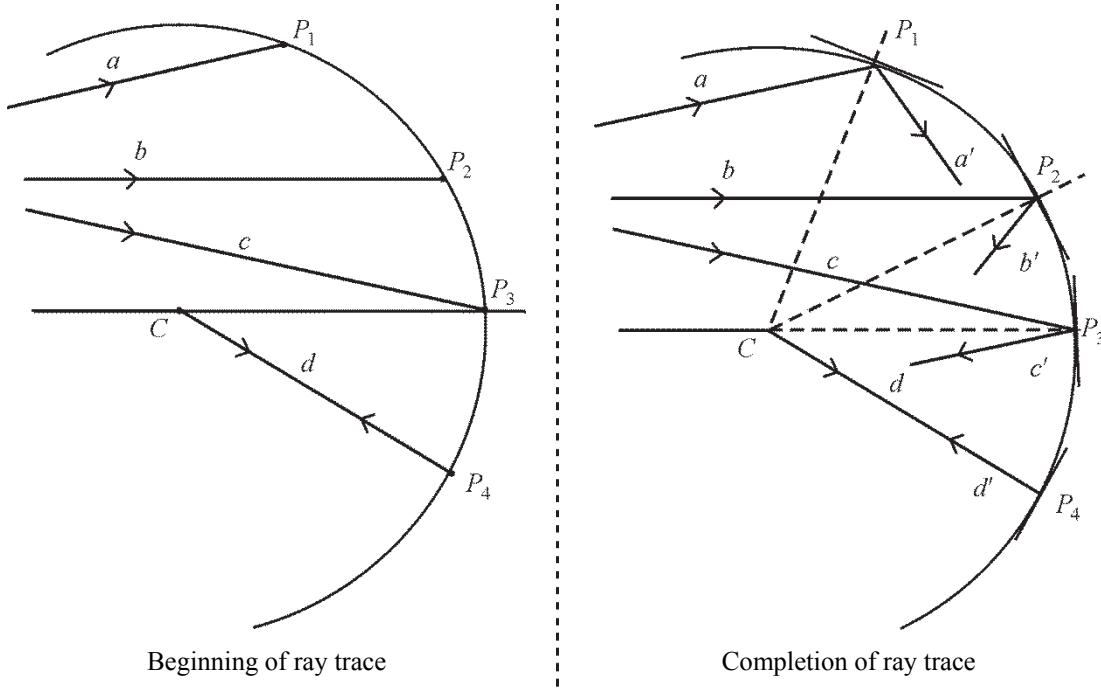


Figure 4-6 Reflection at a curved spherical surface: Angle B equals angle A .

Thus, since point P can be moved anywhere along the curved surface and a normal can be drawn there, we can always find the direction of the reflected ray by applying the *law of reflection*. We shall apply this technique when studying the way mirrors reflect light to form images.

Example 1

Using the *law of reflection*, complete the ray-trace diagram for the four rays (a, b, c, d) incident on the curved surface shown at the left below, given that the center of the curved surface is at point C .



Solution: Draw a normal (shown dashed) from point C to each of the points P_1, P_2, P_3 , and P_4 , as shown above in the drawing at the right. At each point, draw the appropriate reflected ray (a', b', c', d') so that each ray makes an angle with its normal equal to the angle made by its incident ray (a, b, c, d) at that point. Note that ray d reflects *back along itself* since it is incident along the line of the *normal* from C to point P_4 .

Refraction of light from optical interfaces

When light is incident at an *interface*—the geometrical plane that separates one optical medium from another—it will be *partly reflected* and *partly transmitted*. Figure 4-7 shows a three-dimensional view of light incident on a partially reflecting surface (interface), being partly reflected there (according to the *law of reflection*) and partly refracted into the second medium. The bending of light rays at an interface between two optical media is called *refraction*. Before we examine, in detail, the process of refraction, we need to describe optical media in terms of an *index of refraction*.

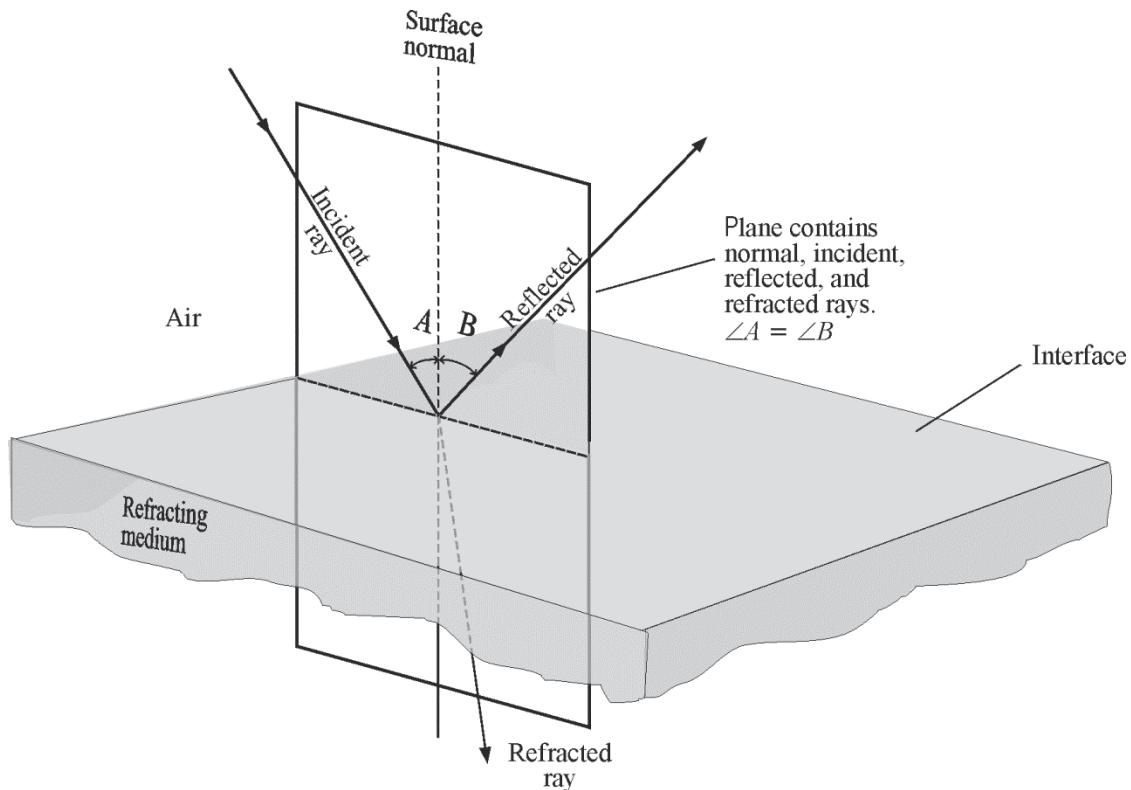


Figure 4-7 Reflection and refraction at an interface between air and a different optical medium

Index of refraction—The two transparent optical media that form an interface are distinguished from one another by a constant called the *index of refraction*, generally labeled with the symbol n . The index of refraction for any transparent optical medium is defined as the ratio of the speed of light in a vacuum to the speed of light in the medium, as given in Equation 4-1.

$$n = \frac{c}{v} \quad (4-1)$$

where c = speed of light in free space (vacuum)

v = speed of light in the medium

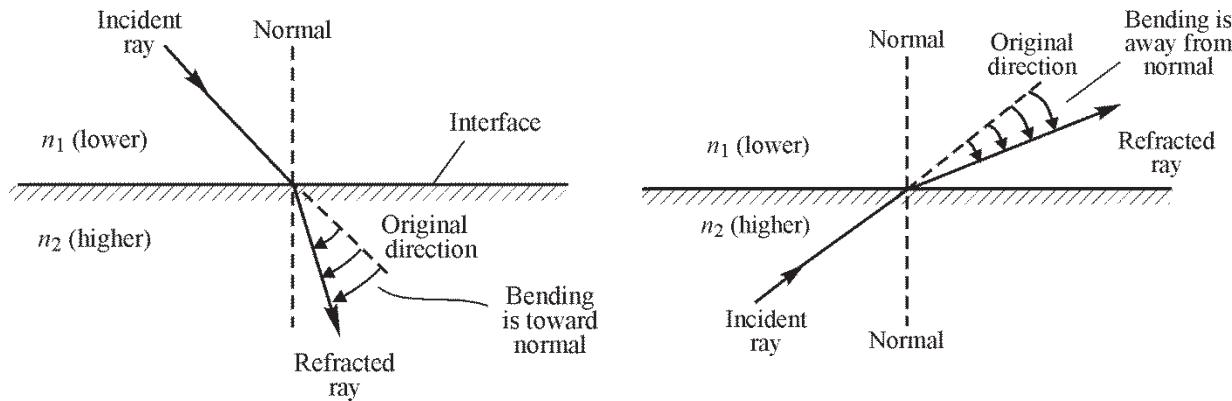
n = index of refraction of the medium

The index of refraction for free space (a vacuum) is exactly *one*. For air and most gases, it is very nearly one, so in most calculations it is taken to be 1.0. For other optical materials—such as glass, silicon, diamond, gallium arsenide, and germanium—it has values greater than one. Table 4-1 lists indexes of refraction for some common materials. Note the relatively high refractive indexes for the semiconductor materials gallium arsenide, silicon, and germanium.

Table 4-1. Indexes of Refraction for Various Materials at 589 nm

Substance	n	Substance	n
Air	1.0003	Glass (flint)	1.66
Benzene	1.50	Glycerin	1.47
Carbon disulfide	1.63	Polystyrene	1.49
Corn syrup	2.21	Quartz (fused)	1.46
Diamond	2.42	Sodium chloride	1.54
Ethyl alcohol	1.36	Water	1.33
Gallium arsenide (semiconductor)	3.40	Ice	1.31
Glass (crown)	1.52	Germanium	4.1
Zircon	1.92	Silicon	3.5

The greater the index of refraction of a medium, the slower the speed of light in that medium and the greater the light ray is bent in going from air into the medium. Figure 4-8 shows two general cases, one for light passing from a medium of lower index into a medium of higher index, such as from air into glass, the other from a medium of higher index into a medium of lower index, such as from glass into water. Note that in the first case (lower-to-higher), the light ray is always *bent toward the normal*. In the second case (higher-to-lower), the light ray is always *bent away from the normal*. It is helpful to memorize these effects since they often help one trace light through optical media in a generally correct manner.



- (a) Lower to higher: refracted ray bends *toward* the normal.
 (b) Higher to lower: refracted ray bends *away from* the normal.

Figure 4-8 Refraction at an interface between media of different refractive indexes n_1 and n_2

Snell's law—*Snell's law of refraction* relates the *sines* of the angles of incidence and refraction at an interface between two optical media to the *indexes of refraction* of the two media. The law is named after a Dutch astronomer, Willebrord Snell, who formulated the law in the 17th century. Snell's law enables us to calculate the direction of the refracted ray if we know the refractive indexes of the two media and the direction of the incident ray. The mathematical expression of Snell's law and an accompanying drawing are given in Figure 4-9.

<p>Snell's Law</p> $\frac{\sin i}{\sin r} = \frac{n_r}{n_i}, \text{ where}$ <p>i is the angle of incidence r is the angle of refraction n_i is the refractive index in the incident medium n_r is the refractive index in the refracting medium</p>	<p>The diagram shows an 'Incident ray' entering from the left into a medium with refractive index n_i. The ray strikes a horizontal 'Interface' at point P. A vertical dashed line labeled 'Surface normal' passes through P. The angle of incidence i is the angle between the incident ray and the normal. The refracted ray emerges into a medium with refractive index n_r (higher), labeled $(n_i < n_r)$. The angle of refraction r is the angle between the refracted ray and the normal.</p>
---	--

Figure 4-9 Snell's law: formula and geometry

Note carefully that both the angle of incidence (i) and the angle of refraction (r) are measured with respect to the surface normal. Note again that the incident ray, surface normal, and refracted ray all lie in the same geometrical plane.

In practice Snell's law is often written simply as

$$n_i \sin i = n_r \sin r \quad (4-2)$$

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Now let's look at an example that makes use of *Snell's law*.

Example 2

In a handheld optical instrument used under water, light is incident from water onto the plane surface of flint glass at an angle of incidence of 45° .

- What is the angle of reflected light off the flint glass surface?
- Does the refracted ray bend toward or away from the normal?
- What is the angle of refraction at the flint glass surface?

Solution

- From the *law of reflection*, the reflected light must head off at an angle of 45° with the normal. (Note: The angle of reflection is **not** dependent on the refractive indexes of the two media.)
- From Table 4-1, the index of refraction is 1.33 for water and 1.63 for flint glass. Thus, light is moving from a lower to a higher index of refraction and will bend **toward** the normal. Thus, we know right away that the angle of refraction r should be less than 45° .
- From *Snell's law*, Equation 4-2, we have:

$$n_i \sin i = n_r \sin r$$

where $n_i = 1.33$, $i = 45^\circ$, and $n_r = 1.63$

$$\text{Thus, } \sin r = \frac{1.33 \sin 45^\circ}{1.63} = \frac{(1.33)(0.707)}{1.63} = 0.577$$

$$\text{So } r = \sin^{-1}(0.577) = 35.2^\circ$$

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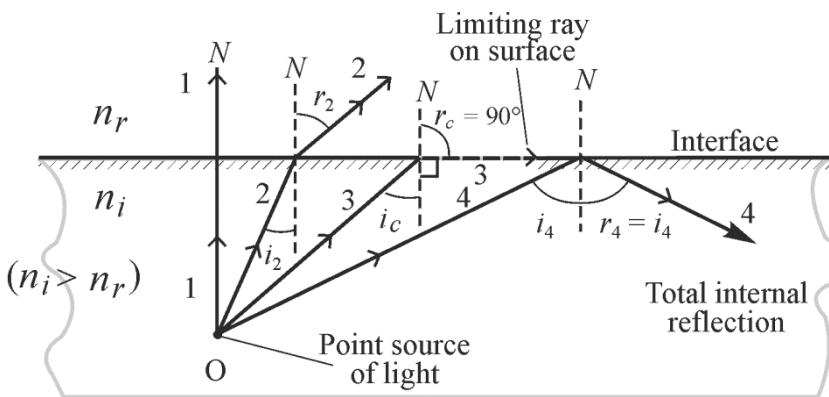
The angle of refraction is about 35° , clearly less than 45° , just as was predicted in part (b).

Note: The function \sin^{-1} is also referred to as the *arcsin*. We will use the \sin^{-1} notation since that is what is found on the keypads of scientific calculators.

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Critical angle and total internal reflection—When light travels from a medium of *higher index to one of lower index*, we encounter some interesting results. Refer to Figure 4-10, where we see four rays of light originating from point O in the higher-index medium. Each ray is incident on the interface at a different angle of incidence. Ray 1 is incident on the interface at 90° (normal incidence) so there is no bending as it moves into the lower-index medium.

The light in the direction along the normal N at the interface simply speeds up in the second medium (why?) as it continues along the same direction. Ray 2 is incident at angle i_2 and refracts (bends away from the normal N) at angle r_2 . Ray 3 is incident at the so-called *critical angle* i_c , large enough to cause the refracted ray bending away from the normal to bend by 90° , at angle r_c , thereby traveling *along the interface* between the two media. Ray 4 is incident on the interface at an angle *greater than* the critical angle and is *totally reflected* into the same medium from which it came. Ray 4 obeys the *law of reflection* so that its angle of reflection r_4 is exactly equal to its angle of incidence i_4 .




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[http://optecvideo
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for a short lesson
about Total Internal
Reflection.

Figure 4-10 Critical angle i_c and total internal reflection

We make use of the phenomenon of total internal reflection when we design light propagation in fibers by “trapping” the light in the fiber through successive internal reflections along the fiber. We do this also when designing “retroreflecting” prisms, i.e., those that redirect the reflected light along the same path as the entering light. Compared with ordinary reflection from mirrors, the sharpness and brightness of totally internally reflected light beams in such prisms is considerably greater.

The calculation of the *critical angle of incidence* for any two optical media—whenever light is incident from a medium of higher index to a medium of lower index—is accomplished with *Snell’s law*. Referring to Ray3 in Figure 4-10 and using Snell’s law in Equation 4-2 appropriately, we have

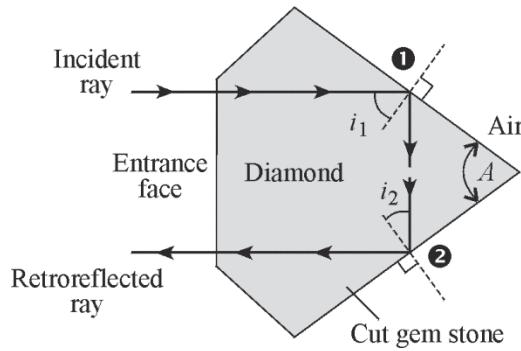
$$n_i \sin i_c = n_r \sin 90^\circ$$

where n_i is the index for the incident medium, i_c is the critical angle of incidence, n_r is the index for the medium of lower index, and $r_c = 90^\circ$ is the angle of refraction at the critical angle. Then, since $\sin 90^\circ = 1$, we obtain for the critical angle,

$$i_c = \sin^{-1} \left(\frac{n_r}{n_i} \right) \quad (4-3)$$

Example 3

The phenomenon of total internal reflection is used by diamond cutters to shape the gem stone in such a way that light incident on the entrance face is totally reflected back out the entrance face. (See accompanying sketch.) Such total reflection causes the diamond to sparkle. What is the *critical angle* for light at the diamond-air interface?



Solution: From Table 4-1, we see that the refractive index for light near wavelength $\lambda = 589 \text{ nm}$ is 2.42. Assume that this value is reasonably the same for all wavelengths in white light. Then at either position ① or ② at the diamond-air interface we can write, using Equation 4-3,

$$i_c = \sin^{-1} \left(\frac{n_{\text{air}}}{n_{\text{diam}}} \right), \text{ where } n_{\text{air}} = 1, n_{\text{diam}} = 2.42$$

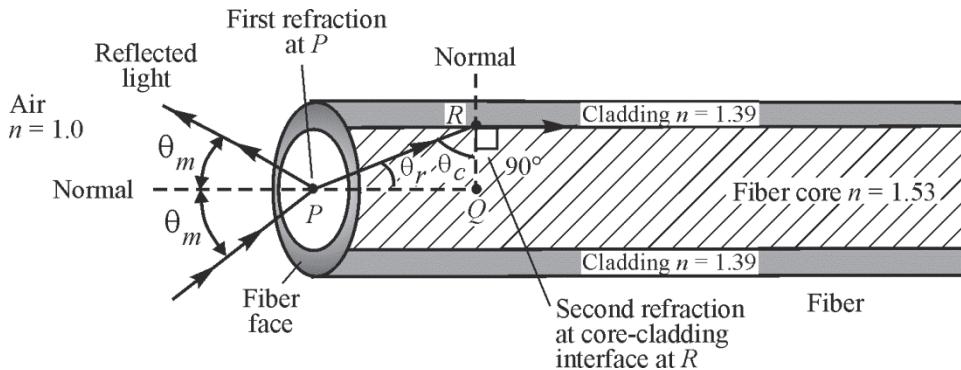
$$\text{Thus } i_c = \sin^{-1} \left(\frac{1}{2.42} \right) = \sin^{-1}(0.4132) = 24.4^\circ$$

Thus, if angle A of the cut stone is 50° or larger, angles i_1 and i_2 will always be larger than 24.4° and total internal reflection will occur. (Can you explain where the value 50° comes from?)

Now, let's use Equation 4-3 in Example 4 to determine the entrance cone for light rays incident on the face of a cladded fiber if the light is to be trapped by total internal reflection at the core-cladding interface in the fiber.

Example 4

A step-index fiber 0.0025 inch in diameter has a core index of 1.53 and a cladding index of 1.39. (See drawing.) Such clad fibers are used frequently in applications involving communication, sensing, and imaging.



What is the maximum acceptance angle θ_m for a narrow beam of light incident on the fiber face such that the refracted ray in the core of the fiber is incident on the cladding at just the critical angle?

Solution: Let's work backwards from the second refraction at the core-cladding interface at R to the first refraction at the fiber face at P . Thus first find θ_c , then θ_m .

- (1) From Equation 4-3, at the core-cladding interface at R ,

$$\theta_c = \sin^{-1} \left(\frac{1.39}{1.53} \right) = 65.3^\circ$$

- (2) In right-triangle PQR, $\theta_r + \theta_c + 90^\circ = 180^\circ$, so $\theta_r = 90^\circ - \theta_c = 90^\circ - 65.3^\circ = 24.7^\circ$

- (3) Then, from Snell's law, at the fiber face at P ,

$$n_{air} \sin \theta_m = n_{core} \sin \theta_r$$

so that $\sin \theta_m = \left(\frac{n_{core}}{n_{air}} \right) \sin \theta_r = \left(\frac{1.53}{1.00} \right) \sin (24.7^\circ)$

from which $\sin \theta_m = 0.639$

Finally, then $\theta_m = \sin^{-1} 0.639 = 39.7^\circ$

Thus, the half acceptance angle is 39.7° and the *acceptance angle* is twice that, or $2 \theta_m = 79.4^\circ$. This acceptance angle indicates that any light ray incident on the fiber face within the acceptance angle 79.4° will undergo total internal reflection at the core-cladding face and remain trapped in the fiber as it propagates along the fiber.

Refraction in prisms

A
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Glass prisms are often used to bend light in a given direction as well as to bend it back again (retroreflection) as we have just seen in the cut diamond. The process of refraction in prisms can be understood with the use of light rays and Snell's law. Look at Figure 4-11a. When a light ray enters a prism at one face and exits at another, the exiting ray is *deviated* from its original direction. The prism shown—with equal base angles—is isosceles in cross section with *apex angle* $A = 30^\circ$ and refractive index $n = 1.50$. The incident angle θ at the left prism face and the *angle of deviation* δ at the right prism face are shown on the diagram.

Figure 4-11b shows how the angle of deviation δ changes as the angle θ of the incident ray changes. The curve shown is for the specific prism drawn in Figure 4-11a. Note that the angle of deviation δ goes through a minimum value as the angle of incidence θ increases. For this prism, δ has a minimum value equal to about 16° when the angle of incidence is near 27° . Each prism shape of refractive index n has its own unique *minimum angle of deviation*.

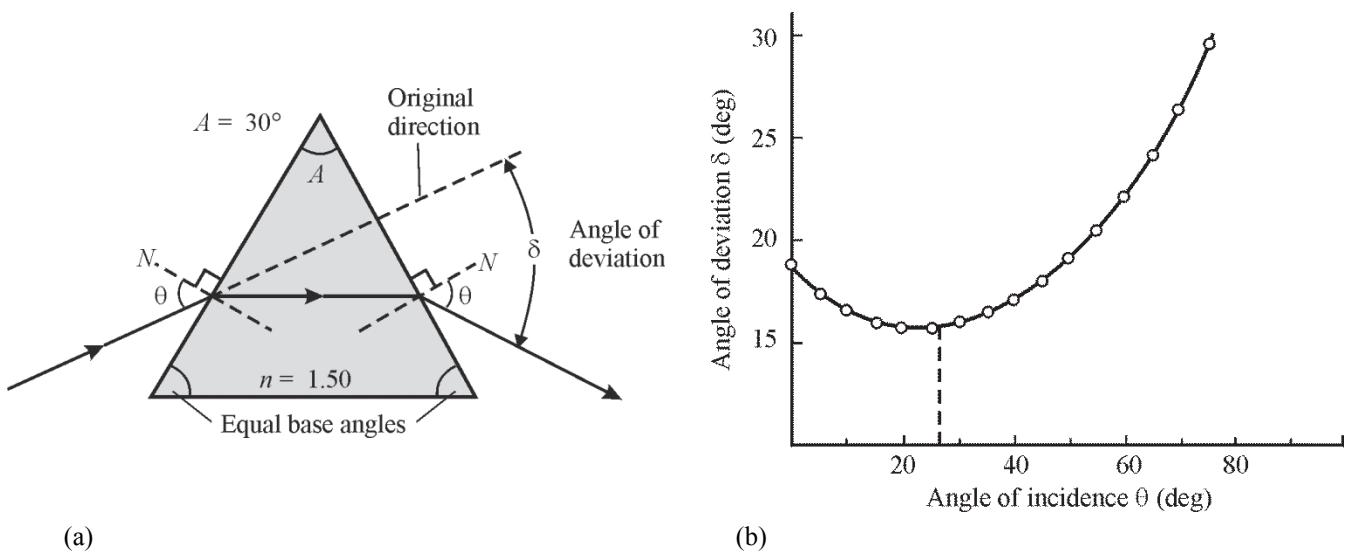


Figure 4-11 Refraction of light through a prism

Minimum angle of deviation—It turns out that we can determine the refractive index of a transparent material by shaping it in the form of an isosceles prism and then measuring its *minimum* angle of deviation δ_m . With reference to Figure 4-11a, the proven relationship between the refractive index n , the prism apex angle A , and the minimum angle of deviation δ_m is given by

$$n = \frac{\sin\left(\frac{A + \delta_m}{2}\right)}{\sin\frac{A}{2}} \quad (4-4)$$

where both A and δ_m are measured in degrees.

The derivation of Equation 4-4 is straightforward, but a bit tedious. Details of the derivation—making use of Snell’s law and geometric relations between angles at each refracting surface—can be found in most standard texts on geometrical optics. (See suggested references at the end of the module.) For now, we’ll be content to just use Equation 4-4 in Example 5 to determine the index of refraction of an unknown glass shaped in the form of an isosceles prism.

Example 5

Your supervisor hands you a piece of transparent optical material of unknown index of refraction. He asks you to determine the refractive index. You take the sample to the glass shop and have it shaped in the form of an isosceles prism with an apex angle of 25° . In the laboratory, with the help of a laser beam and a prism table, the *minimum* angle of deviation for this prism is measured carefully to be 15.8° . What must the refractive index of this glass material be?

Solution: Given that $\delta_m = 15.8^\circ$ and $A = 25^\circ$, we use Equation 4-4 to calculate the refractive index.

$$n = \frac{\sin\left(\frac{A + \delta_m}{2}\right)}{\sin\left(\frac{A}{2}\right)} = \frac{\sin\left(\frac{25^\circ + 15.8^\circ}{2}\right)}{\sin\left(\frac{25^\circ}{2}\right)} = \frac{\sin(20.4^\circ)}{\sin(12.5^\circ)} = \frac{0.3486}{0.2164} = 1.61$$

(Comparing this value of $n = 1.61$ with refractive indexes given in Table 4-1, the unknown glass could well be flint glass.)

Dispersion of light—Table 4-1 lists indexes of refraction for various substances at the wavelength of 589 nm. It turns out that the refractive index is slightly wavelength dependent so values of n change a little as λ changes. For example, the index of refraction for flint glass is about 1% higher for blue light (around 450 nm) than for red light (around 650 nm). The variation of refractive index n with wavelength λ is called *dispersion*. Knowing about dispersion, for example, is important in designing prism spectrometers to measure the wavelengths of spectra from different light sources. Figure 4-12a shows a normal dispersion curve of n_λ versus λ for different types of optical glass. Figure 4-12b shows the separation of the individual colors blended together in white light—400 nm to 700 nm—after passing through a prism. Note that n_λ decreases from shorter to longer wavelengths, thus causing the red light to be less deviated than the blue light as it passes through a prism. Dispersion accounts for the colors seen in a rainbow, where the individual raindrops serve as the refracting “prism.”



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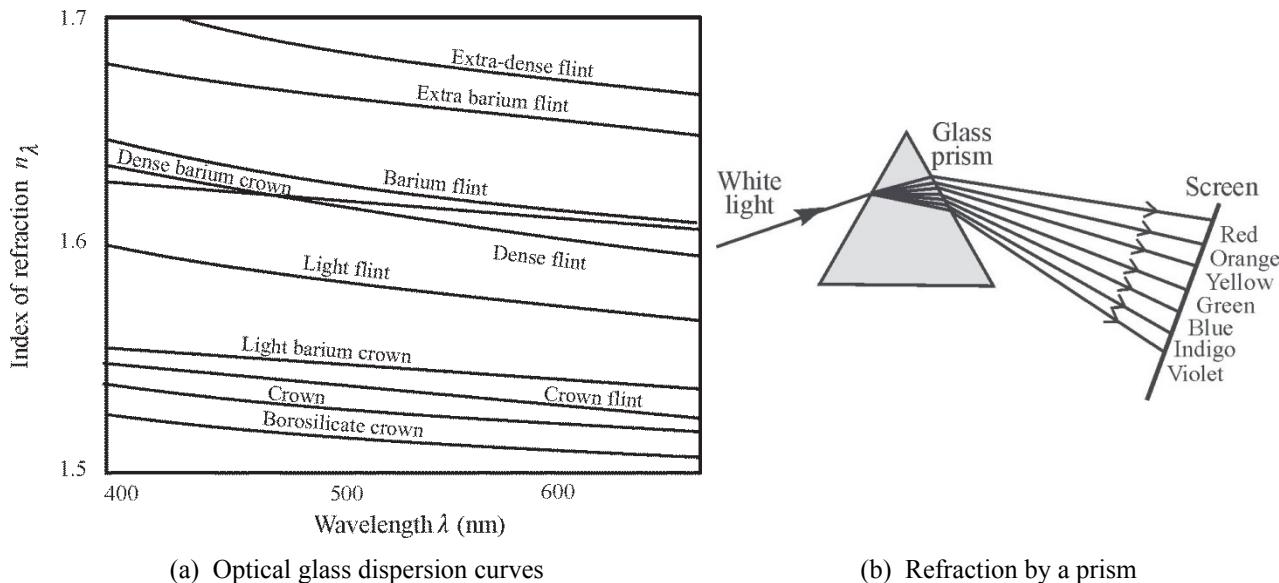


Figure 4-12 Typical dispersion curves and separation of white light after refraction by a prism

Special applications of prisms—Prisms that depend on *total internal reflection* are commonly used in optical systems, both to change direction of light travel and to change the orientation of an image. While mirrors can be used to achieve similar ends, the reflecting faces of a prism are easier to keep free of contamination and the process of total internal reflection is capable of higher reflectivity. Some common prisms in use today are shown in Figure 4-13.

Details of light redirection and image reorientation are shown for each one with the help of straight-line symbols labeled with circles and arrows. If, for example, the Dove prism in Figure 4-13b is rotated about its long axis, the image will also be rotated correspondingly.

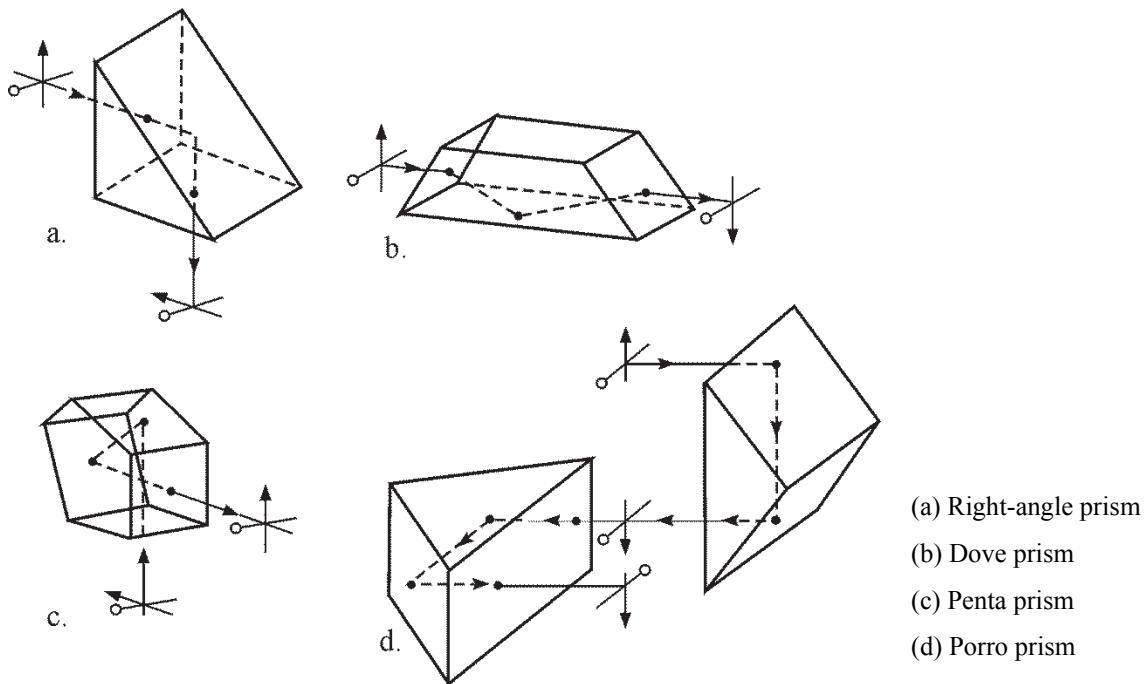


Figure 4-13 Image manipulation with refracting prisms

The Porro prism, consisting of two right-angle prisms, is used in binoculars, for example, to produce erect final images and, at the same time, permit the distance between the object-viewing lenses to be greater than the normal viewer's eye-to-eye distance, thereby enhancing the stereoscopic effect produced by ordinary binocular vision.

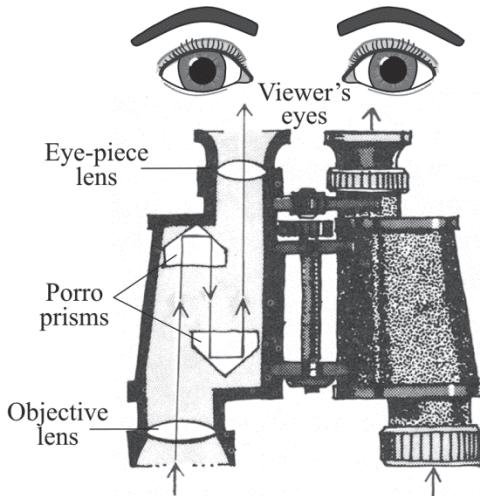


Figure 4-14 The use of Porro prisms in ordinary binoculars

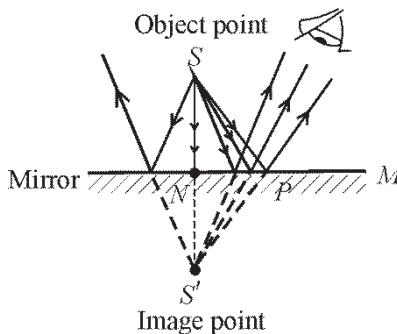
Figure 4-14 shows the light path of a ray entering the objective lens of a set of binoculars, passing through the Porro prisms, and then exiting the eyepiece into the viewer's eyes. Note especially how the presence of the Porro prisms in each tube enables the distance between the two objective lenses to be about twice the distance between the two eye-piece lenses.

Image Formation with Mirrors

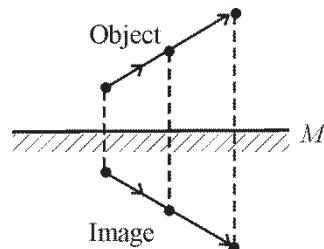
Mirrors, of course, are everywhere—in homes, auto headlamps, astronomical telescopes, and laser cavities—and in many other places. Plane and spherical mirrors are used to form three-dimensional images of three-dimensional objects. If the size, orientation, and location of an object relative to a mirror are known, the *law of reflection* and *ray tracing* can be used to locate the image graphically. Appropriate *mathematical formulas* can also be used to calculate the locations and sizes of the images formed by mirrors. In this section, we shall use both graphical ray tracing and formulas.

Images formed with plane mirrors

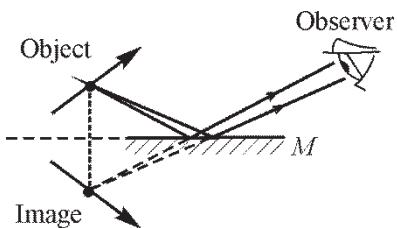
Images with mirrors are formed when many nonparallel rays from a given point on a source are reflected from the mirror surface, converge, and form a corresponding image point. When this happens, point by point for an extended object, an image of the object, point by point, is formed. Image formation in a plane mirror is illustrated in several sketches shown in Figure 4-15.



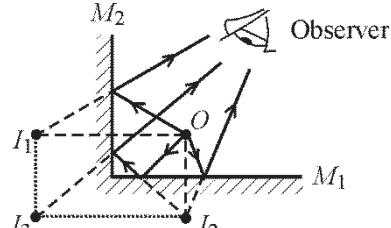
(a) Imaging a point source



(b) Imaging an extended object



(c) Image seen in a plane mirror is same size as object.



(d) Multiple images of point O with inclined mirrors

Figure 4-15 Image formation in a plane mirror

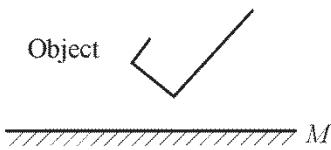
In Figure 4-15a, point object S sends diverging rays toward a plane mirror, which reflects them as shown. The *law of reflection* ensures that pairs of triangles like SNP and $S'NP$ are equal, so that all reflected rays appear to originate at the *image point* S' , which lies along the normal line SN , and at such depth that the *image distance* $S'N$ equals the *object distance* SN . The eye sees a point image at S' in exactly the same way it would see a real point object placed there. Since the actual rays do not exist behind the mirror surface, the image is said to be a *virtual image*, as mentioned earlier. Thus, the image S' cannot be projected onto a screen as in the case of a *real image*.

An extended object, such as the arrow in Figure 4-15b, is imaged point by point by a plane mirror surface in similar fashion. Each object point has its corresponding image point along its normal to the mirror surface and *as far below the reflecting surface as the object point lies above the surface*. Note that image position does not depend on the position of the eye. The construction in Figure 4-15b also makes clear that the image size is identical to the object size, giving a *magnification* of unity. In addition, the transverse orientations of object and image are the same. A right-handed object, however, appears left-handed in its mirror image.

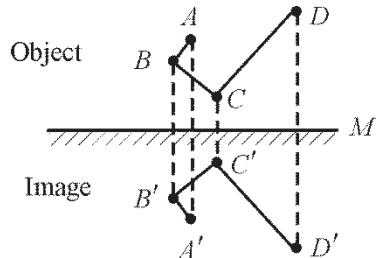
In Figure 4-15c, where the mirror does not lie directly below the object, the mirror plane may be extended, as shown. This extension enables one to determine the position of the image as seen by an eye positioned to receive reflected rays originating at the object. Figure 4-15d illustrates multiple images of a point object O formed by two perpendicular mirrors, M_1 and M_2 . The two images, I_1 and I_2 , result from a single reflection in one of the two mirrors. A third image, I_3 , is formed by sequential reflections involving both mirrors. All parts of Figure 4-14 and the related discussion above should be understood clearly because they are fundamental to the optics of images. Look at Example 6.

Example 6

Making use of the *law of reflection* and the conclusions drawn from Figure 4-14, draw the image of the letter L positioned above a plane mirror as shown below in (a).



(a) Original object and mirror surface M



(b) Point-by-point trace to locate image in mirror M

Solution: Make use of the fact that each point on the image is as far below the mirror—along a line perpendicular to the mirror—as the actual object point is above the mirror. Indicate key points (A, B, C, D) on the object and locate corresponding key points (A', B', C', D') on the image. Sketch in the image as shown in (b).

Summary of ray optics for plane mirrors:

- Each ray of light incident on a mirror from a point on an object obeys the law of reflection at the plane mirror surface.
- A point source of light in front of a mirror forms a virtual image as far behind the mirror as the point source is in front.
- Plane mirrors form virtual images that are the same size as the original objects. Hence, the magnification is unity.

Images formed with spherical mirrors

As we showed earlier in Figure 4-6, the *law of reflection* can be used to determine the direction along which any ray incident on a spherical mirror surface will be reflected. Using the *law of reflection*, we can trace rays from any point on a given object to the mirror, and from there on to the corresponding image point. This is the method of *graphical ray tracing*.

Graphical ray-trace method—To employ the method of ray tracing, we agree on the following:

- Light from an object will be incident on a mirror surface initially from the left.
- The *axis of symmetry* normal to the mirror surface is defined as the *optical axis*.
- The point where the optical axis meets the mirror surface is called the *vertex*, generally denoted by the letter *V*.

To locate an image, we use two important points common to any spherical mirror surface, the *center of curvature C* and the *focal point F*. They are shown in Figure 4-16, with the mirror vertex *V*, for both a *concave* and a *convex* spherical mirror. The *center of curvature C* is the geometrical center for the curved surface of the sphere-shaped mirror. The *focal point F* is the point along the *optical axis* at which light rays parallel to the optical axis converge after reflection from the mirror.

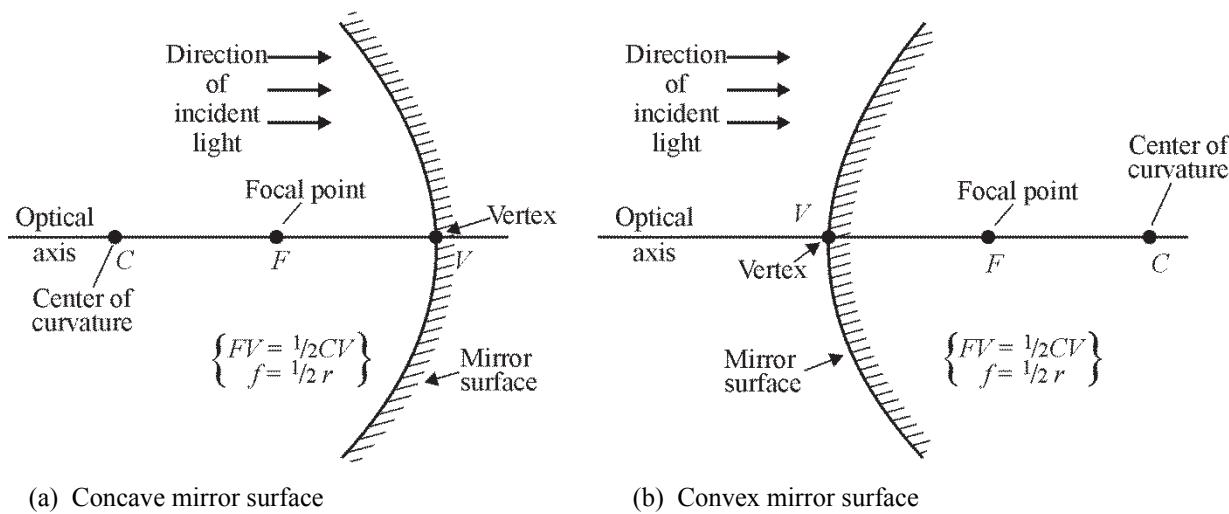


Figure 4-16 Defining points for concave and convex mirrors

The outer edges of *concave* mirrors always curve toward the oncoming light. Such mirrors have their center of curvature *C* and focal point *F* located to the *left* of the vertex as seen in Figure 4-16a. The outer edges of *convex* mirrors always curve away from the oncoming light, and their center of curvature *C* and focal point *F* are located to the *right* of the vertex. See Figure 4-16b.

The important connection between parallel light rays and the focal points for mirror surfaces is shown in Figure 4-17a, b. Parallel rays are light rays coming from a very distant source (such as the sun) or as part of a collimated laser beam. The *law of reflection*, applied to a small tangent segment at each point on the mirror surface where a ray is incident, requires that the ray be reflected so as to pass through a focal point *F* in front of a concave mirror (Figure 4-17a) or be

reflected to appear to come from a focal point F behind a convex mirror (Figure 4-17b). Notice that a line drawn from the center of curvature C to any point on the mirror such as P is a *normal* line and thus bisects the angle between the incident and reflected rays, as shown.

As long as the transverse dimension of the mirror is not too large, simple geometry shows that the point F , for either mirror, is located at the midpoint between C and V , so that the distance FV is one-half the radius of curvature CV . The distance FV is called the *focal length* and is commonly labeled as f . Therefore, one has $f = \frac{1}{2}r$.

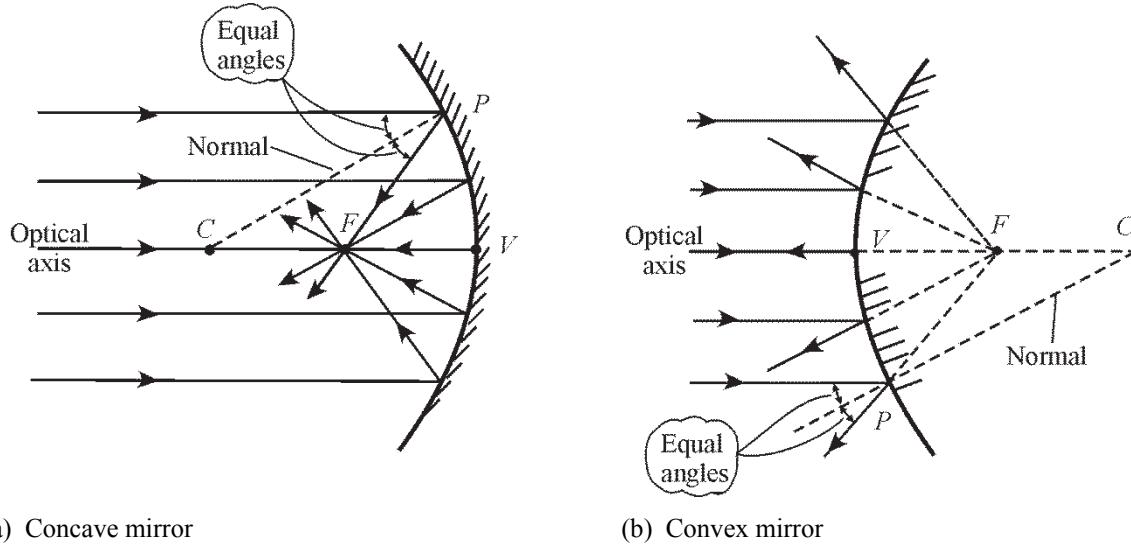


Figure 4-17 Parallel rays and focal points

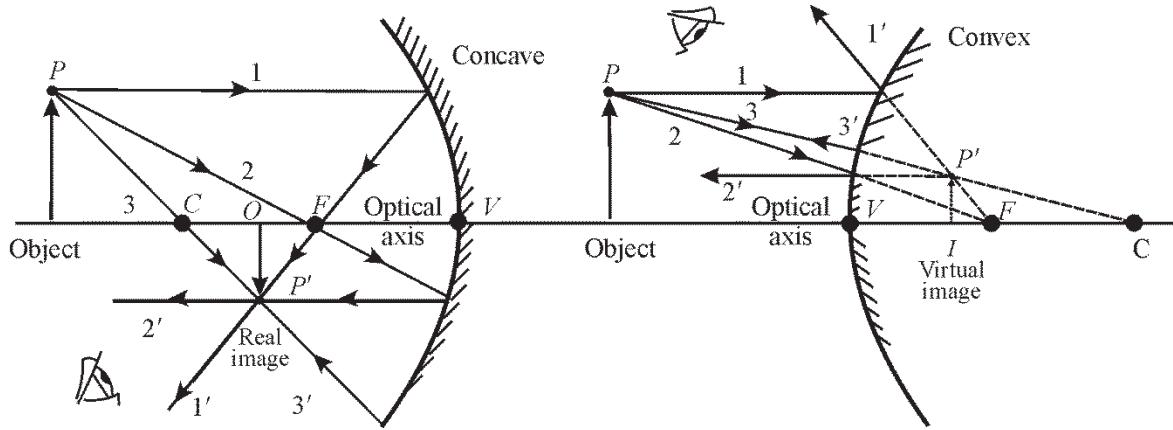
Key rays used in ray tracing—Figures 4-18a,b show three key rays—for each mirror—that are used to locate an image point corresponding to a given object point. They are labeled 1, 2, and 3. After reflection, the corresponding rays are labeled 1', 2', and 3'. Any two rays, drawn from object point P , will locate the corresponding image point P' . In most cases, it is sufficient to locate one point, like P' , to be able to draw the entire image. Note carefully, with reference to Figure 4-18a, b, the following facts:

For a concave mirror:

- An incident ray from object point P , initially *parallel to the axis*, such as ray 1, reflects from the mirror and *passes through the focal point F* (labeled ray 1').
- An incident ray from P passing through the focal point F on its way to the mirror, such as ray 2, reflects from the mirror *as a ray parallel to the axis* (labeled ray 2').
- An incident ray from P passing through the center of curvature C on its way to the mirror, such as ray 3, *reflects back along itself* (labeled ray 3').
- Reflected rays 1', 2', and 3' converge after reflection to locate point P' on the image. The complete image, arrow OP' , is a *real* image that can be formed on a screen located there. It is seen as a real image by an eye located where shown in Figure 4-18a.

For a convex mirror:

- An incident ray from object point P , initially parallel to the axis, such as ray 1, reflects from the mirror *as if it came originally from the focal point F behind the mirror* (labeled ray $1'$).
- An incident ray from P , such as ray 2, which is headed initially on its way to the mirror in a direction toward the focal point F behind the mirror, reflects from the mirror in a direction parallel to the optical axis (labeled ray $2'$).
- An incident ray from P , such as ray 3, which is headed initially on its way to the mirror in a direction toward the center of curvature C behind the mirror, reflects back along itself (labeled ray $3'$).
- Rays $1'$, $2'$, and $3'$ diverge (spread apart) after reflection. A person looking toward the mirror from the left (see eye) intercepts the diverging rays and sees them as if they appear to come from their common intersection point P' , behind the mirror. The complete image (arrow IP') is *virtual* since it cannot be formed on a screen placed there.



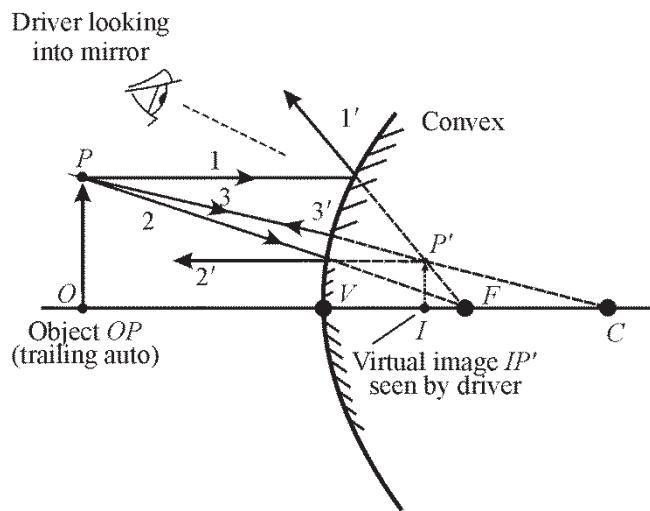
(a) Ray tracing from P to P' for a *concave* mirror (b) Ray tracing from P to P' for a *convex* mirror

Figure 4-18 Key rays for graphical ray tracing with spherical mirrors

Example 7

The passenger-side mirror on an automobile is a slightly *convex* mirror. It provides the driver with a wider field of view, but a significantly reduced image. Assume that object OP shown in the sketch is part of an automobile trailing the driver's car. Use three key rays to locate the reduced, virtual image of the trailing auto.

Solution: Use key rays 1, 2, and 3 incident on the convex mirror from point P on object OP . Use the key points F and C , and the steps for ray tracing light incident on a convex mirror given earlier, to locate P' .



The three reflected rays $1'$, $2'$, and $3'$ *diverge* after reflection. They appear to come from a common point P' *behind* the mirror. Repeating this process for other points on the object, between O and P , then locates the complete image IP' . Note that virtual image IP' is reduced in size, about one-third as large as object OP . As a result, drivers are always cautioned that images they see in the passenger-side mirror are *physically NEARER* to them than they *appear to be* in the mirror. Thus, drivers are cautioned not to change lanes without checking the rear-view mirror and also making a quick “head-check” over the shoulder to verify the *actual position* of the trailing car.

Mirror formulas for image location

In place of the graphical ray-tracing methods described above, we can use formulas to *calculate* the image location. We shall derive below a “mirror formula” and then use the formula to determine image location. The derivation is typical of those found in geometrical optics, and is instructive in its use of combined algebra, geometry, and trigonometry. (*If the derivation is not of interest to you, you may skip to the next section, where the derived formula is used in typical calculations. Be sure, though, that you learn about the sign convention discussed following.*)

OPTIONAL—Derivation of the mirror formula. The drawing we need to help us carry out the derivation is shown in Figure 4-19. The important quantities are the object distance p , from O to V ; the image distance q , from I to V ; and the radius of curvature r , from C to V or C to P . Thus, both p and q are measured relative to the mirror vertex, as shown. A plus or minus sign on r will indicate whether the mirror is concave or convex. All other quantities in Figure 4-19 are used in the derivation but will not show up in the final “mirror formula.”

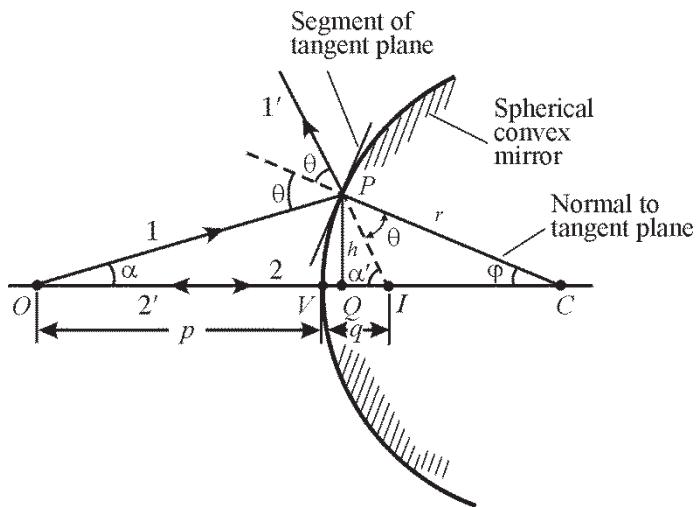


Figure 4-19 Basic drawing for deriving the mirror formula

The mirror shown in Figure 4-19 is convex with center of curvature C on the right. Two rays of light, 1 and 2, originating at object point O —located here on the optical axis—are drawn. One is drawn normal to the convex surface at its vertex V . The other is drawn as an arbitrary ray incident at P . Ray 2 reflects back along itself. Ray 1 reflects at P as if incident on a segment of the plane tangent at P , according to the *law of reflection*. Relative to each other, the two reflected rays (1' and 2') diverge as they leave the mirror. The intersection of the two rays (extended backward) determines the image point I corresponding to object point O . Thus, the image is virtual and located behind the mirror surface.

A perpendicular of height h is drawn from P to the axis at Q . We seek a relationship between p and q that depends only on the radius of curvature r of the mirror. As we shall see, such a relation is possible only to a *first-order approximation of the sines and cosines of angles*, such as α and φ , made by the object and image rays at various points on the spherical surface. This means that, in the expansions of $\sin \varphi$ and $\cos \varphi$ in series, as shown here in part,

$$\begin{aligned}\sin \varphi &= \varphi - \frac{\varphi^3}{3!} + \frac{\varphi^5}{5!} - \dots \\ \cos \varphi &= 1 - \frac{\varphi^2}{2!} + \frac{\varphi^4}{4!} - \dots\end{aligned}$$

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we consider only the *first terms* and write as an approximation.

$$\begin{aligned}\sin \varphi &\approx \varphi \\ \cos \varphi &\approx 1 \\ \text{and } \tan \varphi &= \frac{\sin \varphi}{\cos \varphi} \approx \frac{\varphi}{1} \approx \varphi\end{aligned}$$

These approximate relations are accurate to 1% or less if the angle φ is 10° or smaller. This approximation leads to so-called *first-order (or Gaussian) optics*, after Karl Friedrich Gauss, who in 1841 developed the foundations of this subject. We return now to the problem at hand—that of relating p , q , and r . Notice that two angular relationships may be obtained from Figure 4-19, using the fact that the exterior angle of a triangle equals the sum of its two interior angles. Thus,

$$\text{in } \Delta OPC, \theta = \alpha + \varphi \quad \text{and} \quad \text{in } \Delta OPI, 2\theta = \alpha + \alpha'.$$

After eliminating θ between these two equations, we get

$$\alpha - \alpha' = -2\varphi$$

Using the small-angle approximations, the angles α , α' , and φ above can be replaced by their tangents $\tan \alpha \approx \alpha = \frac{h}{p}$, $\tan \alpha' \approx \alpha' = \frac{h}{q}$, and $\tan \varphi \approx \varphi = \frac{h}{r}$ so that the relationship $\alpha - \alpha' = -2\varphi$ now becomes

$$\frac{h}{p} - \frac{h}{q} = -2 \frac{h}{r}$$

Note that in these tangent relationships, we have neglected the axial distance VQ , which is very small when φ is small. Cancellation of h in the above equation produces the desired relationship,

$$\frac{1}{p} - \frac{1}{q} = -\frac{2}{r} \tag{4-5}$$

If the spherical surface in Figure 4-19 is chosen to be concave instead, the center of curvature will be to the left. For certain positions of the object point O , it is then possible to find a real image point, also to the left of the mirror. In these cases, the resulting geometric relationship analogous to Equation 4-5 consists of the same terms, but with different algebraic signs, depending on the *sign convention* employed. (**END OF OPTIONAL MATERIAL**)

With an appropriate sign convention, a *mirror equation* valid for both convex and concave mirrors is given by Equation 4-6.

$$\frac{1}{p} + \frac{1}{q} = \frac{2}{r} \quad \begin{array}{l} \text{Spherical} \\ \text{mirror} \\ \text{equation} \end{array} \quad (4-6)$$

Sign convention—The sign convention to be used in conjunction with Equation 4-6 and Figure 4-19 is as follows.

- Object and image distances p and q are both *positive* when located to the *left* of the vertex and both *negative* when located to the *right*.
- The radius of curvature r is *positive* when the center of curvature C is to the *left* of the vertex (concave mirror surface) and *negative* when C is to the *right* (convex mirror surface).
- Vertical dimensions are positive above the optical axis and negative below.
- And since the focal length f is equal to one-half of the radius of curvature r , i.e., $f = \frac{r}{2}$, as shown earlier in connection with Figures 4-16 and 4-17, the focal length f is *positive for concave mirrors and negative for convex mirrors*.

In the application of these rules, light is assumed to be directed initially, as we mentioned earlier, from left to right. According to this sign convention, *positive* object and image distances correspond to *real* objects and images, and *negative* object and image distances correspond to *virtual* objects and images. *Virtual objects* occur only with a sequence of two or more reflecting or refracting elements. We shall demonstrate the use of virtual objects in an example that follows later.

Magnification of a mirror image—Figure 4-20 shows a drawing from which the *magnification*—ratio of image height h_i to object height h_o —can be determined. Since angles θ_i , θ_r , and α are equal to each other, it follows that triangles VOP and VIP' are similar triangles. Thus, the corresponding sides of the two similar triangles are proportional and one can write

$$\frac{h_i}{h_o} = \frac{q}{p}$$

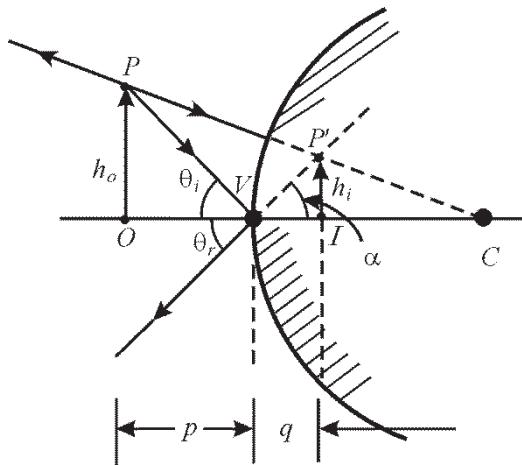


Figure 4-20 Construction for derivation of mirror magnification formula

This gives at once the magnification m —defined as image size divided by the object size—to be

$$m \equiv \frac{h_i}{h_o} = \frac{q}{p}$$

When the *sign convention* for spherical mirrors is taken into account, one has, for the *general case*, a single equation, Equation 4-7, valid for both convex and concave mirrors.

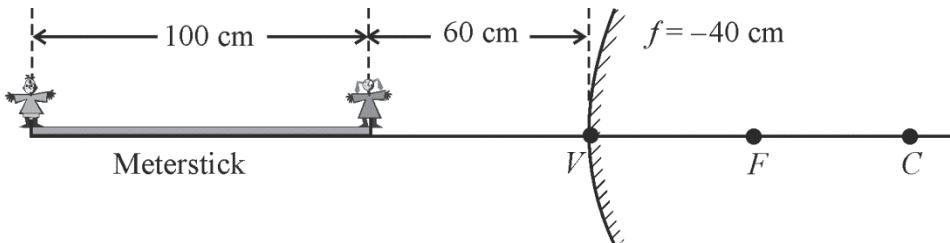
$$m = -\frac{q}{p} \quad \text{Magnification for spherical mirrors} \quad (4-7)$$

If, after calculation, the value of m is positive, the image is erect. If the value is negative, the image is inverted.

Let us now use the spherical mirror formulas in Equations 4-6 and 4-7, and the sign convention, to locate an image and determine its size.

Example 8

A meterstick lies along the optical axis of a convex mirror of focal length 40 cm, with its near end 60 cm from the mirror surface. Five-centimeter toy figures stand erect on both the near and far ends of the meterstick. (a) How long is the virtual image of the meterstick? (b) How tall are the toy figures in the image, and are they erect or inverted?



Solution: Use the mirror equation $\frac{1}{p} + \frac{1}{q} = \frac{2}{r}$ twice, once for the near end and once for the far end of the meterstick. Use the magnification equation $m = -\frac{q}{p}$ for each toy figure.

- (a) **Near end:** Sign convention gives $p = +60$ cm, $r = 2f = 2 \times (-40) = -80$ cm, since f is negative for a convex mirror. Thus the mirror equation becomes:

$$\therefore \frac{1}{60} + \frac{1}{q_n} = -\frac{2}{80}, \text{ so } q_n = -24 \text{ cm}$$

Negative sign indicates that the image of the near end is *virtual*, 24 cm to the right of V .

Far end: $p = +160$ cm, $r = -80$ cm, and the mirror equation becomes:

$$\frac{1}{160} + \frac{1}{q_f} = -\frac{1}{40}, \text{ so } q_f = -32 \text{ cm}$$

Far-end image is *virtual*, 32 cm to the right of V .

\therefore Therefore, the length of the meterstick image is $32 \text{ cm} - 24 \text{ cm} = 8 \text{ cm}$ long.

- (b) **Near-end toy figure:**

$$m_n = \frac{-q}{p} = \frac{-(-24)}{60} = +0.4 \quad (\text{Image is erect since } m \text{ is positive.})$$

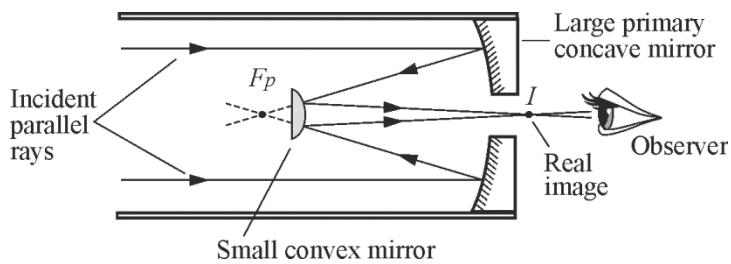
The toy figure is $5 \text{ cm} \times 0.4 = 2 \text{ cm}$ tall, at near end of the meterstick image.

Far-end toy figure:

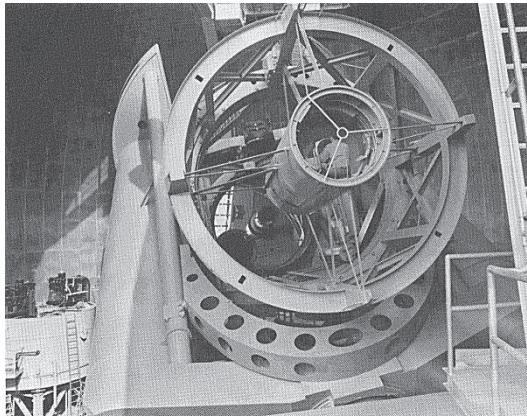
$$m_f = \frac{-q}{p} = \frac{-(-32)}{160} = +0.2 \quad (\text{Image is erect since } m \text{ is positive.})$$

The toy figure is $5 \text{ cm} \times 0.2 = 1 \text{ cm}$ tall, at far end of the meterstick image.

Telescopes and mirrors—Mirrors play an important role in the design of reflecting telescopes used in astronomy. One such design, known as a Cassegrain telescope, makes use of both a concave and convex mirror to form a real image of the “target” object. The huge *concave* mirror is used to collect the light incident from distant stars and then focus the parallel light rays at the mirror focal point F_p . See sketch (a). Before this light reaches the point F_p , however, it is intercepted by a much smaller *convex* mirror, which then reflects the light to a real image point I , as shown.



(a) Ray optics for a Cassegrain telescope



(b) Hale telescope (200-in.) showing observer in prime-focus cage and reflecting surface of 200-in. mirror (California Institute of Technology.)

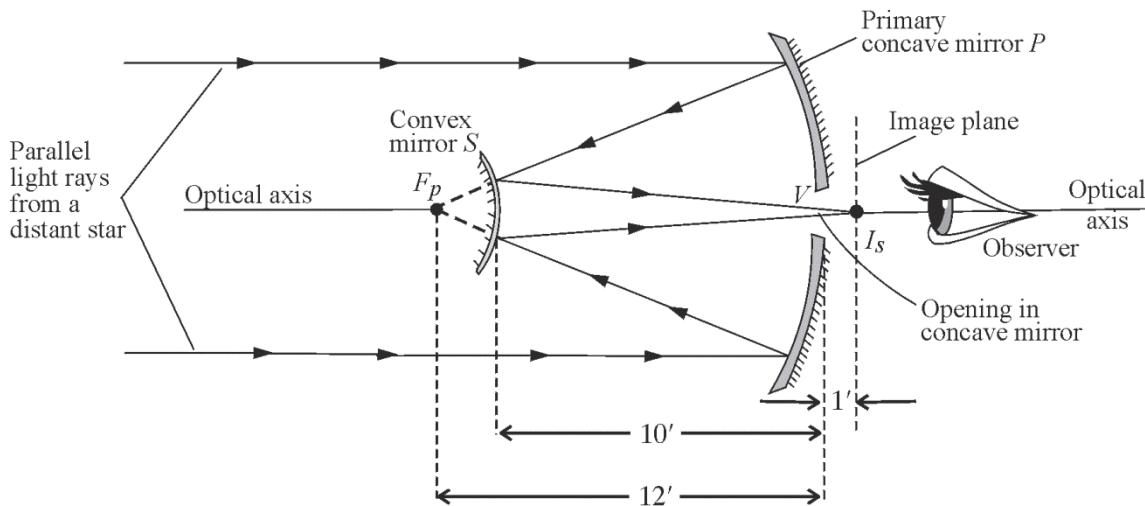
Figure 4-21 Cassegrain telescope

One of the more famous telescopes, located at Mount Palomar, is the 200-inch Hale telescope. The insert shows an astronomer, seated in the prime-focus cage of this telescope, where the image from the primary mirror would be formed.

Example 9

The primary concave mirror of a Cassegrain reflecting telescope has a focal length of 12 feet. The secondary convex mirror is positioned 10 feet in front of the concave mirror along the optical axis. See following sketch.

Light reflected from the primary concave mirror P , heading toward the focal point F_P is intercepted by the secondary convex mirror S before it reaches the focal point F_P and again reflected to form a real image at I_s , one foot behind the concave mirror. Here it can be recorded on film or viewed by an observer, as shown.



For this Cassegrain telescope,

- Where is the image of a distant star formed by the primary concave mirror P ?
- What is the radius of curvature r of the concave mirror?
- What should the radius of curvature of the convex mirror S be so that it forms a real image one foot behind the opening in the concave mirror? What is the focal length of this mirror?

Solution

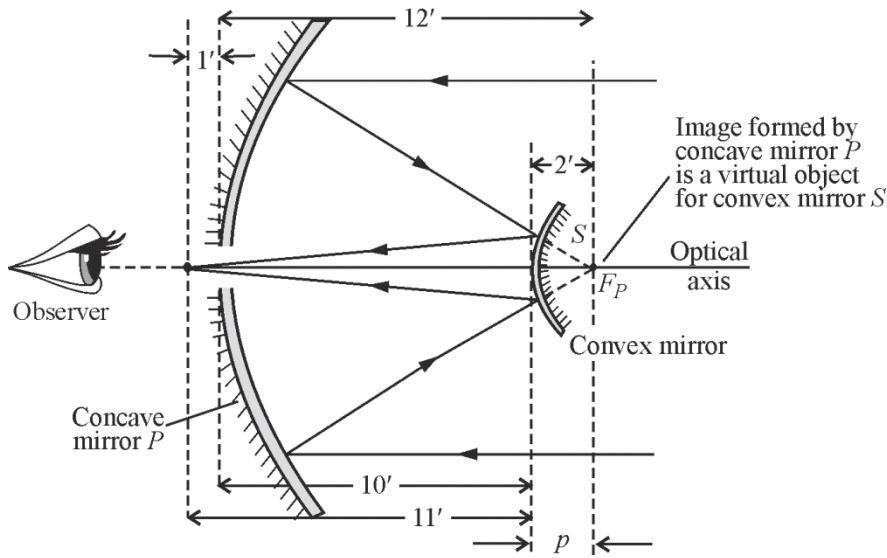
(a) Since light entering the concave mirror from distant stars is made up of parallel light rays, the image of such a star would be formed at the focal point F_p , 12 feet to the left of the mirror vertex V .

(b) Since $f = \frac{r}{2}$, $r = 2f = 2(12') = 24'$. (Note that r is + according to the sign convention for a concave mirror.)

(c) To find the radius of curvature r_s of the secondary mirror, knowing object and image position for the secondary mirror, we can use the formula $\frac{1}{p} + \frac{1}{q} = \frac{2}{r_s}$ and solve for r_s . To do this correctly, we **MUST** pay close attention to the **SIGN CONVENTIONS** already defined.

Thus, according to the basis for our sign convention, we want light to be incident on the convex mirror *traveling from left to right*. In the drawing above, light is incident on the convex mirror from *right to left*. So, in our mind, we position ourselves *behind* the drawing and *look out* through the page, seeing the light then moving from our left to our right.

Second, from this position, the object p for the convex mirror is a *virtual object*, since it is the image (virtual) formed by the concave mirror at F_p , a point behind the convex mirror. Thus $p = -(12' - 10') = -2'$, since virtual objects are negative. The “repositioned” system is sketched below.



Third, the image q is positive since it is on the same side of the convex mirror as the approaching light and thus is equal to $10' + 1' = +11'$.

Solving $\frac{1}{p} + \frac{1}{q} = \frac{2}{r_s}$, with $p = -2'$ and $q = +11'$ we have

$$\frac{1}{(-2)} + \frac{1}{11} = \frac{2}{r_s}$$

$$\frac{(11 - 2)}{(-2 \times 11)} = \frac{2}{r_s} \quad \text{or} \quad \frac{9}{-22} = \frac{2}{r_s}$$

$$\text{so that } r_s = \frac{-44}{9} = -4.89'$$

Note that r_s comes out to be negative as it should in accordance with the sign convention, since the mirror facing the left-to-right traveling light in the repositioned drawing is convex in shape.

And since the focal length is always one-half of the radius of curvature,

$$f = \frac{r}{2} = \frac{-4.89'}{2} = -2.44 \text{ feet.}$$

Image Formation with Lenses

Lenses are at the heart of many optical devices, not the least of which are cameras, microscopes, binoculars, and telescopes. Just as the *law of reflection* determines the imaging properties of mirrors, so *Snell's law of refraction* determines the imaging properties of lenses. Lenses are essentially light-controlling elements, used primarily for image formation with visible light, but also for ultraviolet and infrared light. In this section, we shall look first at the types and properties of lenses, then use graphical ray-tracing techniques to locate images, and finally use mathematical formulas to locate the size, orientation, and position of images in simple lens systems.

Function of a lens

A lens is made up of a transparent refracting medium, generally of some type of glass, with spherically shaped surfaces on the front and back. A ray incident on the lens bends (according to Snell's law) at the front surface, propagates through the lens, and bends again at the rear surface (according to Snell's law). Figure 4-22 shows a rather thick lens bending (refracting) rays from an object OP to form an image $O'P'$. The ray-tracing techniques and lens formulas we shall use here are based again on *Gaussian optics*, just as they were for mirrors.

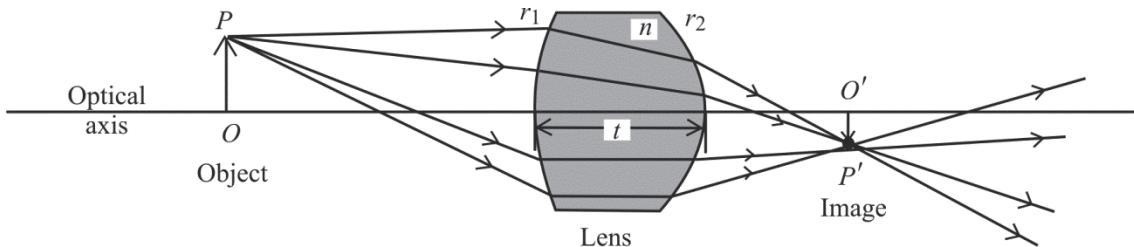


Figure 4-22 Refraction of light rays by a lens

As we have seen, *Gaussian optics*—sometimes also called *paraxial optics*—arises from the basic approximations $\sin \varphi \approx \varphi$, $\tan \varphi \approx \varphi$, and $\cos \varphi \approx 1$. These approximations greatly simplify ray tracing and lens formulas, but they do restrict the angles the light rays make with the optical axis—for practical purposes—to rather small values of 20° or less.

Types of lenses

If the *axial thickness* t of a lens (see Figure 4-22) is small compared with the radii of curvature r_1 and r_2 of its surfaces, it can be treated as a *thin lens*. Ray-tracing techniques and lens formulas are relatively simple for thin lenses. If the thickness of a lens is not negligible compared with the radii of curvature of its faces, it must be treated as a *thick lens*. Ray-tracing techniques and lens-imaging formulas are more complicated for thick lenses. When working with thick lenses, one can make use of available computer programs to trace the rays through the lenses or make surface-by-surface calculations. In this basic introduction of geometrical optics, however, we shall deal only with thin lenses.

Converging and diverging thin lenses—In Figure 4-23, we show the shapes of several common “thin” lenses. Even though a “thickness” is shown, the use of thin lenses assumes that the rays simply refract at the front and rear faces without a translation through the intervening lens medium. The first three lenses are *thicker in the middle than at the edges* and are described as *converging* or *positive* lenses. They cause parallel rays passing through them to bend toward one another and give rise to *positive* focal lengths. The last three lenses are *thinner in the middle than at the edges* and are described as *diverging* or *negative* lenses. They cause parallel rays passing through them to spread as they leave the lens and thereby give rise to *negative* focal lengths. In Figure 4-23, names associated with the different shapes are noted.

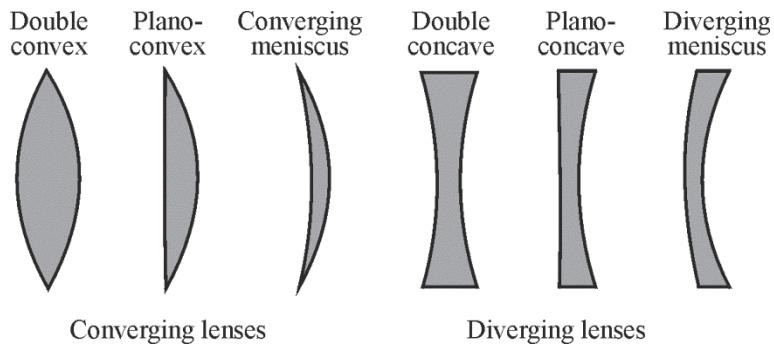
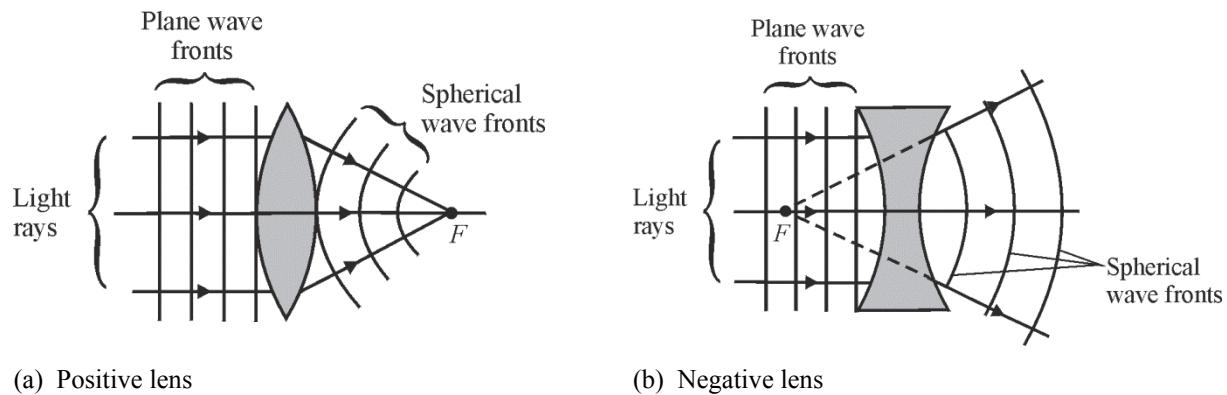


Figure 4-23 Shapes of common thin lenses

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Focal points of thin lenses—Just as for mirrors, the *focal points* of lenses are defined in terms of the effect that lenses have on incident parallel light rays and plane wave fronts. Figure 4-24 shows parallel light rays and their associated plane wave fronts incident on a *positive* lens (Figure 4-24a) and a *negative* lens (Figure 4-24b). For the positive lens, refraction of the light by the lens brings it to a focal point *F* (real image) to the right of the lens. For the negative lens, refraction of the light by the lens causes it to diverge *as if it were coming from focal point F located to the left of the lens*. Note how the *plane wave fronts* are changed to *converging spherical wave fronts* by the positive lens and to *diverging spherical wave fronts* by the negative lens. This occurs because light travels more slowly in the lens medium than in the surrounding air, so the thicker parts of the lens retard the light along the wave fronts more than do the thinner parts.



(a) Positive lens

(b) Negative lens

Figure 4-24 Focal points for positive and negative lenses

Recall that, for mirrors, there is but a *single* focal point for each mirror surface since light remains always on the same side of the mirror. For thin lenses, there are *two* focal points, symmetrically located on each side of the lens, since light can approach from either side of the lens. The sketches in Figure 4-25 indicate the role that the two focal points play, for positive lenses (Figure 4-25a) and negative lenses (Figure 4-25b). Study these figures carefully.

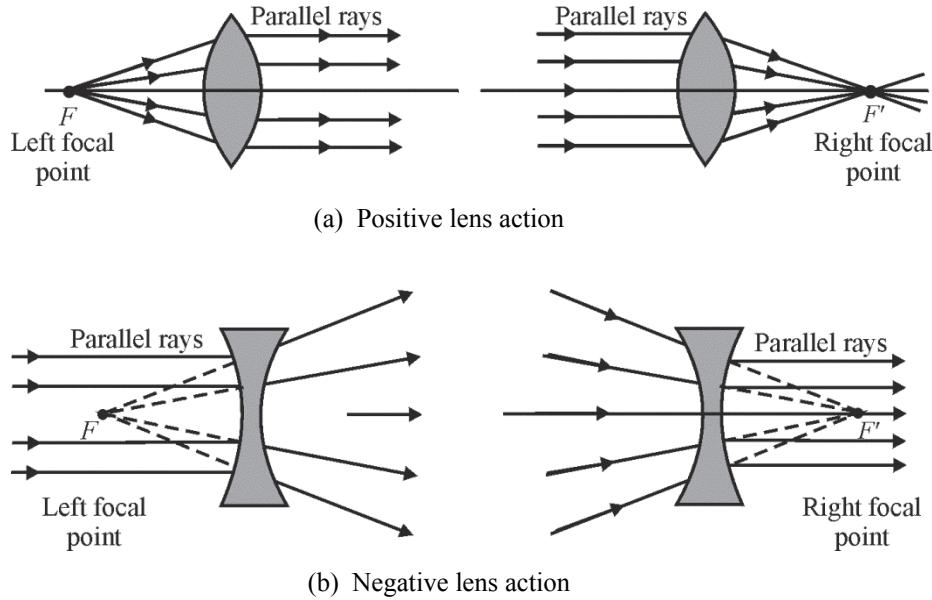


Figure 4-25 Relationship of parallel light rays to right and left focal points in thin lenses

The left sketch in Figure 4-25a shows light rays emerging from the *left focal point* F of the positive lens, striking the positive thin lens and emerging as *parallel rays*. The right sketch in Figure 4-25a shows a set of *parallel rays* incident on a positive thin lens and converging after refraction so as to pass through the right focal point F' .

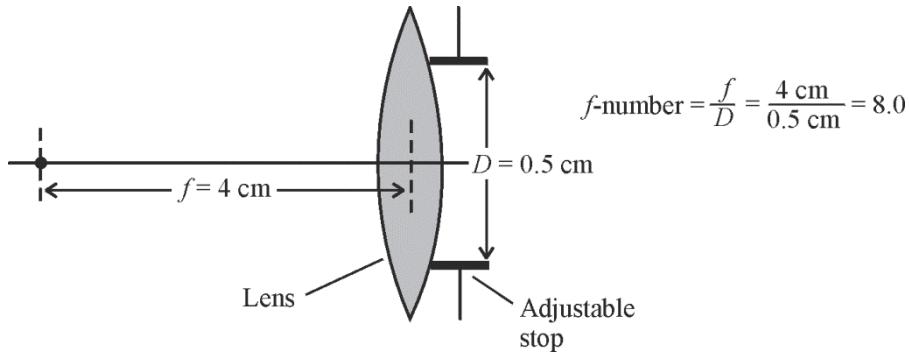
The left sketch of Figure 4-25b shows parallel rays incident on a negative thin lens and diverging after refraction by the lens as if to come from its left focal point F (see dashed lines). The right sketch in Figure 4-25b shows light converging onto a negative thin lens, heading for the right focal point F' (see dashed lines), but being refracted by the lens so as to emerge as parallel rays.

f-number and numerical aperture of a lens—The transverse dimension (size) of a lens determines its light-gathering power and, consequently, the brightness of the image it forms. Two commonly used indicators of this special characteristic of a lens are called the *f-number* and the *numerical aperture*.

The *f-number*, also referred to as the *relative aperture* and the *f/stop*, is defined simply as the ratio of the focal length f of the lens, to its transverse diameter D , as given in Equation 4-8.

$$f\text{-number} = \frac{f}{D} \quad (4-8)$$

For example, a lens of focal length 4 cm *stopped down* to an aperture of diameter 0.5 cm, as shown in the sketch below, has an *f*-number of $4/0.5 = 8$.



Photographers usually refer to the situation pictured as a lens with an *f/stop* of *f/8*. Before fully automated—“point and shoot”—cameras came along, a photographer would routinely select an aperture size D for a given camera lens, an appropriate shutter speed, and a proper focus f to achieve both the desired image brightness and sharpness.

Table 4-2 lists the usual choices of *f/stops* (*f*-numbers) available on cameras and the corresponding image irradiance or “brightness”—in watts per square meter incident on the film surface. The listing gives the irradiance E_0 as the value for an *f/stop* of 1 and shows how the image irradiance decreases as the lens is “stopped down,” that is, as the adjustable aperture size behind the camera lens is made smaller so that D decreases. From Equation 4-8, it should be clear that, for a given camera lens of focal length f , the *f/stop* or *f*-number increases as D decreases, that is, as the lens is “stopped down.” Clearly, then, *increasing* the *f*-number of a lens *decreases* its light-gathering power.

Table 4-2. Relative Image Irradiance (Brightness) as a Function of *f*/stop Setting

<i>f</i> /stop or <i>f</i> -number	Relative Image Irradiance in watts/m ²
1	E_0
1.4	$E_0/2$
2	$E_0/4$
2.8	$E_0/8$
4	$E_0/16$
5.6	$E_0/32$
8	$E_0/64$
11	$E_0/128$
16	$E_0/256$
22	$E_0/512$

Since the *total light energy exposure* in joules/m² on the film is the *product* of the irradiance in joules/(m²·s) and the exposure time (shutter speed) in seconds, a desirable film exposure can be obtained in a variety of ways. Thus, if a particular film—whose speed is described by an ASA number such as ASA 200—is perfectly exposed by light from a particular scene with a shutter speed of 1/50 second and an *f/stop* of *f/8* (irradiance equals $E_0/64$ from Table 4-2), it will also be

perfectly exposed by any other combination that gives the same total exposure in Joules/m^2 . For example, by choosing a shutter speed of 1/100 second and an *f*/stop of *f*/5.6, the exposure time is cut in half while the irradiance ($E_0/32$) is doubled, thereby leaving *no net change* in the film exposure in Joules/m^2 .

The *numerical aperture* is another important design parameter for a lens, related again directly to how much light the lens gathers. If the focal length of a design lens increases and its diameter decreases, the solid angle (cone) of useful light rays from object to image for such a lens decreases. For example, the concept of a *numerical aperture* finds immediate application in the design of the objective lens (the lens next to the specimen under observation) for a *microscope*, as is shown below. Light-gathering capability is crucial for microscopes.

Figure 4-26 depicts the light-gathering power of a lens relative to a point O on a specimen covered by a glass slide. Lens L is the objective lens of a microscope focused on the specimen. For the *sake of comparison only*, we show an *oil-immersion* system and an *air-immersion* system, side-by-side, left and right of the symmetry axis of the microscope lens. On the right side of the symmetry axis of the lens, the light-gathering power of the lens—with *air* between the cover slide and the lens—is depicted in terms of limiting ray 1 and half-angle α_{air} . On the left side, by contrast, the increased light-gathering power of the lens—with *oil* situated between the cover slide and the lens—is shown in terms of limiting ray 2 and the *larger* half-angle α_{oil} .

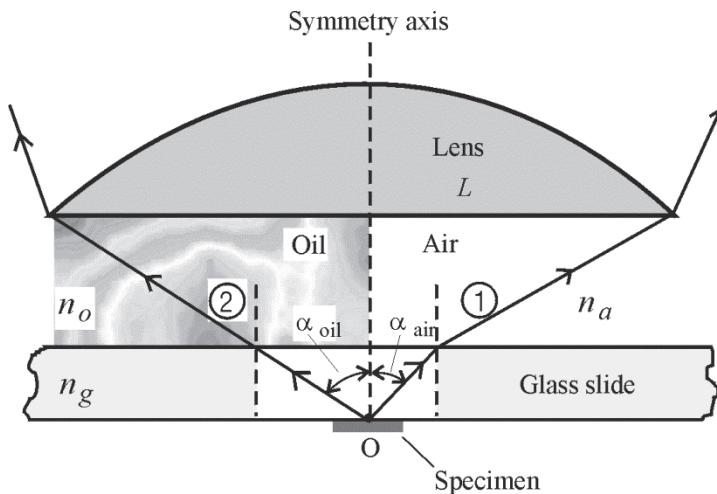


Figure 4-26 Comparison of light-gathering power of an oil-immersion lens system and an air-immersion lens system, showing that the oil-immersion lens system is superior

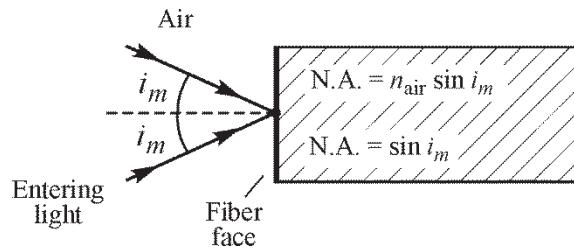
The oil is chosen to have an index of refraction (n_0) very near that of the cover slide (n_g) so that little or no refraction occurs for limiting ray 2 at the glass-oil interface, while considerable refraction does occur at the glass-air interface for limiting ray 1. Consequently, half-angle α_{oil} is greater than half-angle α_{air} . As Figure 4-26 shows, since ray 1 suffers refraction at the glass-air interface, the cone of rays (from point O on the specimen) accepted by the lens is restricted to the smaller half-angle α_{air} . The *numerical aperture* of a lens is defined so as to take into account the difference in solid angles (cones) of light accepted by different optical systems.

The definition of numerical aperture (*N.A.*) is given in Equation 4-9 as

$$N.A. = n \sin \alpha \quad (4-9)$$

where n is the index of refraction of the *intervening medium* between object and lens—such as oil—and α is the half-angle defined by the limiting ray (α_{air} or α_{oil} in Figure 4-26). Thus the “light-gathering” power of the microscope’s objective lens in Figure 4-26 is increased by increasing the refractive index of the intervening oil medium.

The *numerical aperture* (*N.A.*) of an *optical fiber* is an important measure of the fiber’s light capturing ability at its entrance face. In terms of the geometry introduced earlier in Example 4, we see, with the help of the accompanying sketch, that $N.A. = \sin i_m$.



It is shown in most basic books on optics that image brightness is dependent on values of the *f-number* or numerical aperture, in accordance with the following proportionalities:

$$\text{image brightness} \propto \frac{1}{(f\text{-number})^2} \quad (\text{as involved in Table 4-2})$$

$$\text{image brightness} \propto (N.A.)^2$$

In summary, one can *increase* the light-gathering power of a lens and the brightness of the image formed by a lens by *decreasing* the *f-number* of the lens (increasing lens diameter) or by *increasing* the numerical aperture of the lens (increasing an appropriate refraction index and thus making possible a larger acceptance angle).

Image location by ray tracing

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To locate the image of an object formed by a thin lens, we make use of three key points related to the lens and associate each of them with a defining ray. The three points are the *left focal point* F , the *right focal point* F' , and the *lens vertex (center)* V . In Figure 4-27, the three rays are shown leaving object point P and passing through the lens to locate a corresponding image point P' , for both a positive and a negative lens. The complete object is labeled OP and the corresponding image IP' . The defining rays are labeled to show clearly their connection to the points F , F' , and V . In practice, of course, only two of the three rays are needed to locate the desired image point. (The third ray is often used as a “check.”) Note also that the location of image point P' is generally sufficient to sketch in the rest of the image IP' , to correspond with the given object OP .

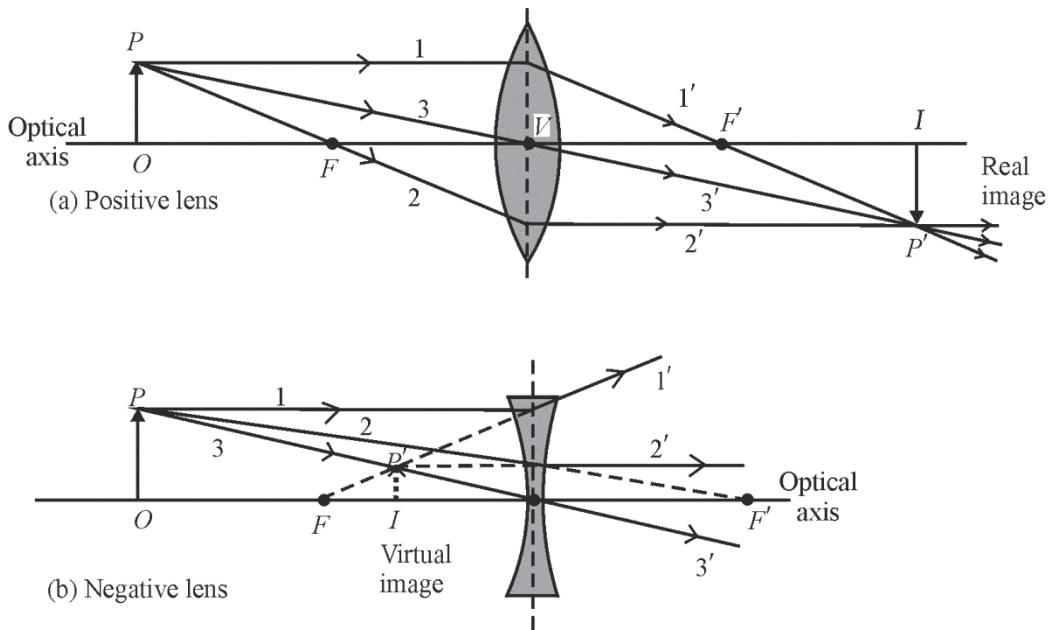


Figure 4-27 Ray diagrams for image formation by positive and negative lenses

The behavior of rays 1 and 2—connected with the left and right focal points for both the positive and negative lenses—should be apparent from a review of Figure 4-25. Thus parallel ray 1 for the *positive* lens is bent by the lens so as to go through the right focal point F' , and ray 2, which passes through the left focal point F on its way to the lens, is bent by the lens so as to emerge as a ray parallel to the optic axis. And for the *negative* lens, parallel ray 1 is bent outward by the lens in a direction such as to appear that it had come from the left focal point F , while ray 2, heading initially toward the right focal point F' , is bent by the lens so as to emerge as a ray parallel to the optic axis. The behavior of ray 3—going straight through either lens at its center V —is a consequence of assuming that the lens has zero thickness. Also, it should be clear in Figure 4-27 that the positive lens forms a real image while the negative lens forms a virtual image.

One can apply the principles of ray tracing illustrated in Figure 4-27 to a train of thin lenses. Figure 4-28 shows a ray trace through an “optical system” made up of a positive and a negative lens. For accuracy in drawing, a common practice (used here) is to show the positive lens as a vertical line with normal arrowheads and the negative lens as a vertical line with inverted arrowheads, and to show all ray bending at the vertical lines. Note that the primary object is labeled RO_1 (real object 1) and its image formed by the positive lens is labeled RI_1 (real image 1). The image RI_1 then serves as a real object (RO_2) for the negative lens, leading finally (in this case) to a virtual image VI_2 .

Test your understanding of ray tracing through thin lenses by accounting for each numbered ray drawn in the figure. What happens to rays 1 and 3 relative to the negative lens? Why are two other rays (4 and 5) introduced in continuing the ray trace from RO_2 to the negative lens? Is it a “correct” procedure to introduce rays 4 and 5, even though they are not extensions of original rays 1, 2, or 3? Can you sketch in where rays 4 and 5 originating from object point P would have had to strike an *enlarged* positive lens so as to become rays 4 and 5, which are shown passing through P' ?

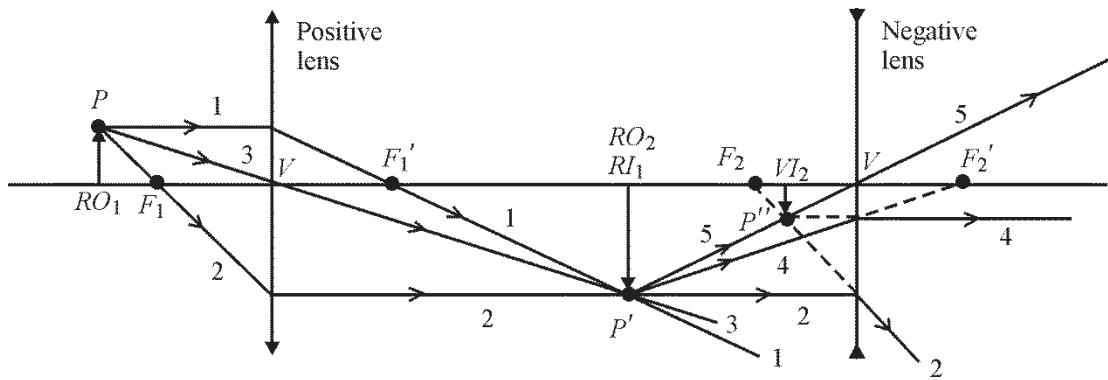


Figure 4-28 Ray diagram for image formation through two lenses

Lens formulas for thin lenses

As with mirrors, convenient formulas can be used to locate the image mathematically. The derivation of such formulas—as was carried out for spherical mirrors in the previous section—can be found in most texts on geometrical optics. The derivation essentially traces an arbitrary ray *geometrically* and *mathematically* from a given object point through the two refracting surfaces of a thin lens to the corresponding image point. *Snell's law* is applied for the ray at each spherical refracting surface. The details of the derivation involve the geometry of triangles and the approximations mentioned earlier— $\sin \varphi \approx \varphi$, $\tan \varphi \approx \varphi$, and $\cos \varphi \approx 1$ —to simplify the final results. Figure 4-29 shows the essential elements that show up in the final equations, relating object distance p to image distance q , for a lens of focal length f with radii of curvature r_1 and r_2 and refractive index n_g . For generality, the lens is shown situated in an arbitrary medium of refractive index n . If the medium is air, then, of course, $n = 1$.

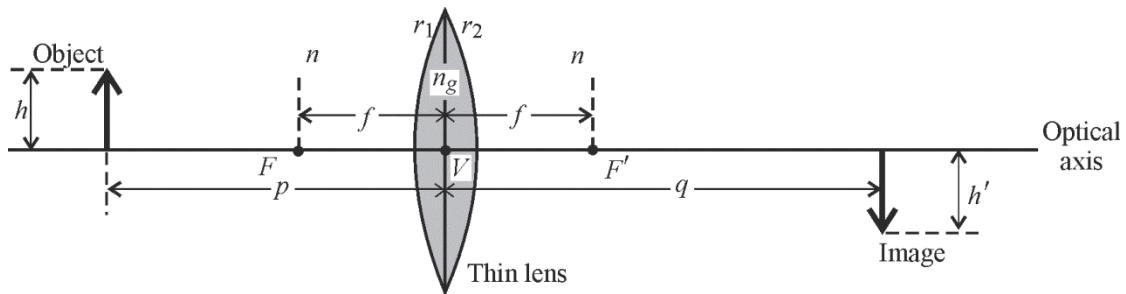


Figure 4-29 Defining quantities for image formation with a thin lens

Equations for thin lens calculations—The *thin lens equation* is given by Equation 4-10.

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \quad (4-10)$$

where p is the object distance (from object to lens vertex V)

q is the image distance (from image to lens vertex V)

f is the focal length (from either focal point F or F' to the lens vertex V)

For a lens of refractive index n_g situated in a medium of refractive index n , the relationship between the parameters n , n_g , r_1 , r_2 and the focal length f is given by the *lensmaker's equation* in Equation 4-11.

$$\frac{1}{f} = \left(\frac{n_g - n}{n} \right) \left(\frac{1}{r_1} - \frac{1}{r_2} \right) \quad (4-11)$$

where n is the index of refraction of the medium surrounding the lens

n_g is the index of refraction of the lens materials

r_1 is the radius of curvature of the *front face* of the lens

r_2 is the radius of curvature of the *rear face* of the lens

The magnification m produced by a thin lens is given in Equation 4-12.

$$m = \frac{h_i}{h_o} = -\frac{q}{p} \quad (4-12)$$

where m is the magnification produced by the lens (ratio of image size to object size)

h_i is the vertical transverse size of the image, measured perpendicularly to the optical axis

h_o is the vertical transverse size of the object, measured perpendicularly to the optical axis

p and q are object and image distance respectively

Sign convention for thin lens formulas—Just as for mirrors, we must agree on a sign convention to be used in the application of Equations 4-10, 4-11, and 4-12:

- We draw the “optical system” such that light travels initially from left to right toward the first lens.
- Object distance p is *positive* for *real* objects located to the *left* of the lens and *negative* for *virtual* objects located to the *right* of the lens.
- Image distance q is *positive* for *real* images formed to the *right* of the lens and *negative* for *virtual* images formed to the *left* of the lens.
- The focal length f is *positive* for a *converging* lens, *negative* for a *diverging* lens.
- The radius of curvature r is *positive* for a *convex* surface, *negative* for a *concave* surface. (Note that this is the *reverse* of the sign convention adopted for mirrors.)
- Transverse distances (h_o and h_i) are *positive above* the optical axis, *negative below*.

Now let's apply Equations 4-10, 4-11, and 4-12 in several examples, where the use of the sign convention is illustrated and where the size, orientation, and location of a final image are determined.

Example 10

A double convex thin lens, such as that shown here, can be used as a simple “magnifier” to read small print. This magnifier has a front surface with a radius of curvature of 20 cm and a rear surface with a radius of curvature of 15 cm. The lens material has a refractive index of 1.52. Answer the following questions to learn more about this simple magnifying lens.

- What is its focal length when used in air?
- What is its focal length if used in water ($n = 1.33$)?
- Does it matter which lens face is turned toward the light?
- How far would you hold an index card from this lens to form a sharp image of the sun on the card?

Solution

- Use the *lensmaker's equation*. With the lens in air and the sign convention given, we have $n_g = 1.52$, $n = 1.00$, $r_1 = +20$ cm, and negative $r_2 = -15$ cm. (Note carefully that with light traveling from left to right, the front face is convex, so r_1 is positive; the rear face is concave, so r_2 is negative.) Then

$$\frac{1}{f} = \left(\frac{n_g - n}{n} \right) \left(\frac{1}{r_1} - \frac{1}{r_2} \right) = \left(\frac{1.52 - 1}{1} \right) \left(\frac{1}{20} - \frac{1}{-15} \right) = 0.0607, \text{ and thus } f = \frac{1}{0.0607} = 16.5$$

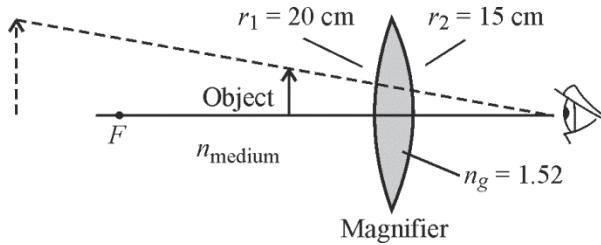
So $f = +16.5$ cm. It is a converging lens so the sign is positive, as it should be.

- With the lens in water and the given sign convention we have $n_g = 1.52$, $n = 1.33$, $r_1 = +20$ cm and $r_2 = -15$ cm. Then

$$\frac{1}{f} = \left(\frac{1.52 - 1.33}{1.33} \right) \left(\frac{1}{20} - \frac{1}{-15} \right) = 0.0167$$

$f = 60$ cm (still a converging but less so than in air)

- No, the magnifying lens behaves the same, having the same focal length, no matter which refracting surface faces the light. You can prove this by reversing the lens and repeating the calculation with Equation 4-11. Results are the same. But **note carefully**, reversing a *thick* lens changes its effect on the light passing through it. The two orientations are *not* equivalent for a thick lens!!
- Since the sun is very far away, its light is collimated (parallel rays) as it strikes the lens and will come to a focus at the lens focal point. Thus, one should hold the lens about 16.5 cm from the index card to form a sharp image on the card. (In fact, this technique of using a lens to focus sunlight on an index card can be used to get a decent estimate of the focal length of the lens. In practice, one can focus the overhead lights in a laboratory or room on the index card with a lens and estimate quite well the focal length of the positive lens.)



Example 11

Multi-lens arrays are used in many optical systems, commonly, as we know, in adjustable or “point-and-shoot” cameras. The following hypothetical two-lens system is made up of a converging (positive) lens followed by a diverging (negative) lens, each of focal length 15 cm.

Suppose that the system is used to form an image of a short nail, 1.5 cm high, standing erect, 25 cm from the first lens. The two lenses are separated by a distance of 60 cm. See diagram. (Refer to Figure 4-28 for a ray-trace diagram of what's going on in this problem.)

Locate the final image, determine its size, and state whether it is real or virtual, erect or inverted.

Solution: We apply the thin lens equations to each lens in turn, making use of the correct sign convention at each step.

$$\text{Lens } L_1: \frac{1}{p_1} + \frac{1}{q_1} = \frac{1}{f_1} \quad \text{or} \quad \frac{1}{25} + \frac{1}{q_1} = \frac{1}{15} \quad (f_1 \text{ is } + \text{ since lens } L_1 \text{ is converging.})$$

Solving, we obtain $q_1 = +37.5$ cm (Since the sign is positive, the image is real and located 37.5 cm to the right of lens L_1 .)

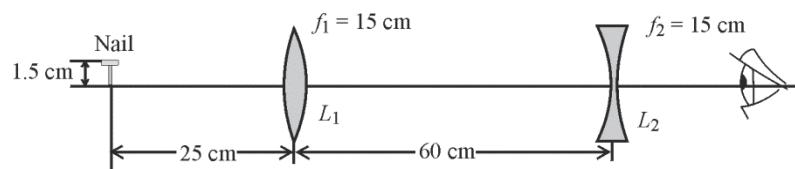
The first image, at a distance of $q_1 = 37.5$ cm, from L_1 , serves as the object for the lens L_2 . This object is real and to the left of lens L_2 . Thus p_2 is positive and equal to $(60 - 37.5) = 22.5$ cm. The focal length for L_2 is negative ($f_2 = -15$ cm) since it is a diverging lens. So, the thin lens equation becomes

$$\text{Lens } L_2: \frac{1}{p_2} + \frac{1}{q_2} = \frac{1}{f_2} \quad \text{or} \quad \frac{1}{22.5} + \frac{1}{q_2} = \frac{1}{-15}, \text{ giving } q_2 = -9 \text{ cm}$$

Since q_2 is negative, it locates a *virtual* image, 9 cm to the left of lens L_2 (See Figure 4-28). An observer looking into lens L_2 from the right would see an image of the nail 9 cm to the left of the lens.

The overall magnification for the two-lens system is given by the combined magnification of the two lenses. Then

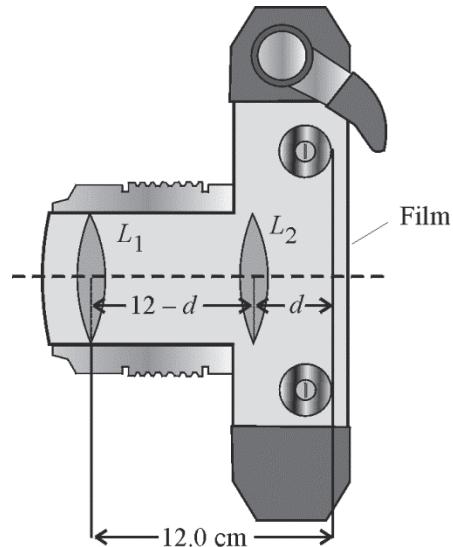
$$m_{\text{sys}} = m_1 \times m_2 = \left(-\frac{q_1}{p_1} \right) \left(-\frac{q_2}{p_2} \right) = \left(-\frac{37.5}{25} \right) \left(-\frac{-9}{22.5} \right) = -0.6$$



Thus, the final image is inverted (since overall magnification is negative) and is of final size $(0.6 \times 1.5 \text{ cm}) = 0.9 \text{ cm}$. (See ray trace in Figure 4-28.)

Example 12

An adjustable 2-lens camera, such as the one shown, has a focal length of 15 cm for converging lens L_1 and 13.3 cm for converging lens L_2 . Lens L_1 is fixed in the camera, a distance of 12 cm from the film plane. Lens L_2 is adjustable and is moved to bring objects into a clear focus on the film. Where must L_2 be situated (i.e., what is d) when the camera is focused on an object 1.33 meters away?



Solution

Step 1: Find image distance q_1 for lens L_1 :

$$\frac{1}{p_1} + \frac{1}{q_1} = \frac{1}{f_1} \quad \text{where } p_1 = 133 \text{ cm and } f_1 = 15 \text{ cm.}$$

$$\text{Thus, } \frac{1}{133} + \frac{1}{q_1} = \frac{1}{15}, \text{ giving } q_1 = \frac{(15)(133)}{(133 - 15)} = 16.9 \text{ cm.}$$

So lens L_1 alone would form a real image, 16.9 cm to its right. This distance is clearly greater than the 12.0 cm dimension of the camera, so this real image, formed to the right of lens L_2 , becomes a *virtual* object for lens L_2 . The virtual object distance p_2 , negative by sign convention, is then $-(16.9 - (12 - d))$. We know that q_2 must be equal to d since the camera is in focus.

Step 2: Find d by using the thin lens equation for lens L_2 :

$$\text{Thus, } \frac{1}{p_2} + \frac{1}{q_2} = \frac{1}{f_2} \quad \text{where } p_2 = -(16.9 - (12 - d)) = -(4.9 + d), q_2 = d \text{ and } f_2 = 13.3 \text{ cm}$$

Substituting we get,

$$\frac{1}{-(4.9 + d)} + \frac{1}{d} = \frac{1}{13.3} \quad \text{or} \quad \frac{d - (4.9 + d)}{-(4.9 + d)d} = \frac{1}{13.3} \quad \text{or} \quad \frac{-4.9}{-4.9d - d^2} = \frac{1}{13.3}$$



This gives the quadratic equation $-d^2 - 4.9d = -(4.9)(13.3)$ or $d^2 + 4.9d - 65.17 = 0$. Using the standard solution for a quadratic equation of form $ax^2 + bx + c = 0$, $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$ where $a = 1$, $b = 4.9$, $c = -65.17$, and $x = d$, we get,

$$d = \frac{-4.9 \pm \sqrt{(4.9^2 - 4(1)(-65.17)}}{2} = \frac{4.9 \pm 16.9}{2}, \text{ or } d = \frac{12}{2} - 6 \text{ cm, or } d = \frac{-21.8}{2} = -10.9 \text{ cm.}$$

Need help with roots?
Go to
<http://optecvideo.optecrm.org/>.

We discard the negative value of $d = -10.9$ cm because it makes no physical sense. Hence, we have, finally, $d = 6$ cm. Thus L_2 is positioned 6 cm in front of the film plane when the 1.33 m distant object is in focus.

LABORATORIES

Laboratory 1-4A: Prisms and Lenses

Go to
<http://optecvideo.opteccrm.org/>
for an introduction to this
activity.



In this laboratory, you will perform the following simple experiments with prisms and lenses:

- Determine the index of refraction of a prism material.
- Demonstrate total internal reflection (TIR) with right-angle prisms and show how to use the prisms to produce (a) 90° bending, (b) retroreflection, and (c) “periscope-type” bending.
- Determine the index of refraction of a thin-lens material.
- Determine the focal lengths of convex and concave lenses.

Equipment

The following equipment is needed to complete this laboratory:

- 1 equilateral prism^a (25-mm faces by 25 mm long works well)
 - 2 45°-45°-90° prisms^a (25-mm legs, 35-mm hypotenuse, 25 mm thick)
 - 2 diode laser pointers^b (5 mW or less)
 - 1 spherometer^b
 - 1 double-convex lens^a (75-mm diameter by 150-mm focal length)
 - 1 double-concave lens^a (75-mm diameter by 150-mm focal length)
 - 1 protractor
 - 1 white cardboard screen
- Index cards, white paper sheet, (8½" × 11" and 11" × 17"), masking tape, and ruler

^a These items are readily available from Edmund Scientific, Barrington, New Jersey, 609-574-6250, as parts of their “Educational Quality Demonstration Optics,” at reasonable prices. See their Industrial Optics Division catalog.

^b These items are also available from Edmund Scientific but are more expensive.

Procedure

A. Index of refraction of a prism material

1. Arrange the laser pointer, equilateral prism, and white cardboard screen on a flat tabletop as shown in Figure 4-30. Center the prism over a sheet of white paper. Fasten down the white paper, cardboard screen, and laser with tape.

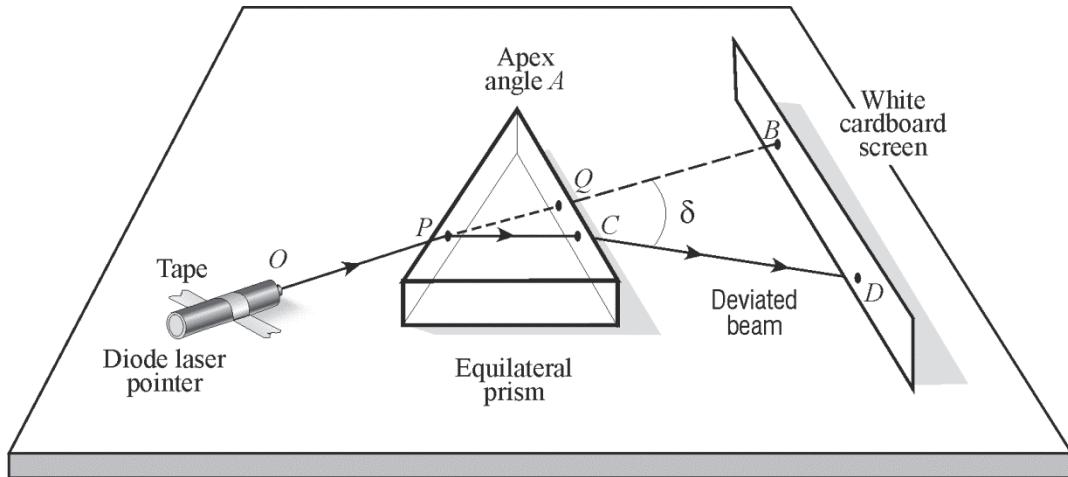


Figure 4-30 Setup for measuring minimum angle of deviation

2. As you rotate the prism relative to the incident laser beam, the laser spot D on the screen moves, so the angle of deviation δ will become larger or smaller. By experimentation, determine the *smallest angle of deviation* (δ_m) between an original beam direction $OPQB$ and the deviated beam CD . (It should be clear that the farther the screen is from the prism the more precise will be your determination of δ_m , since small changes in spot D will then be more exaggerated.)
3. When you have achieved the minimum angle for δ , carefully tape the prism in place. Trace the prism edges on the paper, the straight segments OP and QB along the *original direction*, and the segment CD . (Note: Location of laser spots Q , C on the exit face of the prism and B , D on the screen are needed to be able to draw segments QB and CD .) With the line segments drawn, remove the prism and measure the minimum angle δ_m with a protractor. Complete a ray trace of the incident beam through the prism, deviated at angle δ_m . Is the segment DC parallel to the prism base? Should it be?
4. Record the measured angle δ_m and the apex angle A . Use the formula

$$n = \frac{\sin\left(\frac{A + \delta_m}{2}\right)}{\sin\frac{A}{2}}$$

to calculate the index of refraction n . Compare your value with values given in Table 4-1. Does it agree with any value given there? What is your best guess for the prism material?

B. Total internal reflection (TIR)

(When you have finished this part, you will have three different traces of laser light interacting with right-angle prisms, all on an 11" × 17" sheet of white tracing paper.

1. Set a right-angle prism on one of its parallel sides on a sheet of 11" × 17" white tracing paper. Tape the paper and prism in position. Shine a diode laser beam onto an appropriate face of the prism so that it *undergoes total internal reflection* (TIR) inside the prism and exits the prism at 90° to its original direction of entry. Use index cards as a screen to "locate" the laser beam outside the prism. On the paper, trace the edges of the prism, a line along the incident beam, a line along the path through the prism, and a line along the exit beam. Label the angles of incidence and reflection and their values at the face where TIR takes place. What would you need to know to determine the critical angle at this face? Is the incident angle on the face where TIR occurs larger or smaller than the critical angle?
2. Move the right-angle prism to a different position on the 11" × 17" paper and tape it down. Direct the diode laser beam onto an appropriate face so that the beam returns along a direction parallel to its entering direction. Use index cards to "locate" the beam path. When you have achieved this condition of *retroreflection*, trace the edges of the prism, the entering beam, the path through the prism, and the exit beam. Draw appropriate angles at the faces where TIR occurs and give their correct values.
3. Move two right-angle prisms to a new location on the 11" × 17" paper. Arrange them to produce "periscope action." This action requires, for example, that a horizontal beam that enters at one level be deflected downward 90° and exit horizontally at a different level, as shown in the accompanying sketch. Here the dashed squares indicate the locations of the two prisms. Use index cards to locate the beam through the prism arrangement.

When you have achieved the "periscope" geometry, tape the prisms down. Trace their edges, and trace the laser beam path from initial entry to final exit. Show where TIR occurs and label the incident and reflected angles there correctly, at each position.

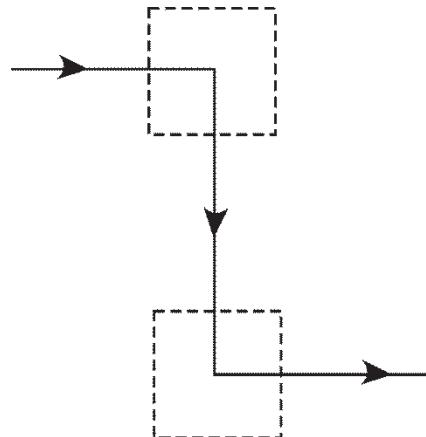


Figure 4-31

C. Index of refraction of a thin lens

Use the lensmaker's equation $\left[\frac{1}{f} = \left(\frac{n_g - n}{n} \right) \left(\frac{1}{r_1} - \frac{1}{r_2} \right) \right]$ to determine the value of n_g for the double-convex lens. Use a ruler, overhead lights, and an index card to obtain a good approximation for the focal length of the lens. (Going outside and imaging the sun would be even better.) Use a spherometer to measure the radii of curvature r_1 and r_2 . (You will have to be especially creative to get r_1 and r_2 if you don't have access to a spherometer.) With the values

off f , r_1 , and r_2 , solve the lensmaker's equation for n_g , the index of refraction of the lens glass. Compare your value with values given in Table 4-1. Do you have a match?

D. Measuring the focal lengths of thin lenses

Set up the two diode lasers on a stand or optical bench so that they emit beams parallel to one another and normal to the plane defining the vertical position of the thin lens. See Figure 4-32. (To see the beams converging on the image side of the lens, you will have to use chalk-dust particles or smoke—some form of cloud—to illuminate the path.) By moving the screen forward and backward, you can locate a position where the beams cross to form the “smallest” spot. This is the *focal point* for the lens. Measuring the optical bench distance from lens to focal point gives the *focal length*. Compare this value to the value you obtained in part C, when you simply imaged a “distant” object on an index card. Which method is more accurate? Which method is easier?

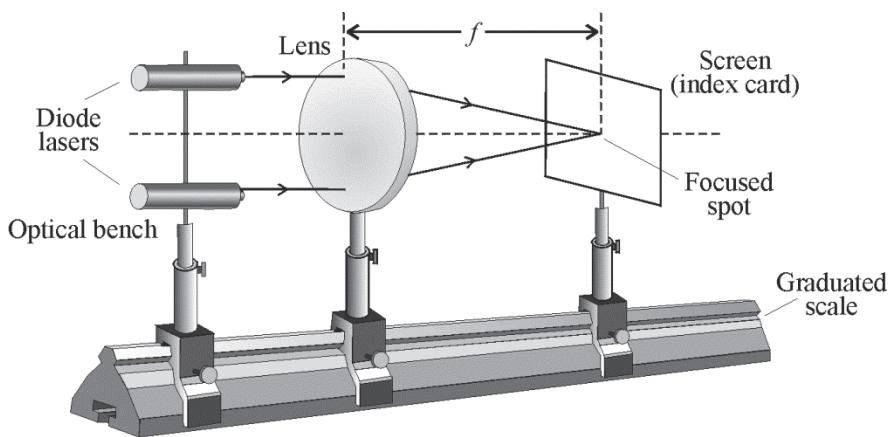


Figure 4-32 Setup for determining focal length of a positive lens

Replace the positive lens in Figure 4-32 with the negative lens. The challenge now is greater since the two laser beams diverge on the right side of the lens—and do not form a real image anywhere. Can you design a method to locate the spots of the two parallel beams at the lens and the spots for the two diverging beams on the right of the lens, then “trace” your way back to locate the focal point on the left side of the lens? If you can locate the focal point on the left, you can then measure its distance from the lens to get the focal length of the negative lens.

Laboratory 1-4B: Optical Alignment Techniques

Go to
[http://optecvideo
.opteccrm.org/](http://optecvideo.opteccrm.org/)
for an
introduction to
this activity.



In this laboratory, you will complete the following task:

- Practice basic optical alignment techniques using an optical breadboard.

Equipment

Newport Kit: OEK-STD

Part	Qty	Description	Also ...
BSA-I	1	Beam Steering Assembly	Meter Stick
TA-II	1	Target Assembly	Long Section of Paper
LCA	1	Lens Chuck Assembly	
LA	1	Laser Assembly	

Optical Breadboard
Index Card

Procedure

1. Construct the following component assemblies:
 - A. Beam Steering Assembly mounted on a rotational stage, BSA-I
 - B. Target Assembly, TA-II
 - C. Lens Chuck Assembly, LCA
 - D. Laser Assembly, LA
 - E. Keep the BSA-I, LCA, TA-II and the LA setup, as they will be used in the next step.
2. Alignment
 - A. Mount the Laser Assembly near a corner of the breadboard so that the beam follows the outermost row of holes. Center the target (+) in a filter holder attached to a post.
 - B. Count 5 breadboard holes from the laser output along the laser beam axis. Mount a post holder.
 - C. Count 5 holes starting from the far end of the breadboard along the laser axis. Mount a post holder.
 - D. Place the card in the filter holder and position the assembly in the post holder nearest the laser so that the + is centered on the row of holes over which the laser beam travels. Adjust the height so that the beam spot is on the +.
 - E. Place the assembly in the post holder farthest from the laser. Does the beam spot lie on the +? If not, make the necessary adjustments to the laser mount until it does.
 - F. Place the assembly again in the post holder nearest the laser. Is the beam still on the +? If it is, proceed to the next section. If not, make adjustments to the laser mount to center the spot.
 - G. Place the assembly in the post holder farthest from the laser. The beam alignment should be improved. You may have to repeat steps E and F a few times before a horizontal beam is achieved.

Show your work to the instructor and sign off _____ (Instructor's Initials)

3. Inserting Components into Aligned Axis

When inserting components into the optical axis, you can begin with the first added component and proceed outward, away from the laser; however, the preferred method is to begin with the farthest component and proceed inward, toward the laser. Most components are aligned on-axis, using the method of retroreflection. As a component is added to the system, it is positioned so that the beam reflected back through the system, centering on the laser output aperture. This is possible when a narrow beam of low-divergence is incident on the component's surface precisely at the center, because there it is normal to the surface. Thus, when a component is added to the system, the orientation of the component is adjusted until retroreflection occurs; once the optical axis has been established, the laser's orientation should not be altered when aligning a component.

When you need to use a component in the system that is intended to deflect the beam, such as a mirror or beamsplitter, they must be aligned using part of the method of establishing an optical axis as described previously.

- A. Once the optical axis is established, set up a BSA-I near the corner of the breadboard along the optical axis so that the beam is deflected 90° along a row of holes.
- B. Use the method of establishing an optical axis (see Alignment) to check the beam along the new path.
- C. Place a +100 mm lens in the lens chuck assembly. Use finger cots to prevent fingerprints from contaminating the lens surface.
- D. Place the LCA assembly in the beam path following the mirror. Confirm that the lens is centered on the optical axis either by centering the return beam onto the laser aperture or by observing that the transmitted beam remains centered using the +.

Show your work to the instructor and sign off _____ (Instructor's Initials)

Laboratory 1-4C: Law of Reflection

Go to
<http://optecvideo.opteccrm.org/>
for an introduction to this
activity.



In this laboratory, you will complete the following task:

- Observe that a beam is deflected from a mirror at an angle that is **twice** the angle of rotation of the mirror.

Equipment

Newport Kit: OEK-STD

Part	Qty	Description	Also ...
LA	1	Laser Assembly	Meter Stick
BSA-I	2	Beam Steering Assembly	Long Section of Paper
TA-I	1	Target Assembly	
RSA-IT	1	Rotation Stage	

Procedure

1. The optical breadboard should be located on a table near a wall. Tape a sheet of paper on the wall at the same height you plan to set your laser.
2. Mount the He-Ne laser as described by your instructor and place it at the rear of the breadboard.
3. Mount a Beam Steering Assembly (BSA-I) onto a Rotation Stage (RSA-IT). The Rotation Stage should be attached to the table with screws. The BSA-I should be located so that the incident laser beam is perpendicular to the wall as shown in Figure 4-33.

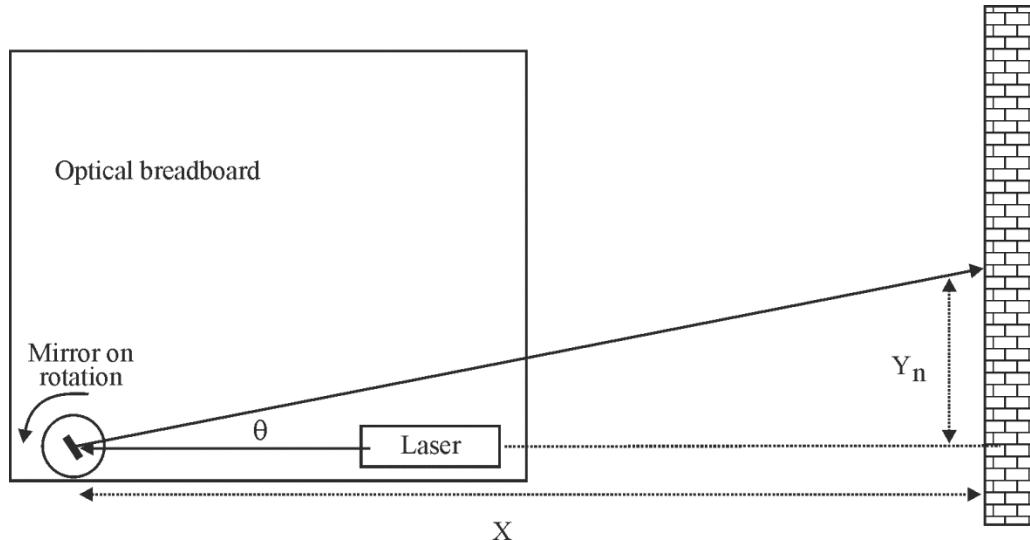


Figure 4-33: From Laser Beam at Mirror to Point on Wall

4. Adjust the rotation stage to read 0 degrees. Then, adjust the beam steering mirror to reflect the beam back onto itself without changing the rotation stage reading.

AVOID SHINING THE REFLECTED BEAM ON SPECULAR REFLECTING SURFACES OR OTHER MEMBERS OF THE CLASS.

5. Adjust the vertical adjustment on the mirror to place the beam on a piece of paper taped to the wall above and behind the laser. Mark the location of the spot and call it “ Y_0 ” in Table 4-3.
6. Rotate the mirror by turning the rotation stage and mark the new location of the spot. Record the angle from the rotation stage. Repeat this for 5 different angles that produce beam positions separated by a foot or more.
7. Measure and record the distance “ X ” from the mirror to the wall. Measure and record the distances from Y_0 to the marks on the piece of paper. Call these measurements Y_1 , Y_2 , etc. Use these measurements along with your knowledge of trigonometry and a calculator to determine the angle between the laser beam direction and the reflected direction. Record your calculations and these angles next to those for the incident angles in Table 4-3.

8. Compare the total reflected angles to the incident angles. You should find that the total beam deviation angle is twice the angle of incidence, thus confirming the law of reflection.

Table 4-3

Angle of Rotation (Degrees)	X (m)	Y _n (m)	Deviation Angle (Degrees)		Error (%)
			Measured	Expected	

Laboratory 1-4D: Lenses

In this laboratory, you will complete the following task:

- Experimentally measure real images formed by converging lenses.

Go to
<http://optecvideo.opteccrm.org/>
 for an introduction to this activity.



Equipment (most from Newport Kit: OEK-STD)

–25 mm Diverging Lens
 1 LCA on a post
 1 LCA on adjustable base
 2 BSA Assemblies
 +50.2 mm Converging Lens
 +75.6 mm Converging Lens
 Filter Holder and Clothespins
 1 mm tall transparent arrow slide

Procedure

1. Install your Laser and two BSA assemblies. Insert the diverging lens as close to the laser as possible. Direct the expanded beam as shown in the diagram.

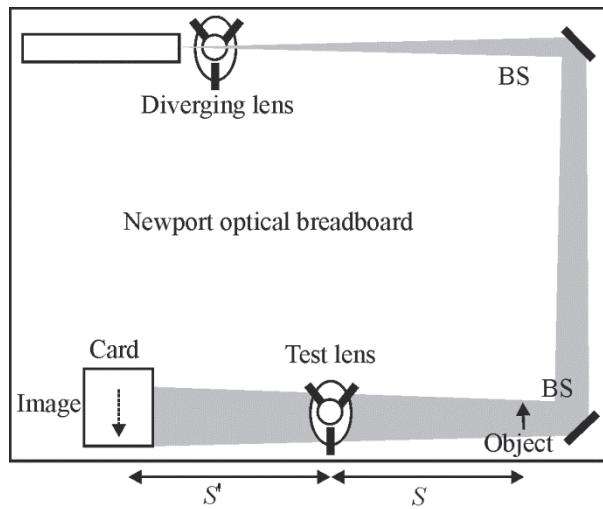


Figure 4-34

2. Mount the object on a filter holder in the middle of the expanded beam. Place this object as close to the mirror as possible.
3. Mount the desired lens into the LCA and place it on an adjustable base. Move the lens to a length of s (the desired object position) from the object.
4. Project the image on a card and record the image position (s') and the image height (y').
5. Make sure to enter all of your data in the Table 4-4.
6. Calculate s' for each measurement and compare to the measured result. Determine % Error.
7. Calculate the magnification (and thus y') for each measurement and compare to the measured result. Determine % Error.

Table 4-4

s (mm)	Y (mm)	f (mm)	s' (mm)	y' (mm)	$s'_{predicted}$ (mm)	%Error	$y'_{predicted}$ (mm)	%Error
100	10	50.2						
150	10	50.2						
200	10	50.2						
100	10	75.6						
150	10	75.6						
200	10	75.6						

WORKPLACE SCENARIO

Here is your opportunity to use the concepts learned in this module to solve an actual problem that could arise in a photonics company. Your instructor will provide directions for developing a solution.

Geometrical Optics – Ray Tracing

Scenario

After graduating with a two year associate degree in photonics technology, you joined a local company that designs and builds imaging systems, including cameras. Your job title is Engineering Photonics Technician Level II and one of your main responsibilities includes supporting the engineering research and design team. This responsibility includes building, testing, and performing failure analysis of engineering design product prototype runs^c. Prototype runs are usually small generating approximately 5 to 10 finished products. After a product has completed prototype testing and gone commercial, product volumes may be as high as a million a month. With volumes this high, problems can be extremely costly to correct!

Your main areas of responsibility during prototype testing are to:

1. Assist with obtaining parts and building the prototype.
2. Test the prototype.
3. Collect data on prototype performance.
4. Perform root-cause failure analysis on any prototype failures.
5. Document and report the results of the prototype run.

A new development engineer, Rick, thinks the company should get into the disposable camera business. His reasoning is that there is still exists a market among non-technical consumers, who are not yet into the digital camera age. With permission from his supervisor, Rick designs a disposable camera for taking pictures of distant objects and brings the design to you. With the design in hand, you order the parts specified in the design, and built the prototype units. Next, you tested these units by taking pictures and evaluating the picture quality. During evaluation of the picture quality, you discover that all of the pictures were slightly out of focus. You immediately recognize there is a problem with camera and begin to look for the root-cause of it.

Your first step in determining this root-cause is to review the camera's optical system physical layout drawing to determine the dimensions and locations of the prototype camera's optical components. The following table summarizes your findings:

^c Prototype runs are used to provide initial validation of the design, and hopefully determine any design problems prior to higher volume production runs, where finding problems would be more costly.

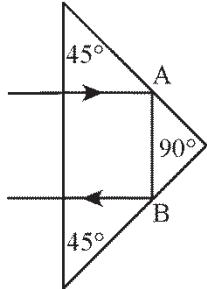
Type Data Parameter	Data
Lens Type	Converging Lens
Lens Focal Length	40 mm
Aperture to Film Distance	60 mm
Aperture to Lens Distance	10 mm

Problem and Solution Strategy

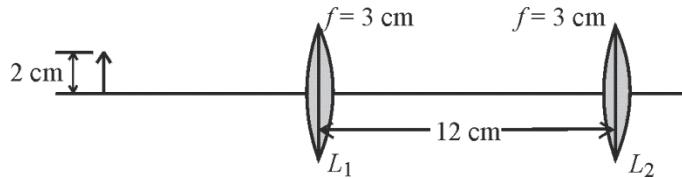
Since a focusing problem was discovered with the new disposable camera during prototype testing, you suspect that one possible cause may be the placement of the film with respect to the lens. To test your suspicion, you decide on two approaches. First, you will use the thin lens equation presented in Module 1-4 of the *Fundamentals of Light and Lasers* text to calculate the distance between the film and lens that will produce a focused image. To double check this calculation, you also decide to use a ray tracing applet that you found on the internet at <http://www.mtholyoke.edu/~mpeterso/classes/phys301/geomopti/twolenses.html>. With the results generated from these two approaches, you will be able to determine the correct placement of the film with respect to the aperture. To document your results, you have decided to prepare a report for Rick that will include your calculations and ray tracing efforts and also explain the reason for the camera's focusing problem.

PROBLEM EXERCISES AND QUESTIONS

Most of the problem exercises that follow are like the examples worked out in the text. Those problems marked with an asterisk (*) may be considered as *challenge* problems.

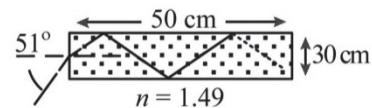
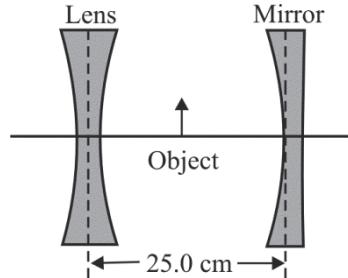
1. The speed of light in a transparent semiconductor material is measured to be 7.37×10^7 m/s. What is the index of refraction of this material? What is a good guess for the identity of this material?
2. A laser beam is incident on a quartz prism of index $n = 1.46$ at an angle of incidence of 60° . What are the angles of reflection and refraction at the air-quartz interface?
3. What is the critical angle for total internal reflection at points A and B in the 45° - 45° - 90° retroreflector prism shown here if the prism has an index of $n = 1.66$?

4. An isosceles prism made of zircon with equal base angles of 75° produces an angle of minimum deviation of $\delta_m = 30^\circ$ when a laser beam is passed through it. What is the index of refraction of this material? How does your value compare with that given in Table 4-1?
5. Based on the dispersion curve for light flint glass given in Figure 4-12, estimate to two decimal places the value of n_λ at $\lambda = 400$ nm and $\lambda = 650$ nm.
6. You are handed a concave mirror with a radius of curvature of 36 cm.
 - (a) What is its focal length?
 - (b) Where is the image of an object placed 36 cm in front of the mirror found?
 - (c) Is it real? Is it larger or smaller than the object?
7. Make a ray-trace diagram to locate the position and size of the image formed in Problem 6.
8. A driver sees a virtual image of a trailing motorcycle in the slightly convex, spherical rear-view mirror on the passenger side. The reduced virtual image seen by the driver “appears” to be about 3 car-lengths (~ 60 feet) behind.
 - (a) What is the actual distance of the motorcycle from the mirror if the radius of curvature of the mirror is 130 ft?
 - (b) How does the size of the motorcycle seen in the mirror compare with its actual size?
9. A camera lens with an f -number of 4 and shutter speed of 1/50 second will give the same film exposure in joules/m² as the lens set at f -number of 5.6 and shutter speed of _____?

- What is the numerical aperture (N.A.) for a fiber optic strand whose maximum acceptance half-angle at the air-fiber interface is 28° ?
- A plano-convex lens of focal length 25.0 cm is to be made with crown glass of refractive index 1.52. Use the lensmaker's equation to determine the radius of curvature of the curved face to be ground and polished by the glass shop.
- Two positive thin lenses, each of focal length $f = 3$ cm, are separated by a distance of 12 cm. An object 2 cm high is located 6 cm to the left of the first lens. See sketch.



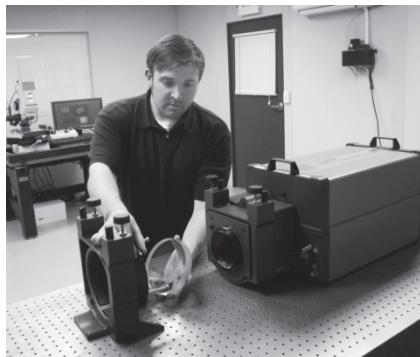
On an $8\frac{1}{2}'' \times 11''$ sheet of paper, make a drawing of the two-lens system, *to scale*. Use ray-tracing techniques to locate the final image and describe its size and nature.

- Use the thin-lens equations to determine the position and size of the final image for the object specified in the two-lens system of Problem 12. Do your calculated results agree with your ray-tracing results?
- The object shown in the accompanying sketch is midway between the lens and the mirror. The radius of curvature of the mirror is 20 cm. The concave lens has a focal length of 16.7 cm. (a) Where is the light that travels first to the mirror and then to the lens finally imaged? (b) Where is the light finally imaged that travels first to the lens? (Note: Be especially careful of applying the sign convention!)
- A laser beam is incident at the center of the end face of a cylindrical rod of material as shown in the sketch. The refractive index of the rod is 1.49. How many internal reflections does the laser beam experience before it exits the rod?



MEET A TECHNICIAN

John A. Crawford



John studied electro-optics at Indiana University of Pennsylvania (IUP) where he earned an Associate of Science Degree in Electro-Optics, which has led John to a rewarding career as an optical engineer at Prematech Advanced Ceramics.

John recognizes a strong link between math and photonics.

“Math is the tool that makes physics work and physics is the tool that makes photonics work; so one needs to start by having a good understanding of mathematics.”

One particular achievement that John takes pride in is the completion of a nine-inch, conventionally-polished, ceramic, parabolic mirror.

“Using a spindle and lapping tool is not the easiest way to produce an aspheric mirror, but the end result is astonishing.”

In the future, John would like to create larger, more specialized optics. Specifically, he would like to work on optics projects for astronomical telescopes, like The James Web Space Telescope.

John is enjoying his career in photonics and is looking forward to many more years pursuing it.

“I wanted to be part of something that is exciting, interesting, and personally challenging. The industry is young and rapidly growing so the professional possibilities are boundless.”

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Basic Physical Optics

Module 1-5
of
Course 1, *Fundamentals of Light and Lasers*
3rd Edition

OPTICS AND PHOTONICS SERIES



PREFACE TO MODULE 1-5

This is the fifth module in *Fundamentals of Light and Lasers*. Following are the titles of all six modules in the course:

1. *Nature and Properties of Light*
2. *Optical Handling and Positioning*
3. *Light Sources and Laser Safety*
4. *Basic Geometrical Optics*
5. *Basic Physical Optics*
6. *Principles of Lasers*

The six modules can be used as a unit or independently, as long as prerequisites have been met.

FEATURES

Mathematics Videos: Math videos are provided to assist students in doing mathematical operations required in this module. The math concepts used in this module are checked ✓ in the following list:

1. Scientific Notation ✓
2. Unit Conversion ✓
3. Introductory Algebra ✓
4. Powers and Roots ✓
5. Ratio and Proportion ✓
6. Exponents and Logarithms
7. Graphing in Rectangular Coordinates
8. Geometry ✓
9. Angle Measure in Two and Three Dimension ✓
10. Trigonometry ✓
11. Special Graphs

This checklist provides instructors a means of front-loading the presentation of material in this module with mathematics instruction. If instructors prefer to provide math instruction using a “just on time delivery” mode, a special icon  appears where the checked mathematics topics are first used within this module. All math videos can be accessed at <http://optecvideo.opteccrm.org/>.

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COURSE 1: FUNDAMENTALS OF LIGHT AND LASERS

Module 1-5

Basic Physical Optics

INTRODUCTION

In Module 1-4, *Basic Geometrical Optics*, we made use of *light rays* to demonstrate *reflection* and *refraction* of light and the imaging of light with mirrors and lenses. In this module, we shift the emphasis from *light rays* to *light waves*—from *geometrical optics* to *physical optics*. In so doing, we move from a concern over the *propagation* of light energy along straight-line segments to one that includes the *spreading* of light energy—a fundamental behavior of all wave motion.

With *wave optics*—commonly referred to as *physical optics*—we are able to account for important phenomena such as *interference*, *diffraction*, and *polarization*. The study of these phenomena lays the foundation for an understanding of such devices and concepts as holograms, interferometers, thin-film interference, coatings for both antireflection (AR) and high reflection (HR), gratings, polarizers, quarter-wave plates, and laser beam intensity patterns, both near the laser and far removed from the laser.

PREREQUISITES

Before you begin your study of this module, you should have completed a study of Module 1-1, *Nature and Properties of Light*; Module 1-2, *Optical Handling and Positioning*; Module 1-3, *Light Sources and Laser Safety*; and Module 1-4, *Basic Geometrical Optics*. In addition, you should be able to use algebra, plane geometry, and trigonometry—especially the use and interpretation of the trigonometric functions (sin, cos, tan) as they relate to sides and angles in triangles.

OBJECTIVES

When you finish this module, you will be able to:

- Describe a *wave front*.
- Describe the relationship between *light rays* and *wave fronts*.
- Define *phase angle* and its relationship to a *wave front*.
- Describe how electromagnetic waves are similar to and different from water waves.
- State the *principle of superposition* and show how it is used to combine two overlapping waves.

- State *Huygens's principle* and show how it is used to predict the shape of succeeding wave fronts.
- State the conditions required for producing interference patterns.
- Define *constructive* and *destructive* interference.
- Describe a laboratory setup designed to produce a double-slit interference pattern.
- State the conditions for an automatic phase shift of 180° at an interface between two optical media.
- Calculate the thickness of *thin films* designed to *enhance* or *suppress* reflected light.
- Describe how *diffraction* differs from *interference*.
- Describe single-slit diffraction and calculate positions of minima in the diffraction pattern.
- Distinguish between *Fraunhofer* (far-field) and *Fresnel* (near-field) diffraction.
- Sketch typical Fraunhofer diffraction patterns for a single slit, circular aperture, and rectangular aperture, and use equations to calculate beam spread and fringe locations.
- Describe a transmission grating and calculate positions of different orders of diffraction.
- Describe what is meant by diffraction-limited optics and describe the difference between a focal point in geometrical optics and a focal-point diffraction pattern in wave optics.
- Describe how *polarizers/analyzers* and the *law of Malus* are used to control light intensity.
- Calculate *Brewster's angle of incidence* for a given interface between two optical media.
- Describe how Brewster windows are used in a laser cavity to produce a linearly polarized laser beam.

SCENARIO

Letitia works for an optical coating company that produces highly transmissive and highly reflecting optics. For the past several weeks, she has been working on protective overcoats for metallic silver mirrors. The particular overcoat she is examining today is a single HR (highly reflecting) coat that increases the reflective properties of the silver mirror while protecting the soft silver surface from scratches and digs. Letitia remembers her work in wave optics at school, where she learned about quarter-wave plates, AR and HR coats, and surface properties of metallic reflectors. She is both pleased and surprised at how much she remembers about light interference in thin films and how much more interesting this makes her work. Today she is disturbed since the light reflecting off of the coated silver mirror surface is too blue—it's not the same as the 550 nm light incident on the silver mirror. She suspects an error in the thickness deposition of the coating material. She makes several other conforming tests and then takes her data to her supervisor. As a result of her observations, the coating department corrects the thickness of the coat and all subsequent HR coated silver mirrors pass inspection.

BASIC CONCEPTS

Light Waves and Physical Optics

In our study of ray optics and image formation, we represented image points as “geometrical points,” without physical extent. That, of course, followed logically since light rays were used to locate the image points and light rays are *lines* that intersect clearly at geometrical points. But in reality, if we were to examine such image points with a microscope, we would see *structure* in the “point,” a structure explained only when we invoke the *wave nature* of light.

In effect, then, we are saying that, with large objects such as prisms, mirrors, and lenses—large in the sense that their dimensions are millions of times that of the wavelength of light—interference and diffraction effects—as described briefly in Module 1-4, *Basic Geometrical Optics*—are still present in the imaging process. But, they occur on a scale so small as to be hardly observable to the naked eye. To a good approximation, then, with “large” objects we are able to describe light imaging quite satisfactorily with geometrical (ray) optics and obtain fairly accurate results. But, when light waves pass around small objects, such as a 100 μ -diameter human hair, or through small openings, such as a 50 μ pinhole, geometrical or ray optics *cannot* account for the light patterns produced on a screen beyond these objects. Only wave optics leads to the correct interpretation of such patterns.

So, now we turn to a study of the wave nature of light and to the fascinating phenomena of *interference*, *diffraction*, and *polarization*—and of such devices as gratings and thin-film coatings. Recall from Module 1-4, *Basic Geometrical Optics*, that *interference* occurs when two or more light waves pass through the same region and add to or subtract from each other; that *diffraction* occurs when light waves pass through small openings or around small obstacles and spread; and that *polarization* occurs due to the transverse nature of the electric field vibration in a propagating electromagnetic wave. Before we look at each of these phenomena, let’s review briefly the nature of waves, wave fronts, and wave motion.

Physics of waves and wave motion

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The numbers below the **A** that appears in several places in this module reference specific applets that demonstrate the concepts being described in the text. These applets are accessible at <http://optecvideo.optecrm.org/>.

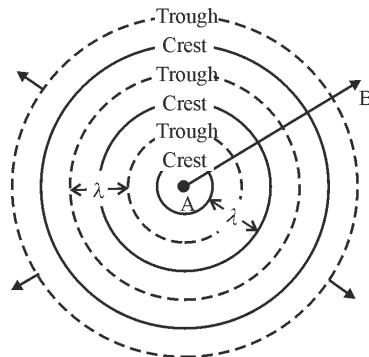
Wave optics treats light as a series of propagating electric and magnetic field oscillations. While we cannot see these extremely rapid oscillations, their wave behavior is similar to that of water waves. Thus, we find it useful to picture waves in terms of simple water waves, such as those created by a bobbing cork on an otherwise quiet pond. See Figure 5-1a.

The bobbing cork generates a series of surface disturbances that travel radially outward from the cork. The surface disturbances are mostly up and down (*transverse* vibrations), propagating in a direction perpendicular to the vibrations. Figure 5-1b shows the same disturbances traveling away from point *A* (the cork) as a series of successive *wave fronts* labeled *crests* and *troughs*. A *wave front* is defined as a series of adjacent points along which all motions of the wave are identical. The solid circles in Figure 5-1b depict outward-moving wave fronts that are wave

crests—maximum displacements up; the dashed circles represent outward moving wave fronts that are wave *troughs*—maximum displacements down. Adjacent crests are always a *wavelength* apart, as are adjacent troughs.



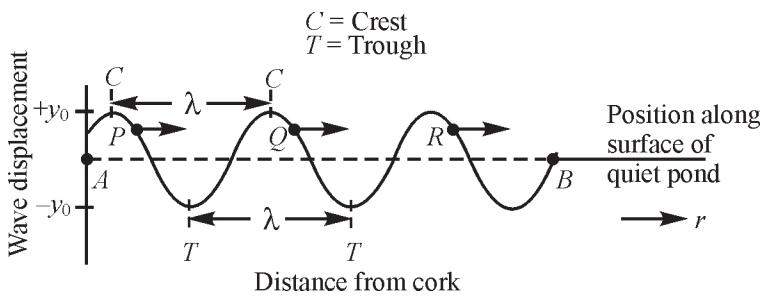
(a) Water waves



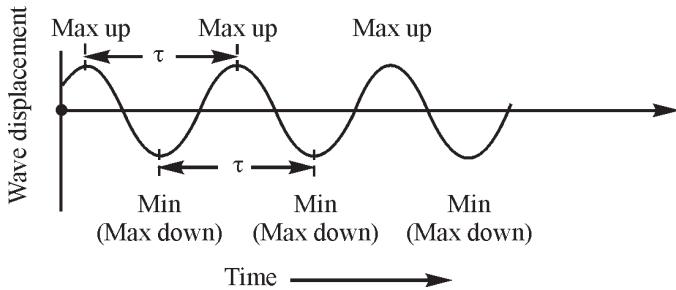
(b) Wave fronts

Figure 5-1 Water waves and wave fronts

A If we were able to look along the surface of the pond, we would see a *sine wave-like* profile of the traveling wave such as that shown in Figure 5-2a. The profile is a *snapshot* of the water displacement at a *certain instant of time* along an outward direction such as *AB* in Figure 5-1b. **5, 8** The water surface rises to a maximum positive displacement ($+y_0$) and falls to a maximum negative displacement ($-y_0$) along the profile. As time varies, the “snapshot” profile in Figure 5-2a moves to the right with a characteristic wave speed. The radial distance measured outward from the cork at position *A*, shown in Figure 5-1b, is denoted by the variable *r* in Figure 5-2a.



(a) Wave profile along the pond at a *certain instant of time*



(b) Wave displacement at a *fixed position* on the pond as a function of time

Figure 5-2 Two aspects of wave motion for a traveling wave

Now suppose that—instead of looking along the surface of the pond—we look at the moving wave at one *definite position* on the pond, such as at point Q in Figure 5-2a. What happens to the wave displacement at this fixed position as the wave disturbances move away from the cork and past Q ? We know from experience that the surface of the pond at Q rises and falls, repeatedly—as long as the wave disturbances move past this position. This wave displacement as a function of time—at a fixed position—is shown in Figure 5-2b. Note again that the shape is *sine wave-like*.

Since we’re concentrating on one position in Figure 5-2b, we cannot “see” the whole wave. All we see is the *up and down* motion of point Q . The time between successive positive maxima or successive negative maxima is defined as the *period* (τ) of the wave. The number of times point Q goes from max-up to max-down to max-up per second is called the frequency (v) of the wave. The period τ and the frequency v are related by the simple relationship $v = 1/\tau$, as presented in Module 1-1, *Nature and Properties of Light*. There we learned also that the wave speed is equal to the product of the wave frequency and wavelength, that is, $v = v\lambda$.

The mathematics of sinusoidal waveforms (optional)*

The two aspects of wave motion depicted in Figures 5-2a and 5-2b—one at a fixed time, the other at a fixed position—can be written in a mathematical equation that describes a *sinusoidally varying* traveling wave. Refer to Equation 5-1,

$$y(r, t) = y_0 \sin \left[\frac{2\pi}{\lambda} (r - vt) \right] \quad (5-1)$$

where: $y(r, t)$ is the wave displacement at position r and time t
 y_0 is the wave amplitude as shown in Figure 5-2a
 λ is the wavelength
 r is the position along the traveling wave
 v is the wave speed, equal to $v \times \lambda$, and
 t is the time



Need help working with trigonometry?
 Go to
<http://optecvideo.opteccrm.org/>.

If we “freeze” time at some value t_0 and see a “still profile” of the wave, for example, we obtain from Equation 5-1 the specialized equation $y(r, t_0) = y_0 \sin \left[\frac{2\pi}{\lambda} (r - \text{constant}) \right]$. Here we have substituted t_0 for t and replaced the product (vt_0) by a constant. The result is a mathematical description of the *wave profile* shown in Figure 5-2a. On the other hand, if we select a fixed position r_0 , we obtain another specialized equation $y(r_0, t) = y_0 \sin \left[\frac{2\pi}{\lambda} (\text{constant} - vt) \right]$. Here we have substituted r_0 for r and replaced r in $(r - vt)$ by a constant. This is a mathematical description of the waveform shown in Figure 5-2b.

*The text material in this section, through Example 1, is optional. Depending on the mathematical background of the class, this section may or may not be covered.

The factor in brackets in Equation 5-1 defines the *phase angle* ϕ of the wave at position r and time t . Thus,

$$\phi = \left[\frac{2\pi}{\lambda} (r - vt) \right] \quad (5-2)$$

The phase angle is the *same for any point on a given wave front*, as mentioned earlier. For example, for successive wave fronts whose values of ϕ are $[\pi/2]$, $[\pi/2 + 2\pi]$, $[\pi/2 + 4\pi]$, and so on—always 2π radians (360°) or one wavelength apart— $\sin \phi$ for *each of these angles* equals $+1$, so that $y(r, t)$ equals $+y_0$, a maximum *positive* displacement. Such wave fronts are *crests*.

Similarly, for successive wave fronts whose values of ϕ are $[3\pi/2]$, $[3\pi/2 + 2\pi]$, $[3\pi/2 + 4\pi]$, etc., always 2π radians apart and one wavelength, $\sin \phi$ for *each of these angles* equals -1 , so that $y(r, t)$ equals $-y_0$, the maximum *negative* wave displacement. Such wave fronts are *troughs*. And so it goes for all other points on the wave fronts between the crests and troughs. For example, points P , Q , and R in Figure 5-2a, all with the same wave displacement, represent wave fronts a wavelength apart with phase angles of values differing by 2π . Example 1 provides an application of Equations 5-1 and 5-2 to circular water waves on a quiet pond.

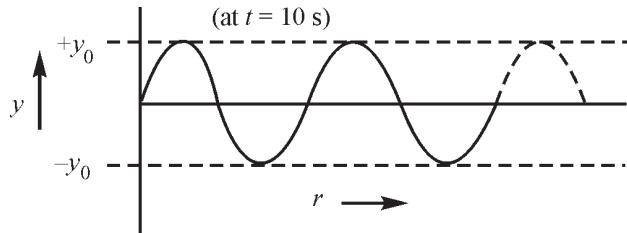


Need help with measuring angles? Go to <http://optecvideo.opteccrm.org/>.

Example 1

Circular water waves, such as those shown in Figures 5-1a and 5-1b, move outwardly from a bobbing cork at A . The cork bobs up and down and back again—a complete cycle—once per second, and generates waves that measure 10 cm from crest to crest. Some time after the wave motion has been established, we begin to time the motion with a stopwatch. At a certain time $t = 10$ s on the watch, we notice that the wave profile has the shape shown below.

- (a) What is the wave frequency v for this water wave?
- (b) What is its wavelength λ ?
- (c) What is its wave speed v ?
- (d) What is the phase angle ϕ for a wave front at position $r = 102.5$ cm at time $t = 10$ s?
- (e) What is the wave displacement y on the wave front at $r = 102.5$ cm?
- (f) What is the phase angle ϕ for a wave front at $r = 107.5$ cm at $t = 10$ s?
- (g) What is the wave displacement y on the wave front at $r = 107.5$ cm?
- (h) If we focus on the wave motion at the position $r = 105$ cm and let time vary, what kind of motion do we observe?



Solution

- (a) The wave frequency is 1 cycle/s; therefore, the period $\tau = \frac{1}{v}$ is 1 second.
- (b) The wavelength λ is the crest-to-crest distance, thus $\lambda = 10$ cm.
- (c) The wave speed $v = \lambda \times v = 10 \text{ cm} \times 1/\text{s} = 10 \text{ cm/s}$.

(d) At $t = 10$ s, $r = 102.5$ cm and $v = 10$ cm/s. Using $\phi = \left[\frac{2\pi}{\lambda} (r - vt) \right]$, we get

$$\phi = \frac{2\pi}{10} [102.5 - (10 \times 10)] = \frac{2\pi}{10} (2.5) = \frac{\pi}{2} \text{ rad, an angle of } \phi = 90^\circ$$

(e) $y = y_0 \sin \phi = y_0 \sin \left(\frac{\pi}{2} \right) = y_0 \sin (90^\circ) = y_0$, since $\sin 90^\circ = 1$. Since $y = y_0$ at this location and y_0 is the maximum positive displacement, the circular wave front at $r = 102.5$ cm from the cork is a *crest*.

(f) At $t = 10$ s, $r = 107.5$ cm and $v = 10$ cm/s. Using the expression for the phase angle ϕ , we get

$$\phi = \frac{2\pi}{10} (107.5 - 10 \times 10) = \frac{2\pi}{10} (7.5) = \frac{3\pi}{2}, \text{ an angle of } 270^\circ$$

(g) $y = y_0 \sin \phi = y_0 \sin \left(\frac{3\pi}{2} \right) = y_0 \sin (270^\circ) = -y_0$, since $\sin 270^\circ = -1$. Since $y = -y_0$, a maximum negative displacement, the circular wave front at $r = 107.5$ cm from the cork is a *trough*.

(h) At $r = 105$ cm, we see the water move up and down, repeatedly, between displacements of $(+y_0)$ and $(-y_0)$, completing a cycle of motion once per second. Thus, the frequency of this vertical motion is 1 cycle/s and its period is 1 s.

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It is helpful to make a connection between the wave motion we are studying here with water waves and the wave motion of light waves. As we learned in Module 1-1, *Nature and Properties of Light*, it is the electric field and magnetic field in light waves that varies between positive and negative maxima—in a direction *transverse* to (perpendicular to) the direction of propagation. That's like the vertical displacement of the water for water waves. Figure 5-3 shows a profile of the transverse electric field E and magnetic field B at one instant of time.

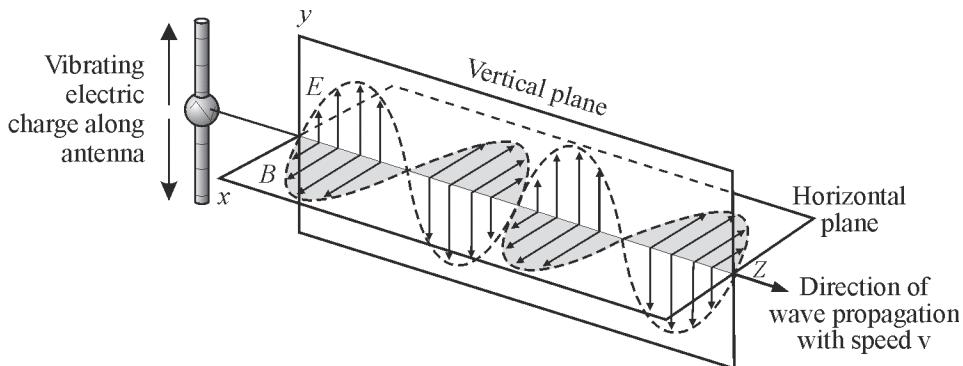


Figure 5-3 Profiles of the electric (E) and magnetic (B) fields in a light wave at an instant of time, E-field vibrations are in the vertical plane; B-field vibrations are in the horizontal plane. The wave propagates with a speed v in a direction perpendicular to both the E and B vibrations.

It is easy to see the *sine wave form* (dashed profile) of the varying E and B values, much like the sine wave form of the varying displacement values for the water wave in Figure 5-2a. And it is clear from Figure 5-3 that the direction of the wave propagation is always perpendicular to *transverse* vibration directions of the E- and B-fields. For example, if the E-field vibrates along

the y direction, and the B -field vibrates along the x direction, the EM wave moves along the Z direction. When we study interference, diffraction, and polarization, we are able to ignore the B -field and concentrate only on the varying E -field.

By way of review of material covered in Module 1-1, *Nature and Properties of Light*, and Module 1-4, *Basic Geometrical Optics*, we recall that the wave speed c in a vacuum ($n = 1$) is given by $c = \lambda_0 v_0$, where λ_0 and v_0 denote the wavelength and frequency in the vacuum. In a medium of refractive index n , the speed v is given by $v = \lambda v$ where $n = \frac{c}{v}$, $v = v_0$, and $\lambda = \frac{\lambda_0}{n}$.

Interaction of Light Waves

The principle of superposition

An understanding of light wave interference begins with an answer to the question, “What happens at a certain point in space when two light waves pass through **that point** at the same time? To answer this question, we make use of the *principle of superposition*, which says:

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When two or more waves move simultaneously through a region of space, each wave proceeds independently as if the other were not present. The resulting wave “displacement” at any point and time is the vector sum of the “displacements” of the individual waves.

This principle holds for water waves, mechanical waves on strings and on springs (the Slinky!), and for sound waves in gases, liquids and solids. Most important for us, it holds for all electromagnetic waves in free space. So, if we have two light waves passing through some common point P , where Wave 1 alone would cause a “displacement” Y_1 and Wave 2 alone would cause a displacement Y_2 , the *principle of superposition* states that the resultant displacement Y_{RES} is given by a *vector* sum of the two displacements. If both displacements are along the same direction—as they will be for most applications in this module—we can add the two displacements *algebraically*, as in Equation 5-3, and not worry about vector addition.

$$Y_{\text{RES}} = Y_1 + Y_2 \quad (5-3)$$

An application of Equation 5-3 is shown in Figure 5-4, where Wave 1 (solid thin curve) and Wave 2 (dashed curve) are moving along the x -direction to the right. Wave 2 is drawn with $\frac{3}{4}$ the amplitude and $\frac{1}{2}$ the wavelength of Wave 1. The resultant wave, obtained by applying Equation 5-3 at each point along the x -direction, is shown by the waveform, Y_{RES} (solid thick curve).

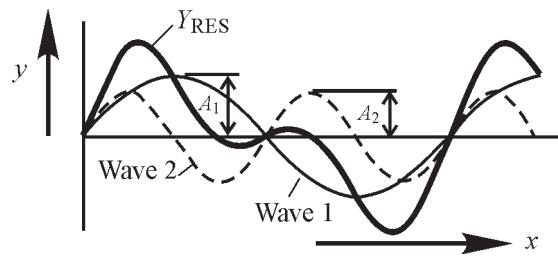


Figure 5-4 Superposition of two waves moving along the same direction

In Figure 5-5, we show the interference of two sinusoidal waves of the same amplitude and same frequency, traveling in the same direction. The two waves are represented by solid thin and dashed curves, the resultant by the solid heavy curve. In Figure 5-5a, the two waves are *exactly in phase*, with their maximum and minimum points matching perfectly. Applying the *principle of*

superposition to the two waves, the resultant wave is seen to have the same amplitude and frequency but *twice* the amplitude $2A$ of either initial wave. This is an example of *constructive interference*. In Figure 5-5b, the two curves are *exactly out of phase*, with the crest of one aligned with the trough of the other, and so on. Since the displacement of one wave effectively cancels the displacement of the other at each point, the resultant wave has *zero displacement* everywhere, as indicated by the straight solid black line. This is an example of *destructive interference*. In Figure 5-5c, the two waves are neither completely in phase nor completely out of phase. The resultant wave then has the same wavelength as the initial waves and an amplitude somewhere between A and $2A$, as shown.

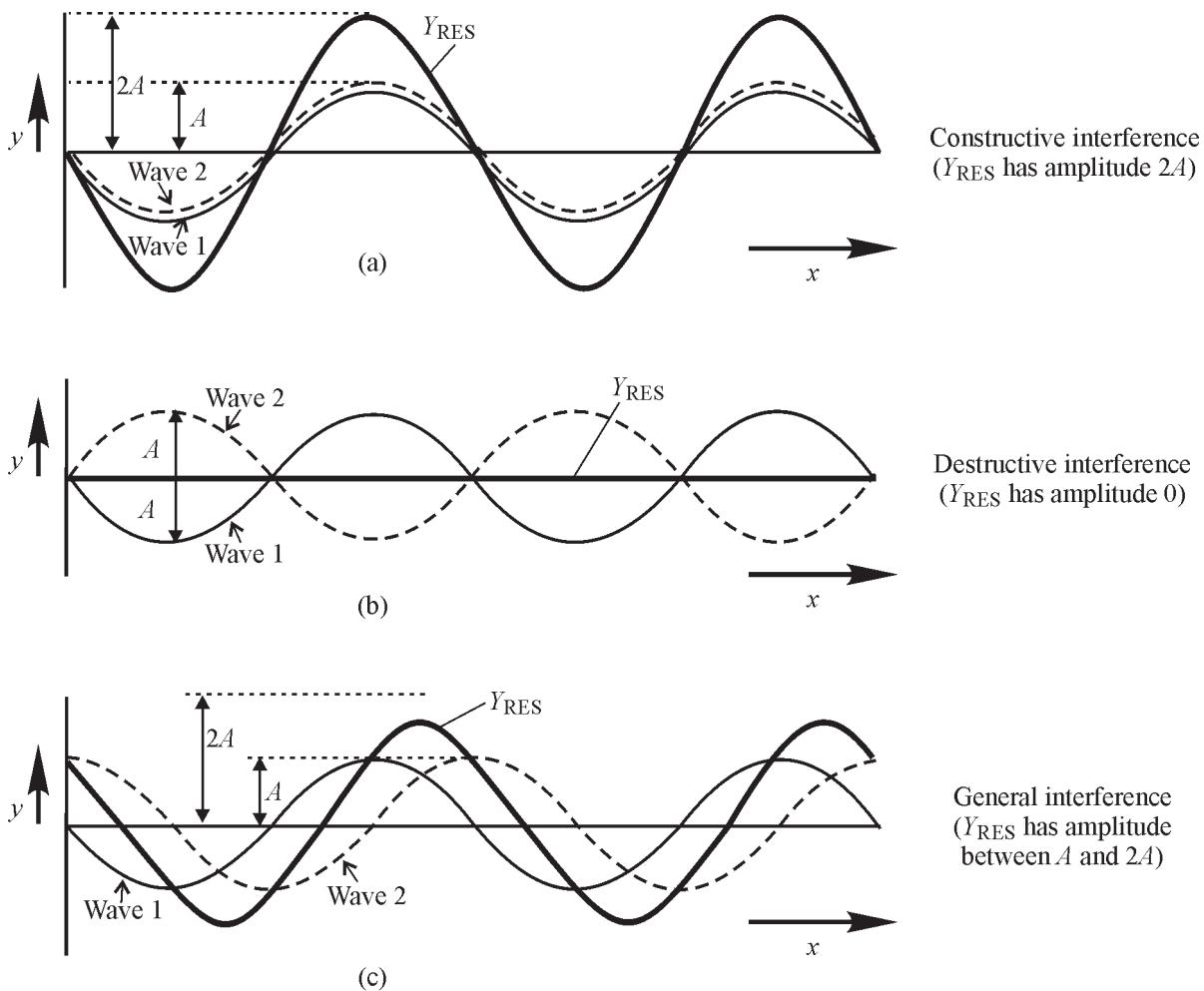


Figure 5-5 Interference of two identical sinusoidal waves

Huygens' wavelets

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Long before people understood the electromagnetic character of light, Christian Huygens—a 17th-century scientist—came up with a technique for propagating waves from one position to another, determining, in effect, the shapes of the developing wave fronts. This technique is basic to a quantitative study of interference and diffraction, so we cover it here briefly. Huygens claimed that:

Each point on a regularly-shaped or oddly-shaped wave front in a given medium can be treated as a point source of secondary, spherically-shaped wavelets. These secondary wavelets spread out in all directions with a wave speed characteristic of that medium. The developing wave front at any subsequent time is the envelope of these advancing secondary wavelets.

Figure 5-6 shows how Huygens's principle is used to demonstrate the propagation of successive (a) *plane* wave fronts and (b) *spherical* wave fronts. Huygens's technique involves the use of a series of points $P_1 \dots P_8$, for example, on a given wave front defined at a time $t = 0$. From these points—as many as one wishes actually—spherical wavelets are assumed to emerge, as shown in Figures 5-6a and 5-6b. Radiating outward from each of the P -points, with a speed v , the series of secondary wavelets of radius $r = vt$ defines a new wave front at some time t later. In Figure 5-6a, the new wave front is drawn as an *envelope tangent* to the secondary wavelets at a distance $r = vt$ from the initial plane wave front. It is, of course, another *plane* wave front. In Figure 5-6b, the new wave front at time t is drawn as an *envelope tangent* to the secondary wavelets at a distance $r = vt$ from the initial spherical wave front. It is an advancing *spherical* wave front.

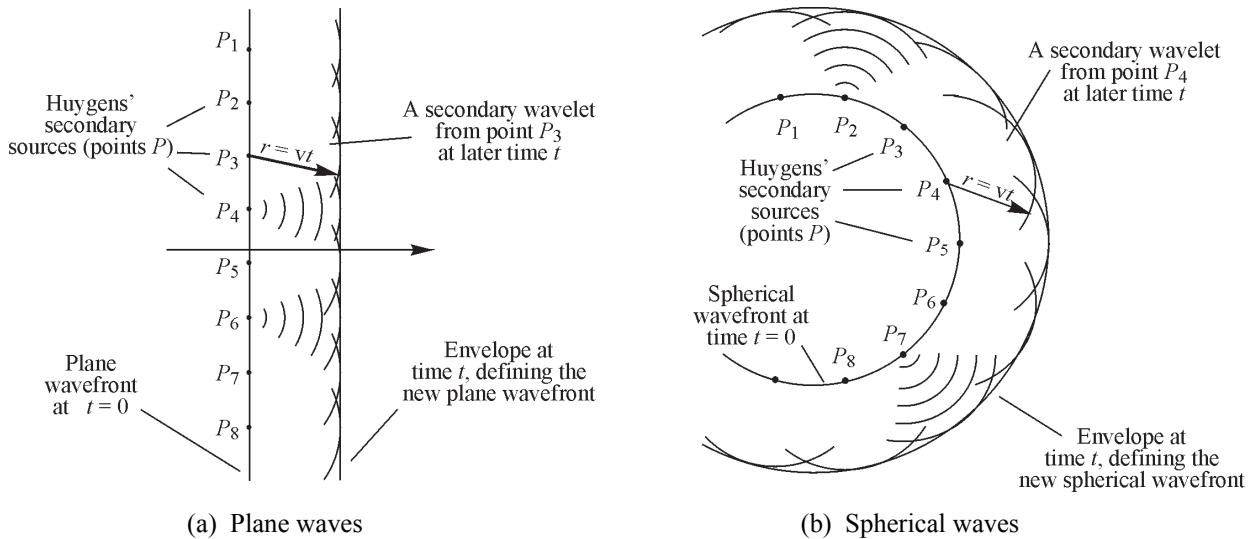


Figure 5-6 Huygens's principle applied to the propagation of plane and spherical wave fronts

While there seems to be no physical basis for the existence of Huygens's “secondary” point sources, Huygens's technique is useful because it does predict accurately—with waves, not rays—both the *law of reflection* and *Snell's law of refraction*. In addition, Huygens's principle forms the basis for calculating, for example, the diffraction pattern formed with multiple slits. We shall soon make use of Huygens's secondary sources when we set up the problem for diffraction from a single slit.

Interference

Today we observe the interference of light waves with not too much difficulty. In the days of Sir Isaac Newton and Christian Huygens, however, light interference was not easily demonstrated. There were several reasons for this. One was based on the extremely short wavelength of visible light—around 20 millionths of an inch. Imagine how hard it would be to see or detect interference patterns formed by overlapping waves of such a short wavelength and with such a rapid vibration—around a million billion cycles per second!

As we have learned through the years, it is possible to show the interference of overlapping light waves coming from two nearby sources. In such a drawing, one can see where the waves from the two sources reinforce (add to) each other and where they weaken (subtract from) each other. We look at this more closely in the next section on “constructive” and “destructive” interference.

Constructive and destructive interference

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Figure 5-7 shows two “point” sources of light, S_1 and S_2 , whose radiating waves maintain a fixed wavelength and fixed phase relationship with each other as they travel outward. We have then a “coherence of sources.” The emerging wavefronts are spherical, but we show them as circular in the two-dimensional drawing. The *solid* circles represent crests, the *dashed* circles, troughs.

Earlier, in Figure 5-5a, we saw the effect of *constructive interference* for waves perfectly in phase and, in Figure 5-5b, the effect of *destructive interference* for waves perfectly out of phase. In Figure 5-7, along directions OP , OP_2 , and OP'_2 (emphasized by straight lines of solid dots) crests from S_1 and S_2 meet each other (as do the troughs), thereby creating a condition of *constructive interference*. As a result, light striking the screen at points P , P_2 , and P'_2 is at a maximum intensity and a bright region appears. By contrast, along directions OP_1 and OP'_1 (emphasized by straight lines of open circles) crests and troughs meet each other and cancel, thereby creating a condition of *destructive interference*. So at points P_1 and P'_1 on the screen, no light appears, leaving a dark region.

Coherence of sources is a stringent requirement if interference is to be observed. To see this clearly, suppose for a moment that sources S_1 and S_2 in Figure 5-7 are, in fact, *two corks bobbing up and down on a quiet pond*. As long as the two corks maintain a *fixed relationship* between their vertical motions, each will produce a series of *related crests* and

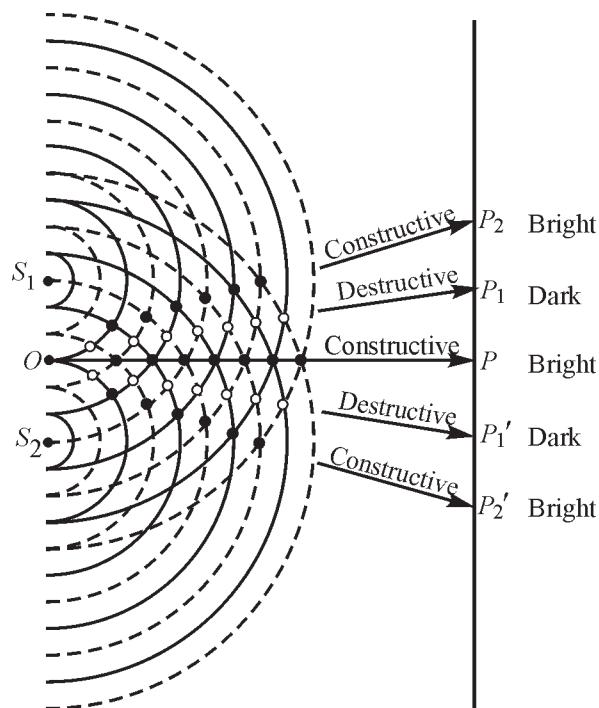


Figure 5-7 Wave interference created by overlapping waves from coherent sources S and S'

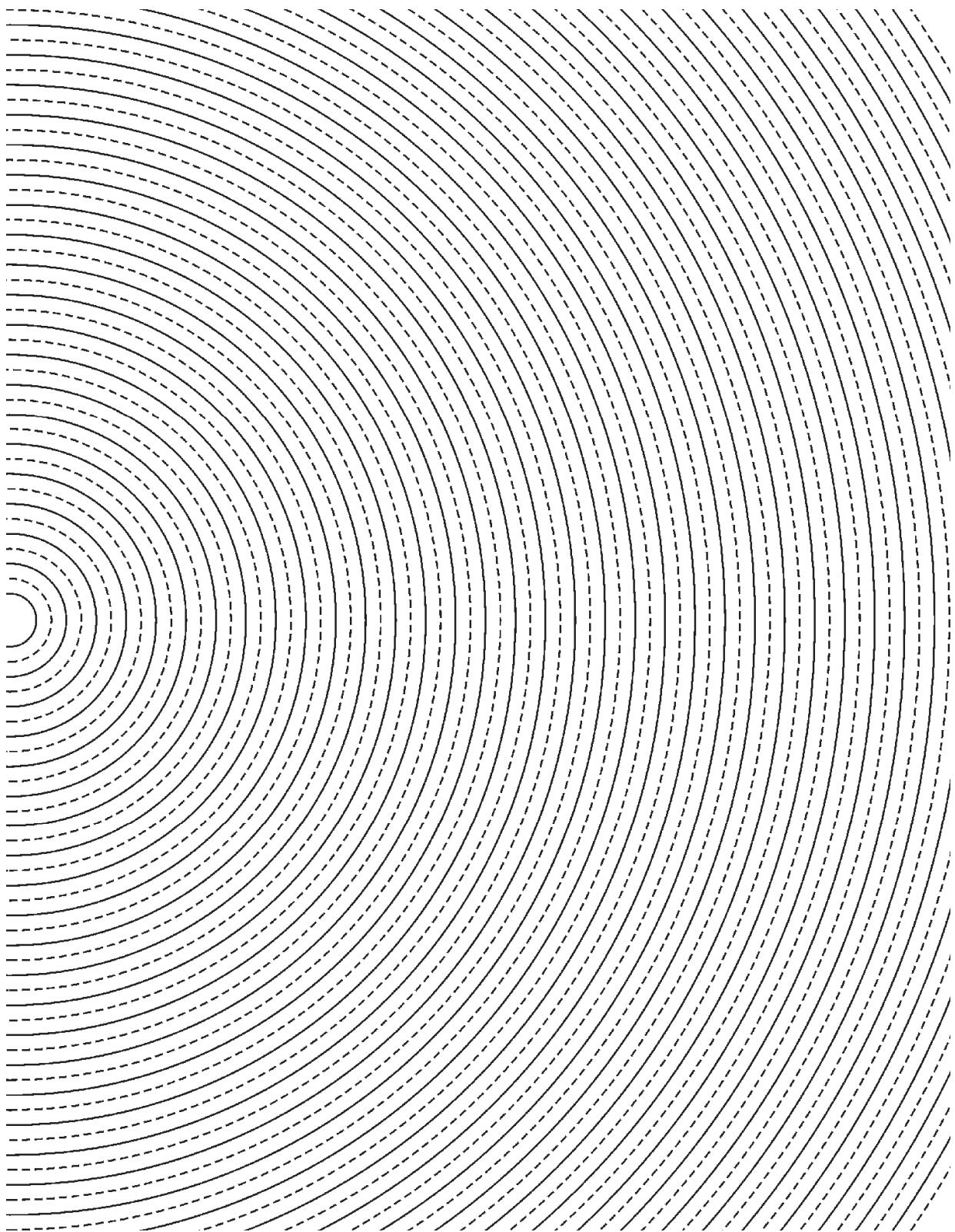
troughs, and observable interference patterns in the region where the waves overlap will occur. But, if the two corks bob up and down in a *random, disorganized manner*, no series of related, fixed-phase crests and troughs will form and no interference patterns of sufficiently long duration can develop; therefore interference will not be observed. Now, let us try to *simulate* interference effects with overlapping waves such as those shown in Figure 5-7.

Example 2

It is instructive to “produce” visible interference patterns by overlapping two sets of concentric circles, such as those shown in Figure 5-7. The set of concentric circles, **on the following page**, represents waves radiating outwardly from point a source such as S_1 or S_2 in Figure 5-7. (The solid curved lines represent crests; the dashed curved lines represent troughs. The distance from solid line to solid line or dashed line to dashed line is *one wavelength*.)

Make a **transparency** of the set of concentric rings shown. Then lay the transparency—with its set of concentric rings—over the master set. Carefully align the **left edge** of each set of circles so that the “point sources” S_1 (for the master set) and S_2 (for the transparency set) lie on the same vertical line. That is, the left edge of each pattern of concentric circles aligns itself exactly with the other.

- (a) Keeping the left edges aligned, separate S_1 and S_2 by *one wavelength*. (A wavelength is the radial distance from solid line to solid line of concentric rings.) Do you see the “lines” such as OP_2 , OP , and OP'_2 forming, just as shown in Figure 5-7? These “lines” designate regions of *constructive* interference. (The “lines” appear as “white lines” as you look down on the overlapping sets of rings.) In between these “white lines,” you should see darker regions, where *destructive* interference is occurring.
 - (b) Still keeping the left edges aligned, now carefully separate S_1 and S_2 , in turn, by distances of 1.5, 2, 3.5, 4, etc. wavelengths. Describe what you see is happening to the number of “white line” regions as you increase the distance between the point sources S_1 and S_2 .
 - (c) Play around with the two patterns, locating lines such as OP_2 , OP , and OP'_2 seen in Figure 5-7, as well as lines OP and OP'_1 . If you imagine a “screen” placed along the **right edge** of the two overlapping patterns of concentric rings, do you see where the “bright” and “dark” regions would be formed?
-



Young's double-slit interference experiment

Figure 5-8a shows the general laboratory setup for producing *interference fringes* with light from two coherent sources S_1 and S_2 . Source S_0 is a monochromatic (single wavelength) point source of light whose spherical wave fronts (circular in the drawing) fall on the two slits to create secondary sources S_1 and S_2 . Spherical waves radiate out from the two secondary sources S_1 and S_2 and maintain a fixed phase relationship with each other. As they spread out and overlap (interfere) at the screen, they produce a series of alternate bright and dark regions, as we saw in Figure 5-7 and Example 2. The alternate regions of bright and dark are referred to as *interference fringes*. Figure 5-8b shows such interference fringes, greatly expanded, for a small central portion of the screen shown in Figure 5-8a.

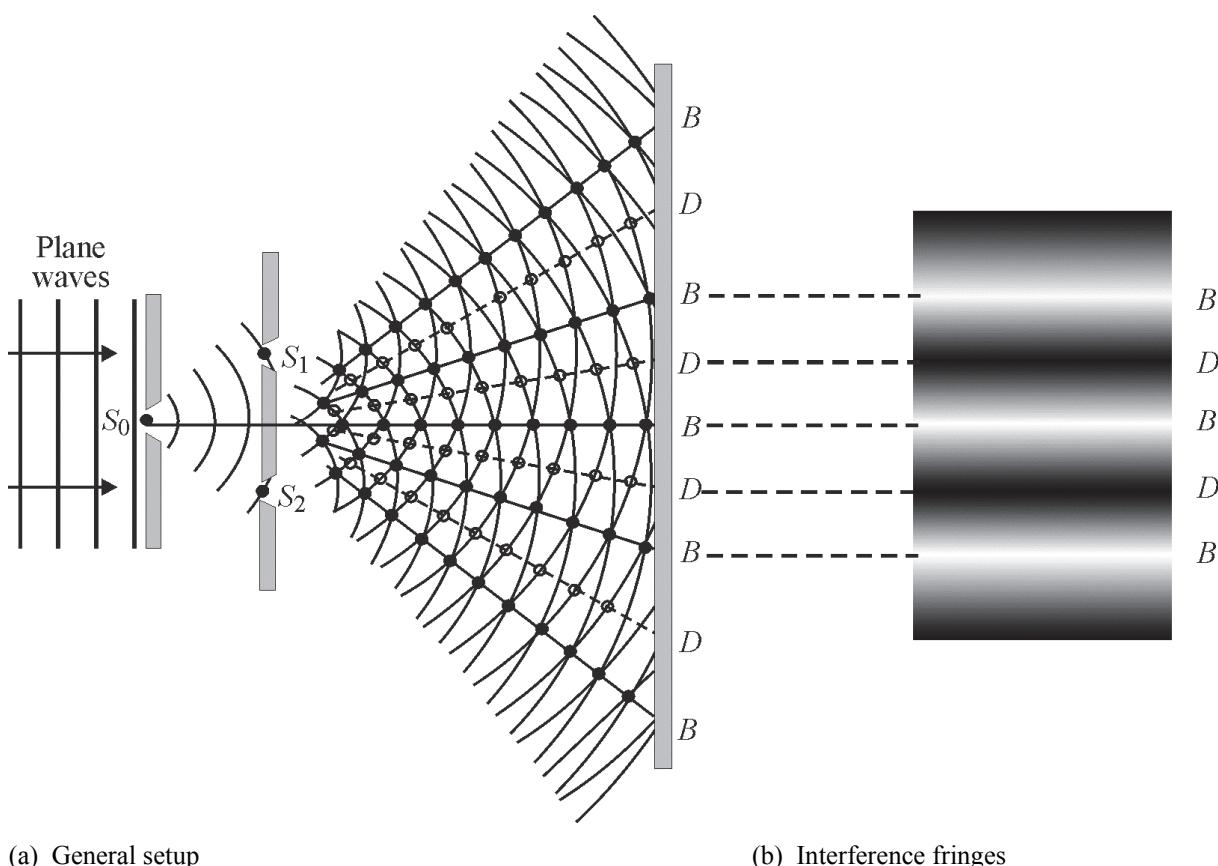


Figure 5-8 Young's double-slit interference experiment showing (a) general setup and (b) typical interference fringes (artistic reproduction)

Positions of interference fringes formed by a double slit—With the help of the *principle of superposition*, one can determine the positions of the alternate maxima (bright regions) and minima (dark regions) as shown on the screen in Figure 5-8a. (Recall that the *principle of superposition* allows one to add algebraically displacements of all individual waves that are passing through a given point. The *algebraic sum* of the individual displacements gives the resultant wave displacement at that point.) To determine the fringe positions, we shall make use of Figure 5-9 and the following conditions:

- (a) Light from slits S_1 and S_2 must be coherent; that is, there exists a fixed phase relationship between the waves from the two sources.
- (b) Light from slits S_1 and S_2 must be of the same wavelength.

In Figure 5-9, light waves from S_1 and S_2 spread out and overlap at an arbitrary point P on the screen. If the overlapping waves arrive in phase, we expect a bright spot at P ; if they arrive out of phase, we expect a dark spot. So the *phase difference* between the two waves arriving at point P is a key factor in determining what happens there. We shall express the *phase difference* in terms of the a *path difference*, which we can then relate to the wavelength λ .

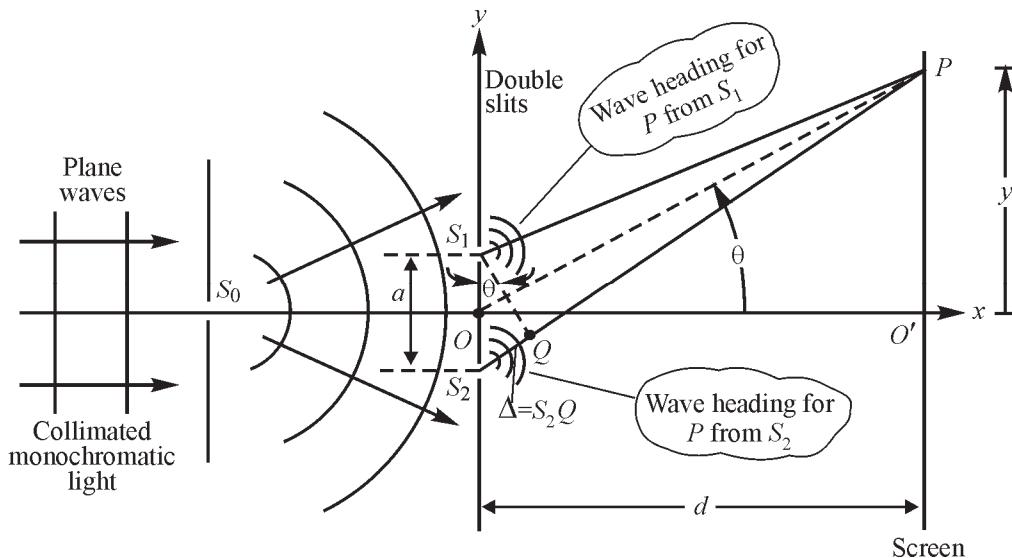


Figure 5-9 Schematic for Young's double-slit interference experiment. Source S_0 is generally a small hole or narrow slit; sources S_1 and S_2 are generally long, narrow slits perpendicular to the page.

For clarity, Figure 5-9 is not drawn to scale. It will be helpful in viewing the drawing to know that, in practice, the distance s from the slits to the screen is about *one meter*, the distance a between slits is *less than a millimeter*, so that the angle θ in triangle S_1S_2Q , or triangle OPO' , is quite small. And on top of all this, the wavelength of light is a fraction of a micrometer.

The path difference $\Delta = S_2Q$ between distances S_1P and S_2P , as seen in Figure 5-9, is given by Equation 5-4, since the distances PS_1 and PQ are equal and since $\sin \theta = \Delta/a$ in triangle S_1S_2Q .

$$\Delta = S_2P - S_1P = S_2Q = a \sin \theta \quad (5-4)$$

If the path difference Δ is equal to λ or some integral multiple of λ , the two waves arrive at P in *phase* and a bright fringe appears there (constructive interference). The condition for bright (B) fringes is, then,

$$\Delta_B = a \sin \theta = m\lambda \text{ where } m = 0, \pm 1, \pm 2, \dots \quad (5-5)$$

The letter m represents the *order number*. The central bright fringe at $\theta = 0$ (point O' on the screen) is called the zeroth-order maximum ($m = 0$). The first maximum on either side of the

central bright fringe, for which $m = \pm 1$, is called the *first-order maximum*, and so on. Five of these maxima, labeled B , are shown in Figure 5-8.

If, on the other hand, the path difference at P is an odd multiple of $\lambda/2$, the two waves arrive *out of phase* and create a dark fringe (destructive interference). The condition for dark (D) fringes—four of which are shown in Figure 8—is given by Equation 5-6.

$$\Delta_D = a \sin \theta = (m + \frac{1}{2})\lambda \text{ where } m = 0, \pm 1, \pm 2, \dots \quad (5-6)$$

Since the angle θ exists in both triangles S_1S_2Q and OPO' , we can find an expression for the *positions* of the bright and dark fringes *along the screen*. Because θ is small, as mentioned above, we know that $\sin \theta \approx \tan \theta$, so that for triangle OPO' we can write

$$\sin \theta \approx \tan \theta = \frac{y}{\lambda d} \quad (5-7)$$

where y is a position along the screen and d is the distance from the plane of the slits to the plane of the screen.

Combining Equation 5-7 with Equations 5-5 and 5-6 in turn, by substituting for $\sin \theta$ in each, we obtain expressions for the position y_B and y_D of bright and dark fringes, respectively, on the screen.



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The location of the bright fringes y_B is given by Equation 5-8,

$$y_B = \frac{\lambda d}{a} m \text{ where } m = 0, \pm 1, \pm 2, \dots \quad \text{BRIGHT} \quad (5-8)$$

and the location of the dark fringes y_D is given by Equation 5-9,

$$y_D = \frac{\lambda d}{a} (m + \frac{1}{2}) \text{ where } m = 0, \pm 1, \pm 2, \dots \quad \text{DARK} \quad (5-9)$$

Based on the derivation details in the *optional* section above, we now have Equations 5-8 and 5-9. These two equations locate for us the *centers* of the bright and dark regions on the screen. We say “centers” because the fringes go from bright to dark to bright, and so on, *gradually*, as artistically depicted in Figure 5-8b.

In Example 3, through the use of Equation 5-8, we recreate the method used by Thomas Young to make the *first* measurement of the wavelength of light.

Example 3

A double-slit source with slit separation $a = 0.2$ mm is located a distance $d = 1.2$ m from a screen. The *distance between successive bright fringes* on the screen is measured to be 3.30 mm. What is the wavelength of the light?

Solution: Using Equation 5-8 for any *two adjacent* bright fringes, say, $m + 1$ and m , we can obtain an equation for Δy , the fringe separation. Thus,

$$\Delta = (y_B)_{m+1} - (y_B)_m = \frac{\lambda d(m+1)}{a} - \frac{\lambda d(m)}{a} = \frac{\lambda d}{a}$$

$$\therefore \Delta y = \frac{\lambda d}{a}, \text{ so that } \lambda = \frac{(\Delta y)a}{d}, \text{ giving}$$

$$\lambda = \frac{(3.30 \times 10^{-3} \text{ m})(2 \times 10^{-4} \text{ m})}{1.2 \text{ m}} = 5.5 \times 10^{-7} \text{ m} = 550 \times 10^{-9} \text{ m}$$



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So the wavelength is about 550 nm and the light is yellowish green in color. (This clever method enabled scientists to measure wavelengths of the order of millionths of a meter.)

Intensity variation in the interference pattern—Knowing now how to locate the positions for the fringes on a screen, we might next ask, “How does the brightness (intensity) of the fringes vary as we move, in either direction, from the central bright fringe ($m = 0$)?” We obtain a satisfactory answer to this question by representing the two separate electric fields at point P , one coming from S_1 as $E_1 = (E_0 \sin 2\pi vt)$ and the other from S_2 as $E_2 = E_0 \sin(2\pi vt + \delta)$. The waves are assumed to have the same amplitude E_0 . Here δ is the *phase angle* difference between the two waves arriving at P . The *path difference* Δ is related to the *phase angle* δ by the straightforward proportion.



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$$\frac{\delta}{\Delta} = \frac{2\pi}{\lambda} \quad (5-10)$$

We see from Equation 5-10 that if $\Delta = \lambda$, then $\delta = 2\pi \text{ rad} = 360^\circ$; if $\Delta = \lambda/2$, then $\delta = \pi \text{ rad} = 180^\circ$, and so on.

Then, by using the *principle of superposition*, we can add the two electric fields at point P to obtain $E_{\text{RES}} = E_1 + E_2$. Since the intensity I of the light goes as the *square* of the electric field E ,



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we square E_{RES} and *average* the result over one cycle of wave oscillation at P . Carrying out these steps involves trigonometry and algebra, the details of which can be found in most basic optics texts. Here we will jump over the details and present the final result for I_{AV} in Equation 5-11.

$$I_{AV} = 4E_0^2 \cos^2\left(\frac{\pi a}{\lambda d} y\right) \quad (5-11)$$

where: I_{AV} = intensity of light along screen at position y

E_0 = amplitude of light wave from S_1 or S_2

d = distance from the plane of the double slit to the plane of the screen

a = slit separation

λ = wavelength of monochromatic light from either S_1 or S_2

y = distance above (or below) the central bright fringe on the screen



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Example 4

Using Equation 5-11 and the double-slit arrangement described in Example 3, determine how I_{AV} varies along the screen as a function of y . In Example 3, the wavelength λ was found to be 550 nm, the distance d from the double slits to the screen given as 1.2 m, and the distance a between the slits given as 0.2 mm.

Solution

$$I_{AV} = 4E_0^2 \cos^2\left(\frac{\pi a}{\lambda d} y\right), \text{ where } a = 2 \times 10^{-4} \text{ m}, \lambda = 550 \times 10^{-9} \text{ m, and } d = 1.2 \text{ m}$$

$$I_{AV} = 4E_0^2 \cos^2\left(\frac{\pi(2 \times 10^{-4})y}{550 \times 10^{-9}(1.2)}\right)$$

$$I_{AV} = 4E_0^2 \cos^2(303 \pi y)$$

Note that, when $y = \frac{1}{303}, \frac{2}{303}, \frac{3}{303}$ and so on, the angle $(303 \pi y)$ becomes π rad, 2π rad, 3π rad, and so on, for which $\cos^2(303 \pi y)$ is always 1. At these values of y , we have the first order, second order and third order of bright fringes—each of intensity $I_{AV} = 4E_0^2$. Since the interval Δy between successive fringes is $\frac{1}{303}$ meter, we get $\Delta y = 3.3 \times 10^{-3}$ m or 3.3 mm, in agreement with the value of Δy given in Example 3.

As a final note, looking back at the study of the overlapping concentric rings in Example 2, one can see that as the slit separation a increases, the fringes become narrower, that is, Δy becomes smaller. As the separation distance decreases, the fringes become broader and Δy becomes larger.

Thin-film interference

Interference effects provide us with the rainbow of colors we often see on thin-film soap bubbles and “oil slicks.” Each is an example of the interference of white light reflecting from opposite surfaces of the thin film. When thin films of different refractive indexes and thicknesses are appropriately stacked, coatings can be created that either enhance reflection greatly (HR or *high-reflecting* coats) or suppress reflection (AR or *antireflecting* coats). A basic appreciation of these phenomena begins with an understanding of interference in a *single thin film*.

Single-film interference—The geometry for thin-film interference is shown in Figure 5-10. We assume that the light strikes the film—of thickness t and refractive index n_f —at near-normal (perpendicular) incidence. In addition, we take into account the following *established* facts:

- A light wave traveling from a medium of lower refractive index to a medium of higher refractive index *automatically undergoes a phase change of π (180°)* upon reflection. A light wave traveling from a medium of higher index to one of lower index *undergoes no phase change* upon reflection. (We state this without proof.)
- The wavelength of light λ_n in a medium of refractive index n is given by $\lambda_n = \lambda_0/n$, where λ_0 is the wavelength in a vacuum or, approximately, in air.

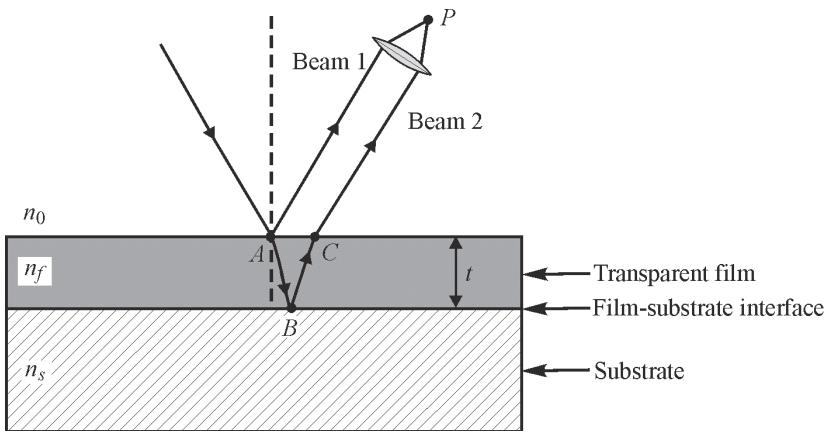


Figure 5-10 Two-beam interference from a thin film. Rays reflected from the film’s top and bottom plane surfaces are brought together at P by a lens.

In Figure 5-10, we show a light beam in a medium of index n_0 incident on a transparent film of index n_f . The film itself rests on a substrate of index n_s . Generally, the initial medium is air, so that $n_0 = 1$. The beam incident on the film surface at point A divides into reflected and refracted portions. The refracted beam reflects again at the film-substrate interface at point B and exits the film at point C, in the same direction as the beam reflected at point A. Of course, part of the beam incident at C reflects internally again at C and continues to undergo multiple reflections within the film layer until it loses its intensity. There will thus exist multiple parallel beams emerging from the top surface, although with rapidly diminishing amplitudes.

Unless the reflectance of the film is large, a *good approximation* to the more complex situation of multiple reflections is to consider only *the first two emerging beams*. The two parallel beams, 1 and 2, leaving the film at points A and C can be brought together by a converging lens—the eye,

for example. The two beams intersecting at P overlap and interfere. Since the two beams travel different paths from point A onward, one in air, the other partly in the film, a phase difference between them develops and this difference can produce either *constructive* or *destructive* interference at P .

If the additional path length ($AB + BC$) which beam 2 travels is equal to a whole number of wavelengths, beams 1 and 2 will reinforce each other. If ($AB + BC$) is equal to an odd number of half-wavelengths, beams 1 and 2 will subtract from one another. We find the number of wavelengths in the geometrical distance ($AB + BC$) by dividing that distance by the wavelength of light λ_n in the medium of index n . We identify the result with the symbol Δ_p , for the wavelength difference, where

$$\Delta_p = \frac{\text{Geometrical path length difference between beams 1 and 2}}{\text{Wavelength in the optical medium for beam 2}}$$

For the case shown in Figure 5-10, this becomes

$$\Delta_p = \frac{(AB + BC)}{\lambda_n}, \text{ where } \lambda_n = \frac{\lambda_0}{n}.$$

We have then,

$$\Delta_p = \frac{n(AB + BC)}{\lambda_0} \quad (5-12)$$

For the case of *normal incidence* of the light on the film, the distance ($AB + BC$) equals $2t$ where t is the film thickness. This then leads us to Equation 5-13, where

$$\Delta_p = \frac{2nt}{\lambda_0} \quad (\text{normal incidence}) \quad (5-13)$$

The product $2nt$ is called the *optical path length*. This product in effect provides a distance larger than the geometrical distance $2t$ shown in Figure 5-10, and allows one to compare that distance with the wavelength λ_0 of the light incident on the film. (One could equally well compare the actual distance $2t$ to the wavelength λ_n in the film to find the number of wavelengths in the path $AB + BC$.) Either way leads us to a correct value for Δ_p . If $\Delta_p = 1$, then $2nt = \lambda_0$. This means that the path length difference between beams 1 and 2 would be equal to one wavelength and such a film thickness would result in constructive interference. If $\Delta_p = \frac{1}{2}$, then $2nt = \frac{\lambda_0}{2}$. In this case, the path difference would be one-half of a wavelength and this film thickness would result in destructive interference. Note also that as the film thickness t increases, the optical path length $2nt$ increases and Δ_p can take on larger values like 2, 3, and 4—constructive interference—or $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ —destructive interference. If $2nt = \lambda_0$ or $\lambda_0/2$, we have the *minimum film thickness* which leads to constructive or destructive interference respectively. And recall from Equation 5-10, $\frac{\delta}{\Delta} = \frac{2\pi}{\lambda}$, if we know Δ we can find δ , the phase angle difference.

In addition to Δ_p , due to path length differences, we must consider an additional phenomenon mentioned above—that of *phase change on reflection*. Suppose that in Figure 5-10 $n_f > n_0$ and $n_f > n_s$. Sometimes it happens that $n_0 = n_s$, because the two media bounding the film are identical, as in the case of a water film (soap bubble) in air. Then the reflection in Figure 5-10 at point *A* (beam 1) occurs with light going from a medium of lower index n_0 (air) toward a medium of higher index n_f (film). The reflection at point *B* (beam 2), on the other hand, occurs for light going from a medium of higher index n_f (film) toward a medium of lower index n_s (air). Thus, the light in beam 1 reflecting at point *A* shifts phase *automatically* by 180° (equivalent to one-half wavelength) while the light reflecting at point *B* does not. As a result, if $2nt = \lambda_0$ due to a path length difference alone and we add to this the additional $\lambda_0/2$ phase shift for the beam reflecting at point *A*, we have a total optical path difference of $(\lambda_0 + \lambda_0/2)$, leading to *destructive*—rather than *constructive*—interference. So, in addition to the phase change introduced by *path differences*, we must always consider the *possible phase change upon reflection* at the interfaces.

If we denote Δ_p as the optical path difference and Δ_r as the equivalent path difference due to phase changes upon reflection, if any, then we can write a general condition for interference:

$$\Delta_p + \Delta_r = m\lambda_0 \quad (5-14)$$

where λ_0 is the wavelength of the incident light in air. If $(\Delta_p + \Delta_r)$ equals an integral number of wavelengths ($m = 1, 2, 3 \dots$), then *constructive* interference occurs. If $(\Delta_p + \Delta_r)$ equals an odd number of half-wavelengths ($m = \frac{1}{2}, \frac{3}{2}, \frac{5}{2} \dots$), then *destructive* interference occurs.

Let us now apply Equation 5-14 to determine the thin-film thickness for several different cases.

Example 5

High reflection (HR) from a soap bubble

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White light is incident *normally* on the surface of a soap bubble. A portion of the surface reflects green light of wavelength $\lambda_0 = 540$ nm. Estimate the *minimum* thickness of the soap bubble film that appears green on reflection.

Solution: The soap bubble is surrounded by air, so that in Figure 5-10, $n_0 = n_s$. Assume that the soap film is mostly water so that $n_f = 1.33$. Our path length difference Δ_p —at normal incidence—is equal to $2n_f t$ where t is the film thickness. And $\Delta_r = \lambda_0/2$, since here there is an automatic phase shift equivalent of $\lambda_0/2$ at the incident surface (air to soap film), but NOT at the near surface (soap film to air). And since we are looking for the *minimum* thickness to yield a strong reflection at $\lambda_0 = 540$ nm, we choose $m = 1$, the smallest whole integral number. Thus, Equation 5-14 becomes

$$\Delta_p + \Delta_r = m\lambda_0 \text{ where } \Delta_p = 2n_f t, \Delta_r = \frac{\lambda_0}{2} \text{ and } m = 1$$

$$\text{Then } 2n_f t + \frac{\lambda_0}{2} = 1 \lambda_0$$

$$t = \frac{\lambda_0 - \frac{\lambda_0}{2}}{2n_f} = \frac{\lambda_0}{4n_f} = \frac{540 \text{ nm}}{(4)(1.33)}$$

$$t = 101.5 \text{ nm}$$

Thus the minimum thickness of the soap bubble wall, which reflects strongly at 540 nm, is about 101 nm. If now we examine the thickness t for $m = 2, m = 3$, and so on, we will determine other (increased) thicknesses which also will reflect strongly at 540 nm, each one being a different thickness for constructive interference.)

A **122** **Single-layer antireflection (AR) coat**—A single-layer film deposited on a glass substrate is a common method of making *antireflecting (AR) coatings* on optical surfaces, such as those found in lenses for cameras and binoculars. The arrangement of a single-layer AR coat is shown in Figure 5-11, with a film made of magnesium fluoride (MgF_2) coated on top of a glass substrate.

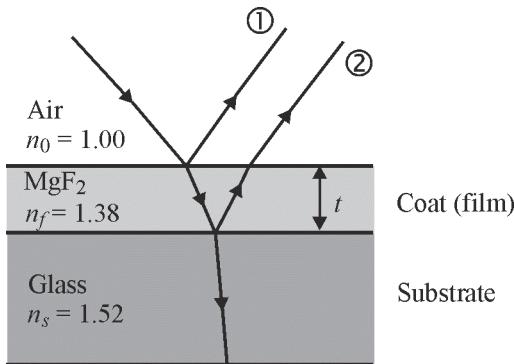


Figure 5-11 Single-layer AR coat on glass substrate

According to the rules for phase change upon reflection, *both* rays 1 and 2 undergo 180° phase shifts equal to $\lambda_0/2$, since both reflections occur at interfaces separating lower-to-higher refractive indexes. Overall then, $\Delta_r = 0$. So, the net difference in phase between rays 1 and 2 comes only from the optical path difference Δ_p due to the coating thickness t .

Example 6

Antireflection (AR) at a coated surface

In accordance with Figure 5-11, determine the *minimum* thickness of an AR coat of magnesium fluoride, MgF_2 , to be deposited on a glass substrate ($n_s = 1.52$) if the coat is to cause white light incident normally on the glass to be highly antireflective at $\lambda_0 = 550 \text{ nm}$. The refractive index for MgF_2 is near 1.38.

Solution: We begin with Equation 5-14:

$$\Delta_p + \Delta_r = m\lambda_0$$

Δ_p at normal incidence is equal to $2n_f t$ where t is the film thickness and $n_f = 1.38$, the index of the MgF₂ coat. And since $n_0 < n_f < n_s$, additional phase changes of equivalent half-wavelength $\lambda_0/2$ occur at both film surfaces, so Δ_r overall is zero. And since we want the *minimum* coat thickness that leads to destructive interference, we select $m = \frac{1}{2}$. Thus

$$\Delta_p + \Delta_r = m\lambda_0 \text{ becomes}$$

$$2n_f t + 0 = \frac{1}{2} \lambda_0, \text{ giving us for } t_{\min}$$

$$t_{\min} = \frac{\lambda_0}{4n_f} = \frac{550 \text{ nm}}{4(1.38)} = 99.6 \text{ nm}$$

This thickness near 100 nm is referred to as the “quarter-wave thickness” for a coat of MgF₂ on glass. It represents the thinnest coat one can deposit to achieve antireflection at 550 nm. If we resolve Equation 5-14 for $m = \frac{3}{2}, \frac{5}{2}$, and so on, we determine increasing coat thicknesses which also antireflect at 550 nm. But, of course, the cost of depositing thicker coats increases, so in general, the thinner the coat the better.

Coating a lens increases the amount of transmitted light. We have seen that at normal incidence on a plane glass surface, about 4% of the light is reflected. But, a lens has curved surfaces so that many rays are not perpendicular to the surface, thereby causing more than 4% of the light to be reflected. Thus, the amount of light reflected from a bare lens, taking into account the varying angles of incidence on the lens, is roughly 30%. With a single MgF₂ layer AR coat of 100 nm on the glass lens surface, the reflected light drops to around 10%; thus, the transmission of light increases from 70% to around 90%. For multiple lens devices, like cameras, this is a significant increase in light transmission.

Interference with multilayer films—As an extension of single-layer interference, consider the multilayer stack shown in Figure 5-12.

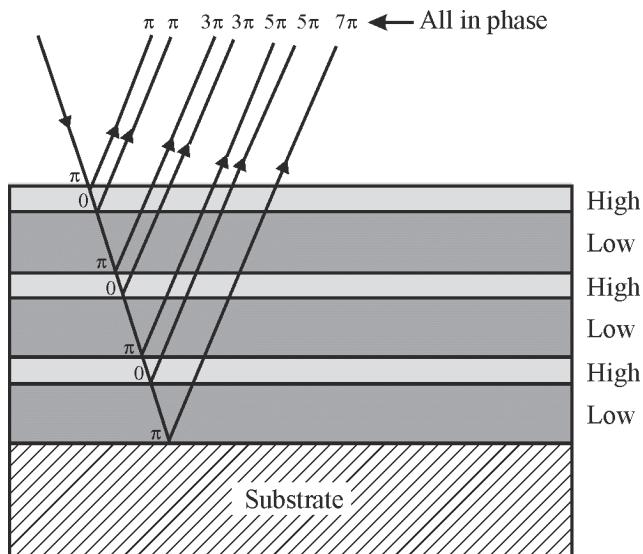


Figure 5-12 Multilayer stack of quarter-wave thin films of alternating high and low refractive indexes. Each film has an optical thickness of $\lambda_f/4$. Automatic phase shifts of $\delta = \pi$ or $\delta = 0$ are shown at each interface. All of the reflected rays exit the stack in phase with one another and interfere constructively.

The stack is composed of alternate layers of identical *high* index and *low* index films. If each film has an optical thickness of $\lambda_f/4$, a little analysis shows that all emerging beams are in phase. Multiple reflections in the region of λ_0 increase the total reflected intensity, and the quarter-wave stack performs as an efficient mirror. Such multilayer stacks can be designed to satisfy extinction of reflected light—AR effect—or enhancement of reflected light—HR effect—over a greater portion of the spectrum than that possible with a single-layer film. HR thin-film stacks are used in laser mirrors.

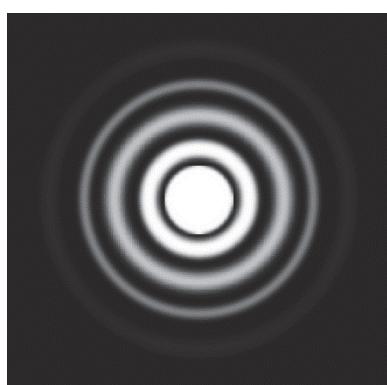
Such multilayer stacks are used in the design of *narrow-band interference filters* that filter out unwanted light, transmitting only light of the desired wavelength. For antireflection over *broader-wavelength* regions, the optical industry produces *HEBBAR™ coatings* (High Efficiency Broadband Anti Reflection) for regions of ultraviolet and infrared light, as well as for visible light. The coating industry also produces *V-coatings*, which reduce reflectance to near zero at one specific wavelength for an optical component. *High-reflection* coatings are produced over broadbands with multilayer stacks of thin films—just as for the antireflection coatings. In addition, *HR* coats are used as overcoatings on *metallic reflectors*, which typically use aluminum, silver, and gold as the base metals. The overcoats protect the metals from oxidation and scratching. This is again important in metallic reflectors used in the laser industry.

Diffraktion

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The ability of light to bend around corners, a consequence of the wave nature of light, is fundamental to both interference and diffraction. *Diffraction* is simply any deviation from geometrical optics resulting from the *obstruction* of a wave front of light by some obstacle or some opening. Diffraction occurs when light waves pass through small openings, around obstacles, or past sharp edges.

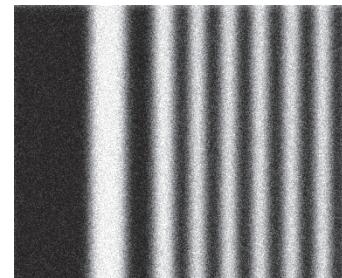
Several common diffraction patterns—as sketched by an artist—are shown in Figure 5-13. Figure 5-13a is a typical diffraction pattern for HeNe laser light passing through a circular pinhole. Figure 5-13b is a typical diffraction pattern for HeNe laser light passing through a single narrow (vertical) slit and Figure 5-13c is a typical pattern for diffraction caused by light passing by a sharp edge.



(a) Pinhole diffraction



(b) Single-slit diffraction



(c) Straight-edge diffraction

Figure 5-13 Sketches of several common diffraction patterns

The structure of the patterns should convince us—once and for all—that geometrical ray optics is incapable of dealing with diffraction phenomena. To demonstrate how wave theory does account for such patterns, we now examine the phenomenon of diffraction of waves by a single slit.

Diffraction by a single slit

The overall geometry for diffraction by a single slit is shown in Figure 5-14. The slit opening, seen in cross section, is in fact a long, narrow slit, perpendicular to the page. The shaded “humps” shown along the screen give a rough idea of intensity variation in the pattern. The sketch of bright and dark regions to the right of the screen is intensified to simulate the actual fringe pattern seen on the screen—even though the “artistic recreation” does not show the actual drop-off of intensity indicated by the “intensity humps.” We observe a wide central bright fringe, bordered by narrower regions of dark and bright. The angle θ shown connects a point P on the screen to the center of the slit.

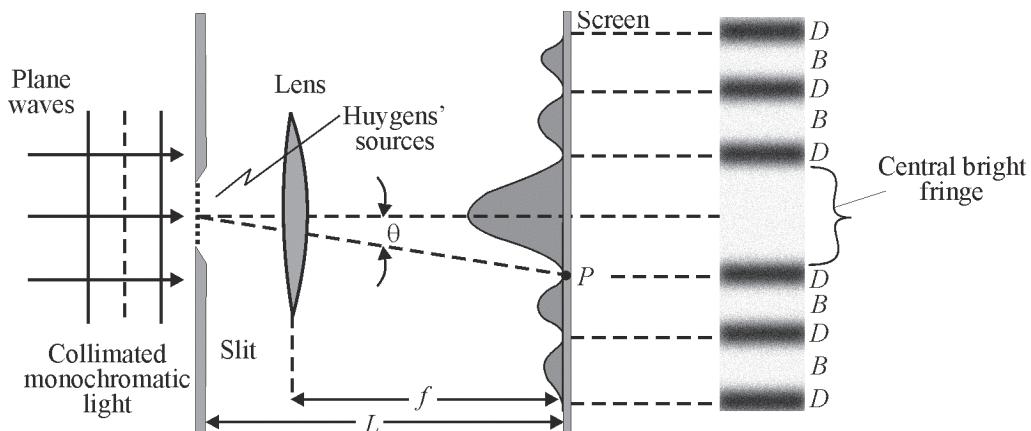


Figure 5-14 Diffraction pattern from a single slit

Since plane waves are incident on the screen, the diffraction pattern—in the absence of the focusing lens—would be formed far away from the slit and be spread out further than that shown in Figure 5-14. The lens serves to focus the light passing through the slit onto the screen, just a focal length f away from the lens, while preserving faithfully the relative details of the diffraction pattern that would be formed on a distant screen without the lens.

To determine the location of the minima and maxima on the screen, we divide the slit opening through which a plane wave is passing into many point sources (Huygens's sources), as shown by the series of tiny dots in the slit opening of Figure 5-14. These numerous point sources send out Huygens's secondary spherical waves, all in phase, toward the screen. There, at a point such as P , light waves from the various Huygens's sources overlap and interfere, forming the variation in light intensity shown in Figure 5-14. Thus, diffraction considers the contribution from *every part of the wave front* passing through the slit. By contrast, when we looked at interference from Young's double slit, we considered *each slit* as a point source, ignoring details of the portions of the wave fronts in the slit openings themselves.

The mathematical details involved in adding the contributions at point P from each of the Huygens's sources can be found in basic texts on *physical optics*. Here we give only the end result of the calculation. Equation 5-15 locates the minima, y_{\min} , on the screen, in terms of the slit width b , slit-to-screen distance L , wavelength λ , and order m .

$$y_{\min} = \frac{m\lambda L}{b} \quad \text{where } m = 1, 2, 3, \dots \quad (5-15)$$

Figure 5-15 shows the positions of several orders of minima and the essential parameters associated with the single-slit diffraction pattern. (The positions of the *maxima* are mathematically more complicated to express, so we typically work with the positions of the well-defined minima.) Note that the central maximum between $+y_1$ and $-y_1$ is twice the width ($2y_1$) of the other maxima. You can see this difference also by looking back at the single-slit diffraction picture shown in Figure 5-13b. Note also that the angles θ_m indicate the orders or measures of diffraction occurring. For example, θ_2 represents a larger spreading (deviation from geometrical optics) of the light than does θ_1 .

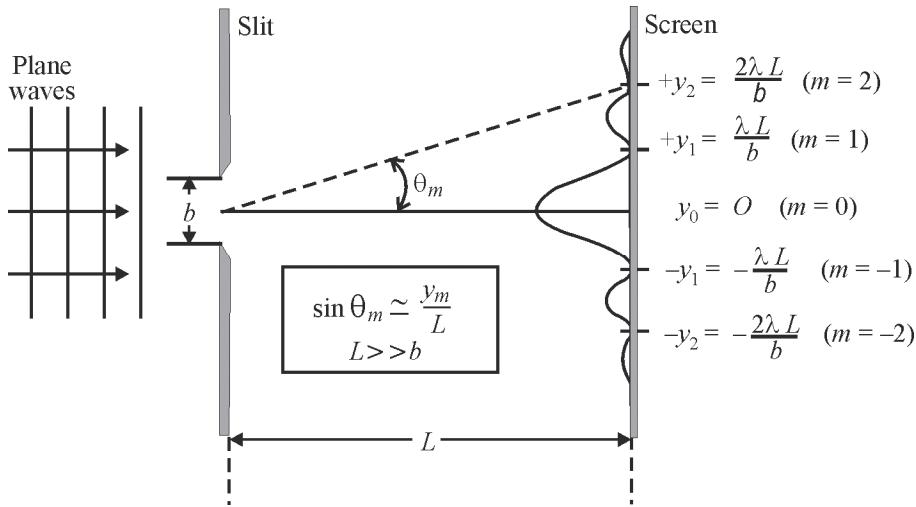


Figure 5-15 Positions of adjacent minima in the diffraction patterns
(Drawing is not to scale.)



Now let's use Equation 5-15 to work several sample problems.

Example 7

A photonics technician wishes to check out the difference between the width of the central maximum and the side maxima as seen in Figure 5-13b or Figure 5-15. She shines coherent laser light of wavelength 633 nm on a single slit of width 0.25 mm. She places the observation screen 2.0 m from the slit. (a) What is the width of the central bright fringe according to Equation 5-15 that she should measure? (b) What is the width of the bright fringe between the 5th and 6th minima that she should measure?

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for a short lesson
about diffraction.

Solution

(a) As seen in Figure 5-15 the width of the central bright fringe is $2y_1$, where y_1 is the distance to the first minimum ($m = 1$) on either side. Thus, using Equation 5-15,

$$\text{Width} = 2y_1 = 2 \left(\frac{m\lambda L}{b} \right) = \frac{(2)(1)(633 \times 10^{-9} \text{ m})(2.0 \text{ m})}{2.5 \times 10^{-4} \text{ m}} = 0.01 \text{ m}$$

The width of the central bright fringe is about 1 cm. This is a large enough distance to be measured fairly accurately.

(b) $\text{Width} = y_6 - y_5 = \left(\frac{6\lambda L}{b} - \frac{5\lambda L}{b} \right) = \frac{\lambda L}{b}$

$$\text{Width} = \frac{(633 \times 10^{-9} \text{ m})(2.0 \text{ m})}{2.5 \times 10^{-4} \text{ m}} = 5.06 \times 10^{-3} \text{ m} \cong 0.5 \text{ cm}, \text{ again a measurable width}$$

Thus our technician finds, in accordance with theory, that the width of bright fringe between the 5th and 6th minima is half the width of the central bright fringe.

Example 8

You are given a lamp source of monochromatic light but you don't know its wavelength. So you set up an experiment like that in Figure 5-15 to determine λ . You shine the monochromatic light on a single slit of width 0.30 mm. You locate a screen 2.0 m away to get a big pattern. On this pattern, you measure the width of the central bright fringe and find it to be near 7.8 mm. From this information, you determine the unknown wavelength as follows.

Solution: Since the width of the central bright fringe is 7.8 mm, equal to $2y_1$, we know that

$$y_1 = 3.9 \text{ mm}. \text{ Then, rearranging Equation 5-15 to find } \lambda, \text{ we have } \lambda = \frac{y_{\min} b}{mL}, \text{ where}$$

$$y_{\min} = y_1 = 3.9 \text{ mm}, m = 1, L = 2.0 \text{ m}, \text{ and } b = 0.30 \text{ mm}. \text{ Thus,}$$

$$\lambda = \frac{(3.9 \times 10^{-3})(3 \times 10^{-4})}{(1)(2.0)} = 5.85 \times 10^{-7} \text{ m}$$

$\lambda \cong 585 \text{ nm}$, very near the principal wavelengths of light from sodium lamps.

Fraunhofer diffraction

In general, if light falling on a diffraction aperture, such as a pinhole or a narrow slit, is collimated, and if the diffracted light is observed on a distant screen, the diffraction pattern formed there is described as *Fraunhofer diffraction*. In the jargon of those involved with high energy lasers, Fraunhofer diffraction is often referred to as *far-field* diffraction or diffraction in the far-field. Such diffraction patterns were first investigated and explained mathematically by Joseph von Fraunhofer (1787–1826). The general setup for observing “far-field” or Fraunhofer diffraction patterns is shown in Figure 5-16.

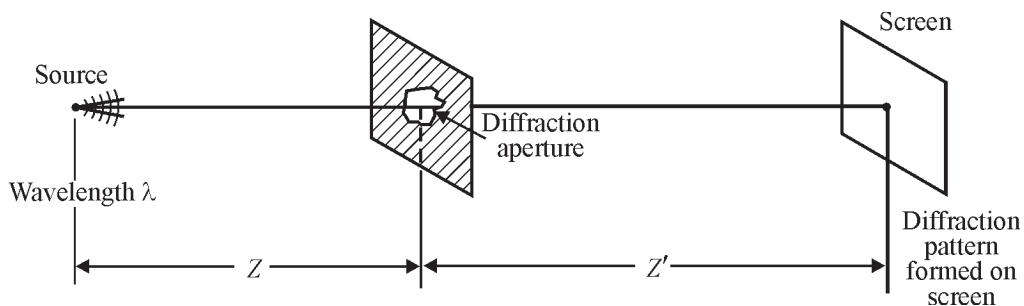


Figure 5-16 General diffraction geometry involving source, aperture, and screen

On the source side of the aperture, if the source is *far removed* (Z large), the light striking the aperture will be parallel (collimated). Or, one can shine laser light—generally highly collimated—and not worry about the source being “far removed.” On the other side of the aperture, the screen distance (Z') should be large. Or, one can place a positive lens of focal length f near the aperture, on the screen side, and form a much reduced, but faithfully-proportioned diffraction pattern a distance f from the aperture. Using a laser on the source side and a positive lens on the screen side allows one to form and study Fraunhofer diffraction patterns with ordinary lab tables.

When the conditions (or their equivalence) for “distant source” and “far-removed screen” are not satisfied diffraction patterns are still formed. These are referred to as *Fresnel* diffraction, or *near-field* diffraction, after Augustin Fresnel (1788–1829), who explained their more complicated details with much more complicated mathematics. Most basic books on optics cover both the Fraunhofer and Fresnel mathematical analyses of diffraction patterns.

Condition for formation of Fraunhofer diffraction—It is a fair question to ask what is meant by “distant” or “far-removed” when setting up a diffraction experiment. Comparison of mathematical theory with observed experimental results indicates the following. When collimated light is incident on the aperture, the screen distance (Z'), in the absence of a focusing lens, should be of a magnitude given by Equation 5-16.

$$Z' > 100 \left(\frac{\text{area of aperture opening}}{\text{wavelength of incident light}} \right) \quad (5-16)$$

where Z' is the aperture-to-screen distance. Let’s see how this works in practice.

Example 9

Minati, a photonics technician, has been asked to produce a Fraunhofer diffraction pattern formed when light from a HeNe laser ($\lambda = 633 \text{ nm}$) passes through a pinhole of $150\text{-}\mu\text{m}$ diameter. In order to set up the correct geometry for Fraunhofer diffraction, Minati needs to know the correct distance Z' from the pinhole to the screen.

Solution: Minati needs first to test the conditions given in Equation 5-16 so she calculates the ratio of $\left(\frac{\text{aperture area}}{\lambda} \right)$ assuming the pinhole to be circular.

$$\text{Ratio} = \frac{\text{aperture area}}{\lambda} = \frac{\pi D^2}{4\lambda} = \frac{(3.14)(150 \times 10^{-6})^2}{(4)(633 \times 10^{-9})}$$

$$\text{Ratio} = 0.0279 \text{ m}$$

Minati knows that light from the HeNe laser is fairly well collimated, so that nearly plane waves are incident on the pinhole. That takes care of the condition for Fraunhofer diffraction on the source side.

Now she considers how to satisfy the condition on the screen side. From her calculation of the ratio $\left(\frac{\text{aperture area}}{\lambda}\right)$, she knows also that the distance Z' must be equal to or greater than (100 times 0.0279 m) or about 2.8 m. So, she can place the screen 3 meters or so from the aperture and form a Fraunhofer diffraction pattern there. **OR**, she can place a positive lens just beyond the aperture and focus the diffracting light on a screen a focal length away. With the focusing lens in place, she obtains a much reduced—but valid—Fraunhofer diffraction pattern located nearer the aperture. She chooses to use the latter setup, with a positive lens of focal length 10 cm, enabling her to arrange the laser, pinhole, and screen, all on a convenient 2-meter optical bench she uses in her laboratory.

Several typical Fraunhofer diffraction patterns—In successive order, we show Fraunhofer diffraction patterns for a *single slit* (Figure 5-17), a *circular aperture* (Figure 5-18), and a *rectangular aperture* (Figure 5-19). Equations that describe the locations of the bright and dark fringes in the patterns accompany each figure.

Single slit

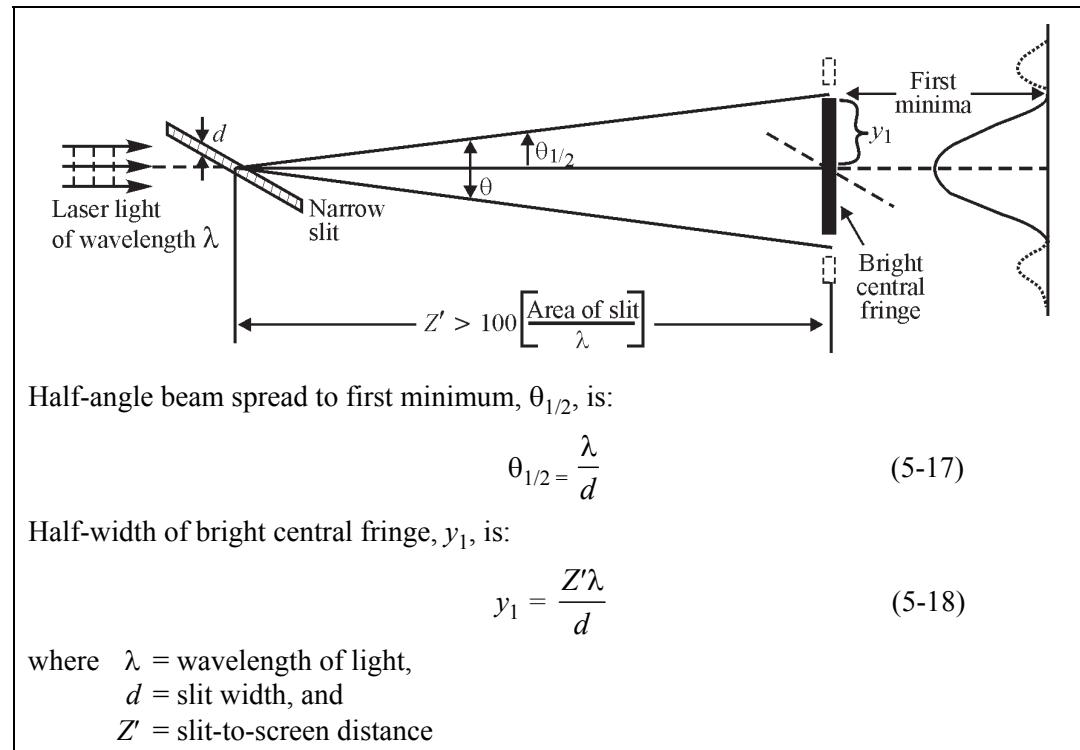


Figure 5-17 *Fraunhofer diffraction pattern for a single slit*

Circular aperture

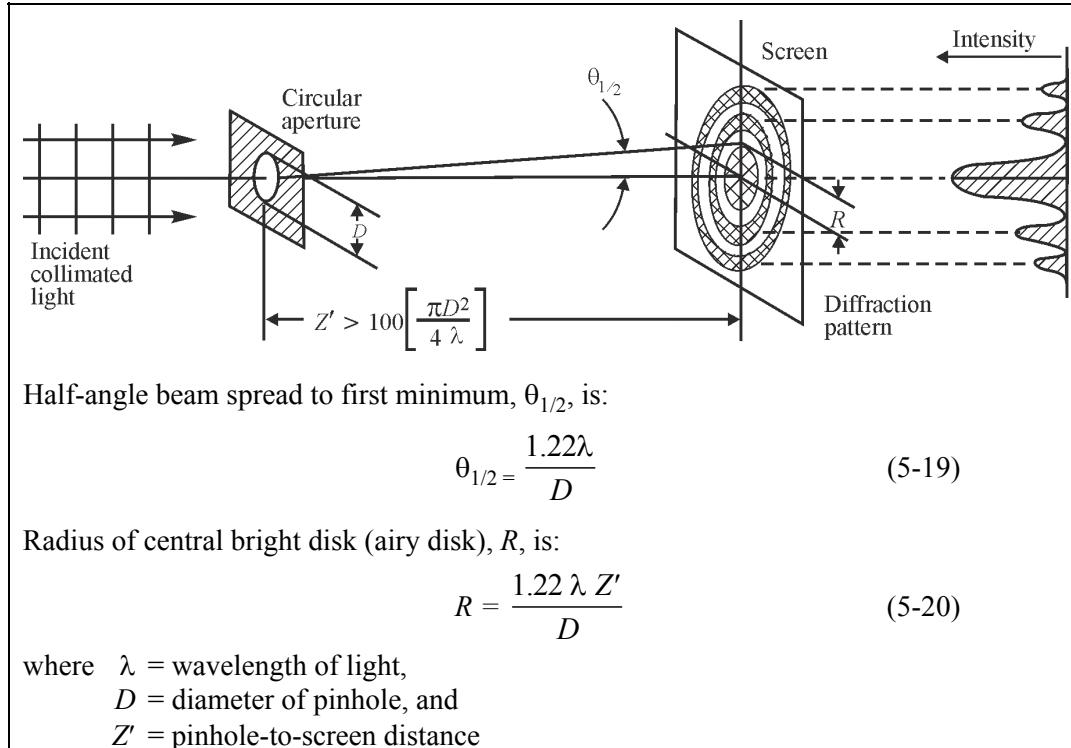


Figure 5-18 *Fraunhofer diffraction pattern for a circular aperture*

Rectangular aperture

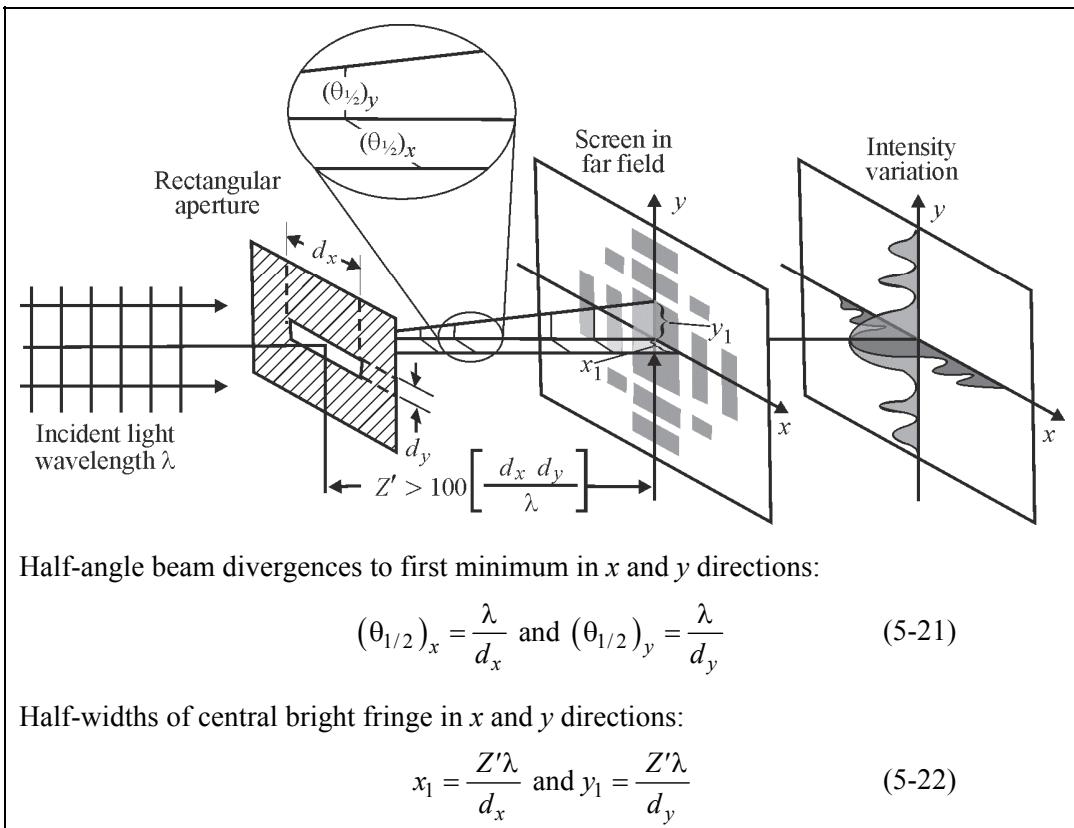


Figure 5-19 *Fraunhofer diffraction pattern for a rectangular aperture*

It can be seen mathematically (from Equations 5-17, 5-19, 5-21, and 5-22) or from experimental observation that a diffraction pattern “spreads out” as the principal dimension of the aperture is reduced. Thus, in Figure 5-17, if the width d of the slit is reduced to $d/2$, the width of the central maximum ($2y_1$) is doubled. This spreading should remind us of a similar spreading of the interference fringes we formed in Example 2 when we moved the two point sources, S_1 and S_2 , closer together.

Diffractive grating

If we prepare an aperture with thousands of slits, separated by equal spacing, we have a so-called *transmission-diffraction grating*. The width of a single slit—the opening—is given by b , and the distance between slit centers is given by a (see Figure 5-20). For clarity, only a few of the thousands of slits normally present in a grating are shown. Note that the spreading of light occurs always in a direction perpendicular to the direction of the long edge of the slit opening—that is, since the long edge of the slit opening is *vertical* in Figure 5-20, the spreading is in the *horizontal* direction—along the screen. For the remainder of this discussion, the terms lines, grooves, or slits are used interchangeably.

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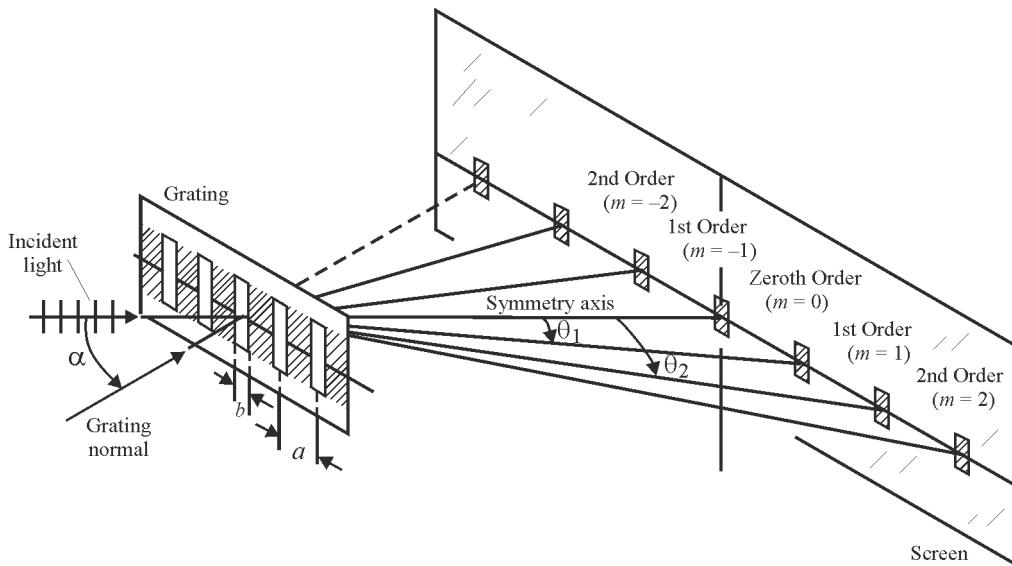


Figure 5-20 Diffraction of light through a grating under Fraunhofer conditions

The resulting diffraction pattern is a series of sharply defined, widely spaced fringes, as shown. The central fringe, on the symmetry axis, is called the *zeroth-order* fringe. The successive fringes on either side are called *1st order*, *2nd order*, etc., respectively. They are numbered according to their positions relative to the central fringe, as denoted by the letter m , and are signed as positive or negative.

The intensity pattern on the screen is a *superposition* of the *diffraction effects from each slit* as well as the *interference effects of the light from all of the adjacent slits*. The combined effect is to cause overall cancellation of light over most of the screen with marked enhancement at the bright regions, as shown in Figure 5-20. The location of the bright fringes is given by the following expression, called the *grating equation*, assuming that Fraunhofer conditions hold.

$$a (\sin \alpha + \sin \theta_p) = m\lambda \text{ where } m = 0, \pm 1, \pm 2, \dots \quad (5-23)$$

where a = distance between slit centers

α = angle of incidence of light measured with respect to the normal to the grating surface

θ_p = angle measured from the symmetry axis, locating the m th-order fringe

m = an integer taking on values of $0, \pm 1, \pm 2$, etc.

λ = wavelength of light

Note that, if the light is incident on the grating along the grating normal ($\alpha = 0$), the grating equation, Equation 5-23, reduces to the simpler form shown in Equation 5-24.

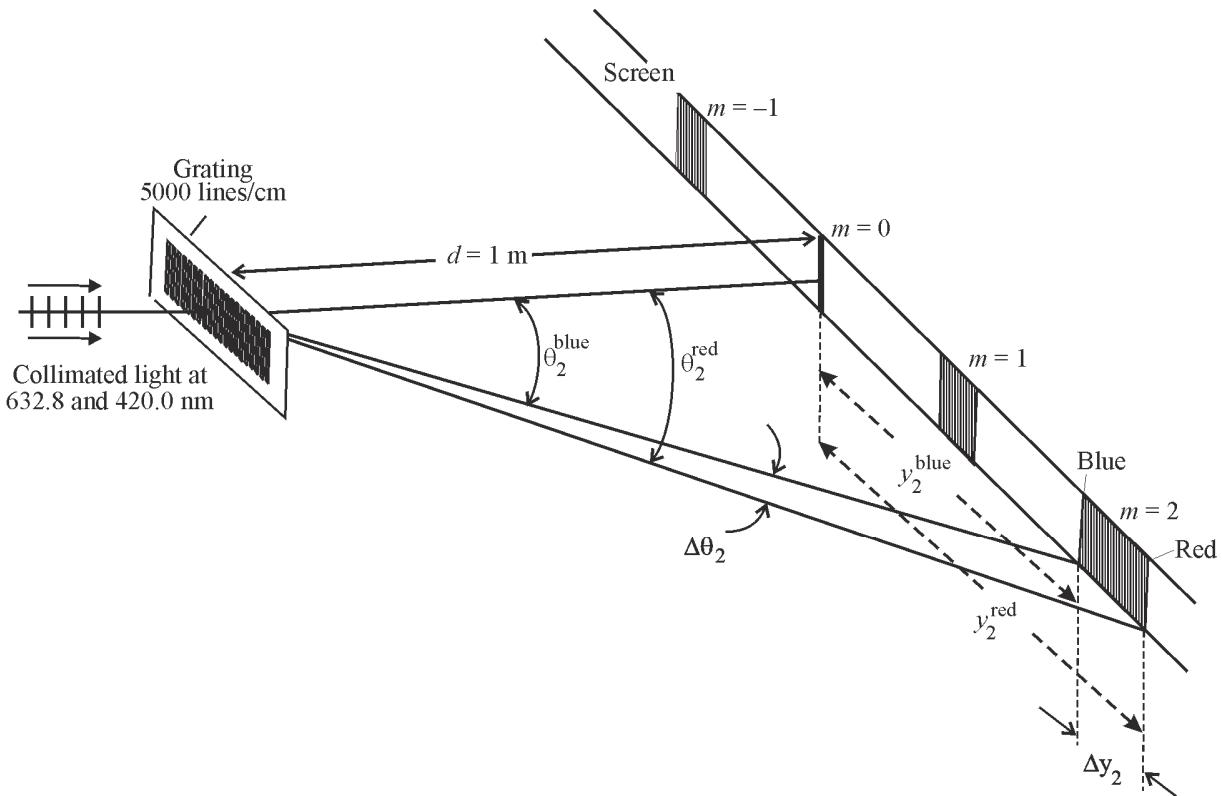
$$a (\sin \theta_p) = m\lambda \quad (5-24)$$

If, for example, you shine a HeNe laser beam perpendicularly onto the surface of a transmission grating, you will see a series of brilliant red dots, spread out as shown in Figure 5-20.

A complete calculation would show that less light falls on each successively distant red dot or fringe, the $m = 0$ or central fringe being always the brightest. Nevertheless, the location of each bright spot, or fringe, is given accurately by Equation 5-23 for either normal incidence ($\alpha = 0$) or oblique incidence ($\alpha \neq 0$). If light containing a mixture of wavelengths (white light, for example) is directed onto the transmission grating, Equation 5-23 holds for *each* component color or wavelength. So each color will be spread out on the screen according to Equation 5-23, with the longer wavelengths (red) spreading out farther than the shorter wavelengths (blue). In any case, the central fringe ($m = 0$) always remains the same color as the incident beam, since all wavelengths in the $m = 0$ fringe have $\theta_p = 0$, hence all overlap to re-form the “original” beam and therefore the original “color.” Example 10 shows calculations for a typical diffraction grating under Fraunhofer conditions.

Example 10

Michael has been handed a transmission grating by his supervisor who wants to know how widely the red light and blue light fringes—in *second* order—are separated on a screen one meter from the grating, as shown below. Michael is told that the separation distance between the red and blue colors is a critical piece of information needed for an experiment with a grating spectrometer. The transmission grating is to be illuminated at *normal incidence* with red light at $\lambda = 632.8$ nm and blue light at $\lambda = 420.0$ nm. Printed on the frame surrounding the ruled grating, Michael sees that there are 5000 slits (lines) per centimeter on this grating. Michael decides he must, in turn:



- Determine the distance a between the slit centers.
- Determine the angular deviation θ_m in 2nd order for both the red (θ_2^{red}) and the blue (θ_2^{blue}) light.

- (c) Determine the separation distance Δy_2 on the screen between the red (y_2^{red}) and blue (y_2^{blue}) fringes.

Solution

- (a) Since there are 5000 slits or grooves per centimeter, Michael knows that the distance a between the slits, center to center, must be $a = \frac{1 \text{ cm}}{5000} = 2 \times 10^{-4} \text{ cm}$.
- (b) At normal incidence ($\alpha = 0$), Equation 5-23 reduces to Equation 5-24, so, for 2nd order ($m = 2$), Michael writes the following two equations and solves them for the deviation angles θ_2^{red} and θ_2^{blue} :

$$\sin \theta_2^{\text{red}} = \frac{m\lambda_{\text{red}}}{a} = \frac{(2)(632.8 \times 10^{-9} \text{ m})}{2 \times 10^{-6} \text{ m}} = 0.6328$$

$$\therefore \theta_2^{\text{red}} = \sin^{-1}(0.6328) = 39.3^\circ$$

$$\sin \theta_2^{\text{blue}} = \frac{m\lambda_{\text{blue}}}{a} = \frac{(2)(420 \times 10^{-9} \text{ m})}{2 \times 10^{-6} \text{ m}} = 0.4200$$

$$\therefore \theta_2^{\text{blue}} = \sin^{-1}(0.4200) = 24.8^\circ$$



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- (c) From the geometry shown in the sketch, Michael sees that the screen distances y_2^{red} and y_2^{blue} to the red and blue fringes in 2nd order respectively, and the grating-to-screen distance d are related to deviation angles by the equation

$$\tan \theta_2 = \frac{y_2}{d}, \text{ where here, } d = 1 \text{ meter.}$$

Thus

$$\Delta y_2 = y_2^{\text{red}} - y_2^{\text{blue}} = (d \tan \theta_2^{\text{red}}) - (d \tan \theta_2^{\text{blue}})$$

which becomes

$$\Delta y_2 = (1 \text{ m}) (\tan 39.3^\circ - \tan 24.8^\circ)$$

$$\Delta y_2 = (100 \text{ cm}) (0.8185 - 0.4621)$$

$$\Delta y_2 = 35.6 \text{ cm}$$

Michael reports his finding of $\Delta y_2 = 35.6 \text{ cm}$ to his supervisor, who decides that this grating will work in the proposed experiment.

Diffraction-limited optics

A lens of diameter D is in effect a large circular aperture through which light passes. Suppose such a lens is used to focus plane waves (light from a distant source) to form a “spot” in the focal plane of the lens, much as is done in *geometrical optics*. Is the focused spot truly a *point*? Reference to Figure 5-18 indicates that the focused spot is actually a tiny diffraction pattern—with a bright disk at the center (the so-called *airy disk*) surrounded by dark and bright rings, as pictured earlier in Figure 5-13a.

In Figure 5-21, we see collimated light incident on a lens of focal length f . The lens serves as both a circular aperture of diameter D to intercept the plane waves and a lens of focal length f to focus the light on the screen. The setup in Figure 5-21 satisfies the required conditions for a Fraunhofer diffraction pattern. The reduced pattern will be formed in the focal plane of the lens as shown.

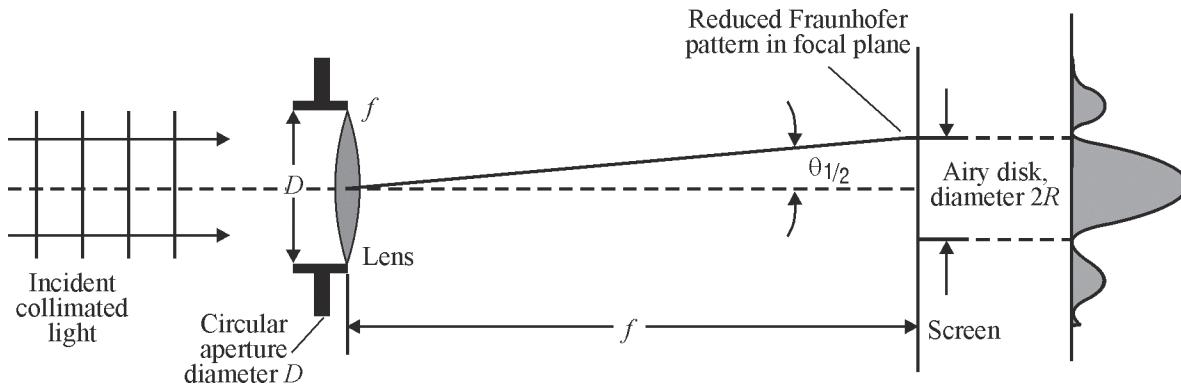


Figure 5-21 Fraunhofer diffraction pattern formed in the focal plane of a lens of focal length f (Drawing is not to scale.)

The diffraction pattern is, in truth then, an array of alternate bright and dark rings, with a bright spot at the center, even though the array is very small and hardly observable to the human eye. From the equations given with Figure 5-18, we see that the diameter of the central bright spot—inside the surrounding rings—is itself of size $2R$, where, from Equation 5-20 and Figure 5-18,

$$2R = 2 \left(\frac{1.22\lambda Z'}{D} \right) \quad (5-25)$$

where $Z' = f$

While indeed small, the diffraction pattern overall is greater than $2R$, demonstrating clearly that a lens focuses collimated light to a small diffraction pattern of rings and not to a point.

However, when the lens is smaller than a few inches, we justifiably refer to the focal plane pattern as a “point,” ignoring all structure within the “point.” Example 11 provides us with a “feel” for the *size of the structure* in the focused spot, a small diameter lens becomes the circular aperture that gives rise to the airy disk diffraction pattern.

Example 11

Determine the size of the airy disk at the center of the diffraction pattern formed by a lens such as that shown in Figure 5-21, if the lens is 4 cm in diameter and its focal length is 15 cm. Assume a wavelength of 550 nm incident on the lens.

Solution: Using Equation 5-25 with $Z' = f$, the diameter of the airy disk is

$$2R = \frac{2.44\lambda f}{D} = \frac{(2.44)(550 \times 10^{-9} \text{ m})(0.15 \text{ m})}{0.04 \text{ m}}$$

$$2R = 5.03 \times 10^{-6} \text{ m}$$

Thus, the central bright spot (airy disk) in the diffraction pattern is **only** 5 micrometers in diameter. So, even though the focused spot is not a true point, it is small enough to be considered so in the world of large lenses, i.e., in the world of geometrical optics.

The previous discussion and example indicate that the size of the focal spot—structure and all—is limited by diffraction. No matter what we do, we can never make the airy disk smaller than that given by $2R = \frac{2.44f\lambda}{D}$. That is the limit *set by diffraction*. So, all optical systems are *limited by diffraction* and consequently limited in their ability to form true point images of point objects. We recognize this when we speak of *diffraction-limited optics*. An ideal optical system therefore can do no better than that permitted by diffraction theory. In fact, a real optical system—which contains imperfections in the optical lenses, variations in the index of refraction of optical components, scattering centers, and the existence of temperature gradients in the intervening atmosphere—will not achieve the quality limit permitted by diffraction theory. Real optical systems are therefore poorer than those limited by diffraction only. We often refer to real systems as *many-times diffraction limited* and sometimes attach a numerical figure such as “five-times diffraction-limited.” Such a reference indicates the deviation in quality expected from the given system compared with an ideal “diffraction-limited” system.

Polarization

We continue our discussion of the main concepts in *physical optics* with a brief look at *polarization*. Before we describe the polarization of light waves, let’s take a look at a simplistic—but helpful—analogy of “polarization” with *rope waves*.

Polarization—A simple analogy

Imagine a “magic” rope that you can whip up and down at one end, thereby sending a *transverse* “whipped pulse” (vibration) out along the rope. See Figure 5-22a. Imagine further that you can change the direction of the “whipped shape,” quickly and randomly at your end, so that a person looking back along the rope toward you, sees the “vibration” occurring in all directions—up and down, left to right, northeast to southwest, and so on, as shown in Figure 5-22b.

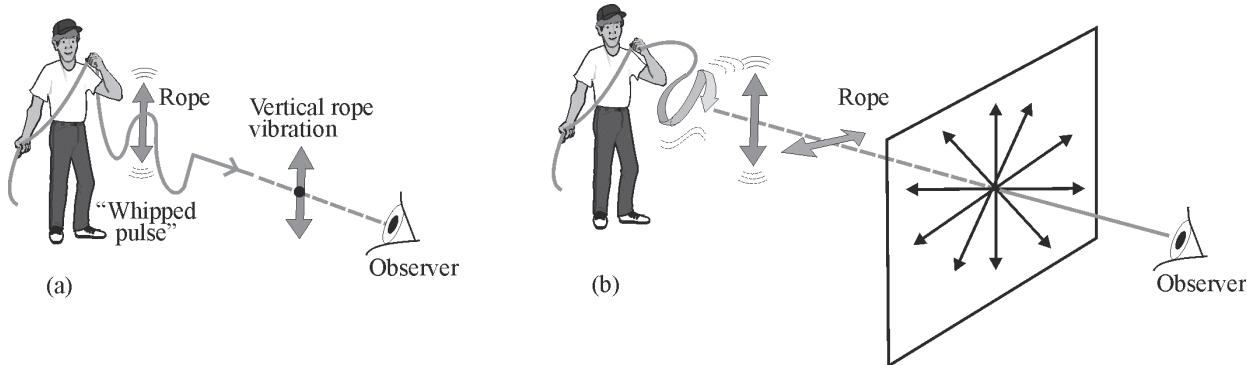


Figure 5-22 *Rope waves and polarization*

In Figure 5-22a, the rope wave is *linearly polarized*, that is, the rope vibrates in only one transverse direction—vertically in the sketch shown. In Figure 5-22b, the rope vibrations are in all transverse directions, so that the rope waves are said to be randomly polarized.

Now imagine that the waves on the rope—representing all possible directions of vibration as shown in Figure 5-22b—are passed through a *picket fence*. Since the vertical slots of the fence pass only vertical vibrations, the many randomly oriented transverse vibrations incident on the picket fence emerge as only vertical vibrations, as depicted in Figure 5-23. In this example of transverse waves moving out along a rope, we see how we can—with the help of a polarizing device, the picket fence in this case—change randomly polarized rope waves into polarized rope waves.

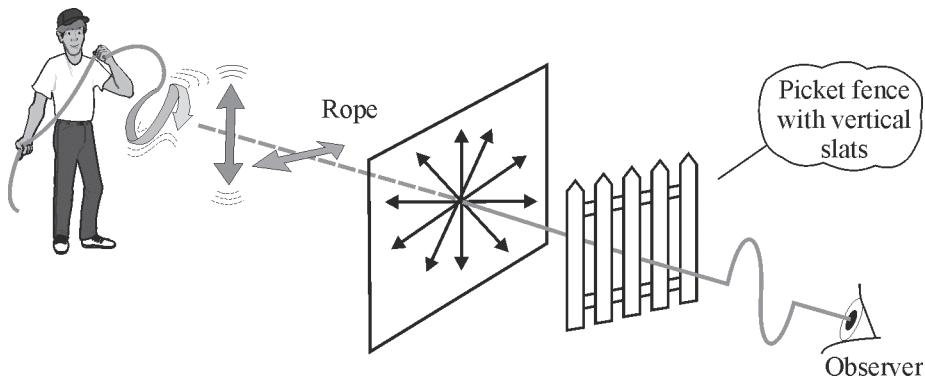


Figure 5-23 *Polarization of rope waves by a picket fence*

Polarization of light waves

The polarization of light waves refers to the *transverse* direction of vibration of the electric field vector of electromagnetic waves. (Refer back to Figure 5-3.) As described earlier, *transverse* means *E*-field vibrations *perpendicular* to the direction of wave propagation. If the electric field vector remains in a given direction in the transverse *x-y* plane—as shown in Figure 5-24—the light is said to be *linearly polarized*. (The “vibration” of the electric field referred to here is not the same as a *physical* displacement or movement in a rope. Rather, the vibration here refers to the oscillation of the electric field in a particular transverse direction—at all given points along the propagation of the wave.) Figure 5-24 shows linearly polarized light propagating along the *z*-direction toward an observer at the left. The electric field *E* increases and decreases in strength, reversing itself as shown, always along a direction making an angle θ with the *y*-axis in the transverse plane. The *E*-field components $E_x = E \sin \theta$ and $E_y = E \cos \theta$ are shown also in the figure.

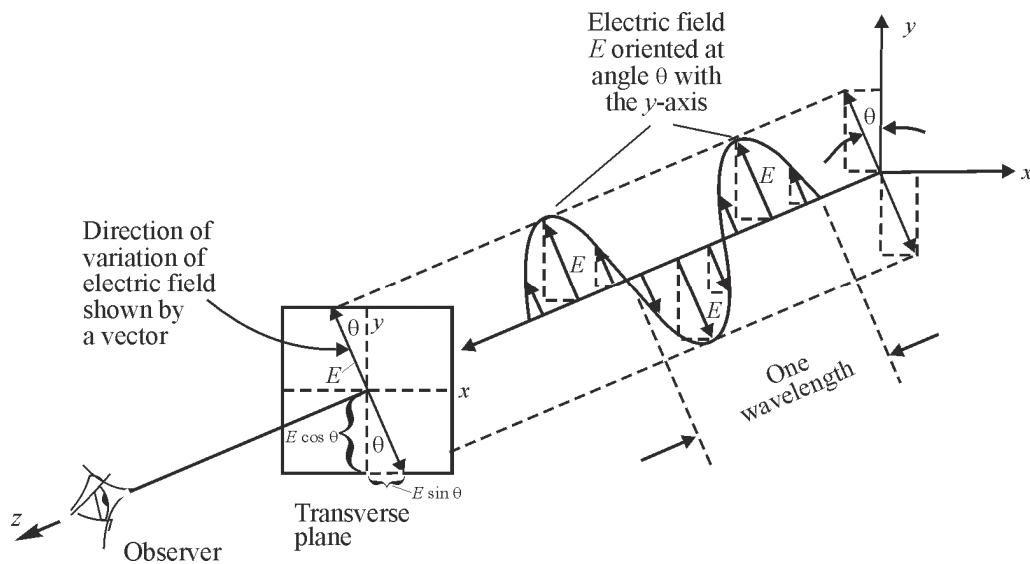


Figure 5-24 Linearly polarized light with transverse electric field E propagating along the z -axis

Table 5-1 lists the *symbols* used generally to indicate *randomly polarized* light (E -vector vibrating randomly in all directions), *vertically polarized* light (E -vector vibrating in the vertical direction only), and *horizontally polarized* light (E -vector vibrating in the horizontal direction only). With reference to Figure 5-24, the vertical direction is along the y -axis, the horizontal direction along the x -axis, and electromagnetic energy is propagated along the z -axis.

Table 5-1. Standard Symbols for Polarized Light

Viewing Position	Randomly Polarized	Vertically Polarized	Horizontally Polarized
Viewed head-on; beam coming toward viewer			
Viewed from the side; beam moving from left to right			

Like the action of the picket fence described in Figure 5-23, a *special optical filter* can be used to transmit only the light wave vibrations of the E -vector that are lined up with the filter's *transmission axis*—like the slats in the picket fence. When the special optical filter is used to change randomly polarized light to linearly polarized light in a certain direction, it is called a *polarizer*. When the same optical filter is used to intercept oncoming light linearly polarized in some direction and is used to yield information on the nature of the polarization, it is called an *analyzer*. The combined action of a polarizer and an analyzer are shown in Figure 5-25. Randomly polarized light, represented by the multiple arrows, is incident on a "polarizer" whose transmission axis (TA) is vertical. As a result, only *vertically polarized* light emerges from the polarizer. The vertically polarized light is then incident on an "analyzer" whose transmission axis is horizontal, at 90° to the direction of the vertically polarized light. As a result, **no** light is transmitted.

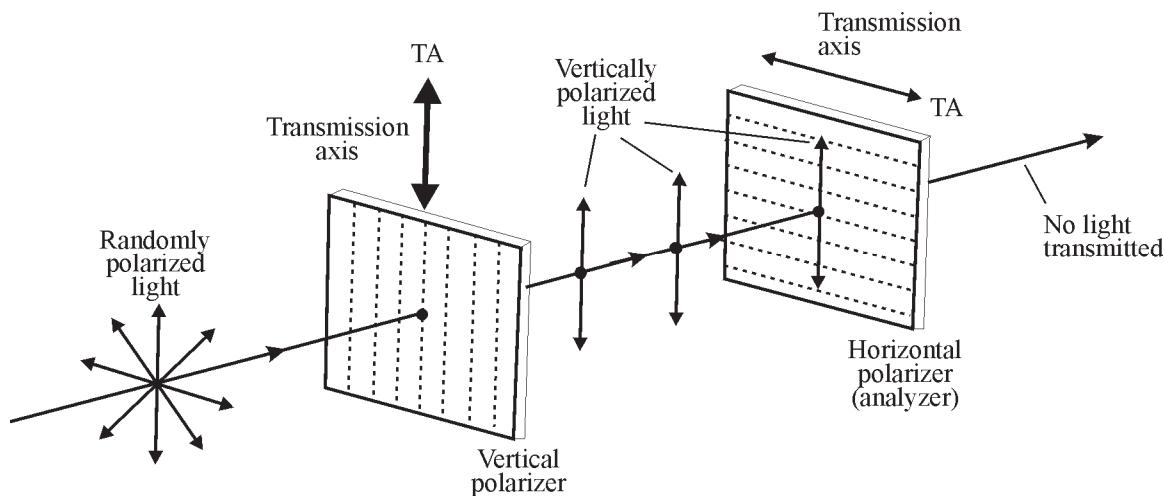


Figure 5-25 Effect of polarizers on unpolarized light

Law of Malus

When randomly polarized light passes through a polarizer, the light intensity—proportional to the square of its electric field strength—is reduced, since only the E -field component along the transmission axis (TA) of the polarizer is passed. When linearly polarized light is directed through an analyzer and the direction of the E -field is incident at an angle θ to the transmission axis of the analyzer, the light intensity is likewise reduced. The reduction in intensity is expressed by the *law of Malus*, given in Equation 5-26.

$$I = I_0 \cos^2 \theta \quad (5-26)$$

Where I = intensity of light that is passed by the polarizer

I_0 = intensity of light that is incident on the polarizer

θ = angle between the transmission axis of the polarizer and the direction of the E -field vibration

Application of the law of Malus is illustrated in Figure 5-26, where two polarizers are used to control the intensity of the transmitted light. The first polarizer changes the incident randomly polarized light to linearly polarized light, represented by the vertical vector labeled E_0 . The second polarizer, whose TA is at an angle θ with E_0 , passes only the component $E_0 \cos \theta$, that is, the part of E_0 that lies along the direction of its transmission axis. Since the intensity goes as the square of the electric field, we see that I , the light intensity transmitted through polarizer 2, is equal to $(E_0 \cos \theta)^2$, or $I = E_0^2 \cos^2 \theta$. Since E_0^2 is equal to I_0 , we have demonstrated how the *law of Malus* ($I = I_0 \cos^2 \theta$) comes about.

We can see, by rotating polarizer 2 to change θ , that we can vary the amount of light it passes. Thus, if $\theta = 90^\circ$ (TA of polarizer 1 is 90° to TA of polarizer 2) no light is passed, since $\cos 90^\circ = 0$. If $\theta = 0^\circ$ (TA of polarizer 1 is parallel to TA of polarizer 2) all of the light is passed, since $\cos 0^\circ = 1$. For any other θ between 0° and 90° , an amount $I_0 \cos^2 \theta$ is passed.

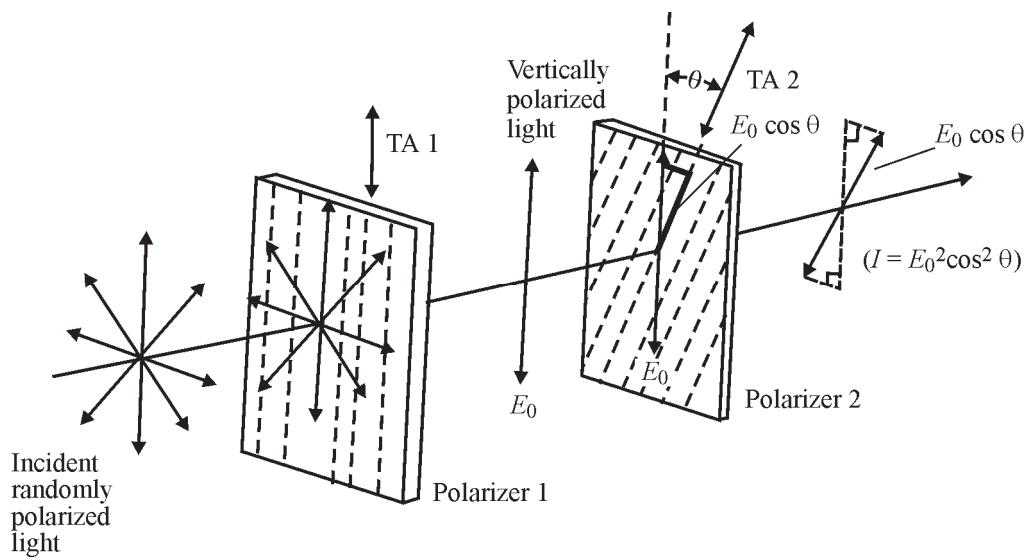


Figure 5-26 Controlling light intensity with a pair of polarizers

Example 12 shows how to use the law of Malus in a light-controlling experiment.

Example 12

Randomly polarized light is incident on a pair of polarizers as shown in Figure 5-26.

- Determine the angle θ required—between the transmission axes of polarizers 1 and 2—that will reduce the intensity of light I_0 incident on polarizer 2 by 50%.
- For this same reduction, determine by how much the field E_0 incident on polarizer 2 has been reduced.

Solution

- Based on the statement of the problem, we see that $I = 0.5 I_0$. By applying the *law of Malus*, we have:

$$\begin{aligned} I &= I_0 \cos^2 \theta \\ 0.5 I_0 &= I_0 \cos^2 \theta \\ \cos \theta &= \sqrt{0.5} = 0.707 \\ \theta &= 45^\circ \end{aligned}$$

So the two TAs should be at an angle of 45° to each other.

- Knowing that the E -field passed by polarizer 2 is equal to $E_0 \cos \theta$, we have

$$\begin{aligned} E_2 &= E_0 \cos \theta \\ E_2 &= E_0 \cos 45^\circ \\ E_2 &= 0.707 E_0 \approx 71\% E_0 \end{aligned}$$

Thus, the E -field incident on polarizer 2 has been reduced by about 29% after passing through polarizer 2.

Polarization by reflection and Brewster's angle

Unpolarized light—the light we normally see around us—can be polarized through several methods. The polarizers and analyzers we have introduced above polarize by *selective absorption*. That is, we can prepare materials—called *dichroic* polarizers—that selectively *absorbs* components of *E*-field vibrations along a given direction and largely *transmit* the components of the *E*-field vibration perpendicular to the absorption direction. The perpendicular (transmitting) direction defines the TA of the material. This phenomena of selective absorption is what E. H. Land made use of in 1938 when he produced a material called *Polaroid*.

Another method of producing polarized light is by *reflection*. See Figure 5-27. Note that the symbols introduced in Table 5-1 are used to keep track of the different components of polarization. One of these is the dot (•) which indicates *E*-field vibrations perpendicular to both the light ray and the plane of incidence, that is, in and out of the paper. The other is an arrow (↔) indicating *E*-field vibrations in the plane of incidence and perpendicular to the ray of light.

Figure 5-27 shows the *complete* polarization of the *reflected light* at a particular angle of incidence B , called the *Brewster angle*.

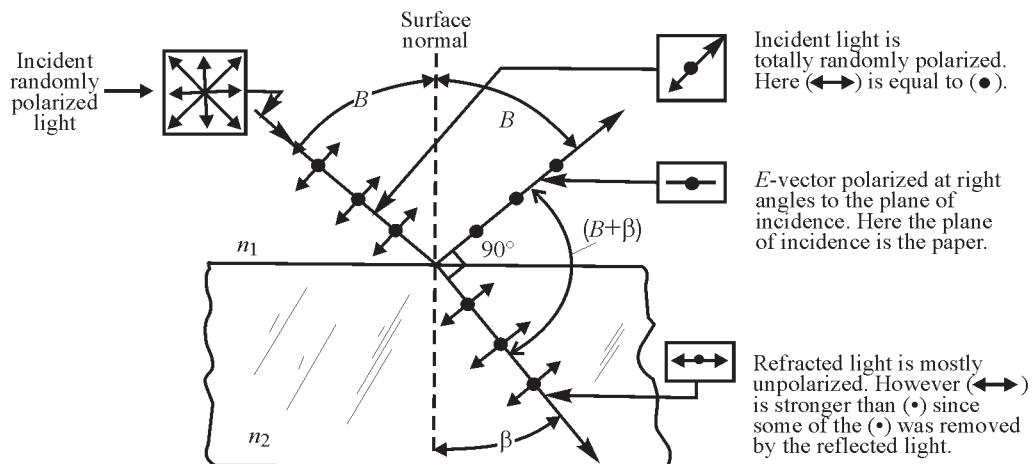


Figure 5-27 Polarization by reflection at Brewster's angle

The *refracted* light, on the other hand, becomes only partially polarized. The reflected *E*-field coming off at Brewster's angle is totally polarized in a direction in and out of the paper, perpendicular to the reflected ray (shown by the dots •). This happens only at Brewster's angle, that particular angle of incidence for which the angle between the reflected and refracted rays, $B + \beta$, is exactly 90° . At the Brewster angle of incidence, the *E*-field component (↔) cannot exist, for if it did it would be vibrating **along** the reflected ray, violating the requirement that *E*-field vibrations must always be transverse—that is, perpendicular to the direction of propagation. Thus, only the *E*-field component perpendicular to the plane of incidence (•) is reflected.



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Referring to Figure 5-27 and Snell's law at the Brewster angle of incidence, we can write

$$n_1 \sin B = n_2 \sin \beta$$

Since $\beta + B = 90^\circ$, $\beta = 90^\circ - B$, which then allows us to write

$$n_1 \sin B = n_2 \sin (90^\circ - B) = n_2 \cos B$$

or

$$\frac{\sin B}{\cos B} = \frac{n_2}{n_1}$$

and finally

$$\tan B = \frac{n_2}{n_1} \quad (5-27)$$

Equation 5-27 is an expression for Brewster's law. Knowing n_1 (the refractive index of the *incident* medium) and n_2 (the refractive index of the *refractive* medium), we can calculate the Brewster angle B . Shining monochromatic light on a reflecting surface at this angle ensures complete polarization of the reflected ray. We make use of Equation 5-27 in Example 13.

Example 13

In one instance, randomly polarized light in air is to be reflected off a glass surface ($n = 1.5$). In another instance, internal randomly polarized light inside a glass window is to be reflected at the glass-air interface, where n for the glass is also 1.5. Determine the Brewster angle for each instance.

Solution

(a) Light going from air to glass: In this case, $n_1 = 1$ and $n_2 = 1.5$.

Using Equation 5-27

$$\tan B = \frac{n_2}{n_1} = \frac{1.5}{1}$$

$$B = \tan^{-1} 1.5 = 56.3^\circ$$

The Brewster angle is 56.3° .

(b) Light going from glass to air: In this case, $n_1 = 1.5$ and $n_2 = 1.0$.

$$\text{Then, } \tan B = \frac{n_2}{n_1} = \frac{1}{1.5} = 0.667$$

$$B = \tan^{-1} (0.667) = 33.7^\circ$$

The Brewster angle is 33.7° . Note that the two angles, 56.3° and 33.7° , total 90° .

They are complementary angles.

Brewster windows in a laser cavity

Brewster windows are used in laser cavities to ensure that laser light—after bouncing back and forth between the cavity mirrors—emerges as linearly polarized light. Figure 5-28 shows the general arrangement of the windows—thin slabs of glass with parallel sides—mounted on the opposite edges of the gas laser tube—in this case a helium-neon gas laser.

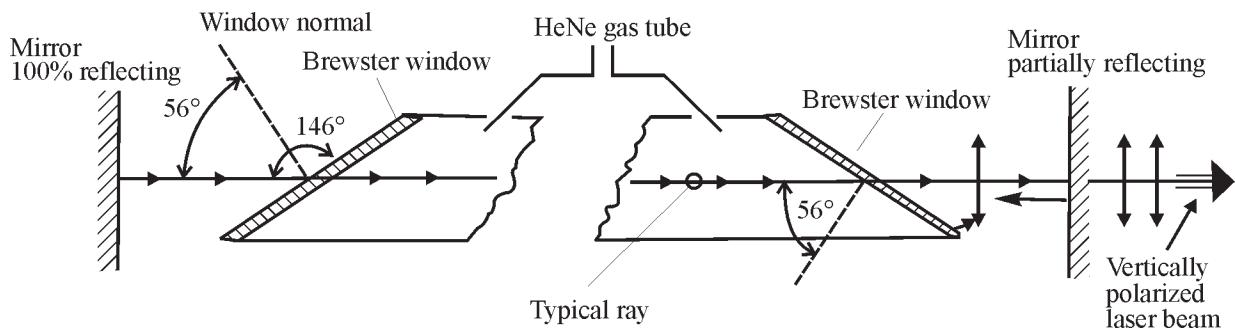


Figure 5-28 Brewster windows in a HeNe gas laser

As you can see, the light emerging from the laser is linearly polarized in a vertical direction. Why this is so is shown in detail in Figure 5-29. Based on this figure and Example 13, Figure 5-29 shows that it is the refracted light—and not the reflected light—that is eventually linearly polarized. Let's go through the process in detail.

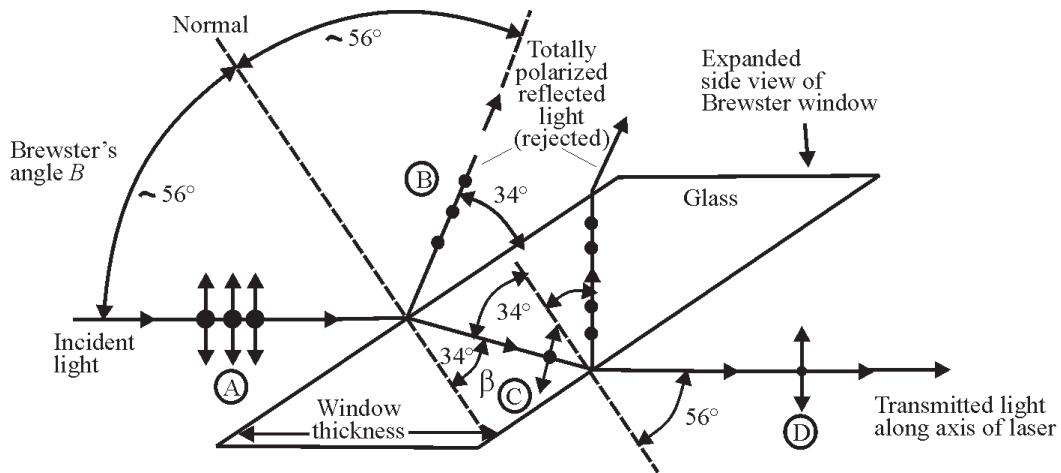


Figure 5-29 Unpolarized light passing through both faces at a Brewster angle

The randomly polarized light at A is incident on the left face of the window—from air to glass—defining, as in Example 13, a Brewster angle of near 56°. The reflected light at B is totally polarized and is *rejected*, that is, deflected out of the laser cavity. The refracted (transmitted) light at C is now partially polarized since the reflected light has carried away part of the vibration perpendicular to the paper (shown by the dots). At the right face—glass to air—the ray is incident at a Brewster angle of near 34° for a glass-to-air interface—as was shown in Example 13. Here again, the reflected light, totally polarized, is *rejected*. The light transmitted through the window, shown at D, now has even less of the vibration perpendicular to the paper. After hundreds of such passes back and forth through the Brewster windows, as the laser light

bounces between the cavity mirrors, the transmitted light is left with only the vertical polarization, as shown exiting the laser in Figure 5-28. And since all of the reflected light is removed (50% of the initial incident light), we see that 50% of the initial incident light *remains* in the refracted light, hence in the laser beam.

As a final note, as Module 1-6, *Principles of Lasers*, will show, the fully polarized light initially produced by the Brewster windows, when passing back and forth through the active laser gain medium, will itself produce—by stimulated emission—linearly polarized light with the same vibration direction.

LABORATORIES



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Laboratory 1-5A: Working with Diffraction Patterns, Wavelengths, and Polarization

In this laboratory, you will complete the following experiments:

- Carry out a quantitative mapping of the intensity variation across a Fraunhofer airy-diffraction pattern.
- Determine the wavelength of light by using a machinist's rule as a reflection grating.
- Convert randomly polarized light to polarized light by reflection at Brewster's angle.

Equipment

The following equipment is needed to complete this laboratory.

1 HeNe laser (unpolarized, TEM₀₀ output, 1–3-mW range, 632.8 nm)

1 diode laser pointer (5 mW or less)

1 precision pinhole aperture (150-μm diameter)

1 photomultiplier with fiber optic probe

1 linear translator capable of transverse motion in 0.1-mm increments

2 optical benches, calibrated, 2 meters long

3 bench mounts with vertical rods

2 laboratory jacks

1 neutral-density filter

1 632.8-nm filter

2 H-type Polaroid sheet mounts with TAs identified

1 diffuser (ground glass plate)

1 reflecting glass plate (microscope slide)

1 machinist's rule, marked off in 64ths of an inch

Procedure

A. Quantitative mapping of airy diffraction pattern

1. Set up the equipment as shown in Figure 5-30. With the help of Equation 5-16 and Example 9, determine the pinhole-to-screen distance Z' to ensure the formation of a *Fraunhofer* airy-diffraction pattern of the $150\text{-}\mu\text{m}$ hole at the “screen.” Set the pinhole-to-screen distance accordingly.

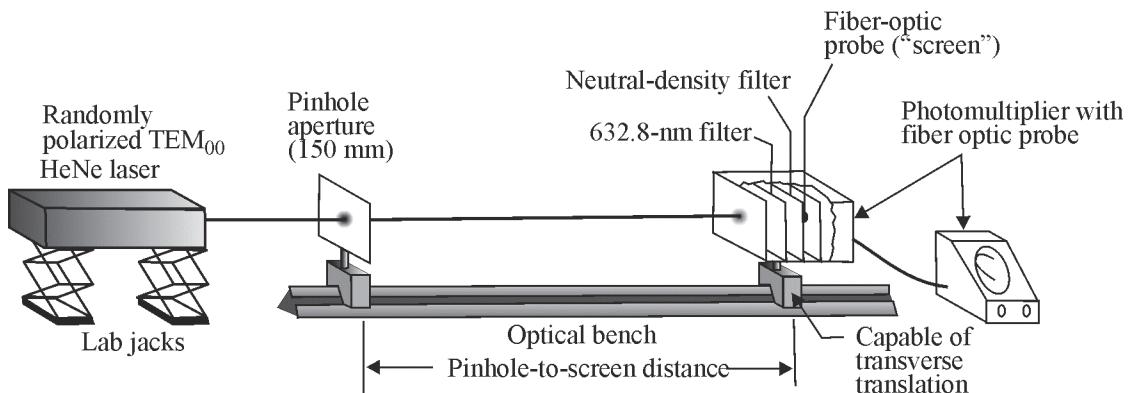


Figure 5-30 Arrangement of apparatus for recording intensity distribution of *Fraunhofer* diffraction pattern from a circular pinhole

2. With room lights off, align the laser, $150\text{-}\mu\text{m}$ pinhole, and the tip of the fiber optic probe so that the laser beam becomes the axis of symmetry for each component. Use a $5'' \times 8''$ index card to observe the airy pattern in front of the fiber optic probe (the *virtual* location of the “screen”), ensuring that clear, sharp airy disk and set of concentric rings are formed. Adjust the positions of the laser pinhole and fiber optic tip relative to one another to obtain a maximum intensity reading at the center of the airy disk. (Be patient!) Note that a 632.8 nm filter is added near the fiber optic tip to let you work with room lights on. The neutral-density filter shown in Figure L-1 may be used—if necessary—as an additional intensity control, to permit scanning the entire airy pattern without a scale change on the photometer.
3. After the laser beam, $150\text{-}\mu\text{m}$ pinhole, and fiber optic tip have been carefully aligned and the 632.8-nm filter is in place, turn on the lights and take intensity readings. With the horizontal translator, move the fiber optic tip assembly back and forth, transversely across the optical bench (and the *Fraunhofer* diffraction pattern) several times. Watch the photometer to ensure that the alternate maxima and minima of intensity in the airy pattern are being detected.
4. During the trial runs, choose sensitivity and scale factor settings on the photometer so that the highest readings remain on scale while the lowest readings are still clearly recorded. When you get satisfactory variations in the photometer readings as the fiber optic tip is scanned across the airy pattern, you can begin to record readings of intensity versus position. Try to obtain, at the very least, intensity variations across the center disk and two of the adjoining rings. (The pinhole-to-screen distance may have to be reduced to around 100 cm to ensure that the translator scan encompasses the desired extent of the airy pattern. In that event, the pattern may be in the *near field* rather than the *far field* and the

equation given in Figure 5-18 may not hold exactly—but it will be close enough.) Readings can be taken every 0.5 mm or so, beginning with the second ring, moving on through the central disk and on to the second ring on the opposite side. Record the photometer readings versus position and plot them on suitable graph paper.

5. Compare the intensity distribution with that shown qualitatively in Figure 5-18. Since the pinhole diameter, wavelength, and pinhole-to-screen distance are all known for the plot, measure the radius of the central airy disk on the plot and compare this result with that predicted by Equation 5-20.

B. Determine the wavelength of light with a reflection grating

1. To perform this experiment, you need only a diode laser pointer, a mount for the laser that allows it to tilt downward, a solid table on which to position the laser mount and the machinist's rule, and a wall (screen), five to fifteen feet from the rule. Figure 5-31 shows the general setup. Choose an appropriate angle α to form a clear diffraction pattern on the wall, locating several orders $y_1, y_2 \dots y_m$, as shown in Figure 5-31.

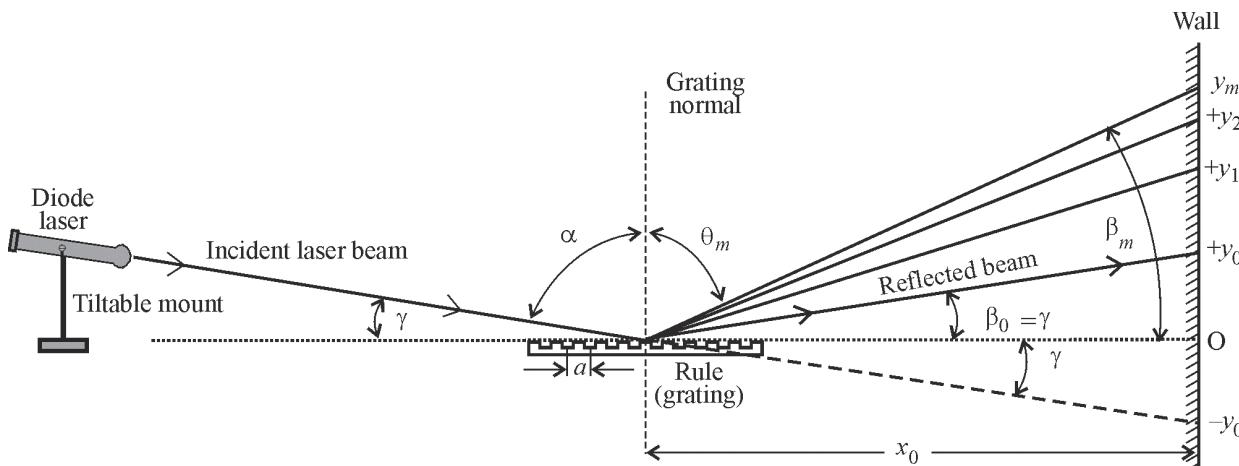


Figure 5-31 Using the grooves on a machinist's rule as a reflection grating

2. In Figure 5-31, the symbols shown are:

γ = slant angle laser beam makes with the grating (rule) surface

α = angle of incidence of laser beam with grating normal

θ_m = the direction angle to the m th diffraction order, measured relative to the normal

$\beta_0 = \gamma$ = angle of laser beam reflected from rule, relative to the surface

β_m = diffraction angle to the m th diffraction order, measured relative to the surface

a = "grating" spacing between adjacent grooves on the rule

x_0 = distance from center of rule to the wall (or screen)

Locate on the wall the reflected beam (at $+y_0$) and the diffraction orders $y_1, y_2, y_3 \dots y_m$. The point $(-y_0)$ locates the spot formed by the laser beam if it had gone through the rule

directly onto the wall. The point $+y_0$ locates the point of regular reflection of the laser beam off of the rule surface. The O position is the halfway point between $+y_0$ and $-y_0$.

3. If you begin with Equation 5-23 and adjust for sign conventions (since α and θ_m are on opposite sides of the normal for a reflection grating), you obtain the modified equation,

$$m\lambda = a (\sin \theta_m - \sin \alpha)$$

From the geometry in Figure 5-31 and a series of substitutions and “reasonable” approximations for $\sin \theta_m$ and $\sin \alpha$, you arrive eventually at a useful working equation for λ that involves only a , m , y_m , y_0 , and x_0 , each directly measurable. This equation is

$$\lambda = \frac{a}{2m} \left[\frac{y_m^2 - y_0^2}{x_0^2} \right]$$

4. Obtain values for several measures of y_m and use the above equation for each measure to determine the wavelength λ of the diode laser. Take the average for your best value of λ . Knowing the true wavelength, determine how close your measured value comes. Express the deviation as a percent.

C. Conversion of randomly polarized light to linearly polarized light

1. Using light from a randomly polarized HeNe or diode laser, arrange your system as shown in Figure 5-32. The incident randomly polarized light passes through a diffuser—such as a ground glass plate—and on toward the reflecting surface (microscope slide). The light reflects off the glass surface and then passes through an analyzer on its way toward the observer. When the reflecting glass surface is rotated around a vertical axis so that the angle of incidence is equal to Brewster’s angle—about 56° —the reflected light is found to be totally polarized with the E -vector perpendicular to the plane of incidence. (Recall that the plane of incidence is the plane that contains the incident ray and the normal to the reflecting surface. In Figure 5-32, therefore, the plane of incidence is horizontal—parallel to the tabletop. Thus the reflected light is vertically polarized.)

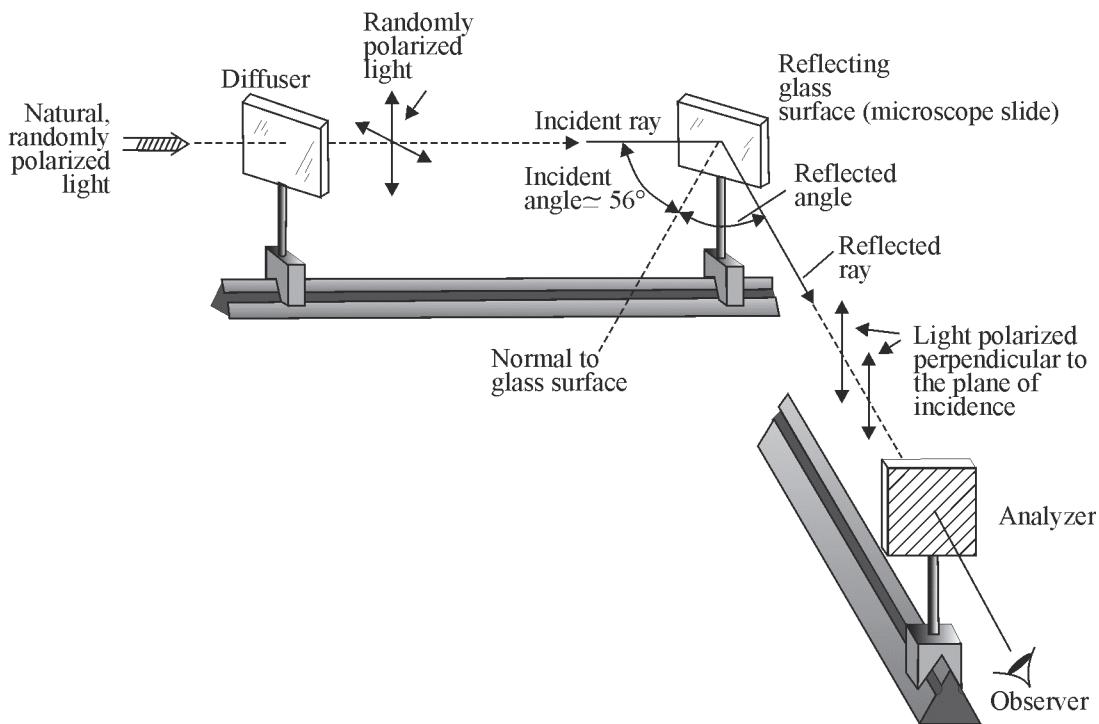


Figure 5-32 Polarization by reflection at Brewster's angle

- With the appropriate analyzer, whose transmission axis (TA) is known, verify that the light reflecting from the surface of the glass microscope slide is indeed vertically polarized, as indicated in Figure 5-32. Explain your method of verification.

As a final note we mention that the standard trick for locating a polarizer's transmission axis (TA) is to simply look through the polarizer at the light reflected from a shiny surface—such as the glass slab on a desk—and rotate the polarizer to cause extinction. If the surface is horizontal, and extinction occurs, the TA of the polarizer is vertical.

Laboratory 1-5B: Interference and Diffraction

In this laboratory, you will complete the following task:

- Measure diffraction effects from a single slit and pinhole
- Experimentally measure the groove spacing of a diffraction grating and human hair.
- Experimentally measure the wavelength range of visible light.

Background Information

There is a difference between interference and diffraction. Interference implies multiple “sources” that interact with each other. Diffraction is a phase change due to light passing through small apertures. Also, there is a small difference in the math. For interference, we use the equation $m*\lambda=d*\sin\theta$ and the angle is between the center bright spot and maxima (bright

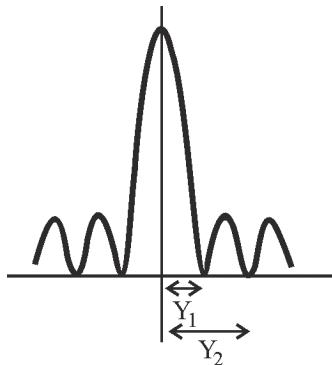
spots). For diffraction, we use the same equation, but the angle is between the center bright spot and minima (dark spots).

Laboratory 1-5B.1: Slit

Equipment (from Newport Kit: OEK-STD)

He-Ne Laser

Single Slit
Meter Stick
Paper & Tape
BSA with Mirror
-25 mm lens
+50 mm lens
+200 mm lens
3 lens chucks
Rotation stage
Posts and post holders



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this activity.

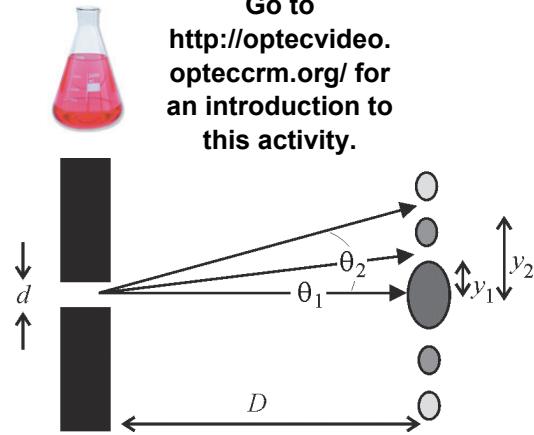


Figure 5-33

Procedure

1. Tape a piece of paper on the wall. Place the single slit exactly 1 meter from the wall. Position the laser such that a diffraction pattern is formed on the wall as shown in Figure 5-33.
2. Turn off the lights and trace the diffraction pattern you observe with a pencil.
3. Take down the paper and measure each value of y from the center of the central bright spot.
4. Since θ is small in this lab, we may substitute y/D for $\sin\theta$ in the equation discussed above. Calculate d for each measurement. All values of d should be about the same. Express the average of all measurements of d as your final answer.

Show work and sample calculations here:

Laboratory 1-5B.2: Pinhole

Background information



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introduction to this
activity.

For this laboratory, you will use a pinhole. Since the aperture is so small, we will have to concentrate light down to a very concentrated spot to get decent transmission through the pinhole. This is why we must build a collimator to reduce the divergence before we condense the light with a lens into the pinhole.

Note also that the formula is slightly different for circular apertures than for rectangular slits. This difference in shape accounts for the factor of 1.22 shown in the formula below.

Equipment (from Newport Kit: OEK-STD)

He-Ne Laser	Single Slit
Meter Stick	Paper & Tape
BSA with Mirror	-25 mm lens
+50 mm lens	+200 mm lens
3 lens chucks	Rotation stage
Posts and post holders	Pinhole

Procedure

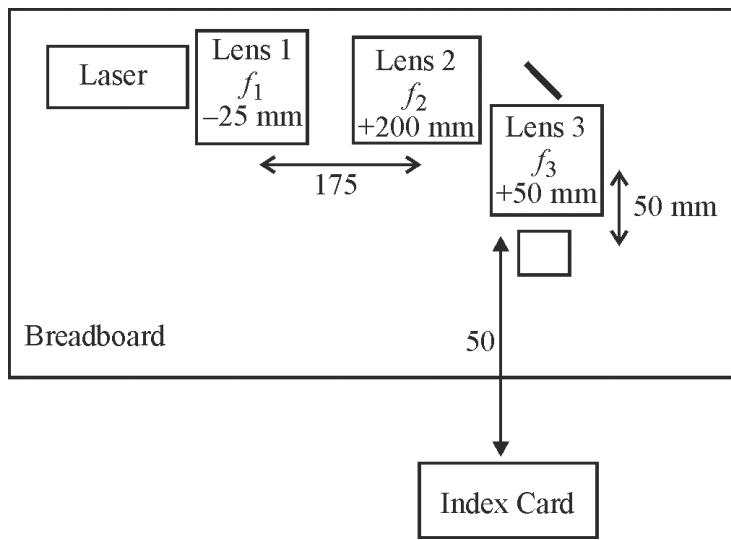


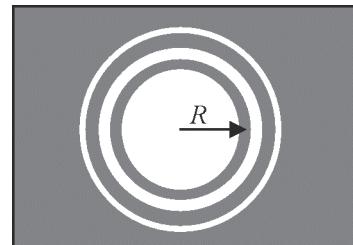
Figure 5-34

- Mount lenses in lens chucks and mount the pinhole in the rotational stage mount (or a 4th lens chuck).
- Place Lens 1 as close as possible to the Laser.
- Place Lens 3 as close as possible to Lens 2 with a mirror in the middle.
- Adjust the mirror to aim the beam at the center of the pinhole.
- You know the beam is centered in the pinhole when the Airy disk pattern is brightest.

$$\text{Formula: } d = 1.22 * \lambda * D/R$$

where d = diameter of pinhole
 D = distance to card;
 R = Radius of Airy disk
 λ = wavelength

1. Mount the laser and mirror first. Establish an optical axis as shown in Figure 5-34.
2. Construct a Galilean collimator as close to the laser as possible. The purpose of this collimator is to reduce the divergence of the beam by a factor of 8.
3. Place a 50 mm lens as close as possible to the mirror.
4. Mount the pinhole inside of the rotational stage or a lens chuck. Place it 50 mm from the 50 mm lens. Make sure that the pinhole is aligned (check by retroreflection).
5. Tweak the mirror mount until you get maximum transmission through the pinhole. Observe the Airy disk pattern on an index card 50 cm from the front of the pinhole. It will be necessary to turn out the lights to view the pattern.
6. When the intensity of the pattern is maximized, draw the airy disk on the card and verify the distance D . To get R , it is most accurate to measure the diameter and divide by 2.
7. Solve for the diameter of the pinhole (d). Compare this to the actual value of 25 μm . The % error should be around 10%.



Show work and sample calculations for Part B here:

Laboratory 1-5B.3

Background information

Light has properties of both particles and of waves. We generally talk about light in terms of its wavelength. The wavelength can be easily calculated by using the equation $\lambda = c/f$ where λ is the wavelength, c is the speed of light $c=3.00 \times 10^8 \text{ m/s}$, and f is the frequency of the radiation. For instance, the frequency of a typical AM radio wave is about 1 MHz, so it will have a wavelength of about 300 m. Light from a laser pointer has a frequency of about 474 THz, so it will have a wavelength of about 632.8 nm.



Go to
<http://optecvideo.opteccrm.org/>
 for an introduction to this
 activity.

Light and radio waves are both forms of electromagnetic radiation; we can easily sense the wave properties of radio signals while we cannot easily see the wave properties of light. Objects on the order of 300 m and smaller would interfere or absorb a radio signal. This can easily be observed (or heard). Conversely, we need a laser beam to interact with very small objects to observe its wave properties.

A diffraction grating is one such small object. The interference of light can be summarized by the relationship $d \cdot \sin\theta = m \cdot \lambda$, where d is the distance between grooves, λ is the wavelength of the light source, m is the order number, and θ_m is the diffraction angle of the m^{th} ray. The diffraction effect is symmetrical, so we only need to develop an equation for the $m=+1$ case. For $m=-1$, s and m will both have negative signs, yielding the same result. See Figure 5-35.

For $m = 1$

θ can be found by geometry since $\tan \theta = y/D$.

Take the inverse tangent $\theta = \tan^{-1}(y/D)$.

Then plug θ into the grating equation to find d .

$$d = \lambda / \sin\theta$$

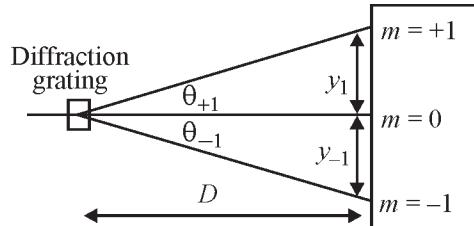


Figure 5-35

Equipment

- 1 Diffraction Grating
- 1 He-Ne Laser
- 1 Small Flashlight (e.g. Maglite)
- 1 Meter Stick
- 1 Long Length of Paper
- 1 Index Card
- Clothespins and Tape

Procedure

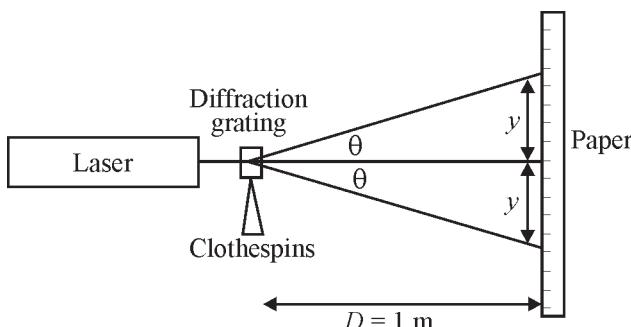


Figure 5-36 Experimental Setup for Procedure A

Table 5-2 – Procedure A

Grating	$\theta = \tan^{-1}(y/D)$	$d = \lambda / \sin\theta$
$D =$ _____	$\lambda =$ _____	
$y =$ _____	$\theta =$ _____	
$d_{\text{meas}} =$ _____	$d_{\text{accepted}} =$ _____	
%Error = _____		
Hair	$d = \lambda * D / y$	
$D =$ _____	$\lambda =$ _____	
$y =$ _____	$d =$ _____	

1. Tape a long length of paper on a wall. Place the diffraction grating between two clothespins and position it so that D is 1 m from the ruler mounted on the wall.
2. Turn on the laser and place it behind the grating. See Figure 5-36 for guidance.
3. Measure and record in Table 5-2 the distance (y) as shown using the meter stick.
4. Calculate the diffraction angle θ . Then calculate the groove spacing (d) from the grating equation.

Note: The grating in the Optics Discovery Kit has a stated groove spacing of 1000 lines/mm. This means that d will be (1/1000)th of a mm. Compare the accepted value of d to the measured value of d to get the % error. You should get a % error less than 10%.

5. The diameter of human hair may be found by replacing the grating with a human hair. (Note: If you don't have any hair of your own, then gently ask the person next to you for a "loaner" hair.) It is best to mount the hair with tape and hold it up with clothespins.
6. Repeat steps 1 through 4 with a human hair. The distance between bright spots will be much smaller than for the grating. Also, most hair has a slightly rough surface. For this reason, θ will be much smaller. You may approximate that $\sin\theta = \tan\theta$ in this case. The equation then simplifies into $d = L*\lambda/y$. Since the diffraction angle is so small, it is better to take the AVERAGE distance between bright spots for s and IGNORE the centermost spots.

Note: Most human hair will have a diameter of between 50 and 100 micrometers.

Laboratory 1-5B.4

Background information

Interference of light is used for a WIDE variety of applications. Two pertinent applications are holography and fiber optic DWDM filters.

A hologram is simply an interference pattern captured on film. The emulsion of the photographic film is deposited in a relatively deep layer on a glass plate. A laser beam illuminates the object and captures three dimensions of information in a very small area. This basic technique may be used for advanced information storage systems.

Another way interference is used is to make filters for Dense Wavelength Division Multiplexing fiber optic systems. The principle of DWDM is to transmit dozens of different lasers down the same optical fiber at the same time. Each laser has a different wavelength. Special filters called "Fiber Bragg Gratings" can be used to separate each wavelength at the demultiplex end of the transmission.

Equipment

- 1 Diffraction Grating
- 1 Small Flashlight (e.g. Maglite)
- 1 Meter Stick
- 1 Long Length of Paper



Go to
<http://optecvideo.opteccrm.org/>
 for an introduction to this
 activity.

Procedure

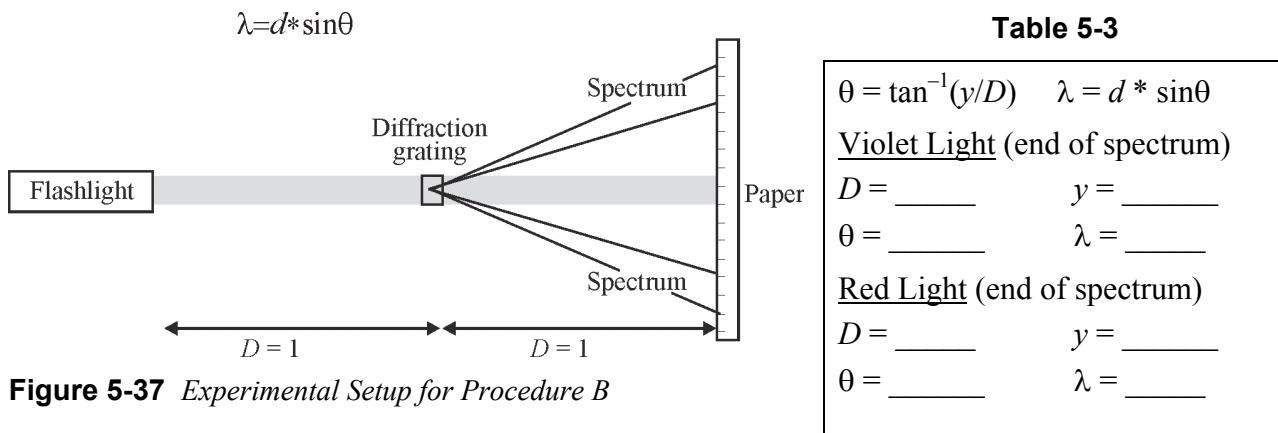


Figure 5-37 Experimental Setup for Procedure B

1. Tape a long length of paper on the wall. Place the diffraction grating between two clothespins and position it so that D is exactly 1 meter from the paper mounted on the wall.
2. Darken the room. Place a flashlight at least 1 meter behind the grating. You should be able to see a spectrum of colors on each side of the grating. Figure 5-37 for guidance.

Note: Don't put the flashlight closer than 1 m from the source. If you do, new set of (much more complicated) equations need to be derived.

3. Note the shadow of the grating on the wall. The center of this shadow is your reference point. Measure and record the distance (y) between the center of the grating to the violet end of the spectrum. Likewise, measure and record the distance between the center of the grating and the red end of the spectrum.
4. Calculate the wavelength range of the visible spectrum. Use the groove spacing (d) that you calculated in Procedure A as the groove spacing in this problem. You should get approximately 390 nm for the violet end of the spectrum and approximately 720 nm for the red end of the spectrum. Record your results in Table 5-3.

Note: Ambient light affects this experiment very much. In a very dark room, a wider spectrum will be measured. The spectrum, however, should be centered at about 555 nm.

Note: The % error should not be higher than 10%, but this lab is very sensitive to ambient light. Different ambient light levels will lead to different results.

Laboratory 1-5C: Polarization

In this laboratory, you will complete the following tasks:

- Investigate the Law of Malus.
- Build a LCD Display.
- Build a Polariscope.
- Build an Optical Isolator.

Laboratory 1-5C.1

Background information



Go to
<http://optecvideo.opteccrm.org/>.
for an introduction to this
activity.

The Law of Malus states that $I_t = I_0(\cos\theta)^2$. As long as the detector captures the entire laser beam, we can simplify this equation to be $P_t = P_0(\cos\theta)^2$. P_0 is the power transmitted through the polarizer and the analyzer when the analyzer is aligned (at 0°) with the polarizer. Refer to the following website for theory about the other parts of this lab:

<http://www.meadowlark.com/AppNotes/appnote1.htm>

Equipment

Newport Kit: OEK-STD

He-Ne Laser	$\frac{1}{4}$ Wave Plate
Two Polarizers	2 lens chucks
Mounted Mirror	Rotation stage

Flashlight or Night-light

Procedure

NOTE: MAKE SURE THE LASER WARMS UP AT LEAST 30 MIN BEFORE STARTING EXPERIMENT.

1. Set up the experiment as shown in Figure 5-38. Secure the polarizer inside the rotation stage.

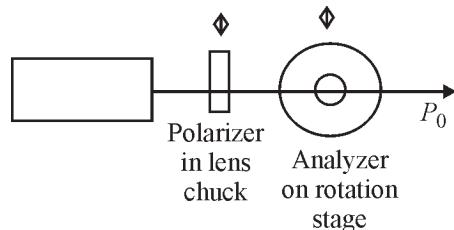


Figure 5-38

2. Adjust the polarizer and analyzer such that maximum power is transmitted. Set the rotation stage to 0 degrees using the setscrew.
3. Once the laser is stable enough, measure the power transmitted through the system P_0 . Record this in the Table 5-4.

4. Measure and record the power transmitted through the system at 5 degree increments.

Table 5-4

Angle (degrees)	Measured P_t (μW)	Calculated P_t (μW)	% Error (%)
0	$P_0 = \underline{\hspace{2cm}}$		N/A
5			
10			
15			
20			
25			
30			
35			
40			
45			

Angle (degrees)	Measured P_t (μW)	Calculated P_t (μW)	% Error (%)
50			
55			
60			
65			
70			
75			
80			
85			
90			

Show sample calculations below. Turn in completed data tables when finished.

Laboratory 1-5C.2

Background information

The liquid crystal in a LCD polarizes light depending on the charge delivered to the LCD. This liquid crystal may be placed between two polarizers in some cases. The $\frac{1}{4}$ wave plate is used to simulate the liquid crystal in this lab.

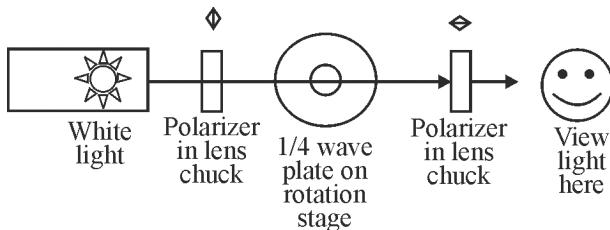


Figure 5-39

Equipment

Newport Kit: OEK-STD

He-Ne Laser

$\frac{1}{4}$ Wave Plate

Two Polarizers

2 lens chucks

Mounted Mirror

Rotation stage

Flashlight or Night-light

Procedure—The Liquid Crystal Display

1. Set up the lab as shown in Figure 5-39. Align one polarizer vertically and one polarizer horizontally. Start with the $\frac{1}{4}$ wave plate aligned vertically.
2. When you initially view the light through this setup, it will be very dim.
3. Slowly rotate the $\frac{1}{4}$ wave plate through a full 360° while observing the transmitted light. At approximately what angle for the $\frac{1}{4}$ wave plate is the maximum light transmitted? Note all of your observations below:

Procedure—Polariscope

1. Remove the $\frac{1}{4}$ wave plate and hold a piece of plastic in its place. Stretch the plastic and record your observations below.
2. Now place a transparent plastic molded object where the plastic was. Record your observations below.

Procedure—Optical Isolator

1. Replace the white light source with a laser and replace the 2nd polarizer with a mirror as shown in Figure 5-40. Adjust the beam so that it is directed back toward the laser, but does not perfectly retroreflect. (Make sure you can see the retroreflected beam.)
2. Position the $\frac{1}{4}$ wave plate at the following angles and observe the transmitted light from both directions. 45° , 90° , 135° , 180° , 225° , 270° , 315° . At what $\frac{1}{4}$ wave plate angle(s) did the optical isolator work?

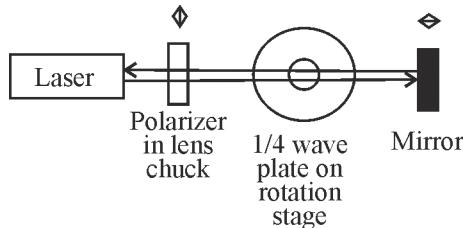


Figure 5-40

WORKPLACE SCENARIO

Here is your opportunity to use the concepts learned in this module to solve an actual problem that could arise in a photonics company. Your instructor will provide directions for developing a solution.

Basic Physical Optics – Diffraction Gratings

Scenario

A local company that designs and builds spectrometers for the pharmaceutical industry has just promoted you to an Engineering Photonics Technician Level II. Your primary responsibility in this new position is to test completed spectrometers and make certain they detect, analyze, and accurately identify the content of plastic containers each filled with a different medication. If a spectrometer fails this test, it is your job to determine the component(s) within the spectrometer that caused this failure and provide the supplier information on why the component(s) failed.

Recently, all of the spectrometers in a particular product line failed your test. After carefully reviewing the test results, you come to the conclusion that the transmission diffraction grating used in the spectrometers is the source of this failure. To confirm your conclusion, you decide to first check the Receiving Department records and see if these gratings were inspected prior to placing them into your company's parts inventory. Your investigation uncovers that these parts were considered in Receiving as a "Free to Stock"¹ item and not inspected. With this information, you decide a quick way to initially check these gratings is to visually inspect them and also see if they meet dimensional specifications. After removing the gratings from a few randomly selected spectrometers, you find there are no serious chips or scratches on the gratings and they fall within dimensional specs. You also confirm the light emitted from medications within the plastic containers strike the grating along the grating normal as specs require. This means the spectrometer aperture and grating are properly aligned. Having eliminated all these potential failure modes, you decide, as a next step, to check the grating line spacing to see if it complies with the 5500 lines/cm specification.

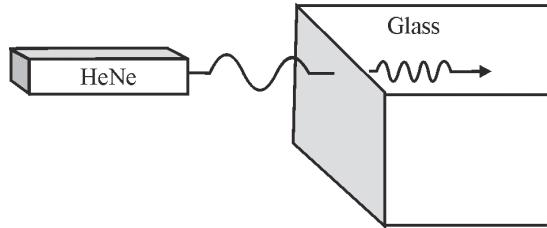
Task and Solution Strategy

Using knowledge gained in Module 1-5 of the *Fundamentals of Light and Lasers* text, your task is to develop a test to verify whether or not the transmission diffraction gratings have the proper line spacing. Since your results may impact the "Free to Stock" status of these grating which would impact product costs, you need to document your test so you can provide it to your supervisor for review and approval. Your written report should mention the physical and dimensional checks you performed, the procedures you intend to use to check the gratings' line spacing, and include calculations of expected test results for "in spec" gratings.

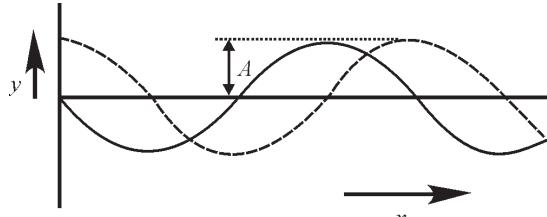
¹ "Free to Stock" is a term used in industry to describe a component that requires no inspection and can be moved directly from the receiving department to inventory. To earn this classification, a component typically has to have a history within receiving of passing inspections. Industry uses this classification as a means for reducing manufacturing costs. No inspection = reduced labor costs.

PROBLEM EXERCISES AND QUESTIONS

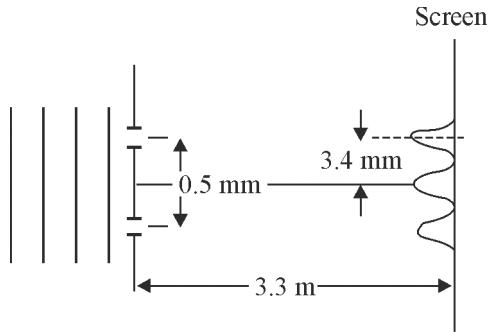
1. A HeNe laser in air emits light at 632.8 nanometers. The beam passes into a glass substance of index 1.35. What are the speed, wavelength, and frequency of the laser light in the glass substance?



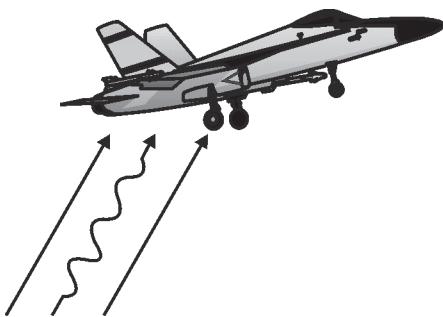
2. Use the principle of superposition to sketch a picture of the resultant waveform for the two waves shown at the right. Does the resultant wave ever reach an amplitude of $2A$?



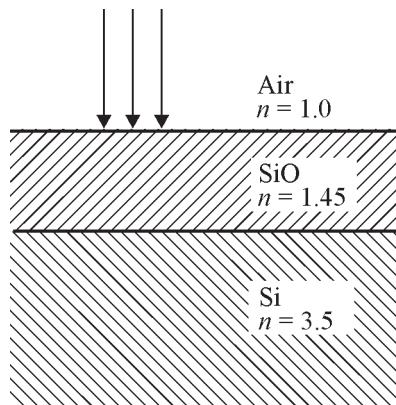
3. A Young's double-slit interference experiment is carried out with blue-green argon laser light. The interference pattern formed on a screen 3.3 m away contains the first-order ($m = 1$) bright fringe 3.4 mm from the center of the pattern. If the separation of the double slits is 0.50 mm, what is the wavelength of the argon laser light?



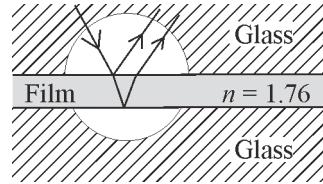
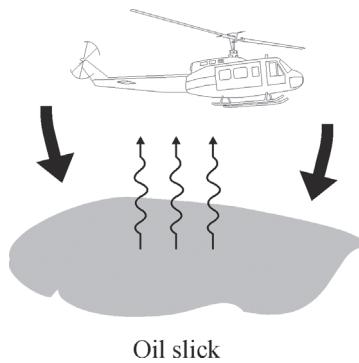
4. Suppose you are asked to design a nonreflecting surface for a Stealth aircraft. Your goal is to select an antireflective polymer of index 1.6 and of optimum thickness, so that radar waves of wavelength $\lambda = 3.5$ cm will not be reflected from the aircraft surface. Assume that the substrate material has a refractive index greater than 1.6. What is the thinnest layer of polymer you can apply to achieve your goal?



5. Solar cells made of silicon (Si) are designed with nonreflecting, thin-film coatings such as silicon monoxide (SiO) to minimize the reflection of incident light. Determine the thickness of the thinnest film of SiO that will cause the least reflection of sunlight. Take the average wavelength of sunlight to be near 550 nanometers.

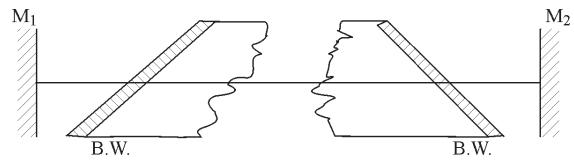


6. An oil spill on an ocean coastline near you produces an oil slick on the water for miles around. After a few days, you take a helicopter ride out over the water and notice—with the help of a handheld spectrometer—that the oil slick produces a first-order maximum of reflected light of wavelength 550 nanometers. What is the thickness of the oil slick at that time? Assume the oil has $n = 1.25$ and saltwater has $n = 1.34$.
7. A laser beam of unknown wavelength is incident on a single slit of width 0.25 mm and forms a Fraunhofer diffraction pattern on a screen 2.0 m away. The width of the central bright fringe is measured to be about 7 mm. What is the wavelength of the laser light? What might the laser be?
8. A thin layer of liquid (methylene iodide) is sandwiched between two glass microscope slides, as shown in the accompanying sketch. Light of wavelength $\lambda = 550 \text{ nm}$ is incident on the glass-liquid interface. The liquid has an index of refraction of $n = 1.76$. (a) Is there an automatic phase shift of $\lambda/2$ for the light reflected at the top face of the liquid film? (b) Is there an automatic phase shift of $\lambda/2$ for the light reflected at the bottom of the film? (c) What is the minimum thickness of liquid film required if the light incident *perpendicularly* on the sandwich is to be strongly reflected?
9. Nearly plane waves of CO_2 laser light of wavelength $\lambda = 10.6 \mu\text{m}$ emerge from a circular aperture 10 cm in diameter. If the CO_2 laser light is to be examined on a target in the *far field*, about how far from the aperture should this examination take place?

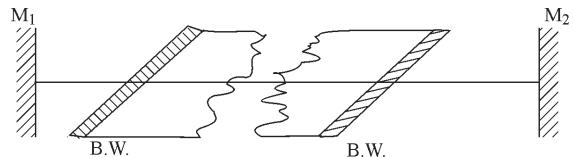


10. Refer to Figure 5-18, which shows a Fraunhofer diffraction pattern for a circular aperture. If the aperture is of diameter $150 \mu\text{m}$ and a helium-cadmium laser of wavelength $\lambda = 442 \text{ nm}$ is used to illuminate the aperture, determine (a) an approximate far-field distance from aperture to screen for a Fraunhofer pattern, (b) the half-angle beam divergence of the laser beam in the far field, and (c) the radius of the airy disk on the screen.
11. If one were to send a laser beam of wavelength 694 nm through a telescope aperture of diameter 2.5 meters on toward the moon, $3.84 \times 10^5 \text{ km}$ away, what would be the diameter of the laser beam when it hit the moon's surface?
12. What is the angular separation in second order between light of wavelength 400 nm and 700 nm when the light is incident normally (perpendicularly) on a diffraction grating of 5000 grooves/cm?
13. Vertically polarized light of intensity I_0 is incident on a polarizer whose TA makes an angle of 30° with the vertical. The light then passes through a second polarizer whose TA makes an angle of 90° with the vertical, as shown in the sketch. (a) What is the intensity of the light, in terms of I_0 , that passes through the second polarizer? (b) What is its orientation?
-
14. A submarine floating on the ocean ($n = 1.34$) transmits a message to a receiver on a 100-m high cliff located at the coastline. The submarine's antenna extends 5.5 m above the ocean surface. (a) If the transmitted signal is completely polarized by reflection from the ocean surface, how far must the submarine's antenna be from the coastline? (b) Relative to the ocean surface, what is the direction of polarization of the polarized signal?
-

15. Figure 5-28 shows the two Brewster windows tilted toward one another, each at the appropriate angle with the horizontal. See sketch (a). What would be gained or lost by having the windows parallel to each other, as in sketch (b)? Hint: Use your knowledge of Snell's law to draw a center ray completely through both windows from M_1 to M_2 . Use Figure 5-29 to help with details at each window. What happens to the center ray for each sketch? Which "deviation" of the center ray makes most sense for keeping the beam centered along the laser cavity axis?



(a) Tilted Brewster windows



(b) Parallel Brewster windows

MEET A TECHNICIAN

Derrick Thomann



Derrick earned an Associates of Applied Science in Laser Electro-Optics from Indian Hills Community College and now works for CVI Melles Griot.

Derrick finds his work personally rewarding. He works in the Engineering Department as an R&D Engineering Tech IV. Many of the projects that he works on at CVI Melles Griot are used in the medical field. For Derrick, the best part of his job is that he helps save lives.

“Knowing that keeps me motivated to do the best job possible. I know that people’s lives are affected; I’m not just creating another product.”

When Derrick works on a project, he knows that what he creates will make a difference in people’s lives. The medical field is just one place where one can apply photonics technology. Derrick encourages students to make the most of their education by learning as many facets of the field as they can.

“Learn as much as possible so that upon entering the workforce, you can apply your knowledge to your job. You must keep up on technology since lasers are progressing at a rapid rate and you always want to be up to date with the newest technology in your field.”

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Principles of Lasers

Module 1-6
of
Course 1, *Fundamentals of Light and Lasers*
3rd Edition

OPTICS AND PHOTONICS SERIES



PREFACE TO MODULE 1-6

This is the sixth module in *Fundamentals of Light and Lasers*. Following are the titles of all six modules in the course:

1. *Nature and Properties of Light*
2. *Optical Handling and Positioning*
3. *Light Sources and Laser Safety*
4. *Basic Geometrical Optics*
5. *Basic Physical Optics*
6. *Principles of Lasers*

The six modules can be used as a unit or independently, as long as prerequisites have been met.

FEATURES

Mathematics Videos: Math videos are provided to assist students in doing mathematical operations required in this module. The math concepts used in this module are checked ✓ in the following list:

1. Scientific Notation ✓
2. Unit Conversion ✓
3. Introductory Algebra ✓
4. Powers and Roots ✓
5. Ratio and Proportion
6. Exponents and Logarithms ✓
7. Graphing in Rectangular Coordinates ✓
8. Geometry ✓
9. Angle Measure in Two and Three Dimension
10. Trigonometry
11. Special Graphs

This checklist provides instructors a means of front-loading the presentation of material in this module with mathematics instruction. If instructors prefer to provide math instruction using a “just on time delivery” mode, a special icon  appears where the checked mathematics topics are first used within this module. All math videos can be accessed at <http://optecvideo.opteccrm.org/>.

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COURSE 1: FUNDAMENTALS OF LIGHT AND LASERS

Module 1-6

Principles of Lasers

INTRODUCTION

A laser is a special kind of light source. It can produce highly directional light with a high intensity within a very narrow range of wavelengths. Its properties differ significantly from those of ordinary light. The special properties of laser light include:

- A nearly monochromatic (single wavelength) beam of light
- A light beam, small in cross section, with a wide range of output powers
- A coherent beam of light that spreads very little in propagation
- A beam of light that can shine continuously or for short periods as pulses
- A beam of light capable of depositing tremendous power per unit area on targets.

These properties make lasers very useful in areas such as materials processing, measurement and inspection, medicine, information handling, military, entertainment, and holography.

Lasers have been developed with powers as low as a few microwatts and as high as several megawatts. Lasers can be operated in a continuous mode and in a pulsed mode. In pulsed modes, lasers can produce pulses as short as one million-billionth of a second (10^{-15} sec) and powers per unit area on targets of trillions of watts per square centimeter (10^{12} W/cm²). Laser wavelengths extend from the microwave to the X-ray region of the electromagnetic spectrum. There are lasers that can produce several wavelengths in the output at the same time and, with appropriate tuning, produce individual wavelengths. There are clever techniques available to control the laser beam to make it suitable for specific purposes. *Q switching*, *mode locking*, and *frequency doubling* are some of these techniques used to produce high intensity, pulsed laser beams which are useful in many applications.

PREREQUISITES

To understand this module, the student should have completed modules 1-1, *Nature and Properties of Light*; 1-2, *Optical Handling and Positioning*; 1-3, *Light Sources and Laser Safety*; 1-4, *Basic Geometrical Optics*; and 1-5, *Basic Physical Optics*. In addition, the student should also understand the basics of high school algebra, trigonometry, logarithms, scientific nomenclature, and units of conversion.

OBJECTIVES

At the completion of this module, the student will be able to understand:

- The distinction between spontaneous and stimulated radiation
- The basics of energy level diagrams
- The mechanism of coherent light generation
- The conditions required for gain in a laser
- The function of various components of a laser
- The longitudinal modes and mode separation
- TEM modes and their significance
- Laser cavity configurations and losses in a laser cavity
- Laser beam properties—line width, far-field and near-field beam divergence, beam power transmission through an aperture, irradiance, coherence, and focus ability
- Basics of laser pulse properties
- Characteristics of some of the principal types of lasers

SCENARIOS

Mr. Jones works for X-Laser Manufacturing Company that produces HeNe and Ar⁺ gas lasers. He works in a group consisting of design engineers, assembly technicians, and testing and quality control specialists. At the entry level, he is associated with assembling and aligning cavity mirrors to ensure that maximum power is delivered by the laser. He works with his group to determine the optimum reflectivity of the mirrors and best cavity configurations. He learns how to obtain maximum laser power output while holding the cost of developing the laser in the production line to a minimum. He participates in employee training and learns how to maintain quality control of laser components. As he advances in his career, he plans to be more involved in the design, manufacture and cost analysis of the products developed in the company.

BASIC CONCEPTS

Generation of Laser Light

Energy levels

A number of assumptions are made in order to explain the operation of a laser in a simple and understandable way. First, the classical *Bohr model* of the atom is chosen to describe orbits around a positive nucleus where electrons with different energies move. Second, though billions of atoms with billions of electrons are involved in a real situation, here we consider only a

single atom with its cloud of electrons. Further, it is assumed that this atom is stationary and not disturbed by oscillations, rotations, or translations. These assumptions are not valid in a real situation, but they do allow us to describe simply the process involved.

As a review of the atomic model presented in Module 1-1, *Nature and Properties of Light*, we reproduce a simple model of atomic structure. See Figure 6-1. Here the model shows a nucleus, positively charged, with a series of concentric orbits or shells surrounding the nucleus. The Bohr model assumes that the shells, lettered K, L, M, N, and O, can be filled with electrons. If, for example, there is only one electron, and it is in the K-shell, the element is *hydrogen* in its lowest energy state, the *ground state*. Outside energy can be directed onto the atom and when this energy is absorbed, the electron moves to outer shells (or orbits). It is then in an *excited* energy state (or level.) If an atom has two electrons and they are both in the K-shell, *filling it up*, the atom is *helium* in its ground state. As atoms continue to take on electrons to populate the L-shell (filled with eight electrons), the M-shell (filled with 18 electrons), and so on, each new addition of an electron forms a different chemical element. For example, *lithium*, with three electrons, is an atom with two electrons in the K-shell and one in the L-shell. Neon, with 10 electrons, is an atom with two electrons in the K-shell and eight in the L-shell.

Figure 6-1 shows an atom with 12 electrons—which corresponds to the element *magnesium*. Note that the M-shell, which can hold up to 18 electrons, has only two. With the 12 electrons shown, the element magnesium is in its ground state, here called E_1 . If energy is given to the magnesium atom to move one electron in the L-shell to the higher-energy M-shell, this new configuration of electrons corresponds to a higher energy level, denoted as E_2 . The M-shell, which can hold up to 18 electrons, is partially filled with two electrons and is called a *valence shell* with two valence electrons. Valence electrons are the easiest to add energy to, in order to move them into higher energy levels.

The simplest atom is hydrogen with one electron moving around the nucleus. The positive nucleus attracts the negative electron and holds it in a given orbit. Figure 6-2a shows five orbits (lettered $n = 1$ through $n = 5$) that the electron can occupy, and Figure 6-2b shows the corresponding energy levels, E_1 through E_5 , also lettered $n = 1$ through $n = 5$.

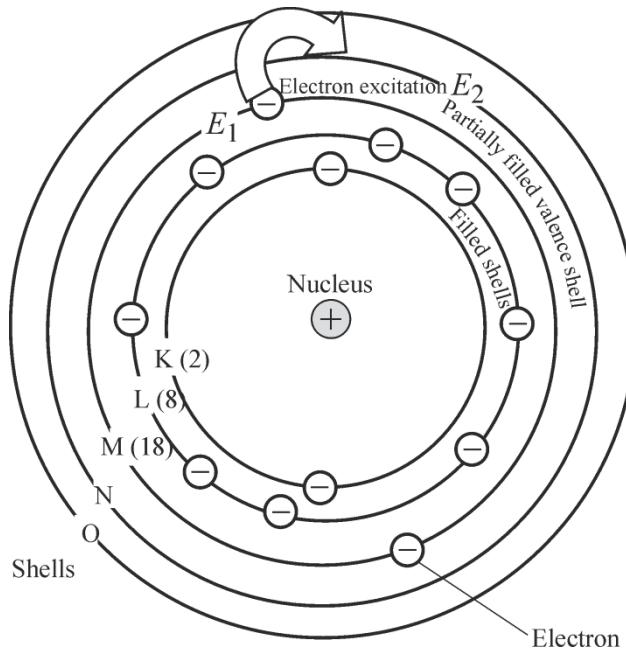
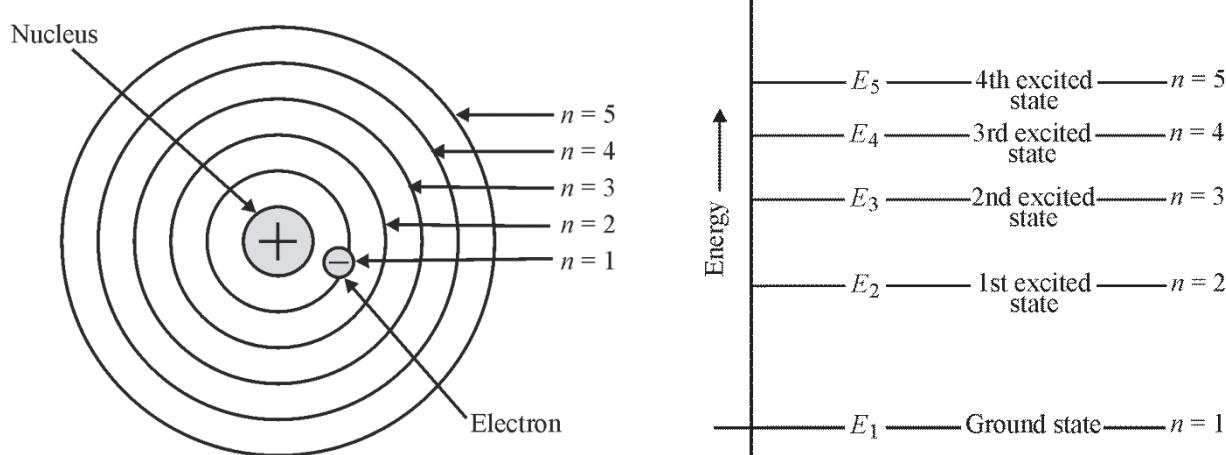


Figure 6-1 A model of the atom based on Bohr's theory of atomic structure. The model shows five shells (K, L, M, N, O) that can be filled with electrons. The electrons in the shells move around the positive nucleus.



(a) Hydrogen atom with allowable electron orbits showing electron in the innermost orbit—the lowest energy level

(b) Ground state energy level and first four excited energy states for a hydrogen atom

Figure 6-2 Bohr electron orbits and corresponding energy levels for a hydrogen atom

Note that the energy levels do *not* form a continuum of energy values, wherein any energy value is acceptable. Instead, the energy levels are clearly separated, indicating that the hydrogen atom—the nucleus and electron—can exist with *only certain discrete values*, such as E_1 , E_2 , E_3 , E_4 , E_5 , and so on, as pictured in Figure 6-2b.

Ordinary absorption and emission of light by atoms

A

84

The numbers below the **A** that appears in several places in this module reference specific applets that demonstrate the concepts being described in the text. These applets are accessible at <http://optecvideo.opteccrm.org/>.

Let us use the hydrogen atom as a simple model to help us understand *absorption* and *emission* of light. As we have said, the hydrogen atom can exist in only certain energy states, E_1 through E_5 and beyond, as depicted in Figure 6-2. Thus, the amounts of energy that can be absorbed by the atom in its ground state level E_1 can only be definite amounts such as $\Delta E_{21} = E_2 - E_1$, $\Delta E_{31} = E_3 - E_1$, and so on. Absorption of energy ΔE_{21} causes the atom to move from the ground state to the first excited state, absorption of ΔE_{31} to the second excited state, and so on. These allowable energy transitions are shown in Figure 6-3.

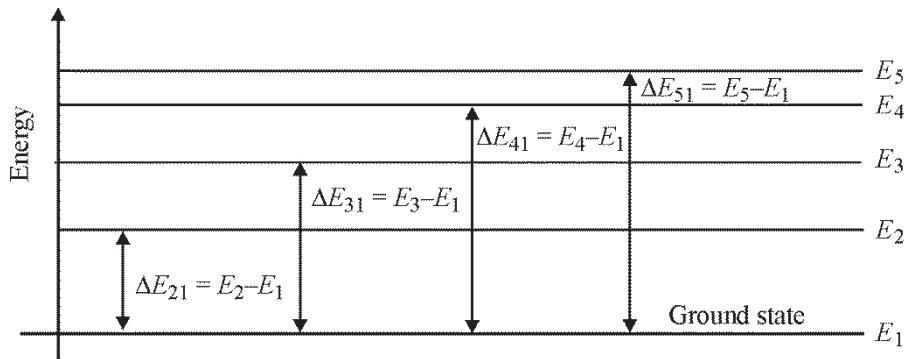


Figure 6-3 Allowable amounts of energy that can be absorbed or emitted by a hydrogen atom in certain energy states

The reverse process—one of *emission*—is also true. Thus, if the atom is in excited state E_2 , it can give up (emit) an amount of energy ΔE_{21} and fall to the ground state. If the atom is in excited state E_3 , it can give up energy ΔE_{31} and fall all the way to the ground state. Or, it can give up first an amount ΔE_{32} , moving to level E_2 , and later give up an amount ΔE_{21} , thereby completing its move to the ground state.

The light energy—electromagnetic energy in general—absorbed or emitted in moving the atom from one energy level to another, is contained in a packet of energy we call the *photon*. Thus photons are absorbed in the absorption process and given off in the emission process. As we know, the energy of a photon is given in terms of the frequency or wavelength of the light represented by the photon, by the relation $\Delta E = h\nu$ or $\Delta E = \frac{hc}{\lambda}$.

The electrons excited to higher energy level do not stay there indefinitely. The nature of the material and its higher energy state dictates how long the electron can remain there. This time is typically of the order of 10^{-8} to 10^{-9} seconds and is called the *lifetime* of the level. Ultimately, the electrons fall to a lower energy state or to the atom's ground state, releasing a photon in the process. The released photon has a wavelength λ and frequency ν determined by Equations 6-1 and 6-2.

$$\lambda = \frac{hc}{\Delta E} \quad 6-1$$

$$\nu = \frac{\Delta E}{h} \quad 6-2$$

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Where λ is the wavelength of the emitted photon,
 ν is the frequency of the emitted photon,
 ΔE is the energy difference between the two energy levels in Joules,
 h is Planck's constant, and
 c is the speed of light in a vacuum (3×10^8 m/sec).

Example 1

The energy difference ΔE between two energy levels in a particular atom is 4 eV. If the electron moves from the higher level to the lower level, find the wavelength and frequency of the photon emitted in the emission process.

Solution: An electron volt (eV) is an alternate unit of energy equal to 1.6×10^{-19} J, $h = 6.625 \times 10^{-34}$ J-s, and $c = 3 \times 10^8$ m/s

$$\lambda = \frac{hc}{\Delta E}$$

$$\lambda = \frac{6.625 \times 10^{-34} \times 3 \times 10^8}{4 \times 1.6 \times 10^{-19}}$$

$$\lambda = 311 \times 10^{-9} \text{ m}$$

$\lambda = 311$ nanometers (The photon represents light in the near ultraviolet region of the EM spectrum.)



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From the relationship $v = \frac{c}{\lambda}$, we can determine the corresponding photon frequency as follows:

$$v = \frac{3 \times 10^8}{3.11 \times 10^{-7}} = 9.65 \times 10^{14} \text{ Hz}$$

It can be seen from Equations 6-1 and 6-2 that, the larger the electron energy jump ΔE , the smaller will be the wavelength and the larger the frequency of the emitted photon. If the energy level difference between two energy levels is very small, the kinetic energy exchanged in the collision process between the two—due to thermal energy—may be sufficient to cause movement of the atom from one level to the other. Such an energy transfer is called *nonradiative transfer*. Electron jumps from higher to lower energy levels during emission generally occur randomly, and the photons emitted in this process do not have a fixed phase relation between each other. Such a collection of emitted photons is called *spontaneous emission*. This is the same type of emission as that given off by ordinary light sources. In general, *spontaneous emission* is characterized as follows:

- a) A number of wavelengths—involving photons coming from transitions between many different energy levels—are simultaneously produced and hence the light is *non-monochromatic* radiation.
- b) The energy of the radiation is distributed among all of the wavelengths and hence the energy per wavelength is very small.
- c) The photons produced go off in random directions and do not have any phase correlation between them. This type of emitted light is called *incoherent light*.
- d) The spontaneously emitted light cannot be focused to a very small spot.

Stimulated emission

So far, we have discussed the processes of *absorption* and *emission* that are involved in changing an atom's energy states. Summarizing, absorption comes about when photons of a definite energy move the atom from one allowable energy state to another. *Emission*, a reverse process, occurs when photons are given up randomly as the atom drops to a lower energy state. We have called this *spontaneous emission* because it occurs *spontaneously* and *randomly* within certain *lifetime intervals* of the upper energy state.



Go to

<http://optecvideo.optecrcm.org/> for a short lesson about stimulated emission.

But there is another emission, described by Albert Einstein, which is called *stimulated emission*. This type of emission occurs only when photons of a specific energy, say $\Delta E_{mn} = (E_m - E_n) = hc/\lambda$, are passing by an atom in upper state E_m . This energy is just right to cause (to *stimulate*) the atom to drop to lower state E_n . In the process, this drop gives up a photon with direction, phase, and wavelength *identical* to the one that caused the stimulated emission in the first place. It is this stimulated emission—as opposed to spontaneous emission—that lies at the heart of the amplification of light by laser action. And that is why the “laser” acronym refers to “light amplification by *stimulated emission of radiation*.”

As a summary, Figure 6-4 recaps the radiative processes that affect the number of atoms N_m and N_n at energy levels E_m and E_n , respectively.

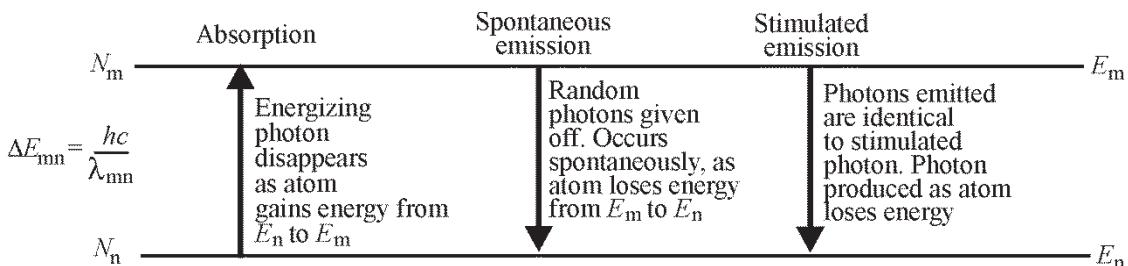


Figure 6-4 Three radiative processes that involve photons and atoms and how they affect the populations N_m and N_n of two energy levels E_m and E_n

The laws of thermodynamics tell us that the number of atoms in an excited state can never be greater than those in its ground state—so long as the atoms are in *thermodynamic equilibrium*. Any substance in thermodynamic equilibrium—the normal state of matter at a fixed temperature T —has as many atoms rising to higher energy states as there are atoms in excited states falling to lower energy states. Thus, in Figure 6-4, the number of atoms N_m at energy level E_m , the number of atoms N_n at energy level E_n , and the number of photons being absorbed and emitted remain constant. So, the atoms and the radiation (the photons) are in equilibrium. This means, then, that when more atoms are “pumped” from the ground state E_1 of an atom to a higher energy state E_m , an equal number of atoms will come back to the ground state, such that the *population* of the excited state (N_m) will always be lower than the population of atoms in the ground state (N_1). In the process of stimulated emission, **one** incident photon colliding with an atom produces **two** photons of exactly the same wavelength and phase, and they both move in the same direction. This process, as we have said, is an *amplification* process. Under normal circumstances, the ratio between stimulated photons to spontaneous photons will be as low as one to several million! This is the main reason that stimulated emission is normally not observed.

Population inversion

There is a method by which the atom population of an excited level can be made *greater than* the atom population in the ground state *for a short period*. Without actually stating how this is achieved in practice, consider a hypothetical situation wherein an energy level E_3 with a “long” lifetime (approx 10^{-6} sec) is located at about the same energy level as another excited state E_2 . This other state can belong to either an external atom or to the atom of the original (host) material. In the former case, this external atom is called the “guest” atom. When electrons of the “host” atom are raised to excited state E_2 , a few of them can be transferred to the metastable state (longer lifetime) E_3 of the guest atom by vibrational transfer or by “collisions” depending on the nature of the medium. See Figure 6-5.

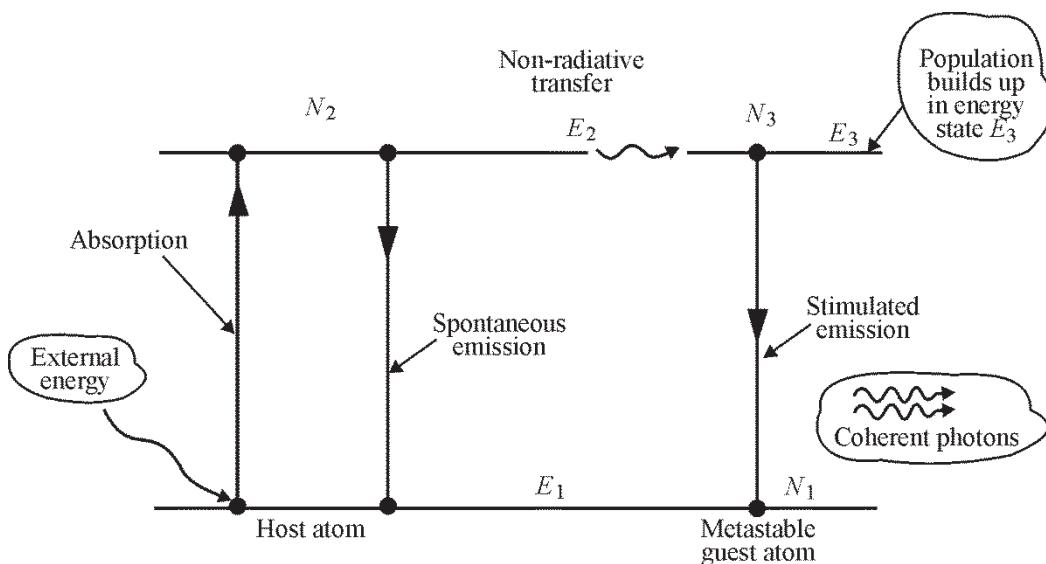


Figure 6-5 Energy level diagram showing the process for producing a population inversion and the subsequent creation of coherent photons

Since the metastable state E_3 has a longer lifetime, atoms can remain in this excited state for a longer period than in the excited state E_2 of the host atom. For this short duration, it is possible that the population of N_3 can become larger than N_1 . This situation is called a *population inversion*. If the atoms in energy level E_3 are stimulated by an external mechanism such as incident photons of energy $(E_3 - E_1)$, these atoms will return to the ground state E_1 simultaneously, producing photons of the same energy, wavelength, and phase. These photons thus are “monochromatic” and *in phase with each other*. These coherent photons result from the important *stimulated emission* process.

Basics of lasing action

Let us now set up a simple model of a two-level atom to develop the basics of laser action. Our two-level model is shown in Figure 6-6, with energy levels E_1 and E_2 , and corresponding atom populations N_1 and N_2 , with $N_2 > N_1$.

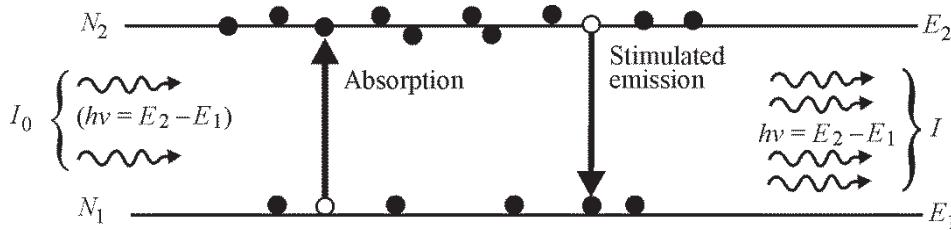


Figure 6-6 Two-level atom with a population inversion $N_2 > N_1$, showing both absorption and stimulated emission. Initial beam intensity, I_0 , is amplified, thereby making I greater than I_0 .

Suppose a light beam of intensity I_0 , made up of photons of exact energy $\Delta E = (E_2 - E_1)$, is passing through the collection of two-level atoms in our laser medium. Some photons in the initial beam I_0 will be lost since they will be absorbed as they cause atoms in level E_1 to jump to level E_2 . But, since we have established a population inversion, the process of *stimulated emission*—on the other hand—will **add** photons to the beam and tend to increase I_0 . If those added are greater than those lost, the laser medium will amplify the beam intensity and lasing action will take place. The competing process between loss and gain are combined in Equation 6-3, which we give without proof.

$$I = I_0 e^{+\sigma_{21}(N_2 - N_1)x} \quad 6-3$$

Where I_0 is the beam intensity incident on the lasing medium (our collection of two-level atoms). Photon energy in the beam is $h\nu = (E_2 - E_1)$

I is the intensity of the beam after passing through a distance x of the lasing medium. Photon energy in the beam is $h\nu = (E_2 - E_1)$

σ_{21} is a cross section coefficient characteristic of energy transition, up or down, between energy levels E_2 and E_1 , and is different for different laser materials.

N_2 is the atom population in upper laser level E_2

N_1 is the atom population in lower laser level E_1 , and

x is the distance the incident beam travels into the laser medium.

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From Equation 6-3, we can see that when N_2 is greater than N_1 (our condition for population inversion), then the exponent $\sigma_{21}(N_2 - N_1)x$ is *positive*, and I grows larger than I_0 as the beam moves through a distance x of the lasing material. Thus, the incident beam is *amplified* and we have lasing action.

It is helpful at this point to “look inside” a laser—pictured in Figure 6-7 as a laser medium situated between two reflective end mirrors—and trace the action from startup to beam output.

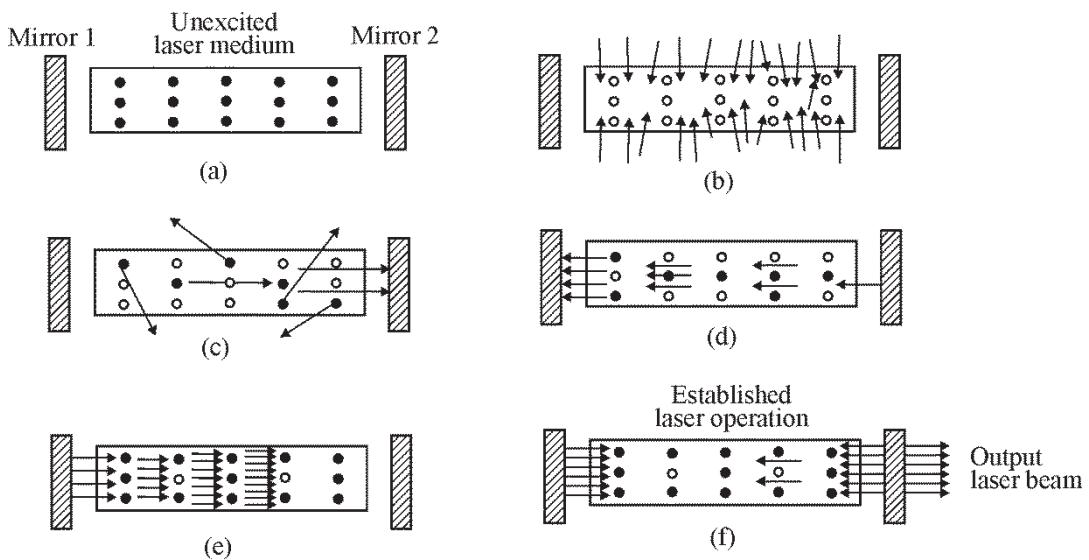


Figure 6-7 Step-by-step development of laser oscillation in a typical laser cavity: (a) unexcited laser medium; (b) pumping of laser medium; (c) spontaneous and stimulated emission; (d) light amplification begins; (e) light amplification continues; (f) established laser operation

In (a), the laser medium is shown situated between the mirrors of the optical cavity. Mirror 1 is essentially 100% reflecting, while mirror 2 is partially reflecting and partially transmitting. Most of the atoms in the laser medium are in the ground state. This is shown by the black dots. In (b), external energy (light from a flashlamp or from an electrical discharge source) is pumped into the medium, raising most of the atoms to excited levels. Excited states are shown by empty circles. During the pumping process, *population inversion* is established. The light amplification process is initiated in (c) when excited atoms (some of the atoms at level E_2 in Figure 6-6) spontaneously decay to level E_1 . Since this is spontaneous emission, the photons given off in the process radiate out randomly in all directions. Many, therefore, leave through the sides of the laser cavity and are lost. Nevertheless, there will generally be several photons—let us call them “seed” photons—directed *along* the optical axis of the laser. These are the horizontal arrows shown in (c) of Figure 6-7, directed perpendicularly to the mirrors. With the seed photons of energy ($E_2 - E_1$) accurately directed between the mirrors and many N_2 atoms still in the inverted state E_2 , the stage for stimulated emission is set. As the seed photons pass by the inverted N_2 atoms, stimulated emission adds identical photons in the same direction with the same phase, providing an every-increasing population of *coherent photons* that bounce back and forth between the mirrors. This buildup process, shown in (d) and (e), continues as long as there is a population inversion and photons of energy ($E_2 - E_1$) in the cavity. Since output mirror 2 is partially transparent, a fraction of the photons incident on the mirror pass out through the mirror. These exiting photons constitute the external laser beam, as shown in (f). Those that do not leave through the output mirror are reflected, recycling back and forth through the cavity gain medium, to keep the laser operation going.

In summary, then, the laser process depends on the following:

1. A *population inversion* between two appropriate energy levels in the laser medium. This is achieved by the pumping process and the existence of a metastable state.

2. *Seed photons* of proper energy and direction, coming from the ever-present spontaneous emission process between the upper and lower laser energy levels. These initiate the stimulated emission process.
3. An *optical cavity* that confines and directs the growing number of resonant energy photons back and forth through the laser medium, continually exploiting the population inversion to create more and more stimulated emissions, thereby creating more and more photons directed back and forth between the mirrors, and so on.
4. Coupling a certain fraction of the laser light (the cavity photon population) out of the cavity through an *output coupler mirror* to form the external laser beam.

Returning to Equation 6-3, we find it useful to define a *small-signal gain coefficient* g_{21} , as shown in Equation 6-4.

$$g_{21} = \sigma_{21}(N_2 - N_1) = \sigma_{21}\Delta N_{21} \quad 6-4$$

Which then permits us to write Equation 6-3 as follows:

$$I = I_0 e^{g_{21}x} \quad 6-5$$

It is clear that the larger the value of g_{21} , the better the chance for stimulated emission to grow. In practice, the actual gain obtained in a laser is less than the value g_{21} and is called “saturated gain.” Values of σ_{21} , ΔN_{21} and wavelengths of emission for some important lasers are given in Table 6-1.

Table 6-1. Cross-Sections and Small-Signal Gain Coefficients of Some Important Lasers

Type of laser	$\sigma_{21}(\text{cm}^2)$	$\Delta N_{21} (\text{cm}^3)$	$g_{21} (\text{cm}^{-1})$	$\lambda_{21} (\text{nm})$
HeNe	3×10^{-13}	7×10^9	2×10^{-3}	632.8
Argon	2.5×10^{-12}	1×10^{15}	5×10^{-3}	488.0
CO ₂	3×10^{-18}	5×10^{15}	8×10^{-3}	10,600
Excimer	2.6×10^{-16}	1×10^{16}	2.6×10^{-2}	248.0
Dye(Rh6-G)	2×10^{-16}	2×10^{18}	2.4	577
Ruby	2.5×10^{-20}	4×10^{19}	1.0	694.3
Nd:YAG	6.5×10^{-19}	3×10^{19}	2.0	1064.1
Ti:Al ₂ O ₃	3.4×10^{-19}	3×10^{19}	1.0	760
Semiconductor	1×10^{-15}	1×10^{18}	1×10^3	800

Three- and four-level lasers

In our attempt to simplify the basics of lasing action, we concentrated on two energy levels—the upper laser level E_2 and lower laser level E_1 , as was shown in Figure 6-6. In fact, for most lasers there are three or four energy levels that are involved in lasing action. In Figure 6-8, we show diagrams of three-level and four-level lasers.

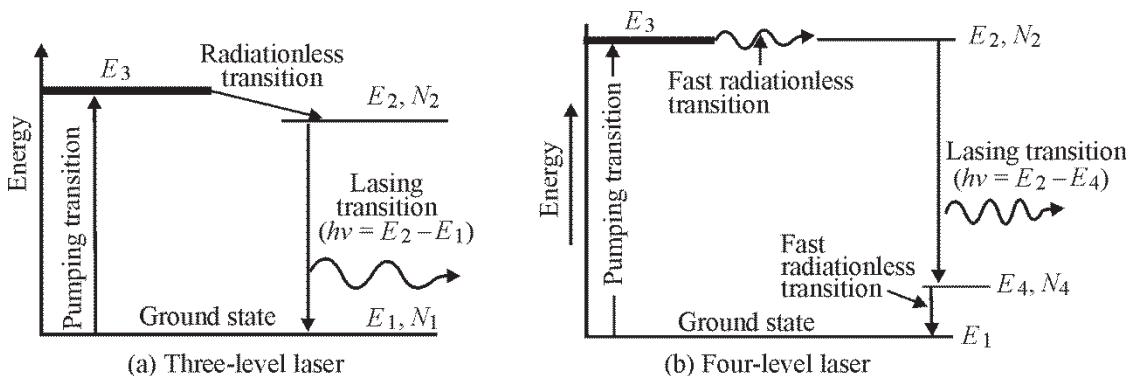
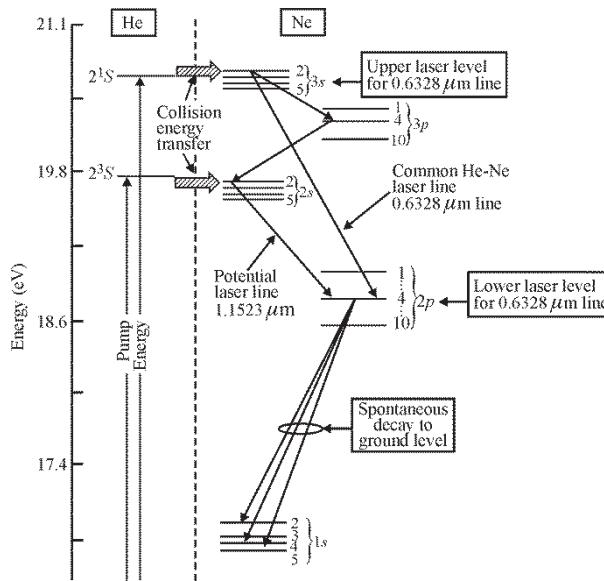


Figure 6-8 Energy level diagrams for three-level and four-level lasers

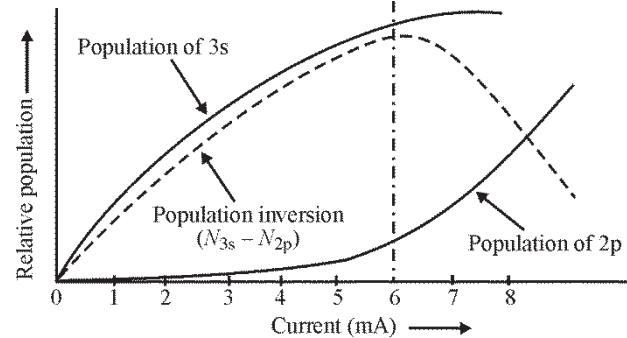
In a three-level laser, Figure 6-8a, optical pumping raises atoms from the ground state E_1 to excited levels E_3 . From here, many decay via a fast radiationless transition to a metastable level E_2 . This is the upper laser level with energy E_2 and population N_2 . When $N_2 > N_1$, we have a population inversion and lasing begins, with the emission of stimulated photons of energy $h\nu = E_2 - E_1$. While three-level lasers can be made to work, they are not very efficient. That's because it takes too much pumping to make N_2 greater than N_1 , since the ground state (N_1) is always—by far—the most heavily populated energy state in the atom.

In some lasing materials, there exists an energy level E_4 , just above the ground state E_1 . See Figure 6-8b. With this additional level, we have the makings of a four-level laser. The excitation process takes atoms from the ground state E_1 to the excitation level E_3 , as before. Here again, many atoms in level E_3 decay via a fast, radiationless transition to a metastable level E_2 . This level, E_2 , becomes the upper laser level. A population inversion is now established between levels E_2 and E_4 , with E_4 becoming the lower laser level. The population inversion ($N_2 > N_4$) is now much easier to achieve, since energy level E_4 , always less populated than ground state E_1 , decays rapidly to the ground state, and is thus almost always nearly empty. As a result, four-level lasers are more efficient than three-level lasers, since they are much easier to “pump” in order to set up a population inversion.

Figure 6-9a shows the operation of a HeNe laser. The pumping energy is given to the 2^3s and 2^1s energy levels in helium. The helium atoms in the excited 2^1s level collide with neon atoms and transfer energy to the $3s$ excited energy level of neon. This becomes the upper laser level for the well-known 0.6328 um HeNe laser line. The laser transition takes place when stimulated atoms jump from the “ $3s$ state” to the “ $2p$ state.” The notations 2^1s , 2^3s , $3s$, and $3p$ refer to allowable energy states in the helium and neon atoms, as dictated by quantum theory and the Bohr model of the atom.



(a) HeNe laser energy levels



(b) Energy level populations versus ionization current

Figure 6-9 (a) Simplified energy level diagram for a HeNe laser and (b) effect of increasing ionization current on output power

The excitation of the HeNe laser (Figure 6-9b) is accomplished by initially striking an electric discharge through the gas and then maintaining a steady voltage and current. Initially, when the ionization current is low, the population of the lower laser level 2p is very small, and the relative population inversion ($N_{3s} - N_{2p}$) is high. Thus the power output increases. But, as the ionization current continues to increase, population of the lower laser level 2p increases due to atoms in the neon ground state being raised to the neon 2p state. The power output actually decreases with further increase of ionization current, as indicated by the fall in the dashed line at higher ionization currents.

Optical Cavities and Modes

Cavity configurations

In Figure 6-10, we show a schematic diagram illustrating the basic structure and elements of a laser. This structure includes the *excitation mechanism*, the *amplifying medium*, the *high reflectivity mirror*, and the *output coupler mirror*. The laser beam is shown emerging from the output coupler mirror.

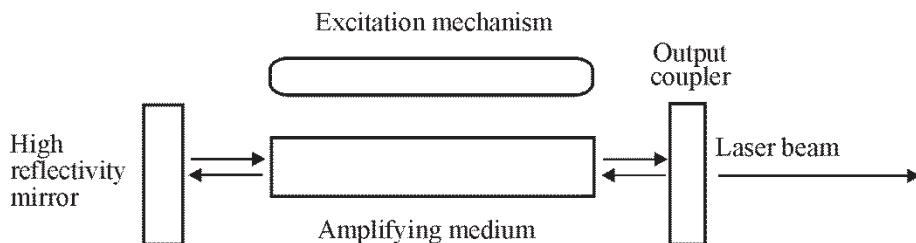


Figure 6-10 Schematic diagram showing the basic structure of a laser

In determining what types of mirrors to be used, the following factors are important to consider.

1. Mode volume
2. Ease of alignment
3. Diffraction losses
4. Cost of manufacturing the mirrors.

Mode volume refers to the actual lasing medium volume that exists inside the cavity. This is an important quantity because it determines the number of stimulated photons that participate in the amplifying process. The larger the mode volume, the greater will be the laser output. The ease of alignment involves one's ability to align the two mirrors to maximize the laser beam output. For example, it is more difficult to align two plane-parallel mirrors than to align two slightly concave mirrors. Diffraction losses are concerned with the loss of photons due to the passage of laser light beyond the mirrors that occurs at the edge of the mirrors. Finally, the cost of the mirrors is also important, since this cost affects the overall cost of the total system. Several cavity configurations in use are shown in Figure 6-11. The cavity length, from mirror to mirror, is denoted by L , the mirror radii by r_1 and r_2 .

Plane-parallel mirror cavity—This type has the highest mode volume but has the highest diffraction losses and is the most difficult to align. This mirror configuration is most useful in high-powered, pulsed lasers where the large mode volume is useful. The mirrors have to be coated on optical flats, and hence, are quite expensive.

Spherical mirror cavity—With spherical mirrors, the radii of curvature of both mirrors are exactly equal to half the length L of the cavity. This system is the easiest to align and has the lowest diffraction losses. However, it has the least mode volume, and hence is not used in any laser systems except in dye lasers where focusing the beam is necessary.

Long-radius mirror cavity—In this cavity, the radii of curvature of both mirrors are much larger than the cavity length L . This increases the mode volume considerably but makes the laser more difficult to align and increases the diffraction losses. This cavity is useful for CW laser operation.

Confocal mirror cavity—In this configuration, the radius of curvature of both mirrors is exactly equal to the cavity length L . This is a better configuration than the long-radius cavity in terms of ease of alignment and its low diffraction losses. However, the mode volume is still small. This configuration can be used for a CW laser operation.

Hemispherical cavity—In this cavity, the output coupler is a plane mirror and the high reflectivity mirror has a radius of curvature exactly equal to the cavity length. The mode volume

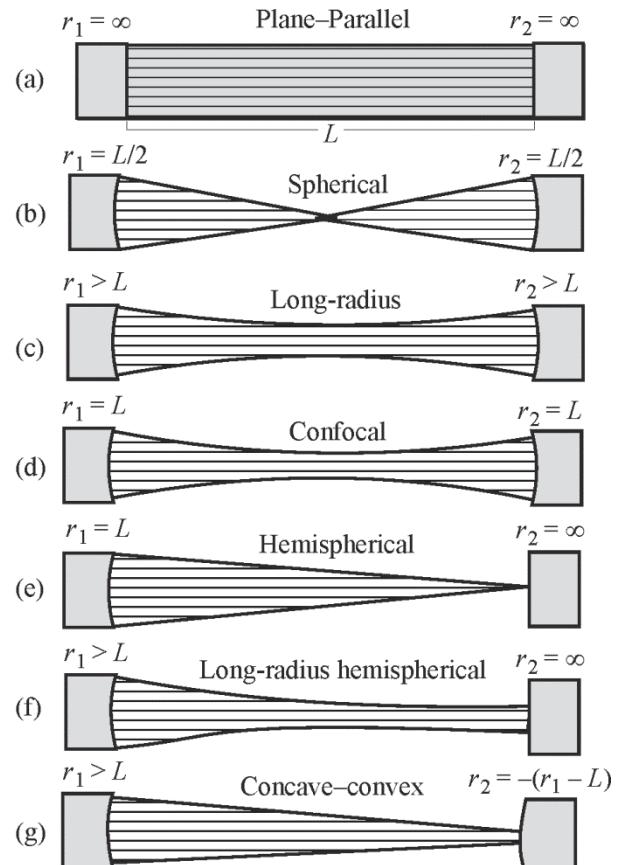


Figure 6-11 Different cavity configurations used in lasers

is less than that for the plane-parallel geometry, but sufficiently large. The ease of alignment, low diffraction losses, and low cost makes this configuration most suitable for low power HeNe lasers.

Long radius, hemispherical cavity—One plane mirror for the output coupler and a concave mirror with a radius of curvature larger than the cavity length are used in this configuration. This configuration combines the low cost and improved mode volume with low diffraction losses. This is the *most commonly used configuration for CW lasers*.

Concave-convex mirror cavity—One concave and one convex mirror are used in this configuration. In practice, the diameter of the convex mirror is smaller than the beam diameter at the mirror. This allows the beam not to be concentrated on the output coupler but to pass around it. This is very useful in extremely high-powered CO₂ lasers where the high intensity of the beam can damage the output coupler. The output beam has a “doughnut” configuration.

All of the mirrors used in laser cavities are multi-layer, anti-transmission-coated, front-surfaced mirrors. They have reflectivities close to 99.9% for the high reflectivity mirrors and 96-98% for the output couplers.

Laser cavity alignment technique

It is necessary to adjust/position the cavity mirrors and the amplifying medium so that they are in perfect alignment along the optic axis of the cavity. This will ensure an output of maximum power from the laser. This task is difficult in the case of gas lasers since the beam has to pass through a long, narrow tube without touching the sides. The longer the tube, the more difficult it is to align. A technique using a low powered HeNe laser to adjust a gas laser is described here.

The end mirrors of the laser are usually mounted on mirror mounts with adjusting screws to move the mirrors along two perpendicular axes. These mirror mounts are described in Module 1-2, *Optical Handling and Positioning*. Using the two screws, it is possible to adjust the mirrors to align the laser. However, before doing this, the laser tube has to be made coaxial with the reflecting beam. In order to do this, a low-powered HeNe laser is placed on a 3-point table and the laser plasma tube is mounted on an optical bench as shown in Figure 6-12.

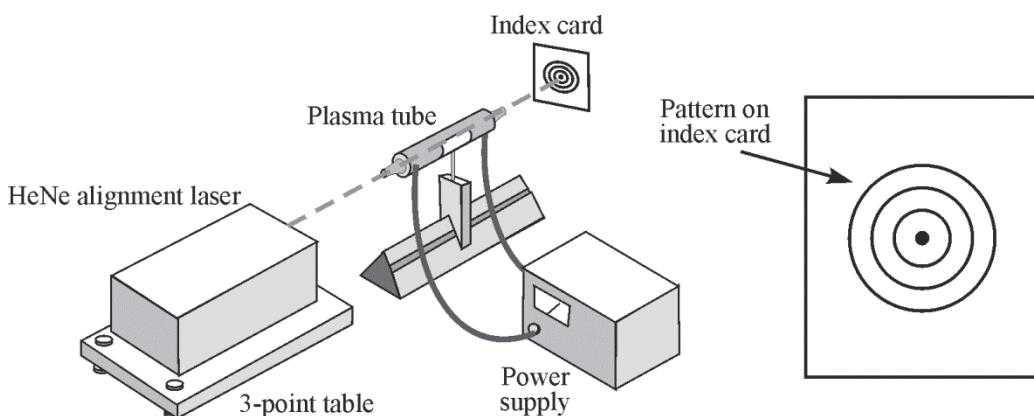


Figure 6-12 Initial setup for alignment

With the HeNe laser turned on, the three-point table and the optical bench of the plasma tube are adjusted so that the beam passes through the plasma tube without touching the sides. This can be

a difficult process, requiring patience and skill. When the beam is perfectly aligned, the image of the beam is displayed on an index card and it will look like a small spot with a series of circular rings around it, as shown in Figure 6-12.

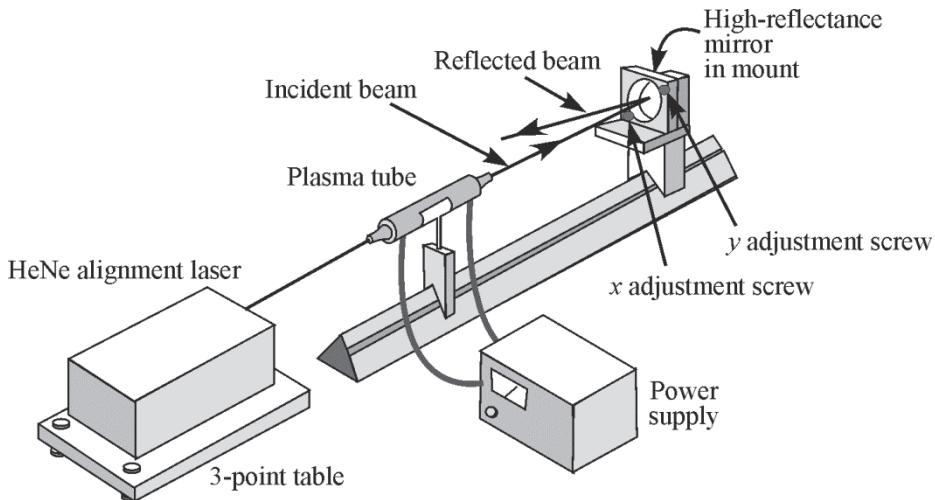


Figure 6-13 Initial alignment of HR mirror

The next step is to place the high reflectance mirror in its mount at the far end of the optical bench (Figure 6-13). The “*x*” and “*y*” adjustment screws of this mirror have to be adjusted such that the beam is reflected back perfectly along itself through the plasma tube and onto the exit port of the HeNe laser.

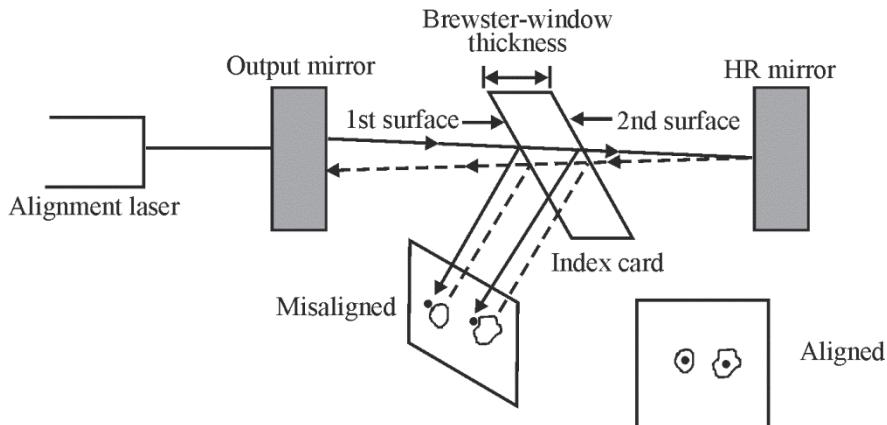


Figure 6-14 Final alignment of HR mirror

When this adjustment is carried out, some rings of light will be seen on the face of the HeNe laser. The *x-y* positioners have to be adjusted such that these rings are minimized. Usually, the plasma tube has Brewster's windows on either end. In such a case, reflection of the alignment laser's beam on the Brewster window closest to it will show two spots corresponding to the reflection from the first and second surfaces of the Brewster window. If the alignment is perfect, the two spots and the faint rings surrounding them will be concentric (Figure 6-14). If this is not so, then the *x-y* positioners of the reflecting mirrors have to be readjusted to make the spots concentric with the circles.

Finally, the output coupler is positioned on the rail close to the aligning laser (Figure 6-15). At first, the *x*-*y* positioners of the output coupler must be adjusted to make the aligning laser beam reflect back on itself. The aligning laser is now removed. The laser to be aligned is switched on. Now the *x*-*y* positioners of the output coupler are finely adjusted until the output power of the laser beam is maximized. This can be done by checking with a power meter. Commercial lasers that are factory aligned need not be adjusted often. From time to time, minor adjustments of *x*-*y* positions can maximize the power output.

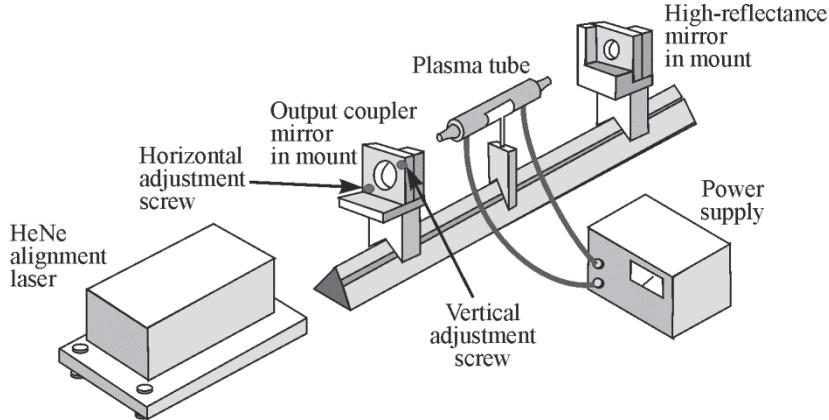


Figure 6-15 Alignment of the output mirror

Gain in a laser medium

We can see how the overall gain in a laser cavity occurs by considering the gains and losses during one roundtrip of the laser photons. The roundtrip gain is referred to as a *loop gain*. As we discussed earlier in connection with Figure 6-7, the initial number of “seed” photons—with the correct energy and direction—is very small. However, through repeated reflections back and forth through the gain medium, this small number is continually amplified. The loop gain for one roundtrip can be calculated as follows. See Figure 6-16.

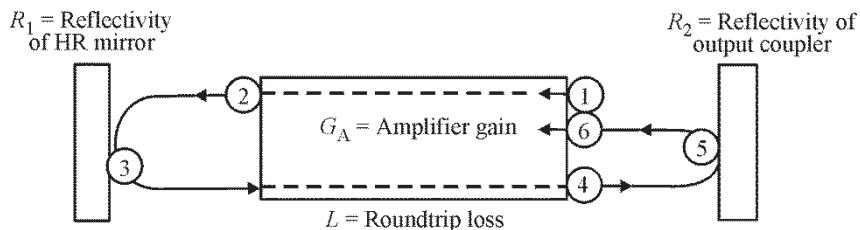


Figure 6-16 Loop gain of a laser

Let’s assume that a certain number n_0 of stimulated laser photons are initially at position ① in the cavity. As they move from ① to ② through the laser medium, they experience a gain in photons via additional stimulated emission. Let’s call this gain multiplier G_A , so now there are $G_A n_0$ photons. At ③, most are reflected back with a percent reflectivity R_1 , so now there are $R_1 G_A n_0$ photons in the beam. Another pass through the gain medium gives another multiplication of G_A , so at ④ there are now $R_1 G_A^2 n_0$ photons. After reflection at the output coupler ⑤, with a reflectivity R_2 , there are $R_1 R_2 G_A^2 n_0$ photons. However, along the way, while

experiencing gain, some photons are lost. Let's call this *distributed* loss factor—due to a combination of absorption, scattering, and diffraction— L , so that the number $R_1 R_2 G_A^2 n_0$ remaining at ⑤ must be multiplied by $(1 - L)$ to determine the true number arriving at position ⑥, the end point for the loop gain. Thus we have, after one loop, n photons, given by Equation 6-6.

$$n_{\text{Loop}} = R_1 R_2 G_A^2 (1 - L) n_0 \quad 6-6$$

The *loop gain*, G_L , is equal to $\frac{n_{\text{Loop}}}{n_0}$, given by Equation 6-7.

$$G_L = R_1 R_2 G_A^2 (1 - L) \quad (\text{Loop gain}) \quad 6-7$$

If the laser operates in a CW mode, defined by $n_{\text{Loop}} = n_0$ for each roundtrip, we set $G_L = 1$ and solve for G_A to find the *threshold gain*, as given in Equation 6-8.

$$(G_A)_{\text{Th}} = \sqrt{\frac{1}{R_1 R_2 (1 - L)}} \quad (\text{Threshold gain}) \quad 6-8$$

Where R_1, R_2 are the fractional reflectivities at the mirrors,
 L is the fractional loss taken during the entire roundtrip, and
 (G_A) is the threshold laser medium gain for CW laser operation.

Example 2

A Nd:YAG laser has mirrors whose reflectivities are $R_1 = 0.995$ and $R_2 = 0.65$. The distributed roundtrip loss $L = 0.08$ and the amplifier gain $G_A = 3.5$. Find the loop gain $G_L = \frac{n_{\text{Loop}}}{n_0}$.

Solution: According to Equation 6-7,

$$G_L = \frac{n_{\text{Loop}}}{n_0} = G_A^2 R_1 R_2 (1 - L)$$

$$G_L = G_A^2 R_1 R_2 (1 - L)$$

$$G_L = (3.5)^2 \times 0.995 \times 0.65 \times (1 - 0.08)$$

$$G_L = 7.3 \quad (\text{The loop gain } G_L \text{ is much greater than that needed for CW operation.})$$

Example 3

A CW Nd: YAG laser contains mirrors whose reflectivities are $R_1 = 0.998$ and $R_2 = 0.88$ and whose roundtrip loss L is 0.5 %. Find the *threshold* amplifier gain for CW operation.

Solution: According to equation 6-8,

$$(G_A)_{\text{Th}} = \sqrt{\frac{1}{R_1 R_2 (1 - L)}}$$

$$(G_A)_{\text{Th}} = \sqrt{\frac{1}{0.998 \times 0.88 \times (1 - 0.005)}}$$

$(G_A)_{\text{Th}} = 1.07$ [Very near $(G_A)_{\text{Th}} = 1$, as it should be for CW operation]

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[http://optecvideo.
optecrcm.org/](http://optecvideo.optecrcm.org/).



As it turns out, a CW laser is not a very efficient laser. The reasons can be explained with Figure 6-17. Here time is plotted on the x -axis and loop gain (solid line) and power output (dashed line) on the y -axis. When the laser is switched on ($t = 0$), there are not yet enough stimulated photons in the cavity. Thus, the loop gain G_L is less than 1, since losses exceed gains. Hence, no output is possible from the laser. As time increases to t_2 , the photons make many roundtrips and the loop gain increases to a value equal to 1. Just beyond t_2 , laser power begins to emerge from the output coupler as a laser beam.

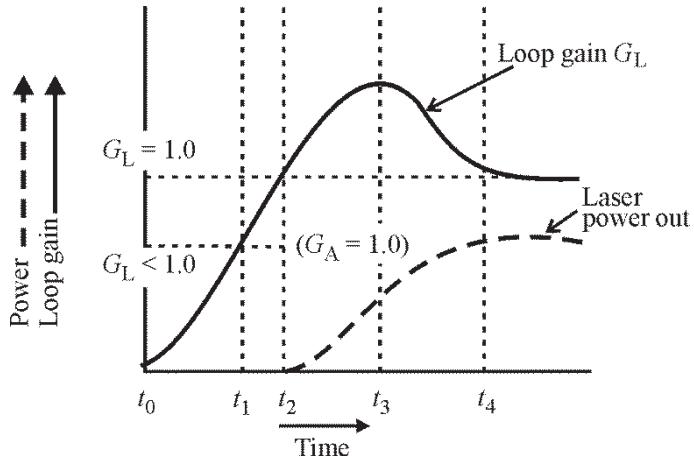


Figure 6-17 Loop gain and output power in CW laser

But, as power is drawn from the laser in the output beam, the system continually loses some of its stimulated photons. The loop gain G_L is not allowed to reach its maximum value due to this process. This can be seen by the fact that the gain peak for G_L and the maximum power output do not coincide. In fact, the maximum power output coincides with the downward slope of the loop gain curve. The most efficient situation occurs when the peak of the loop gain coincides with the peak of the power output. This can be achieved by preventing power output via a shutter that remains closed until the loop gain G_L reaches its peak value. The shutter is then opened to release the output beam at maximum power. This allows large numbers of photons to emerge in a small burst. This technique is called *Q-switching*. Details of this technique are beyond the scope of this module. The actual gain obtainable in a laser is smaller than the *small signal gain* given in Equation 6-4. This is due to the many losses in the cavity and the continuous extraction of beam power from the laser. This reduced gain is called *saturated gain*.

Longitudinal modes

A laser beam consists of a number of *longitudinal modes* that are characteristic of different lasers. These modes are based on *standing waves* created between the two reflecting mirrors on either end of the cavity. The stimulated photons in the cavity do not all have exactly the same wavelength—due to *line broadening*, which will be explained later. Hence, the photons take slightly different times to travel between the mirrors. This results in a slight difference in the relative phase of the photons. Amplification can only occur for those photons that have exactly the same phase. It turns out that there will be several sets of “standing waves,” with slightly different wavelengths, oscillating independently. This is shown in a simplified diagram of independent sets of standing waves in Figure 6-18.

Several of these modes will oscillate simultaneously and are equally spaced (Figure 6-19).

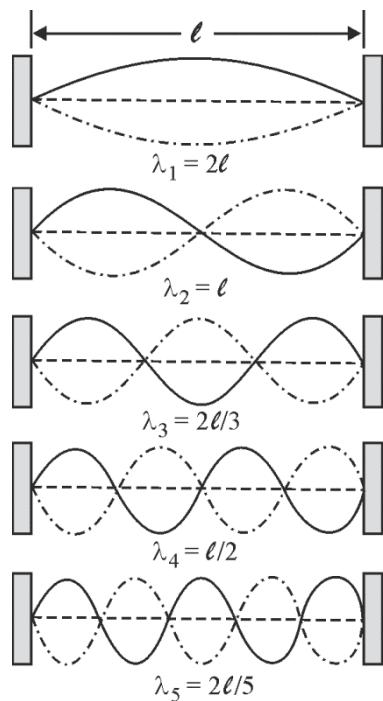


Figure 6-18 Longitudinal modes as determined by standing waves set up between the cavity mirrors

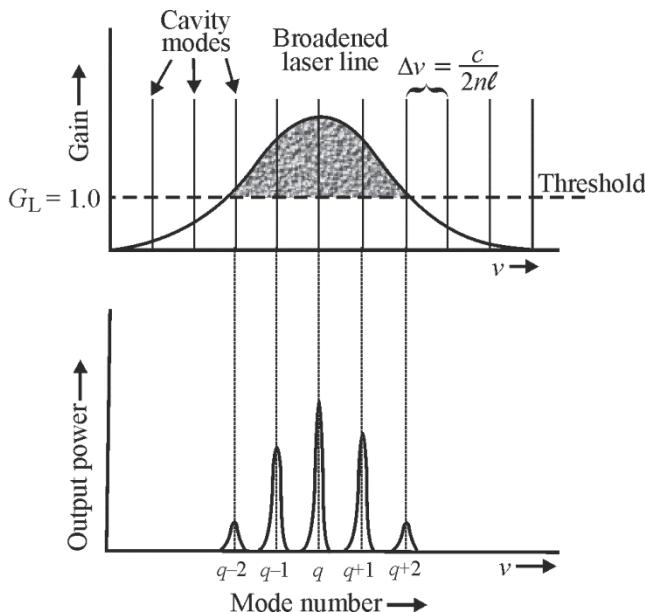


Figure 6-19 Spectral distribution of laser output showing several longitudinal modes with various loop gains G_L

Each of these modes tries to gain more photons at its own wavelength. Thus, all of these modes compete for amplification. This results in a reduction of amplification for the central mode represented by mode number q and frequency ν . Furthermore, among all the modes, only those with an amplification greater than the threshold gain, $(G_A)_{Th}$, will be sustained, and the others will die out. (Figure 6-19). The distance between these equally-spaced, longitudinal modes is given by:

$$\Delta\nu = \frac{c}{2(n_1\ell_1 + n_2\ell_2 + \dots)} \quad 6-9$$

where $\Delta\nu$ = frequency interval between longitudinal modes

ℓ_1 = length of laser medium 1 in the cavity with refractive index n_1

ℓ_2 = length of laser medium 2 in the cavity with refractive index n_2 , and so on

For a laser with one single gain medium of refractive index n , which fills the space between the mirrors separated by a cavity length ℓ , Equation 6-9 simplifies to

$$\Delta\nu = \frac{c}{2n\ell} \quad 6-10$$

Example 4

A HeNe laser ($n = 1$) has a cavity length ℓ of 60 cm and an output wavelength of 632.8 nm. Find the longitudinal mode spacing $\Delta\nu$.

Solution: According to Equation 6-10,

$$\Delta\nu = \frac{c}{2n\ell}, \text{ where } c = 3 \times 10^8 \text{ m/s, } n = 1.0, \text{ and } \ell = 0.6 \text{ m}$$

$$\Delta\nu = \frac{3 \times 10^8}{2 \times 1 \times 0.6} = 2.5 \times 10^8 \text{ Hz}$$

The number of longitudinal modes n_m in a laser beam is given by:

$$n_m = \frac{(\Delta\nu)_{\ell w}}{\Delta\nu} \quad 6-11$$

where $(\Delta\nu)_{\ell w}$ = line width of the laser line

$\Delta\nu$ = spacing between the modes

Example 5

A certain laser has a longitudinal mode spacing $\Delta\nu$ of 260 MHz and a fluorescence linewidth of $(\Delta\nu)_{\ell w}$ equals to 35 GHz. Find the number of longitudinal modes.

Solution: According to Equation 6-11,

$$n_m = \frac{(\Delta v)_{\ell W}}{\Delta v} = \frac{3.5 \times 10^{10}}{2.6 \times 10^8} = 135 \text{ modes}$$

Thus there are 135 longitudinal modes—such as those labeled q , $q+1$, $q-1$, etc., in Figure 6-19.

Transverse modes

The electromagnetic wave that makes up the laser beam has both electric and magnetic fields, as we know. If we examine in detail the variation in intensity—due to electric field—across the beam, we find many different intensity patterns that are possible, made up of patterns of bright and dark regions. These patterns of dark and bright in a plane perpendicular to the beam itself are called *transverse modes*. Different cavity geometries give rise to pure modes such as the TEM₀₀ mode or a combination of many modes. Some of the transverse mode patterns one finds are shown in Figure 6-20.

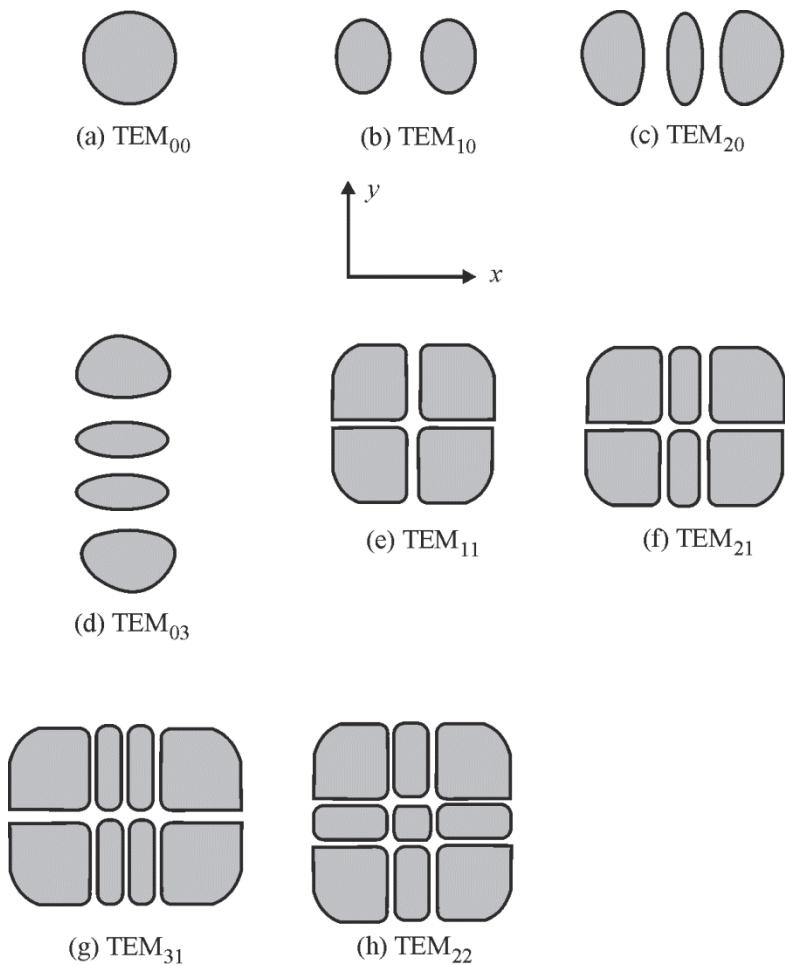


Figure 6-20 Transverse electromagnetic modes of a laser beam. The “dark regions” are regions of high brightness; the “white” vertical and horizontal lines are regions of low or zero brightness.

These different modes are identified as Transverse Electromagnetic Modes (TEM_{xy}). They are given with two suffixes, *x* and *y*. The subscript *x* indicates the number of zero-intensity regions along the *x*-direction. The subscript *y* indicates the number of zero-intensity regions along the *y*-direction. For example, in Figure 6-20, the pattern labeled TEM₃₁ has 3 zero-intensity regions (the white lines) along the *x*-direction and 1 zero-intensity region along the *y*-direction. TEM₀₀ refers to one single bright spot with no regions of zero intensity.

In practice, several TEM modes exist at the same time and overlap each other as shown in Figure 6-21. In order to operate the laser in a pure TEM₀₀ mode, for example, an aperture has to be placed in the beam such that the higher order modes are blocked.

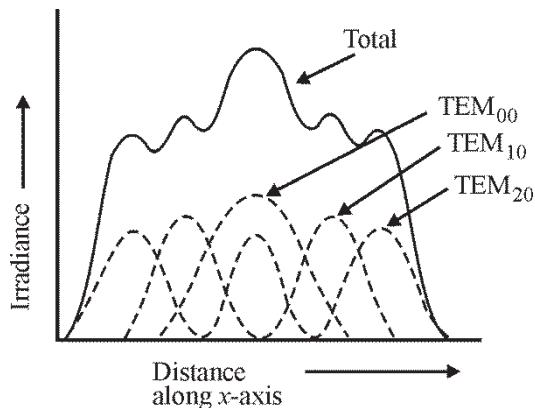


Figure 6-21 Superposition of three transverse modes

Laser pumping sources

The active medium in a laser has to be excited by an appropriate energy source. For example, gas atoms and molecules can be excited by an electrical discharge. Atoms in solids can be excited by optical methods. The excitation mechanism for gases and solids are briefly described below.

Electrical discharge—Gases can be excited by a D.C. current flow. When a very high voltage is applied for a short period, a valence electron is removed from an atom and the atom becomes ionized. The positive ions move toward the cathode (negative electrode) and the electrons move toward the anode (positive electrode). This results in an ionization current. A much lower voltage can then sustain this state of ionization. The power supply for a gas laser such as a HeNe laser consists of a high voltage starter circuit, a running circuit to maintain a continuous voltage supply through the ionized gas, and a resistance (ballast resistor) to maintain the current. Power supplies for ion lasers and molecular lasers are more complex.

Flash lamps—These are high intensity discharge lamps containing inert gases such as Xenon or Krypton. These can be run both continuously and intermittently. A high voltage between two electrodes at the ends of a tube containing the gas ionizes the gas. The ionized gas produces high-intensity light via non-stimulated emission. These light sources are broadband sources and the intensity is distributed over several wavelengths in the visible region. While these sources produce high intensities, very little of the light they produce is absorbed by the active laser medium because of the narrow absorption bands that exist in most of the laser materials. Hence, much of the intensity is converted into heat, requiring cooling of the lasing medium. A typical flash lamp with water-cooling is shown in Figure 6-22.

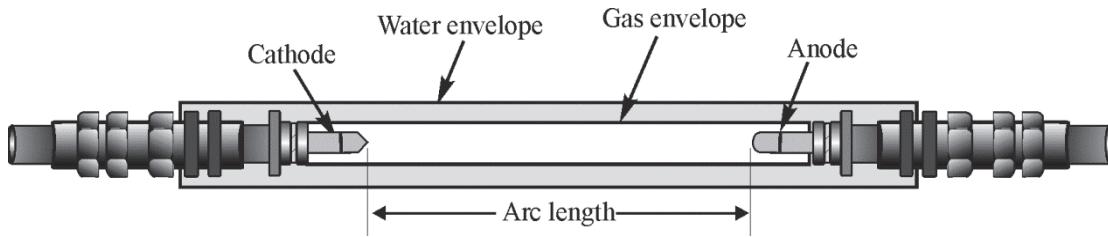


Figure 6-22 Schematic diagram of a water-cooled flash lamp

Diode laser pumping—Diode lasers are semiconductor P-N junction devices. They produce coherent light at a particular wavelength. The wavelength of these lasers can be adjusted by changing the structural parameters of the P-N junction. Since diode lasers give specific wavelengths, they can be matched to the absorption bands of the laser medium atoms. This allows the entire output of the diode laser to be absorbed by the solid laser medium. Diode lasers are small. Several lasers arranged in rows can be used either to pump along the length of the laser or perpendicular to the laser medium. In recent years, diode pumped Nd•YAG lasers have become readily available. This allows reduction in cooling systems and overall size of the laser.

Lasers pumping lasers—In many situations, one laser can be used to pump another laser. A common example is the pumping of a Ti sapphire or YLF laser by an Nd: YAG laser. The high intensity of the pumping laser allows high power outputs of the pumped laser.

Laser Beam Characteristics

Laser linewidth

In an *ideal* situation, electrons jump simultaneously from the laser's upper, metastable energy level that has zero energy width to a lower laser level, also of zero energy width. Hence, all of the stimulated photons produced during the transition would have exactly the *same* wavelength and phase. In a real laser, this is far from the truth. First, the atoms in any laser medium are at a temperature higher than absolute zero and are in motion.

Depending on the nature of the medium, the atoms and molecules collide with each other, vibrate, rotate, and translate. All of these motions and their combinations broaden the lasing medium's energy levels. This results in electrons jumping from different positions within the upper energy level to different positions within the lower energy level. See Figure 6-23.

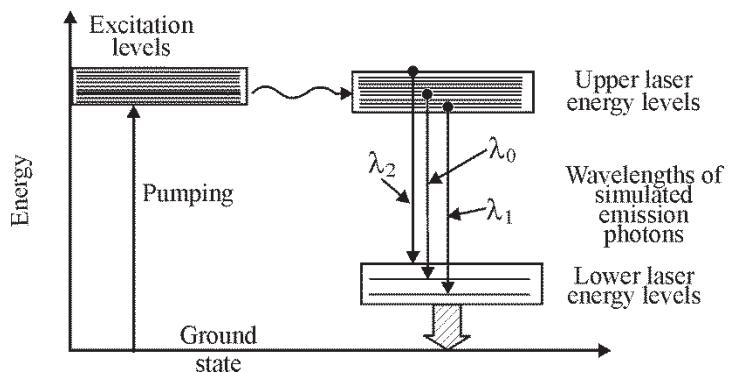


Figure 6-23 Different wavelengths of photons produced by transitions of atoms between different energy positions in the broadened upper and lower energy levels

The resulting stimulated photons will have slightly different wavelengths (λ_0 , λ_1 , λ_2) and different phases. This leads to a *broadening* of the laser beam's wavelength. The actual linewidth contains a number of closely-spaced wavelengths on either side of the central wavelength. (See Figure 6-24).

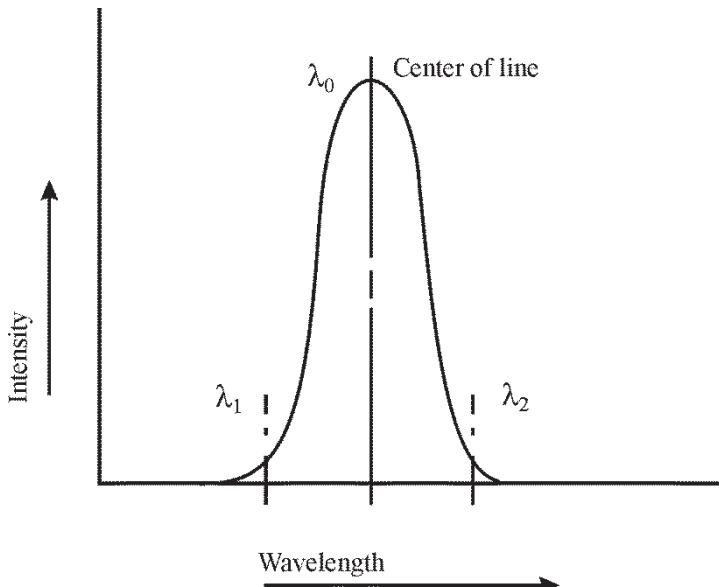


Figure 6-24 A linewidth-broadened laser line

There are three types of line broadening mechanisms. Each will affect the actual linewidth to a different degree, depending on the nature of the medium and the temperature.

Collision broadening—This type of broadening is due to the collision of atoms and molecules, resulting in broadening of the metastable state. This type of broadening is most prevalent in gases and increases with increasing temperature. Since gas pressure can be changed in a gas laser, the collision rate will change with change of pressure. Cooling the laser medium can reduce collision broadening to some extent.

Thermal broadening—This broadening is due to the oscillatory motion of the atoms and molecules and is most common in solid-state lasers. This broadening also increases with an increase in temperature.

Doppler broadening—The Doppler effect refers to the change in frequency due to the relative motion between a source and an observer. In the case of a vibrating atom, it moves either toward or away from an atom at rest. (See Figure 6-25.) In the first case, the wavelength of the photon emitted by the approaching atom will be slightly shorter than the wavelength emitted by a stationary atom. In the latter case, the wavelength emitted by the receding atom will be slightly larger than the wavelength emitted by a stationary atom. Particularly in solids, the atomic motions are complicated due to the fact that the crystal structure, nature of the bondings, temperature, and many other factors determine the motions and frequencies of the resulting photons. Collision and thermal broadening are uniform and apply to each atom. Hence, broadenings due to these are called *homogeneous* broadening. Doppler broadening is more complex and is affected by local inhomogeneities in the crystal lattice. This broadening is called *inhomogeneous* broadening. The actual line width of the emitted laser light is due to a

combination of all three types of broadening and, therefore, difficult to calculate precisely. It is usually determined experimentally.

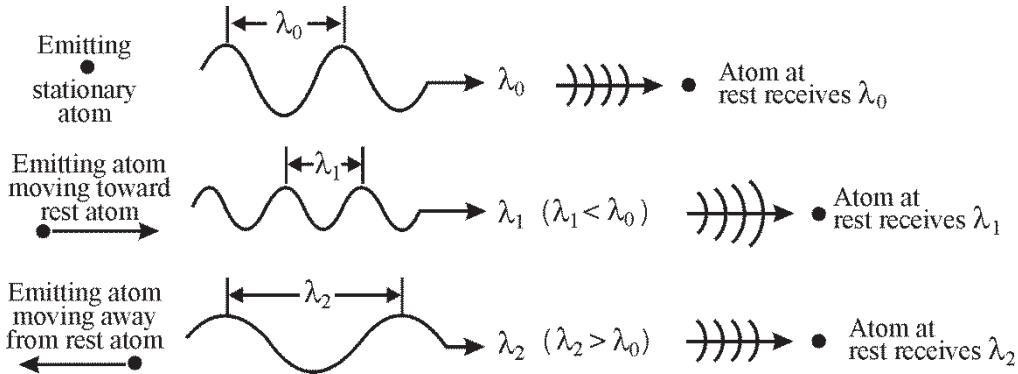


Figure 6-25 Wavelength of a photon emitted by a stationary or moving atom as “seen” by an atom at rest

Coherence

Temporal coherence—Coherence deals with the phase relationship between two waves whose wavelengths are close to each other. If two waves are of exactly the same wavelength and continue to be either in phase or out of phase with each other, for an infinite distance, then perfect coherence exists between them. But, a real laser is not a completely coherent source. Hence, coherence exists only during a limited time.

The distance along which two waves maintain the same phase relationship as they travel forward is called *coherence length*. The coherence length and the coherence time are related by the simple equation

$$\ell_c = c\tau_c \quad 6-12$$

where ℓ_c is the coherence length, τ_c is the time during which the phase of the wave remains fixed, and c is the speed of light in vacuum. For example, for ordinary neon light from neon signs, τ_c is of the order of 10^{-10} seconds and the coherence length is of the order of 3×10^{-2} m, about 3 cm. In contrast, lasers can have coherence lengths of many meters. This type of coherence is called *temporal coherence* since it depends on a *coherence time*. Temporal coherence is maximum for highly monochromatic radiation and such radiation will have long coherence lengths.

Spatial coherence—This type of coherence concerns the phase relationship of different parts of the laser beam *across the width* of the laser beam. The larger the width of the emitting light source, the smaller will be the *spatial coherence width* of the emitted light. For example, a quasi-monochromatic source such as a sodium vapor lamp has a spatial coherence width of about 0.005 cm. On the other hand, a laser whose beam width is much smaller than a quasi-monochromatic source will have a much larger spatial coherence width.

Beam divergence

An ideal laser would have no beam divergence (or spread) as it moves forward. Such an ideal beam is monochromatic and hence will have an infinite coherence length. However, a real laser

does have a beam divergence. In fact, beam divergence is indirectly a measure of the coherence of the beam. Smaller beam divergences are indications of better coherence and longer coherence lengths. An exaggerated, diverging laser beam is shown in Figure 6-26.

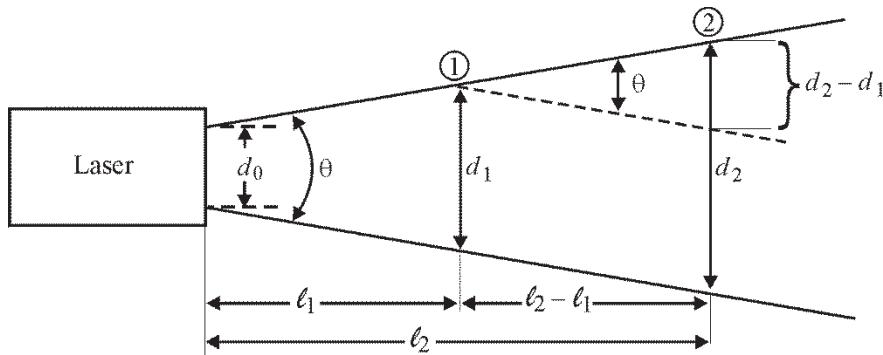


Figure 6-26 Beam divergence of a laser beam

The diameter of the beam at the output mirror of the laser is d_0 . At a distance ℓ along the beam, the beam diameter is d . This beam diameter is given by Equation 6-13.

$$d = (\ell \times \theta) + d_0 \quad 6-13$$

where d is the beam diameter at distance ℓ from the laser,
 d_0 is the beam diameter as it exits the laser,
 ℓ is a distance along the beam at which the beam diameter is d , and
 θ is the beam divergence, generally measured in radians.

A more useful equation can be written in terms of two diameters d_1 and d_2 at distances ℓ_1 and ℓ_2 , as shown in Figure 6-26. The beam divergence can now be given by Equation 6-14 as:

$$\theta = \frac{d_2 - d_1}{\ell_2 - \ell_1} \quad 6-14$$

By measuring the beam diameters at two different places along the beam, the beam divergence can be determined. Measurement of the beam diameter has to be done carefully and correctly in order to determine θ accurately. We will revisit this concern later.

Example 6

A laser beam has a diameter of 2.8 mm at a distance of 2.5 m from the laser. If the diameter increases to 4.3 mm at a distance of 6.8 m, find the beam divergence.

Solution: According to Equation 6-14,

$$\theta = \frac{d_2 - d_1}{\ell_2 - \ell_1} = \frac{4.3 \times 10^{-3} - 2.8 \times 10^{-3}}{6.8 - 2.5} = 0.35 \times 10^{-3} \text{ radians}$$

$$\theta = 0.35 \text{ milliradians}$$

Near- and far-field divergence—In the design of cavity mirrors, it is sometimes desirable to design the output coupler as a converging lens, with the inner surface of the lens serving as the output coupler mirror. See Figure 6-27. In such a design, the emitted beam first converges and then diverges as shown in the figure.

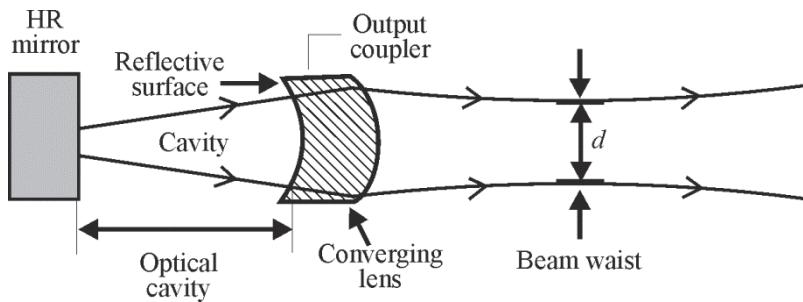


Figure 6-27 Collimation of a laser beam by a mirror/lens output coupler

If the beam diameter is measured near to the output coupler, the measurement of beam divergence will be in error because the beam is not yet uniformly diverging. The position where the beam converges to a minimum diameter before diverging is called the *beam waist*. In order to correctly measure the beam divergence, the beam diameters have to be measured at a sufficiently long distance from the beam waist. Two regions for beam divergence are specified. The *near-field divergence* region extends a distance ℓ_{NF} from the beam waist, where ℓ_{NF} is given by Equation 6-15.

$$\ell_{\text{NF}} \leq \frac{d^2}{\lambda} \quad 6-15$$

Here λ is the wavelength of the beam, d is the diameter of the beam waist, and ℓ_{NF} is the limiting distance of the near-field region from the beam waist. By contrast, the *far-field divergence* is given by Equation 6-16.

$$\ell_{\text{FF}} \geq 100 \frac{d^2}{\lambda} \quad 6-16$$

Where ℓ_{FF} is any distance from the laser greater than $100 \frac{d^2}{\lambda}$.

So, one should perform measurements of beam diameters at distances ℓ greater than ℓ_{FF} to obtain the actual beam divergence.

Example 7

A laser whose output beam wavelength is $1.06 \mu\text{m}$ has an effective output aperture diameter of 1.3 mm . Find the near- and far-field divergence. (Assume that the beam waist is at the effective output aperture diameter.)

Solution:

$$\ell_{\text{NF}} \leq \frac{d^2}{\lambda}$$

$$\text{Near-field divergence: } \ell_{\text{NF}} \leq \frac{(1.3 \times 10^{-3})^2}{1.06 \times 10^{-6}} = 1.59 \text{ m}$$

Thus, the near field extends from the beam waist out to a distance of 1.59 m.

$$\begin{aligned} \text{Far-field divergence: } \ell_{\text{FF}} &\geq 100 \times \frac{d^2}{\lambda} = 100 \times 1.59 \text{ m} \\ \therefore \ell_{\text{FF}} &= 159 \text{ m} \end{aligned}$$

One must therefore measure the true beam divergence far from the laser at distances of 159 meters (longer than a football field) or longer.

Diffraction-limited beam divergence—When a laser beam passes through an aperture of diameter d , a certain amount of light spreads outside of the aperture edges. Since diffraction is a natural occurrence, one cannot obtain a beam divergence or spread of **lesser** value than that dictated by diffraction. The minimum value permitted, in the presence of diffraction, is referred to as the *diffraction-limited beam divergence*. This minimum beam divergence, according to laser theory, is given by Equation 6-17. It is always less than that given by Equation 6-14.

$$\theta_{\min} = \frac{1.27\lambda}{d} \quad 6-17$$

The constant 1.27 is a value derived from cavity parameters, d is the diameter of the beam waist or effective aperture, and λ is the wavelength of the laser beam.

Example 8

A laser has an effective output aperture diameter d of 1.3 mm at a wavelength of 514 nm. Find the diffraction-limited beam divergence θ_{\min} .

Solution: According to Equation 6-17,

$$\theta_{\min} = \frac{1.27\lambda}{d}$$

$$\theta_{\min} = \frac{1.27 \times 514 \times 10^{-9}}{1.3 \times 10^{-3}} = 5.02 \times 10^{-4} \text{ radians}$$

$$\theta_{\min} = 0.5 \text{ milliradians} \quad (\text{The measured beam divergence would be larger than this.})$$

Laser light intensity

Intensity E of light (often called irradiance) is given by Equation 6-18:

$$\text{Intensity } (E) = \frac{\text{Power } (P)}{\text{Area } (A)}, \text{ usually in units of } \frac{\text{watts}}{\text{meter}^2} \quad 6-18$$

Power of a laser beam is the rate at which the optical energy is delivered by the beam. It is the ratio of energy and time.

$$\text{Power } (P) = \frac{\text{Energy}}{\text{Time}}, \text{ usually in units of Joules/sec or watts} \quad 6-19$$

Since intensity (irradiance) $E = \frac{P}{A}$ and the area, if circular, is $A = \frac{\pi d^2}{4}$, we have another form of

Equation 6-18.

$$E = \frac{4P}{\pi d^2} \quad 6-20$$

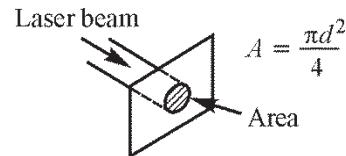
Example 9

A 5-mW laser irradiates a target area of diameter 0.2 cm. Find the irradiance E if all of the laser power falls within the circle of 0.2 cm diameter.

Solution: According to Equation 6-20,

$$E = \frac{4P}{\pi d^2} = \frac{(4)(5 \times 10^{-3} \text{ W})}{(3.14)(0.2 \times 10^{-2} \text{ m})^2} = 1.59 \times 10^3 \text{ W/m}^2$$

the irradiance on target is about 1,600 watts per square meter or 0.16 W/cm².



Laser beam diameter

The profile of a laser beam can be obtained by measuring the intensity across the beam. The cross-sectional intensity profile of a TEM₀₀ laser beam is shown in Figure 6-28.

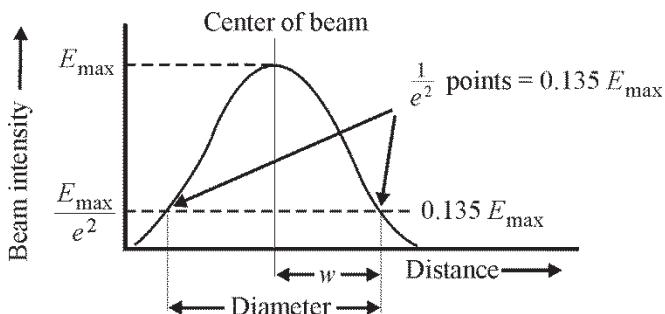


Figure 6-28 Width of a TEM₀₀ laser beam at the $1/e^2$ points

The beam intensity falls off on either side of the beam center. The intensity decreases gradually to zero. Hence, it is difficult to define exactly what the beam width is. In order to compare beam diameters of different laser beams, a beam diameter is defined. This is the distance between the $(E_{\max} \times 1/e^2)$ points of beam intensity on either side of the beam center. Half of the distance is denoted by the symbol w .

The relationship between the diameter of the beam and the diameter of an aperture in the path of the beam has a significant effect on how much power is transmitted through the aperture.

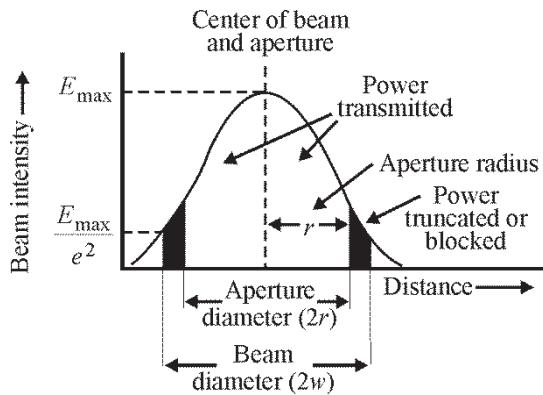


Figure 6-29 Transmission of a TEM_{00} laser beam through an aperture smaller than the beam diameter

The beam power transmitted through a circular aperture of radius $r = a$, compared to the total power incident on the aperture, is given by Equation 6-21.

$$\Phi_{\text{frac}} = 1 - e^{-2\left(\frac{a}{w}\right)^2} \quad 6-21$$

Where a is the radius of the circular aperture, w is the beam radius at the $1/e^2$ points, and Φ_{frac} is the fraction of incident beam power that is transmitted. As can be seen from Figure 6-30, as the ratio a/w becomes smaller, the transmission is reduced considerably.

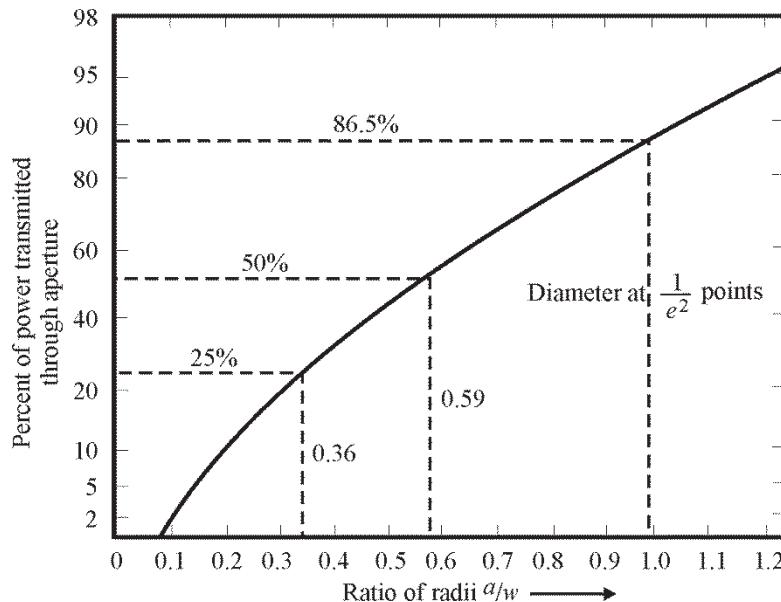


Figure 6-30 Graph showing percent of beam power transmitted versus the ratio of aperture radius to beam radius for a TEM_{00} beam

For very small values of a/w , the intensity drops almost exponentially. At a ratio of $a/w = 1$, where the $1/e^2$ beam diameter equals the aperture diameter, 86.5% of the beam power gets through. So, one must choose the aperture size relative to the beam size carefully when trying to get power through an aperture. To obtain a pure TEM₀₀ output from a laser, a small aperture is used in the laser cavity. A small aperture blocks the higher-order modes, such as those shown earlier in Figure 6-21, and passes only the TEM₀₀ mode. However, such a small aperture inevitably reduces the TEM₀₀ beam power and increases the diffraction losses.

Example 10

An aperture of diameter 0.8 mm is placed in the path of a TEM₀₀ beam of 1.3 mm diameter. Find the fraction of incident beam power that is transmitted through the aperture.

Solution: According to Equation 6-21, where $a = 0.4$ mm and $w = 0.65$ mm,

$$\Phi_{\text{frac}} = 1 - e^{-2\left(\frac{a}{w}\right)^2} = 1 - e^{-2\left(\frac{0.4}{0.65}\right)^2}$$

$$\Phi_{\text{frac}} = 1 - e^{-0.76} = 1 - 0.47$$

$$\Phi_{\text{frac}} = 0.53 = 53\%$$

So 47% of the incident beam is blocked while 53% gets through.

Focusing a laser beam

Laser beams can be focused to a very small *spot size*. The ability to focus the beam to a very small size depends both on the quality of the beam and the quality of the lens used to focus the beam. The diameter of the *spot* of a focused beam (Figure 6-31) is given by Equation 6-22.

$$d = f\theta \quad 6-22$$

Where f is the focal length of the convex lens, d is the diameter of the focused spot, and θ is the beam divergence of the incident beam. The smaller the beam divergence and the smaller the focal length of the lens, the smaller will be the spot size. Focusing a laser beam is extremely important in laser applications in surgery and micro welding.

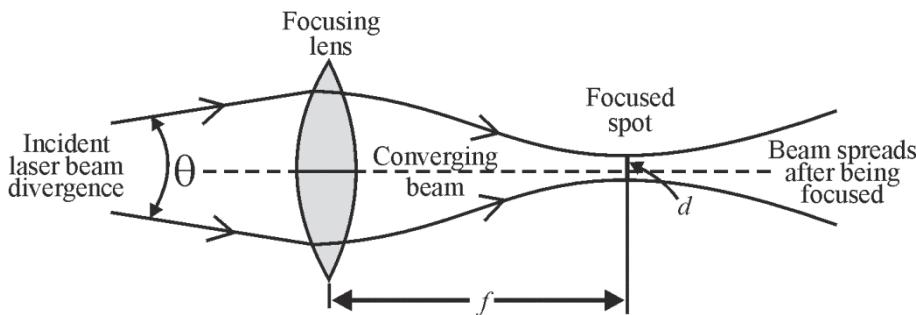


Figure 6-31 Focusing a laser beam

Example 11

A laser has a beam divergence of 3.2 mrad. The beam is focused by a lens of focal length 1.95 cm. Find the diameter of the focused spot.

Solution: Making use of Equation 6-22,

$$d = f \times \theta$$

$$d = (1.95 \times 10^{-2} \text{ m}) \times (3.2 \times 10^{-3} \text{ rad})$$

$$d = 6.24 \times 10^{-5} \text{ m} = 62.4 \mu\text{m}$$

Pulse properties of a laser

Using a laser in a pulse mode has many advantages. The beam parameters can be manipulated to suit the application. Pulse properties are briefly discussed here. A pulse of power versus time has a bell shape. For simplicity, it is assumed to be a triangle. See Figure 6-32.

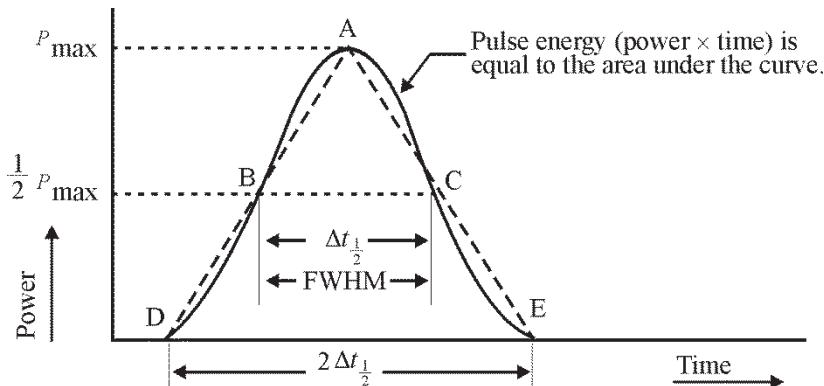


Figure 6-32 Energy in a laser pulse

The peak of the triangle at A is P_{\max} (the peak power of the pulse). The *pulsewidth* $\Delta t_{1/2}$, distance BC, is the width of the pulse at half the height of the pulse, and is given in seconds. The pulsewidth is referred to as the full width at half maximum (FWHM). The total time duration of the pulse is represented by the width at the bottom of the pulse, distance DE. It is equal to $2 \times \Delta t_{1/2}$. The area of a triangle is $\frac{1}{2} \times \text{base} \times \text{height}$. The energy of the pulse, which is given by the product of power \times time, can be approximated by substituting the shape of the triangle for the true shape of the pulse. Thus,

$$\text{Area of a triangle} = \frac{1}{2} \times \text{base} \times \text{height}$$

$$\text{Area of pulse} \approx \text{area of triangle DAE} = \text{energy of pulse}$$

$$\therefore \text{Energy of pulse (E)} \approx \frac{1}{2} \times \text{base} \times \text{height} = \frac{1}{2} \times (2\Delta t_{1/2}) \times P_{\max} = (\Delta t_{1/2}) \times P_{\max}$$

So,

$$E = \Delta t_{1/2} \times P_{\max}$$

6-23

When the laser output consists of a series of pulses, it is called a *pulse train*. The characteristics of such a pulse train are as follows. The time from the beginning of a pulse to the beginning of the next pulse is called the pulse repetition time (*PRT*). The energy of the pulse, which is equal to the area of the triangle, is also the same as the rectangle whose width is *PRT* and whose height is P_{avg} (the average power of the pulse). See Figure 6-33.

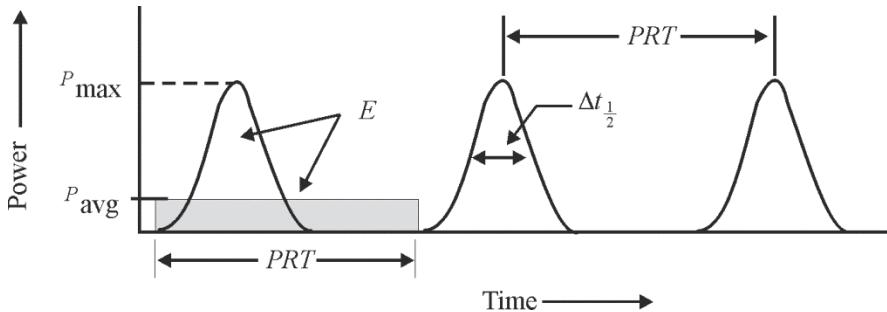


Figure 6-33 Average power and pulse repetition time of a pulse in a pulse train

The pulse energy in terms of *PRT* and P_{avg} is

$$E = \Delta t_{1/2} \times P_{\text{max}} = P_{\text{avg}} \times PRT \quad 6-24$$

The ratio of pulse width $\Delta t_{1/2}$ and pulse repetition time *PRT* is called the *duty cycle (DC)*. Rewriting Equation 6-24 in terms of the ratio of P_{avg} and P_{max} , we get an expression for the duty cycle *DC*:

$$DC \equiv \frac{P_{\text{avg}}}{P_{\text{max}}} = \frac{\Delta t_{1/2}}{PRT} \quad 6-25$$

The reciprocal of the pulse repetition time (*PRT*) is called the pulse repetition rate (*PRR*) and is given by Equation 6-26.

$$PRR = \frac{1}{PRT} \quad 6-26$$

Additionally, the pulse energy can be expressed in terms of the pulse repetition rate *PRR* as given by Equation 6-27.

$$E = \frac{P_{\text{avg}}}{PRR} \quad 6-27$$

In practice, *PRT* (and hence *PRR*), along with the pulse width, pulse height, and duty cycle *DC* can be controlled. This gives great flexibility in controlling the beam parameters of pulses in a laser pulse train.

Example 12

A particular pulsed laser has an average power of 28 mW. The pulse width is 2.8 μ s and the pulse repetition time is 1.3 ms. Find the duty cycle, maximum power and energy per pulse.

Solution: From Equation 6-25, we can find the duty cycle DC as follows:

$$DC = \frac{\Delta t_{1/2}}{PRT} = \frac{2.8 \times 10^{-6} \text{ s}}{1.3 \times 10^{-3} \text{ s}} = 2.15 \times 10^{-3}$$

This tells us that the FWHM of a pulse in the train is about two thousandths of the time between the pulses in the pulse train. So, the pulses are narrow and widely separated.

Again, using Equation 6-25, we can change the form and solve for P_{\max} to obtain:

$$P_{\max} = \frac{P_{\text{avg}}}{DC} = \frac{28 \times 10^{-3} \text{ W}}{2.15 \times 10^{-3}} = 13.0 \text{ Watts}$$

Then, using Equation 6-24, we can solve for the pulse energy E :

$$E = P_{\text{avg}} \times PRT$$

$$E = (28 \times 10^{-3} \text{ W}) (1.3 \times 10^{-3} \text{ s}) = 36.4 \times 10^{-6} \text{ Joules}$$

$$E = 36.4 \mu\text{J}$$

Equivalently, using a different part of Equation 6-24, we can solve for E as follows:

$$E = P_{\max} \times \Delta t_{1/2} = (13.0)(2.8 \times 10^{-6}) = 36.4 \times 10^{-6} \text{ Joules}$$

Thus, $E = 36.4 \mu\text{J}$, the same result.

Example 13

The output pulse of a Q-switched laser has a pulse width of 6 ns and energy 1.2 J. Find the peak power.

Solution: Using Eq. 6-24, we have:

$$P_{\max} = \frac{E}{\Delta t_{1/2}} = \frac{1.2 \text{ J}}{6 \times 10^{-9} \text{ s}} = 0.2 \times 10^9 \text{ Watts}$$

$$P_{\max} = 200 \text{ megawatts}$$

A Brief Survey of Different Types of Lasers

A brief survey of the different types of lasers is given here. A table with some of the important parameters of different types of lasers is given in Table 6-2.

Neutral atom lasers

These are lasers where the active medium is electrically neutral. Subjecting the medium to a high voltage ionizes the atoms. Ionization current is produced with electrons moving towards the positive electrode and the positive ions moving towards the negative electrode. The excited states of these gases have longer lifetimes. Hence, for a brief period, a population inversion can be produced. Neon and cadmium are well-known laser hosts in this category. In the HeNe laser, Helium atoms, which are light and can be easily excited, collide and transfer energy to the excited state of Neon through non-radiative collision transfers. The stimulated photons are

produced when electrons jump from the metastable energy level to the lower laser energy level. These photons are optically amplified. Such lasers are four-level lasers and produce output in the visible (HeNe) and ultraviolet (HeCd) regions. The output power of these lasers is low and is mostly used for low power applications. The most commonly used wavelength for HeNe lasers is 632.8 nm, though this transition is not the most efficient. HeNe lasers can also produce a green wavelength (543 nm). These lasers operate with a voltage difference of a few hundred volts and current of a few milliamperes. Beam divergence of these lasers is quite small and line broadening is mainly due to collision and Doppler broadening.

Ion lasers

The active medium of an ion laser is a gas consisting of a singly-ionized inert gas such as Argon or Krypton. The gas is subjected to a low voltage/ high current, which produces ionization. The terminal level for lasing in an ion laser is an ionized state rather than an atomic state. The atoms have to be constantly kept in an ionized state and further excited to a higher state with a longer lifetime. The constant high current requires complicated current stabilization circuits and cooling systems.

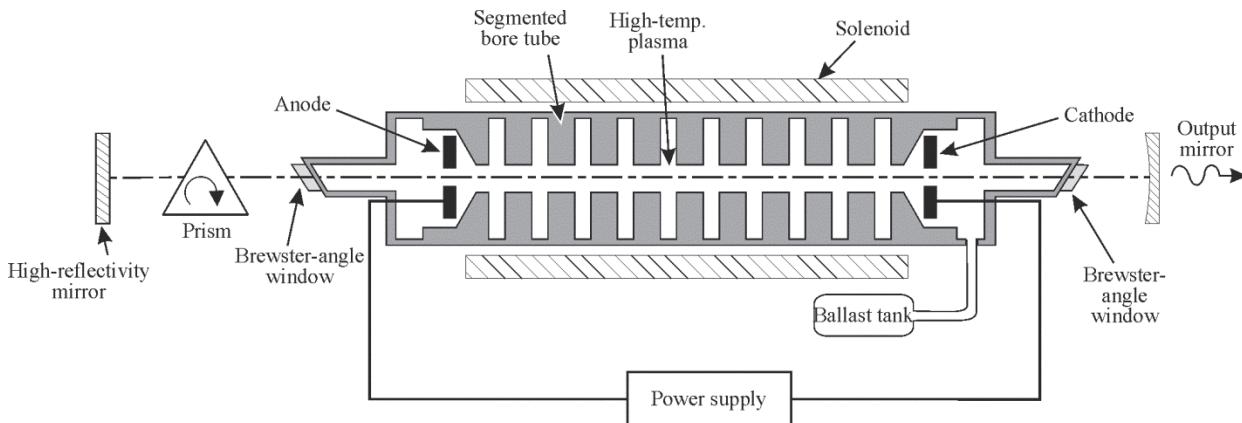


Figure 6-34 Schematic diagram of an Argon laser

The advantage of ion lasers is their ability to be *tuned* for different wavelengths. These lasers produce several wavelengths simultaneously. Thus, by using a prism in the cavity, a particular wavelength can be selected. See Figure 6-34. In general, ion lasers have a small beam divergence and long coherence length.

Molecular lasers

The active medium of these lasers consists of molecules instead of atoms or ions. Molecules have rotational and vibrational levels within which lasing action can take place. Among the molecular lasers, CO₂ is the most well-known. It can produce several thousands of kilowatts of power, and hence, it is used in materials processing. A mixture of He, N₂, and CO₂ in the ratio of 8:3:1 is used in the CO₂ lasers. These lasers are low current (5–30mA), high voltage (5–10kV) devices and require only commercial carbon dioxide gas. The CO₂ laser has a wavelength output in the far infrared (10.6 μm). In the CO₂ lasing medium, nitrogen molecules are excited by an electrical discharge and they in turn transfer energy to CO₂ molecules by collision. Lasing takes

place between allowed rotational/vibrational levels in CO₂. The CO₂ molecules return to the ground state by colliding with He atoms. These lasers can be used in a pulsed mode to produce peak pulses of several mega joules with pulse widths of a few hundred nanoseconds and pulse repetition rates (PRR) of 0.5 to 500 pulses per second (pps). Nitrogen lasers operate in the ultraviolet region (337.1 nm). The N₂ laser can produce very large peak powers (>100 kW) at 100 pps. Nitrogen lasers are mostly used to pump dye lasers.

Excimer lasers

These lasers have an active media made up of molecules that are formed during a chemical reaction. For example, Xenon, an inert gas, and chlorine, a very active halogen, normally do not form a molecule. However, under high pressures and temperature, they can be made to form the molecule XeCl. This molecule has an excited state from which lasing action can take place. Most excimer lasers produce wavelengths in the ultraviolet region and can produce pulses with peak powers of the order of 10⁹ W. In addition, these lasers can produce “ablation” of solid materials (direct conversion from solid to gas), and hence, are very useful. The excimer gases are toxic, and hence great care must be taken in the waste disposal of these gases.

Solid-state lasers

Single crystals of transparent solids are used as the active medium in these lasers—such as Nd:YAG. A suitable “guest” material (Nd) is “doped” into the host material (YAG) while the single crystal is growing. The guest atoms have sharp electronic levels with long lifetimes. Most often, these solids are pumped by flash lamps. In recent years, diode lasers have been used as pumping sources. Both axial and transverse pumping is possible. Most of the solid-state lasers have several devices such as Q-switches, mode lockers, and frequency doublers in the cavity (Figure 6-35). These devices enable a better manipulation of the output beam. Solid-state lasers require very little maintenance since the crystals remain unchanged over many years.

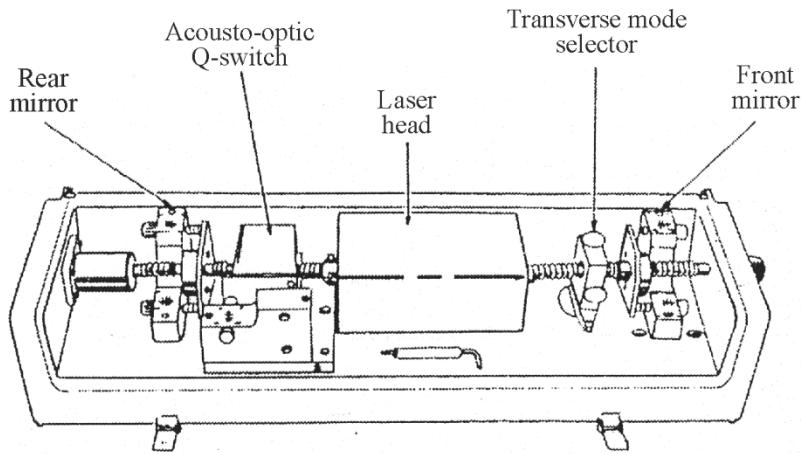


Figure 6-35 Schematic diagram of a Nd:YAG laser

Solid-state lasers have slightly larger beam divergences compared to gas lasers. The best-known solid-state lasers are RUBY (Cr:Al₂O₃), Nd:glass and Nd:YAG. In recent years, “vibronic” lasers have been developed. These lasers can be “tuned” like dye lasers. Several “bands” of

tunable wavelengths can be produced in these lasers. Ti•Sapphire, Alexandrite (Al_2O_3), and YLF are tunable lasers. These lasers can be operated in continuous as well as pulse modes.

Dye lasers

Many organic dyes when dissolved in alcohol have wide bands of fluorescence and are suitable as amplifying media for tunable lasers. The most well-known among these are Rhodamine 6G and Rhodamine B. Tunable wavelengths for these lasers include practically the entire visible region. Dye lasers can be pumped by Argon lasers (Figure 6-36). Dye degradation and turbulence are two factors that make these lasers unstable compared to the tunable vibronic lasers. Dye lasers can also be used in continuous and pulsed modes.

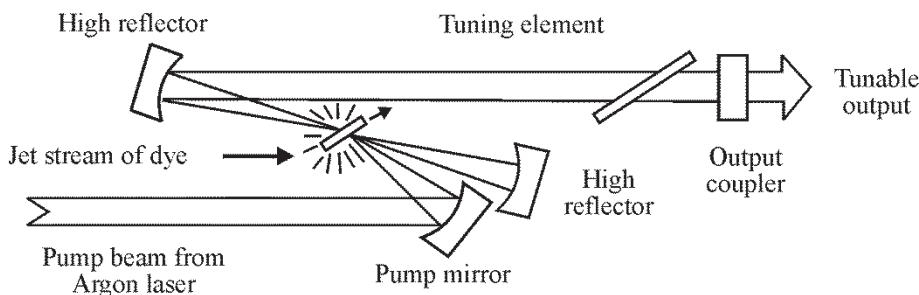


Figure 6-36 Schematic diagram of a dye laser pumped by an Argon laser

Diode lasers

Semiconductor diode lasers are solid-state lasers. However, the lasing action in them is different from that of the solid-state lasers such as Nd:YAG. Compound semiconductors such as gallium arsenide or indium antimonide can be doped with certain materials to make them behave like materials with excess electrons (N-type) or excess “holes” (P-type). If two such materials are joined to form a sandwich, it is called a P-N junction. Many interesting phenomena take place at this junction when a positive or negative voltage “bias” is applied to this junction. For example, a P-N junction in which both the P-side and the N-side are heavily doped creates an “unstable” junction. If a forward bias is applied to such a junction, electrons and holes rush from opposite sides of the junction and knock off further electrons to produce photons. Under certain circumstances, these photons can be stimulated photons. Mirrors coated on either side of the junction amplify the photons (Figure 6-37). In some cases, the semiconductor’s cleaved faces themselves can function as mirrors.

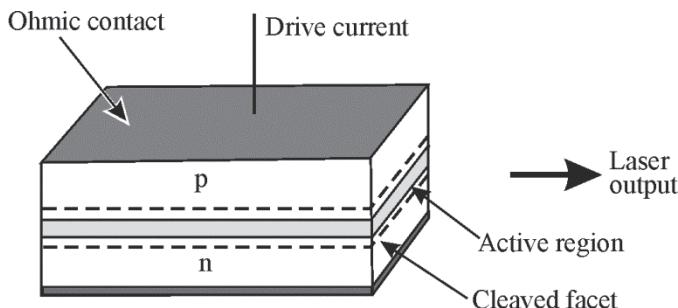


Figure 6-37 Schematic diagram of a diode laser

The great advantage of diode lasers is their small size and the low voltage needed to operate them. Semiconductor lasers can produce several watts of power when the diodes are used in arrays. A basic knowledge of solid-state physics is needed to understand the intricacies of diode lasers.

In Table 6-2, by way of a summary of this module, we present laser output parameters (wavelength, power, and beam divergence) of some well-known gas, liquid, solid-state, and diode lasers.

Table 6-2. A Survey of Some Laser Output Parameters

Type		Wavelength (nm)	Power output TEM_{00} (W)	Beam Divergence (mrad)
Gas	Atomic			
	HeNe	632.8	80×10^{-3}	1.0
	He-Cd	325.0	50×10^{-3}	0.5
	Ion			
	Ar	457-514	10.0	0.8
	Kr	350-799	8.0	0.8
	Molecular			
	CO ₂	10.6×10^3	10^6 (multimode)	1.0
	CO	4.0×10^3	10^3 (multimode)	1.0
	N ₂	337.1	3×10^5	1×7
	Excimer			
	XeFl	351	125	4.5×1.5
	XeCl	308	110	4.5×1.5
Liquid	Dye			
	R6G	540-630 (Ar ⁺ pumped)	1.0	2.0
Solid-state	Ruby	694.3	5.7×10^3	5.0
	Nd:YAG	1.06×10^3	5.0	5.0
	Nd:glass	1.06×10^3	1.0×10^4	5.0
	Ti•Sapphire	660–1100	1.8	2.0
	Alexandrite	700–818	20.0	2.0
	YLF	1.05×10^3	0.5	2.0
Diode	GaAs (single)	904	2.0	20×200
	GaAs (array)	850	25.0	20×200

LABORATORIES

Laboratory 1-6A: Measurement of Beam Diameter and Beam Divergence

Go to
[http://optecvideo
.opteccrm.org/](http://optecvideo.opteccrm.org/) for
an introduction to
this activity.



Equipment

HeNe laser
Optical power meter
Linear translator with micrometer
Sharp-edged blade, lab jacks and meter stick.

Procedure

The sharp-edged blade is vertically mounted on a linear translator such that the blade can be moved slowly across the laser beam by turning the adjusting micrometer screw. The laser, linear translator, and detector head are mounted on lab jacks and aligned such that the laser beam, razor blade edge, and detector are in a straight line, as shown in Figure 6-38.

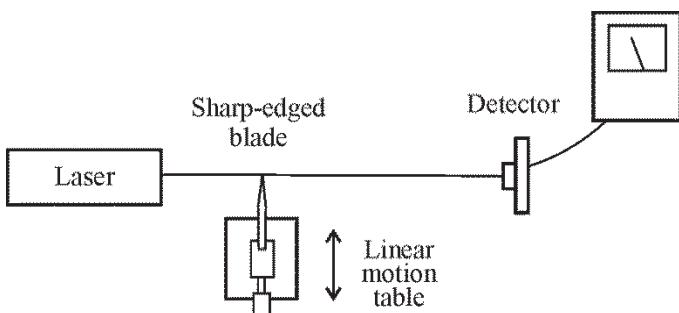


Figure 6-38 Experimental set up for measuring beam diameter

First, the distance between the laser (at the output coupler) and the detector is measured (ℓ_1). The micrometer screw is turned until the blade completely blocks the laser beam. Obviously, there will be no reading on the detector since no light is falling on the detector head. Now, the blade is slowly withdrawn until a small amount of light reaches the detector head. The micrometer position and the reading on the detector are noted. The micrometer is turned continually in the same direction in small but equal steps. The micrometer readings and the corresponding detector readings are noted. This is continued until the detector reads a maximum power. A graph plotting detector reading (power) versus sharp-edge blade position (micrometer reading) is shown in Figure 6-39. Since the beam will be symmetrical on either side of the central point, the bell-shaped curve can be completed. Such a curve was shown earlier in Figures 6-28 and 6-29. The $1/e^2$ points are noted on the curve. The distance between the $1/e^2$ points on either side of the central point gives the beam diameter (d_1). The detector head is moved to a farther distance (d_2) and the entire procedure is repeated to find the $1/e^2$ diameter

(d_2) again. The beam divergence is calculated using Equation 6-14. The results are tabulated in Table 6-3.

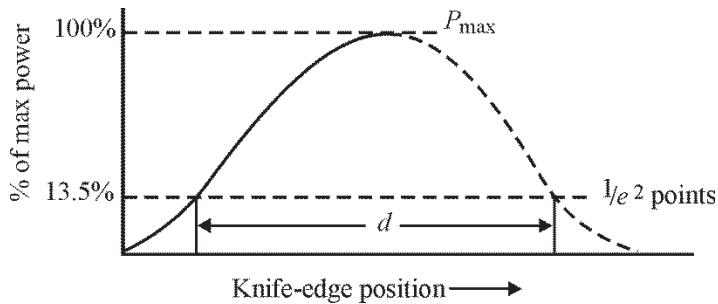


Figure 6-39 Graph showing power read by detector head versus knife-edge position in the beam. The dotted portion of the curve is completed based on symmetry.

Table 6-3. Measurement of Beam Diameter and Beam Divergence

Position of detector	Micrometer position	Power	$1/e^2$ position on left	$1/e^2$ position on right	Diameter	$\theta = \frac{d_2 - d_1}{\ell_2 - \ell_1}$
$\ell_1 =$						
			=	=	$d_1 =$	
$\ell_2 =$						
			=	=	$d_2 =$	$\theta =$

Questions

1. Why are the $1/e^2$ points used for measuring the diameter of the beam?
2. Does the diffraction-limited beam divergence of a laser change with wavelength? (See Equation 6-17.)
3. How is beam divergence related to the effective output aperture of a laser?
4. Were your measurements of the beam divergence θ carried out in the laser's far field?

Laboratory 1-6B: Laser Basics

In this laboratory, you will complete the following tasks:

- Explore the history of lasers and review laser fundamentals

Equipment

None required

Procedure

1. Review the following module and answer the following questions:
<http://www.cyberstreet.com/laserone/lasers/>

- A. What does the Acronym LASER stand for?

- B. What scientist first proposed stimulated emission was possible?
_____ What year? _____

- C. Who built the first operating laser? _____
What year? _____

- D. For a gas laser, explain the following terms:

Gain Medium

Pumping Source

Absorption

Metastable State

Polarization

Resonant Cavity

- E. Clearly describe three ways in which laser light is different than normal light.

2. Review the following module and answer the following questions:
<http://www.howstuffworks.com/laser.htm>
 - A. Compare and contrast the operation of a Coleman lantern to that of a laser.
 - B. Explain each of the following terms.
Population Inversion
 - Stimulated Emission*
 - C. Explain how laser light is created in a three level laser system (Ruby Laser)
 - D. List and provide an example from each of the five different types of active media. State the wavelength of each cited example.

Laboratory 1-6C: HeNe Lasers and High Voltage Testing

In this laboratory, you will complete the following tasks:

- Measure the operating efficiency of a He-Ne laser.

DANGER: You MUST wear safety glasses when working with any un-terminated laser beams. Make sure that the beam is properly terminated into a non-reflective beam stop prior to removing any safety glasses. Never look directly into the beam of a laser!

DANGER: You will be working with DC voltages that could be as high as 1,500 V and a voltage pulse that could be as high as 5,000 V. Proper electrical safety procedures will be followed without exception.

Equipment

High Voltage Probe
He-Ne Laser Tube
Triangular Optical Rail
Electrical Tape
He-Ne Power Supply (from Newport Kit)
Two He-Ne Tube Clips
Alden Connector
75 k Ω Ballast Resistor (2 Watt Minimum)
Optical Power Meter
Alligator Clips

Procedure

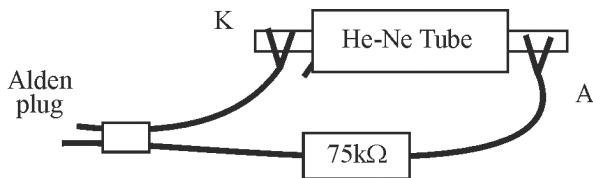


Figure 6-40

1. Connect the He-Ne tube as shown. Make sure that all connections are isolated from your person and from other conducting surfaces.
2. Connect the Alden plug to the power supply. If the tube does not come on after the three-second-safety delay, then immediately turn power supply off and wait until the tube is discharged before touching it.
3. Measure the steady-state operating voltage at the anode. This should be between 1000 and 1500 Volts. Measure this by holding the probe on the anode and noting the voltage after about 5 seconds of laser operation.
4. Turn off the laser and discharge the tube with the HV probe. Carefully connect the ammeter in series with the ballast resistor. This should be only a few millamps.

5. Use the optical power meter to measure the optical power emitted by the tube. This should only be about 1 milliwatt.

Laser Tube Identification _____

Tube Voltage _____

Tube Current _____

Power Into Tube = $V \cdot I =$ _____

Optical Power = _____

Tube Efficiency = $(P_{out}/P_{in}) \cdot 100\% =$ _____

WORKPLACE SCENARIO

Here is your opportunity to use the concepts learned in this module to solve an actual problem that could arise in a photonics company. Your instructor will provide directions for developing a solution.

Principles of Lasers: Solid State Laser Crystals

Scenario

After graduating with a two year associate degree in photonics technology, you joined a company that manufacturers crystals for solid state lasers that include those used in Nd:YAG lasers. Your company has three main departments: Crystal Growth, Crystal Preparation, and Crystal Test.

Your title is Senior Photonics Engineering Technician and you work in the Crystal Test Department. Your job involves measuring critical crystal rod parameters to ensure they meet specifications. To do your job, you insert completed crystals into the optical cavity of a Nd:YAG laser and tune it by aligning the high reflectivity and optical coupling mirrors located at each end of the optical cavity. Once the laser is aligned, you test the performance of the inserted crystal by measuring its power output and beam quality as well as some other critical parameters. These measurements are then compared to the specifications developed by the engineers in your company.

In a recent meeting with your manager, you were told that an important customer is very concerned with the Polarization Extinction Ration (PER) of recently purchased laser crystal rods (Part Number 21451). The customer said crystal rods with a PER less than 40 dB significantly impact the beam quality and output power of the company's lasers. Your manager has asked you to investigate this problem and report your initial findings to her. To help with this investigation, your manager gives you a package of ten laser crystal rods she received from the concerned customer. These rods were tested by the customer and as shown in the Table I, five were found acceptable and five were deemed defective.

Rod #	PER (dB)	Output Power (W)	Customer Comments
1.	25	406	Defective
2.	31	450	Defective
3.	37	467	Defective
4.	32	422	Defective
5.	30	437	Defective
6.	49	523	Acceptable
7.	54	562	Acceptable
8.	44	508	Acceptable
9.	51	553	Acceptable
10.	47	511	Acceptable

Table I

To begin the investigation, you decide on two courses of action:

1. Assign a junior level technician to verify the customer's PER and output power measurements of the rods.
2. Research the specifications for the rods to see how the readings reported by the customer compare to the values agreed upon during contract negotiations.

After the junior level technician performed the verification test, the results were sent to you as an email attachment. Table II below contains these results.

Rod #	P ₁ (With Linear Polarized Input) (mW)	P ₂ (With Crossed Polarizer at Output) (μW)	P _{out} (Random Polarization) (mW)
1.	100	316.23	405
2.	110	110.00	448
3.	115	18.23	469
4.	105	66.25	422
5.	108	135.96	436
6.	134	2.12	520
7.	142	0.56	562
8.	128	4.05	510
9.	139	1.39	552
10.	130	2.59	512

Table II

Preliminary Results and Tasking

Your research into the “21451” crystal rod’s specification revealed some unexpected results. There is not a PER specification in your company for the “21451” crystal rods. You also learned from your research that your company’s minimum output power specification for the “21451” crystal rod is 400 mW. Records also indicated that during negotiations with your concerned customer, nothing was mentioned about a PER specification. When you provide this information to your manager, she confers with the Vice President of Sales. They decide that the concerned customer is such a high volume buyer that all future orders from them must meet their 40dB or more specification. She assigns you the following tasks:

1. Research Polarization Extinction Ratio (PER), what it is, how to measure it, and what causes it.
2. Determine how PER caused the customer’s complaint of low output power and reduced laser beam quality.
3. Use the data provided by the junior technician to calculate the PER and compare these results with the customer’s data. Comment on any discrepancies.
4. Develop an outline for implementing a PER test.

The manager asks you to summarize your results from these tasks in an e-mail to her.

PROBLEM EXERCISES AND QUESTIONS

1. Explain how spontaneous and stimulated emissions are produced. What are the differences in their properties?
2. If an atom moves to its ground state from an energy level 4.6 eV above the ground state, find the wavelength of the photon emitted.
3. Explain with a diagram the major components of a laser and how they work. Why should mirrors of high reflectivity be used in a laser?
4. Why is a three-level laser less efficient than a four-level laser? Explain why the position of the terminal level with respect to the ground state is important.
5. Why is a CW laser less efficient than a pulsed laser? Using a diagram, explain the relation between the loop gain and power output of a CW laser.
6. What are the different types of cavity configurations that can be used in lasers? What are the criteria by which the efficiency of the configuration is decided?
7. Why is it important to align the mirrors in a laser cavity? Explain how a gas laser cavity can be aligned using a low-powered HeNe laser.
8. What are the losses in a laser cavity? Explain the meaning and significance of the term *threshold gain condition*. A CW Nd:YAG laser contains mirrors whose reflectivities are $R_1 = 0.988$ and $R_2 = 0.78$ and a roundtrip loss of 0.6 %. Find the amplifier gain G_A during CW operation.
9. Why do longitudinal modes occur in a laser beam? A HeNe laser ($n = 1$) has a cavity length of 65cm and an output wavelength of 632.8 nm. Find the mode spacing.
10. Do all the longitudinal modes share the same gain? Is it better to have a larger number or a fewer number of modes? Explain. A laser has a mode spacing of 280 MHz and its fluorescence line width is 45 GHz. Find the number of longitudinal modes under the fluorescence linewidth.
11. A laser beam has a diameter of 3.4 mm at a distance of 2.35 m from the laser. If the diameter increases to 5.3 mm at a distance of 7.8m, find the beam divergence .
12. A laser whose wavelength is $1.06 \mu\text{m}$ has an effective output aperture diameter of 1.65 mm. Where are the near-field and far-field regions relative to the laser?
13. A laser has an effective output aperture diameter of 1.6 mm at 488 nm. Find the beam divergence
14. An aperture of diameter 0.9 mm is placed in the path of a beam of 1.8 mm diameter. Find the fraction of incident laser power transmitted by the aperture.
15. A laser has a beam divergence of 4.2 mrads. The beam is focused by a lens of focal length 2.05 cm. Find the diameter of the focused spot.
16. Explain the terms *pulse width*, *PRT*, and *PRR*. The output pulse of a Q-switched laser has a duration of 8 ns and an energy of 1.4 J. Find the peak power.

17. Explain the terms *Full Width at Half Maximum* and *duty cycle*. A particular pulsed laser has an average power of 32 mW. The pulse duration is $2.5\mu\text{s}$ and the pulse repetition time is 1.6 ms. Find the duty cycle, maximum power and energy per pulse.
18. What is the difference between gas lasers and solid-state lasers?
19. What role does Helium play in a HeNe laser?
20. What is the approximate beam divergence of atomic gas lasers such as HeNe and HeCd? How does this compare to the beam divergence of diode lasers?

MEET A TECHNICIAN

Michelle I. Redish



Michelle I. Redish is a proud employee of Northrop Grumman Corporation and plays a major part in homeland security. Michelle's education started in a university, but finished with an AAS in Lasers and Photonics Technology from Central Carolina Community College (CCCC).

"I saw some of the applications for which a laser can be used, and I was hooked. I wanted to do that. It was like that little light bulb going off. The same day, I transferred from the university to CCCC."

Having recently been promoted from Laser Technician I to Laser Technician II, Michelle also works on a program for land forces, creating thermal-view range finders.

"It is a measuring device for both short and long distances. A soldier can look through the range finder and report to the commanding officer, "We have spotted an enemy at this location, this many feet away."'"

Michelle sees more education in her future.

"I'm planning to go back to school to get a bachelor's degree in either optical engineering or chemical engineering," she says. "There are special coatings for optical components. I'd like to be a part of devising new and better ways to make those coatings."

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GLOSSARY OF TERMS

Absorption – when a substance takes in the electromagnetic radiation of light, converting it to internal energy, often thermal energy

Amplitude – the maximum displacement of the wave

Angle of deviation – an angle equal to the difference between the angle of incidence and the angle of refraction of a ray of light passing between two mediums with different refractive indexes

Antireflection coating – a coating that greatly reduces reflection

Beam divergence – the increase of the diameter of the laser beam as it travels, which is an indirect measure of beam coherence

Beam waist – the position where the beam converges to a minimum diameter before diverging

Blackbody radiation – also called thermal radiation is the spectrum of electromagnetic radiation emitted by an object at some absolute temperature T

Broadband filters – filters that transmit a certain band of wavelengths of light and block the light outside of this band

Coherent light – light consisting of waves which all have the same wavelength and phase angle

Concave – curving inward, like the topside of a spoon (where the food goes)

Convex – curving outward, like the underside of a spoon

Crest – the high point of a wave's amplitude

Critical angle – the angle of incidence beyond which rays of light passing from a medium with a higher refractive index to a medium with a lower refractive index are no longer refracted, but are totally reflected

Cut-off filters – filters that allow radiation up to a specific wavelength to pass through and abruptly cut off the remaining wavelengths

Diffraction – the slight bending of light as it passes around an object

Displacement – the vertical distance measured from the equilibrium position at any point along the wave

Focal length – the distance between the center of a lens or cured mirror and its focal point

Focal point – the point at which rays meet after reflection or refraction

Frequency – the number of cycles of the optical/laser wave in one second expressed in the unit hertz (Hz)

Ground state – the lowest energy level of an atom

High-reflection coating – a coating that significantly increases the surface reflectance of a surface

Incoherent light – light consisting of waves with differing wavelengths and/or differing phase angles

Index of refraction – the ratio of the speed of light in a vacuum to its speed in a material or the ratio of the sine of the angle of incidence over the sine over the angle of refraction

Interface – where two mediums meet

Interference – when two or more waves are superimposed to form a resultant wave of greater, lesser, or equal amplitude

Irradiance – radiant power per unit area upon the surface with a symbol E expressed in watts per centimeter squared.

Joule – the unit of energy in the international system of units (SI). 1 joule = 1 watt-second

Light ray – an imaginary line directed along the path that light energy follows

Light-emitting diodes (LEDs) – semiconductor devices that are directly modulated by varying input current

Longitudinal modes – modes based on standing waves created between the two reflecting mirrors on either end of the cavity

Luminous efficiency – the ratio of the visible light energy produced by a light source to the electrical energy needed to power the light source

Maximum permissible exposure (MPE) – limits that indicate the greatest exposure that most individuals can tolerate without sustaining injury

Monochromatic Radiation – the laser light's property of containing only one pure color and a narrow range of wavelengths

Narrow-band filters – filters that are usually interference based, where many layers are coated on a substrate so that only a specific wavelength is transmitted and the rest are reflected

Neutral-density filters – filters that have the same transmission for all wavelengths over a broad range of the spectrum

Nominal hazard zone (NHZ) – see *normal hazard distance*

Normal hazard distance (NOHD) – the region within which the level of direct, reflected, or scattered laser radiation is above the allowable MPE

Numerical aperture – a number [NA] that depends on the index of refraction of the cladding to that of the core of an optical fiber

Optical bench – see *optical rail*

Optical density (OD) – the logarithm to the base ten of the reciprocal of the transmittance at a particular wavelength.

Optical filters – devices that attenuate a certain portion of the electromagnetic spectrum, either in terms of wavelength or intensity

Optical rail – a long stable base on which optical components can be mounted

Optical tables – used instead of optical rails when optical elements must be aligned along more than one axis, and when vibration isolation is required

Optical thickness – a medium's optical thickness is the product of its refractive index and thickness

Period – the interval of time over which the wave repeats itself

Phase – the angular displacement of a point from the last positive zero crossing of the wave

Phase difference – the difference between the phase between two waves

Photometric filters – filters that mimic the human eye and transmit maximum light at 550 nm

Photon – the smallest division of a light beam that retains the properties of the beam, it is an elementary particle

Polarization – the direction or orientation of vibration of the electric field as the wave propagates through space

Polarized light – light in which the electric field oscillates all in the same direction

Q-switching – a method for obtaining short pulses from a laser by modulating the intracavity losses

Radiometric filters – filters that transmit light equally at all wavelengths

Reflection – when light waves bounce off of a surface

Refraction – when light waves are bent as they enter a medium from another medium with a different index of refraction

Refractive index – see *index of refraction*

Scattering – the redirection of light caused by its interaction with matter

Selective absorption – a substance only absorbs certain wavelengths of light and transmits

Sputtering – a technique used for larger substrates, which uses high voltage to knock particles onto the substrate where they condense and form a uniform coating

Substrate – the optical element on which the material is deposited

Surface abrasion – abrasion of a surface includes scratches on the surface due to harder materials coming into contact with the surface or by improper cleaning procedures

Total internal reflection (TIR) – a phenomenon that occurs when light strikes an interface at an angle greater than the critical angle, and is totally reflected within the initial medium

Transverse – perpendicular to or across an optical or electromagnetic wave front

Transverse modes – the pattern of the cross-section of a laser, in a plane perpendicular to the beam itself, caused by electric and magnetic fields

Trough – the low point of a wave's amplitude

Unpolarized light – light that has no specific orientation of electric field

Wave front – a series of adjacent points along which all motions of the wave are identical

Wavelength – the distance over which the wave repeats itself can be measured from crest to crest or trough to trough along the wave front

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