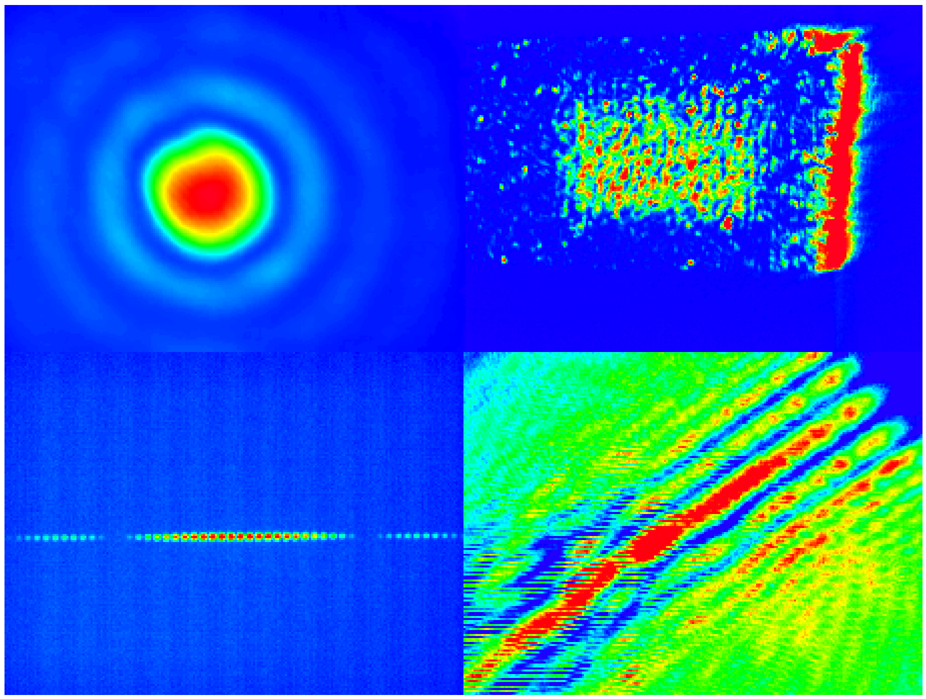
Modern Experimental Optics Laboratory Manual



Physics 3330
and
Applied and Engineering Physics 3300

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Introduction

Welcome to Physics 3330. The main purpose of this course is to explore the physical nature of light and its applications to current optical technology with a series of fundamental experiments. Each experimental setup is equipped with standard, off-the-shelf optics and opto-mechanical components to give you hands-on experience in practical laboratory techniques. Description of most components can be found in the Newport optics catalog which you can find in the laboratory and on the web at http://www.newport.com. Another good sources of information are catalogs of Edmund Optics (http://www.edmundoptics.com), CVI Melles Griot (http://www.cvimellesgriot.com), Thorlabs (http://www.thorlabs.com). They have sections with explanations and theoretical background information.

The projects cover a wide range of topics including geometrical optics (light rays), interference, diffraction, and polarization (classical wave properties). Nonlinear optics and quantum phenomena are not covered in this course. No particular book is mandatory for this course. However, it is a good idea to have one of the first two books described below. The first book is **Optics** by E. Hecht (4^{th} edition). This book covers almost all the important areas of optics and has many nice pictures and diagrams. **Fundamentals of Photonics** by B.E.A. Saleh and M.C. Teich is the other book worth having even if it's the *only* book on optics you are ever going to get. Its scope not only includes all the physics needed for this course, but also extends much beyond making it a definitive (yet easily accessible) reference on photonics (a more modern version of 'optics'). **Exploring Laser Light** by T. Kallard is another book you may find useful for the course. It concisely describes many different experiments and gives you an idea of how to perform an experiment. However, it does not give you any answers as to "WHY" it is going to work.

This lab manual is based on an earlier PHYS330 lab book (1990) by L. Hand, P. Krasicky, R. Warner and R. Silsbee. We are very grateful to the P330 TA's for many helpful suggestions.

Guidelines and Policies

The scheduled lab time is 6 hours per week. This amount of time may **not** be enough unless you have read the lab instructions and the supplementary chapters in the textbooks and **have thought** about what will be measured and why. Complete expertise of the material covered by the experiment being performed is not expected. With some prior understanding, you will master the experiment in a reasonable time.

My advice is: read the lab manual and the text, noting anything you don't understand so that you can ask the instructor during the lab. Remember, the lab manual is neither a "cookbook" nor a textbook. The explanation of the physics is kept to an absolute minimum and it is impossible to understand the subject from reading only the manual. **You will need to complete the assigned readings and go to lectures to understand fully the underlying principles of the experiments.**

A rather extensive and careful job is expected of the lab write-ups (a.k.a. lab reports), as detailed below. You should buy a laboratory notebook (a.k.a. logbook – graphed paper ideally with prenumbered pages) and to keep log of what you have been doing. You have to be able to produce the original raw data recorded (and dated) in your logbook to support any of your analysis in your report. Failure to do so may disqualify your lab write-up.

The lab write-ups and your lab performance (includes the class/lecture attendance, attitude, and ability to incorporate the feedback) will account for 85% of your grade. At the end of the semester there will be a final quiz that counts 15% towards your course grade. The final quiz will cover the lectures/experiments. It will also have an experimental section where you have to design your own short experiment.

These and additional guidelines are summarized below.

General:

1. Read the Laser Warning on one of the following pages. This is very important. Make sure you understand what is said there. If you have questions talk to the instructor.
2. We will be covering in the lectures most of the material you will need to understand the experiments, but occasionally you will be required to do some additional reading. You are responsible for reading the relevant sections in the textbook of your choice.
3. Depending on the number of students enrolled, you will be working in pairs in the laboratory. In that case, you and your partner can set up the experiments together. However, you will be required to take data separately, maintain your own logbook, and write lab reports independently.
4. If you must miss a lab, consult with the instructor **ahead** of time.
5. All data from a lab as well as the corresponding lab report must be kept in your laboratory notebook/logbook.
6. The lab **reports are due one week after the completion of the experiment**. You will not be allowed to start the next experiment before you have handed in your lab report. Unexcused late reports will be docked ***10% per day***. *If you receive no credit for two lab reports, you will fail the course!* This policy is necessary, since postponing lab reports

inevitably leads to a disaster for the student. If you feel that you have a valid excuse, talk to the instructor first, NOT after the report is overdue. Being too busy with other courses or having prelims is not a valid excuse.

During Lab Sessions:

1. Write the date for each lab session into your logbook.
2. You must take notes chronologically and number the pages consecutively. A good laboratory notebook has prenumbered pages. Whenever possible, you should also title your experiments or sub-experiments.
3. All data taken should be recorded as neatly as possible. You have lots of room in the lab book -- use it. Your writing should be LEGIBLE to other readers. **You should write in ink. Do not erase anything.** If something is recorded incorrectly, line it out with a single line and record the correct value next to it. Do not erase any data that you record. Don't be surprised if it turns out that the lined-out data is useful after all!
4. Make legible sketches of your experimental setup. Photographs taken from above can be helpful if all parts are properly labeled on them.
5. Make notes of any tricks you used to arrive at your results. Don't assume you will remember later -- write them down!
6. Use diagrams and tables! Make sure to give the units -- otherwise you might get confused later. For example, you might not know whether the data measured was in "cm" or "mm".
7. Use graphical analysis wherever possible. **Always** plot and record the data while you are doing the experiment.
8. Write down your estimates for measurement errors.

Lab Report:

1. Write the report on a computer word processor. LaTeX is recommended.
2. Labs should be written in the style of a Physical Review article (Go to the Web or to the library and look at a Physical Review paper, you might want to check at http://www.aps.org and go to the link for Physical Review A or Physical Review E from the Cornell Library homepages). Use a single column format, with one inch margins, and double line spacing. A basic template is given below.
3. Make use of graphs and tables wherever possible. If the data are plotted, only show the data in tables if you really think they add to the write-up.
4. The lab report must stand by itself without any reference to the Laboratory Manual.
5. Make use of citations within the text. You do not have to derive every equation; you can simply cite the sources. For example, give a citation in the references section of your lab report: S.G. Lipson, H. Lipson, and D.S. Tannhauser, *Optical Physics*, 3rd edition, Cambridge Univ. Press, Cambridge, 1995, Eq. (4.12), page 12.
6. Error analysis is an essential part of any experiment. It need NOT become an impossible tedious exercise if it is done sensibly. If you find it a burden, consult with the instructor; you are doing probably more than is useful or reasonable.

PHYS3330/AEP3300

Title

Your Name

Date

Abstract

The abstract is a brief, three- or four-sentence summary of what experiments will be described and what results were obtained. Describe the goal of the experiment, the method used for achieving it, give a short summary of the results and possibly a list of especially interesting findings.

Introduction

You should use one or two paragraphs to describe the physical phenomena to be studied and to motivate your experiments. Describe the topic or phenomenon being investigated; argue why the goal of the experiment is of interest, how similar measurements have been done in the past, and why the method used here is especially appropriate. Include general theory, meaning theory that does not only apply to your experiment. For experiment 1, for example, the introduction should mention Snell's law. If you need to cite a reference, use a footnote such as [1].

Theory

Review of the theory that is used in the experiment. Here you should use some judgment on whether a theory is very general and should be in the introduction, or whether it is more special to the experiment, and should therefore be in this section. The theory of Fresnel's equations is general and should be in the introduction. Brewster's angle is a corollary of that theory and could therefore also be in the introduction. However, you could also take the view that it is the specific corollary that you use for experiment 2, and you could therefore put it into this theory section.

Include derivations of specific formulas that will be used. For experiment 1C, for example, this would include the derivation of how n is related to the minimum angle of refraction. For experiment 2, for example, the last equation in the manual with tan over sin to get the difference between the phase advances in the overhead transparency should be derived here. This particular formula might not be easy to derive without help, ask the TA for help if needed.

Experimental Set-Up and Results

Describe your experimental set-up(s) and illustrate it in a graph. In the case of experiment 1, for example, you could describe how the prism is mounted and how you measured the minimum angle of refraction. Show the equations that relate what you measured to the quantity that is to be determined. List the results using tables and graphs, and discuss the sources of errors in your measurements. Tables that list results should also list errors, and figures that display data or results should also show error bars. Equations for the error analysis should be shown, but complex formulas for the error analysis should be in an appendix

Conclusions

Use this final paragraph to summarize your results with perhaps some mention of how the measurement technique(s) could be improved. Emphasize especially interesting findings.

Acknowledgement

Acknowledge help you have received from your instructor, the TA, your lab partner, etc.

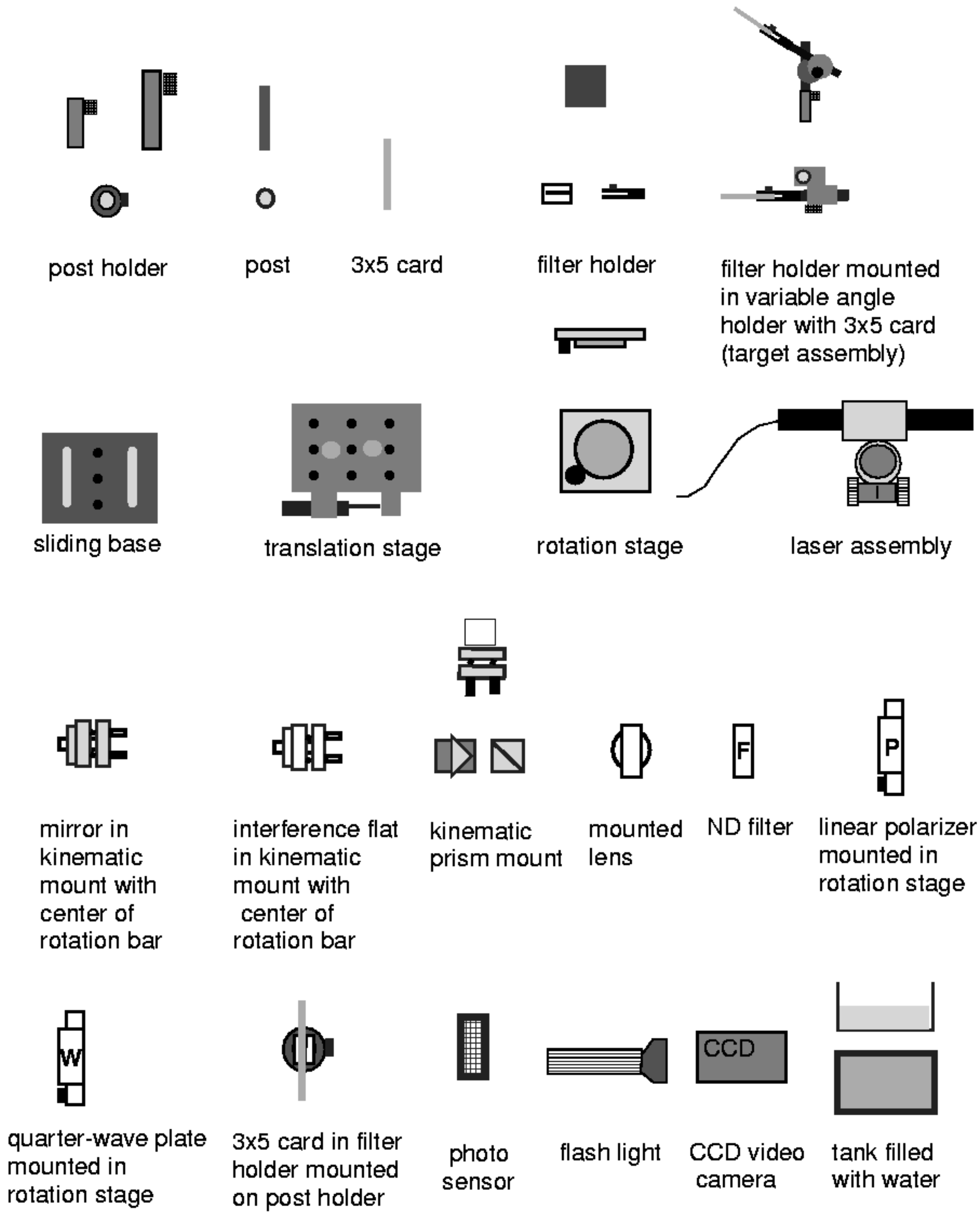
Appendix

Use this section for your lab notes and perhaps for any derivations (e.g., formulae for relating experimental parameters in your set-up, error analysis, etc.) that you think are too long to include in the main body of the text.

References

[1] E. Hecht, *Optics* (Addison-Wesley, Reading, 1998), pp. 68-70.

List of Symbols



LASER WARNING

All experiments are performed using a helium neon (HeNe, 632.8 nm) laser as the light source. The power of the laser is sufficient to cause permanent damage to the eye.

- **NEVER look directly into the laser tube or at a reflection from a specular surface!**
- **Do not wear rings or other shiny jewelry when working with lasers!**
- **Turn the laser off or block the beam close to the laser while the experiment is unattended or while you are setting up some optical equipment!**
- **Use the laser only when mounted in the laser holder! Never use the laser while holding it in your hand!**
- **View the laser beam with a 3” x 5” card (index card) or the CCD camera!**
- **Never place your head towards the beam!**
- **Ask before you enter an area where a laser is used!**
- **Never point a laser at an entrance door or at anyone else.**
- **Keep the beam at waist height and parallel to the table whenever possible.**
- **Protect your fellow co-workers from accidental exposure to the laser beam!**
- **In the lab, sit only on high stools and not on low chairs to avoid the possibility of a table-height beam accidentally entering your eyes.**

Project 1: Reflection and Refraction

Introduction

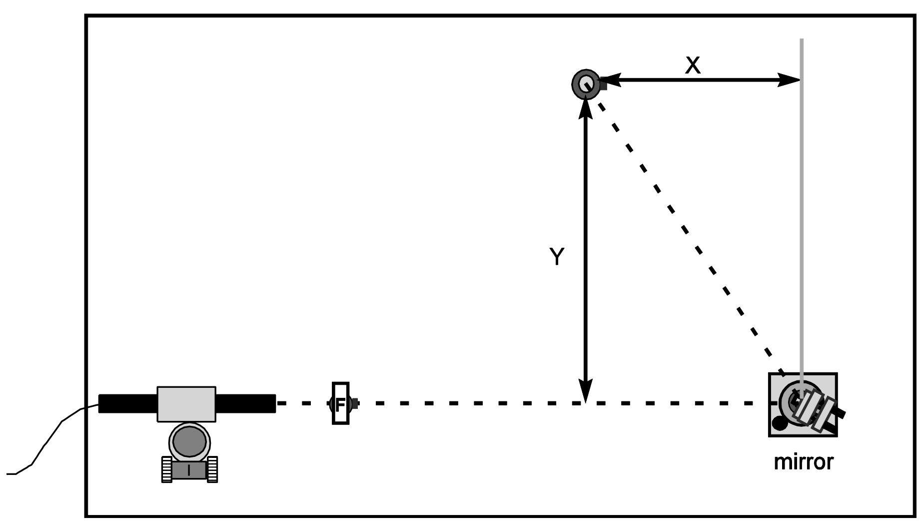
The propagation of light can be described mathematically by the three-dimensional wave equation, which can be derived from Maxwell's equations. All the properties of light that we will investigate in this course can be understood in this context. From our everyday experience, however, where objects are usually large compared to the wavelength of light, we can often think of light as consisting of rays. Most of you have seen rays of sunlight coming through the leaves of a tree on a foggy autumn morning. (The "light rays" are made visible by scattering from the water droplets in the fog.) This very simplified approach to optics along with the laws of reflection and refraction constitutes a major, fundamental part of optics and is termed RAY OPTICS or GEOMETRICAL OPTICS. Please read Chapter 4 in Hecht or Chapter 1 in Saleh&Teich. This project will also familiarize you with the fundamental building blocks used in any optics laboratory.

This project consists of six different experiments. First, you will prove the laws of reflection and refraction. Next, you will measure the index of refraction of glass by angles of refraction, total internal reflection, and reflection at normal incidence.

(1A) Law of Reflection

Objective: The law of reflection will be verified by showing that the angle through which a beam of light is reflected by a mirror is twice the angle made by the incident beam and the surface normal of the mirror. Estimate the errors. What is needed to make an accurate measurement? Can you suggest a method to check whether the reflected angle is *exactly* twice the mirror angle, i.e. an experiment that would measure accurately the *deviation* from this law? (Hint: use the fact that the angles of a triangle add up to 180^o exactly).

Suggested experimental setup and procedure:



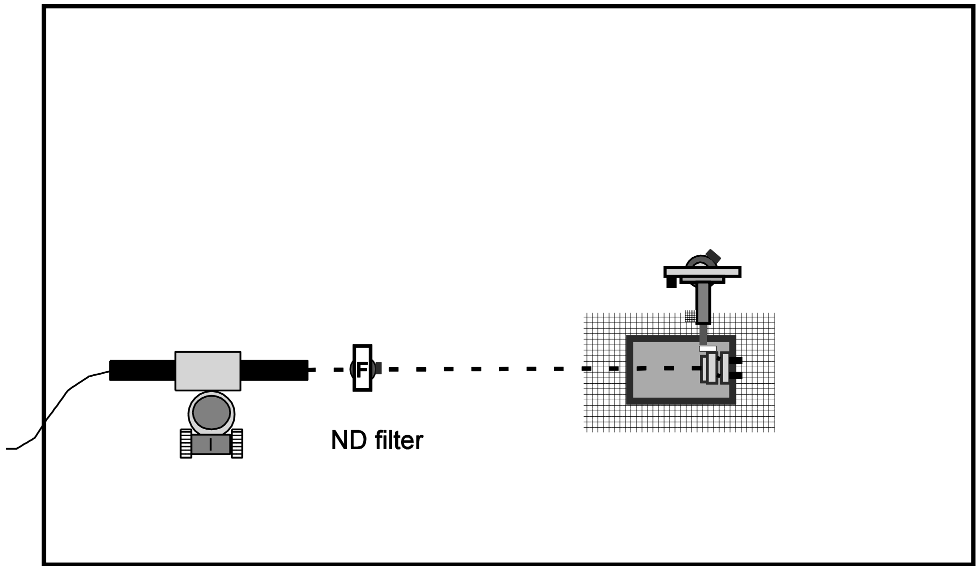
1. Mount the laser in the holder and place it at the one side of the breadboard as shown. Do not turn it on.
2. Mount a post in a post holder with the small black screw (#8-32) pointing up.
3. Next we align the laser along a straight row of the ¼"-20 holes on the breadboard. Screw the post holder down on the other end of the breadboard in a hole that is in line with the holes that come straight from the laser.
4. Turn the laser on and adjust the laser so that the beam hits the post. You might have to adjust the height of the laser mount or that of the post.
5. The laser beam is very bright. To reduce the output power you can place the 0.5 neutral density (ND) filter in front of it, which will reduce the power by a factor of $10^{0.5}$, i.e. approximately three. Mount a post holder in front of the laser and place the mounted filter into it. Alternatively, use two polarizers and mount them behind each other. By crossing them, you can reduce the light intensity. Why does it work?
6. Adjust the laser and post so that the laser beam hits the black screw at the top in the middle. Now the laser is aligned along the ¼"-20 holes. Let's hope that you were lucky and got the right height. (Otherwise you might have to repeat this procedure.)
7. Turn the laser off and unscrew the post holder.
8. Mount the mirror assembly on the rotation stage. <u>Be careful not to touch the mirror.</u> Your fingertips are full of fats and acids. If you have touched the mirror, please inform the instructors so that they can remove the fingerprints before the acid of your fingers has destroyed the surface. Screw the rotation stage down at the right side of the table, and set the rotation stage to read 0^o. Orient the mirror so that its surface normal is pointing towards the laser. Turn the laser on.
9. Adjust the two knobs (screws) of the kinematic mirror mount so that the laser beam is reflected back onto itself. Note that one knob moves the beam horizontally and the other vertically. This kind of mount is called an orthogonal mount. Block the laser beam and check the mechanical design to see how it works.

   NOTE: By reflecting the laser back onto the incident laser beam, some of the light will go back to the laser cavity. This may cause the output of the laser to fluctuate. To minimize this, place an aperture in front of the laser. For example, you may use a piece of index card with a hole slightly larger than the size of the laser beam. Hold it down with a piece of tape. By reflecting the laser beam very close to, but not through the aperture, you can avoid this effect. Here, however, we can use the fluctuations as a good sign that the beam is aligned.
10. Now you are ready to conduct the experiment. Mount a post holder away from the mirror (see schematic). Adjust the mirror at an angle such that the laser beam hits the small black screw right in the middle.
11. Measure X and Y with a ruler, or by counting the number of ¼"-20 holes. Note that all the holes are located on a 1" grid. Think about how you can get the incidence angle and the reflected angle from your measurements.
12. Take enough data at different angles to get the best and most reasonable result.

(1B) Snell's Law

Objective: The law of refraction will be verified by measuring the incident and transmitted angles of a He-Ne laser beam incident upon an air-water interface. Estimate the errors. What is needed to make an accurate measurement?

Suggested experimental setup and procedure:



1. Mount the laser in the holder and place it at the left side of the breadboard. Do not turn it on.
2. Mount the 0.5 ND filter in front of it to reduce the intensity by about a factor of 3. Since this is not a large reduction of intensity, it is even better to use two polarizers.
3. Fill the glass container with water up to 1 cm below the rim. Note that in the above diagram, a rectangular water tank is shown. You may use either a rectangular, or a circular water tank, whichever is available for your workstation.
4. Lay a piece of graph paper on the breadboard (aligned with the laser). Place the water tank on top of it. Fix the graph paper with tape to the breadboard.
5. Mount a post holder next to the container. Mount a rotation stage on this postholder so that it's plane of rotation is perpendicular to the breadboard. Set the rotation stage to read 0^o.
6. Insert a postholder with a mirror in the rotation stage. Turn the mirror by rotating the mirror post in its holder so that the mirror is rotated towards the water surface, at $\sim 45^o$ relative to the laser and the water surface. (This configuration will allow the mirror to reflect the laser beam towards the water surface later.)
7. Turn the laser on and adjust the knobs on the mirror so that the back reflection form the water surface is coming back to the laser.
8. Move the container to the side and mark the zero setting on the graph paper.
9. Now you are ready to conduct the experiment. You will have to measure distances and deduce angles. You may align the laser beam with the container in place such that it hits a

line on the graph paper, remove the container, and mark the direct reflection of the mirror on the graph paper. Be sure to measure all the distances you need. What are those distances?

Index of Refraction Measurements:

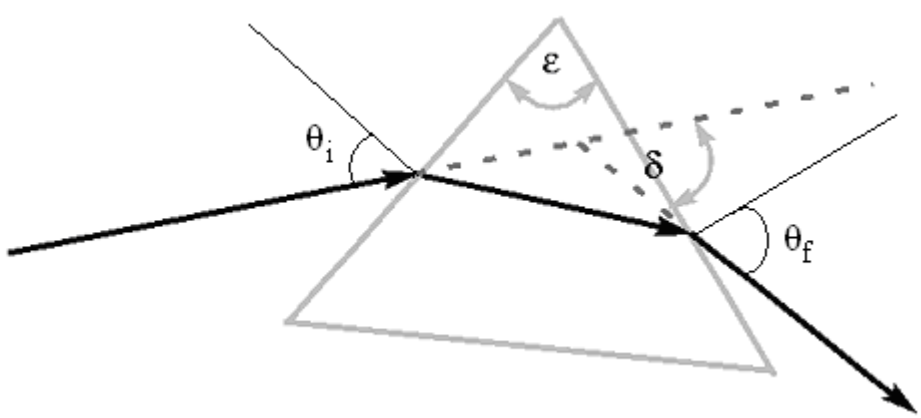
So far you have verified the laws of reflection and refraction. Now, you will measure the index of refraction by four different methods. You will be using a prism made of BK7 glass with a nominal index of refraction of n = 1.517 at the wavelength (632.8 nm, red) of the HeNe laser. Later in this lab you will measure this wavelength yourself.

(1C) Index of Refraction Measurement using a Glass Prism

Objective: The index of refraction for a glass prism is measured by determining the minimum deviation angle of light from the prism. Derive the formula

$$n = \frac{\sin\left(\frac{\varepsilon + \delta_{\min}}{2}\right)}{\sin\left(\frac{\varepsilon}{2}\right)},$$

where n is the index of refraction for the glass prism, ε is the angle of the prism at which refraction occurs, and $\delta_{\min}$ is the minimum angle of deviation as shown in the following figure. For your prism, you can use $\varepsilon = 45^{\text{o}}$.

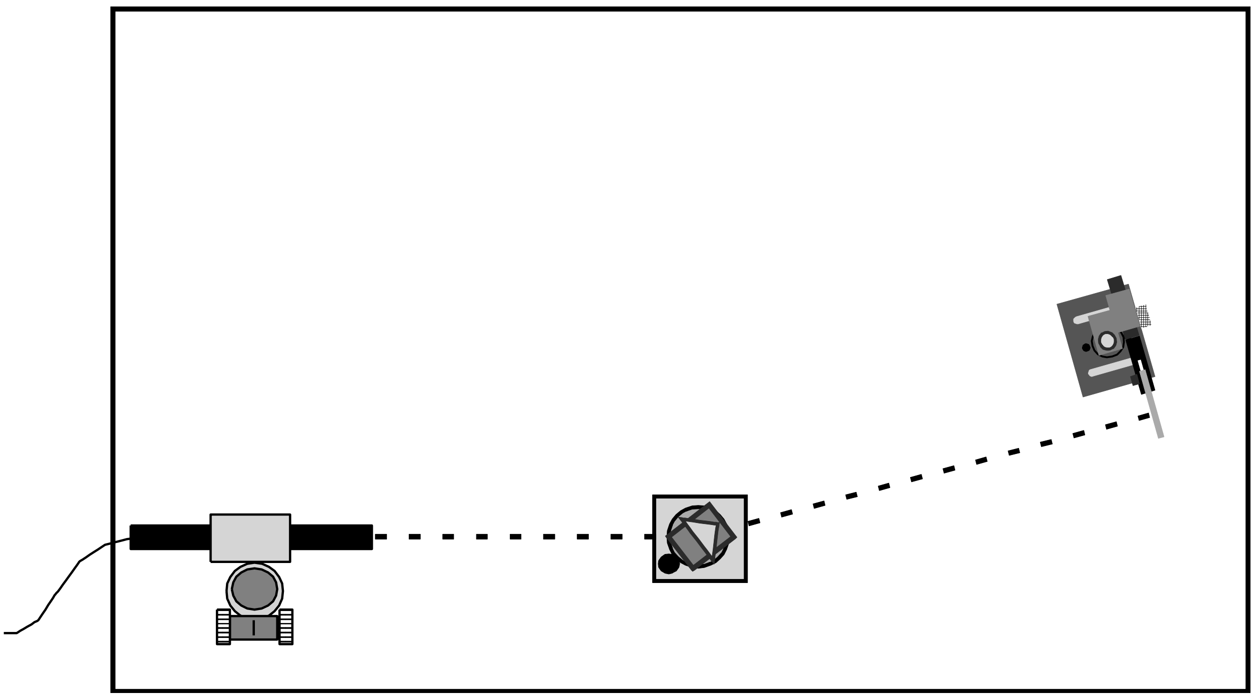


The derivation is greatly simplified if you use mirror symmetry to argue that the case of minimum angle of refraction δ occurs in the symmetric arrangement, i.e. when $\theta_i = \theta_f$. In the figure, a laser beam comes from the left, enters the prism with an angle θ_i and leaves it with θ_f, producing an angle of refraction δ. A laser beam traveling in the opposite direction, from right to left, would take the same trajectory, i.e. enter with angle θ_f and leave with θ_i. Because the prism is symmetric, a ray that enters from the left with an incoming angle θ_f would therefore produce the same angle of refraction δ. The angle of refraction as a function of the incoming angle, δ(θ), therefore has a special property. There always have to be at least two angles θ that produce the same value δ, except for the symmetric case where $\theta_i = \theta_f$. Imagine the function $\delta(\theta)$ close to this symmetric case. When the incoming angle is slightly increased, the outgoing angle slightly decreases. And $\delta(\theta)$ for the slightly decreased angle as to be the same as for the slightly increased angle, and this function therefore has a minimum or maximum for the case with $\theta_i = \theta_f$.

In this symmetric arrangement, the angle between the incoming ray and the horizontal is $\delta/2$, so that the angle to the normal is $\delta/2+\varepsilon/2$. Inside the prism the beam is horizontal, so that it's angle to the normal of the surface is $\varepsilon/2$. The equation above therefore simply describes Snell's law for the symmetric arrangement.

Our goal is to measure the value of *n* to within 0.5% and possibly to 0.1% of its true value. To do this, you need to use the method of error propagation that was covered during lectures. What is needed to make an accurate measurement?

Suggested experimental setup and procedure:



1. Mount the laser as shown in part (1A) and align the laser along a straight row of the ¼"-20 holes on the breadboard.
2. To provide flexibility in translating the prism across the laser beam, we will first mount a translation stage onto the breadboard. Note that this is slightly different from the drawing above. Make sure that the translation axis is perpendicular to the laser beam. Tighten the translation stage onto the breadboard with ¼"-20 screws.
3. Mount a rotation stage onto this translation stage with ¼"-20 screws.
4. Mount a 90^{o} glass prism with its holder into the rotation stage.
5. Mount the target assembly into a sliding base and place it on the table.

6. Turn the laser on.
7. Align the prism by rotating its post holder and the knobs on the prism holder, such that the laser beam reflected from its front surface returns back onto itself.
8. Use the target assembly as a beam stop and rotate the prism until you find the angle of minimum deviation.
9. Measure the angle and estimate errors!

Notes:

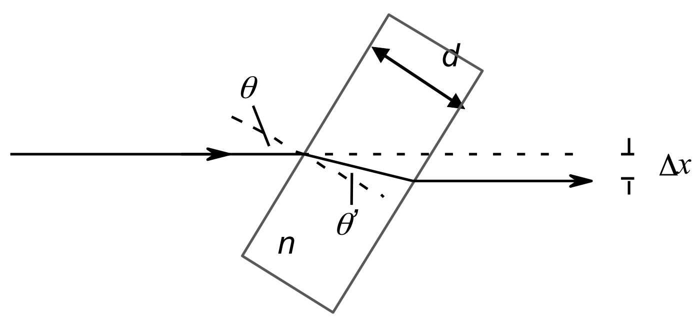
i) Reading the angle off the rotation stage is not very precise. Can you think of a better way to measure the angle? (*Hint:* recall experiment 1A)

ii) When you take a measurement, always try to increase the sensitivity of your experimental procedure. Often it helps to increase the baseline length, e.g. when angles have to be measured.

iii) Your prism is not ideal, so the angles at its base might not be exactly 45º. What kind of experimental procedure will help to reduce this uncertainty?

(1D) Index of Refraction Measurement Using a Glass Slab

Objective: The index of refraction for a slab of transparent material is measured by determining the amount the beam translated after passing through the slab when the beam is incident at an oblique angle.



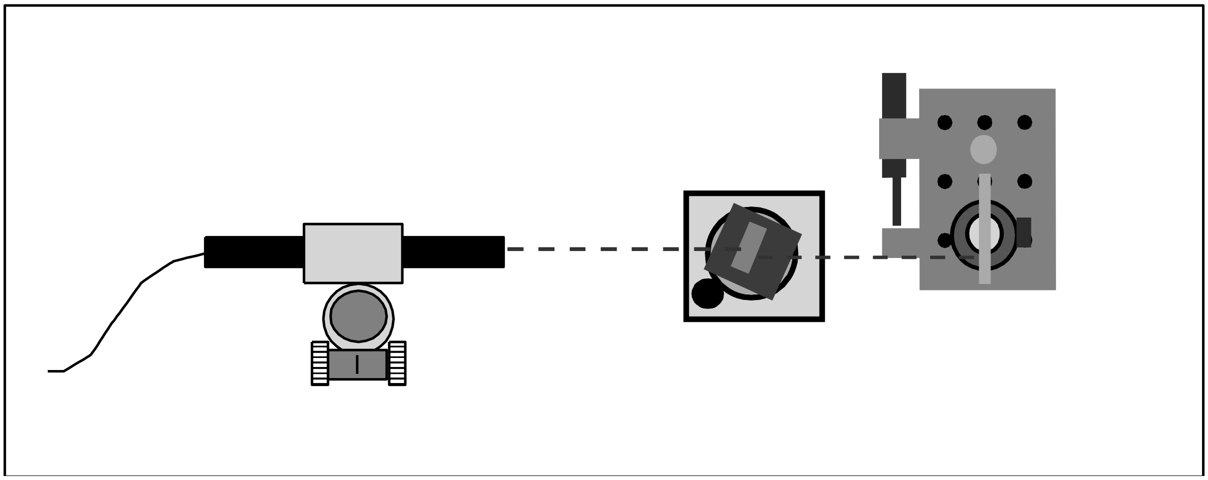
In the geometry shown above, the displacement Δx of the beam is shown to relate to the refractive index n through the following equation:

$$\Delta x = d \sin\theta \left\{ 1 - \frac{\cos\theta}{\left(n^2 - \sin^2\theta\right)^{1/2}} \right\}.$$

This is derived with Snell's law:

$$\Delta x = (d \tan\theta - d \tan\theta')\cos\theta = d \sin\theta \{1 - \frac{\cos\theta}{n \cos\theta'}\}.$$

Suggested experimental setup and procedure:



1. Mount the laser as shown.
2. Mount the slab on the platform mount and place onto a rotation stage. Adjust the stage and the slab so that the front face is normal to the laser beam. Set the rotation stage to read 0^o.
3. Mount the target assembly onto a translation stage and place it behind the slab. You can use a razor blade instead of an index card in this experiment.
4. Place a photosensor behind the target assembly. Carefully read the instructions prior to operating it. Don't forget to zero it before taking any measurements.
5. Record the power meter reading for a beam that is unobstructed by the razor blade. Then translate the target assembly until the blade blocks half of the beam (according to the power meter). Record the corresponding micrometer reading on the translation stage.
6. Rotate the slab until you see that the beam has been translated an observable amount. Translate the stage until the blade once again blocks half the beam and record the new reading on the micrometer to determine how far the beam has been displaced by the slab.
7. Repeat for various angles.

Note:

Sometimes you can observe double reflection of the laser beam from the slab. This indicates that the front and back planes of the slab are not parallel. Make an estimate of this deviation. How will it affect your results? Think of the experimental parameters you can vary in order to reduce the error caused by this effect.

(1E) Index of Refraction Measurement Using Total Internal Reflection

<u>Objective:</u> The index of refraction of a 90^o glass prism is measured using the phenomenon of total internal reflection. Total internal reflection occurs when light travels from a medium of high index of refraction to a medium of low index of refraction, such as a glass/air interface. As the incidence angle approaches the critical angle, the angle of refraction approaches 90^o. When the incidence angle is greater than the critical angle, the incident light is not transmitted and

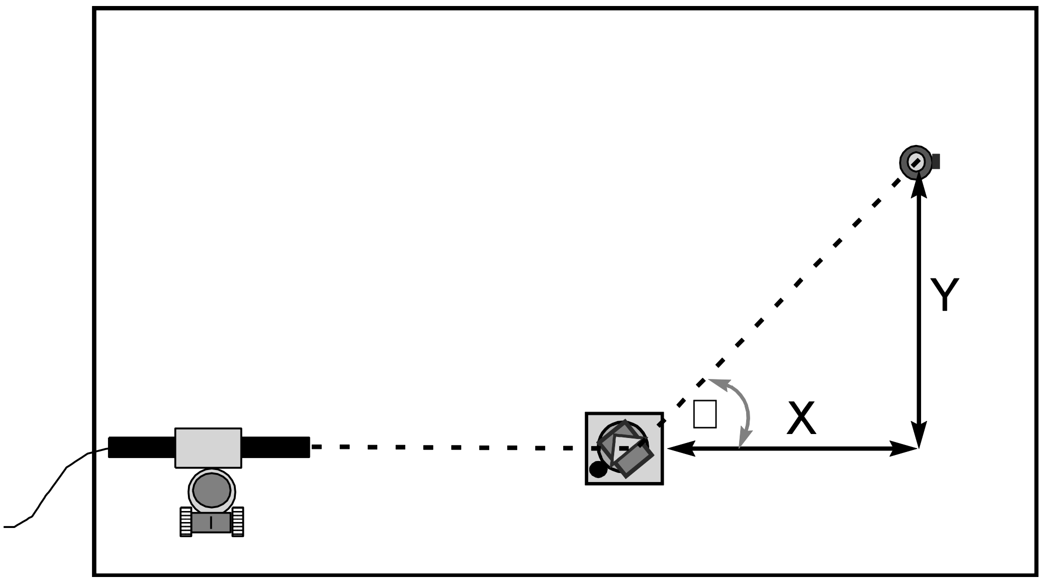
undergoes total reflection. For a glass/air interface, the critical angle is related to the index of refraction of the glass n by $\sin\theta_c = 1/n$. Show that this is the correct formula! How can this effect be understood with the wave theory of light? What is an evanescent wave?

In this experiment, you have to rotate the prism until the critical angle for total internal reflection is reached. You will measure the angle α between the original laser beam direction and the refracted beam emerging from the prism at the critical angle. The relation between the refractive index n of the prism and the incident angle to the prism ϕ_c when total internal reflection occurs is

$$n^2 = 1 + \left(\frac{\cos\varepsilon + \sin\phi_c}{\sin\varepsilon}\right)^2$$

where ε is the relevant angle of the prism, i.e. the one that is close to $45°$. The incident angle is related to the measured angle by $\alpha = 90° - \varepsilon + \phi_c$. Prove these relations in your lab write-up.

Suggested experimental setup and procedure:



1. Mount laser (align the ¼"-20 holes) and filter (if necessary).
2. Mount the prism assembly on a rotation stage and rotate until the transmitted beam vanishes. You may use a piece of index card to follow the beam all the way to the back surface.
3. Measure the lengths X and Y and determine the angle α. This can be done similarly to experiment (1A) by using the hole pattern of the table. Alternatively, you may determine ϕ_c directly from the reading of the rotation stage. How do these two measurements compare? Is there a way to measure ϕ_c more precisely? See also note iii) for experiment 1C.
4. Analyze your results. Perform an error analysis and compare your result with the value given in the literature.

(1F) Index of Refraction Measurement Using Reflection

Objective: The index of refraction of glass is measured from the reflected power of a light beam incident perpendicular to a glass surface. Measure the index of refraction for the prism used in part (1C). Make sure you understand the derivation of the Fresnel formula for reflection at an air/dielectric interface:

$$R = \frac{\text{intensity reflected}}{\text{intensity incident}} = \left(\frac{n-1}{n+1}\right)^2,$$

where R is the reflection coefficient and *n* is the index of refraction. Describe this derivation in your lab report. Note that here we have set the permeability in the optical medium equal to 1, which is usually valid for light waves. Estimate the errors. What is needed to make an accurate measurement?

However, it is difficult to measure the reflected laser power from normal incidence. The best we could do is to approximate using a small angle incidence. Unfortunately, *R* has some dependence on the incidence angle, and the small angle approximation will introduce some errors in measurements. Describe how this dependence can be derived. To circumvent this problem, we will have to go through a rather elaborate procedure. Here we first measure *R* of a mirror. This is easy since for a metal mirror, *R* stays constant even for rather large incidence angle. Show a derivation for this fact. As you will discover, we will be able to determine *R* of a prism from *R* of a mirror using a beam splitting setup. We shall then compare our results with a direct measurement of *R* using small angle incidence.

The idea is quite simple. Basically, we compare the intensity reflected from the prism with that reflected from the front surface of an aluminized mirror using the voltage from the photosensor as a measure of light power.

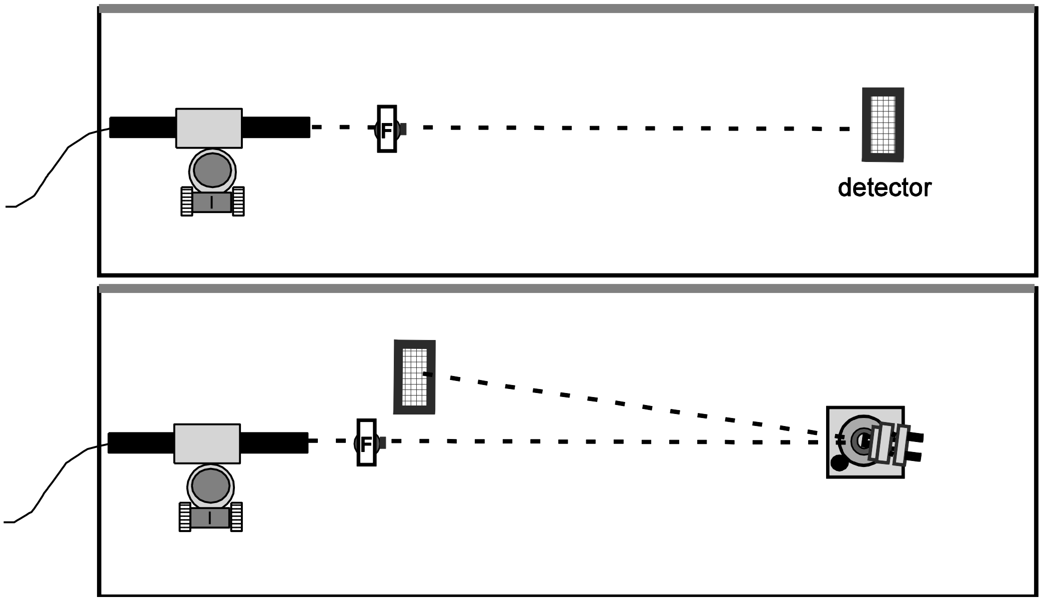
The major problem of this setup is that we are losing light that is reflected from the glass/air interfaces of the beam splitter. Furthermore, the front surface of the mirror reflects only about 90% of the incident light (typical value for a clean aluminum surface). A variety of steps are necessary to get the right answers. A suggestion is given below. Does it make sense?

Make sure that the reflecting surfaces are clean. If the interface is clean, you should not see where the laser beam hits the surface; otherwise, please talk to the instructors. They will show you how to clean an optical surface with methyl alcohol and lens paper.

Avoid spurious reflections. You might want to reduce the aperture of the photodiode by covering it with a piece of an index card with a hole. Use tape to hold it. Or attach two strips of tape to make a slit opening.

(i) Measurement of the reflection coefficient of the front surface mirror.

Suggested experimental setups and procedures:

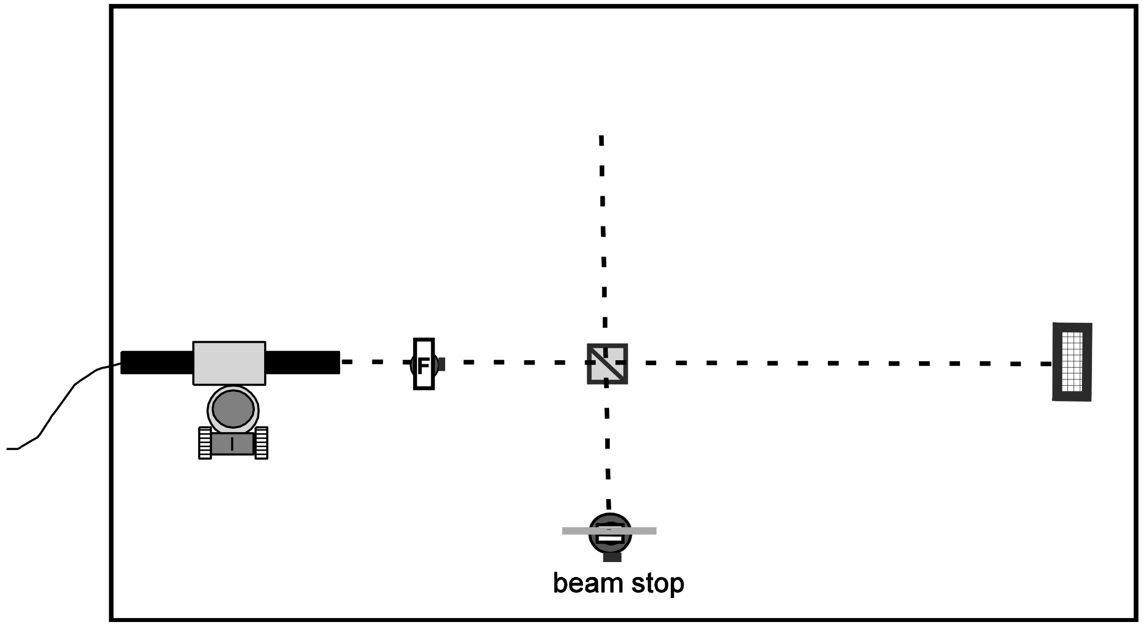


1. Mount laser (align the ¼"-20 holes) and filter (if necessary).
2. Mount the photo sensor and connect it to the voltmeter.
3. Measure power of the laser beam (the voltage is proportional to the power). Estimate the error. Make sure to correct for the background signal from the room lights.
4. Mount a mirror assembly on a rotational stage and measure the reflected intensity for small angles on one side of 0^o. Verify that the reflected intensity does not strongly depend on the reflection angle.
5. Calculate $R(\alpha)$ and interpolate to get $R(\alpha = 0)$. Be sure to perform an error analysis.

(ii) Measurement of the laser power after the beam splitter.

Now measure the power of the laser beam incident on the mirror if you find this step necessary.

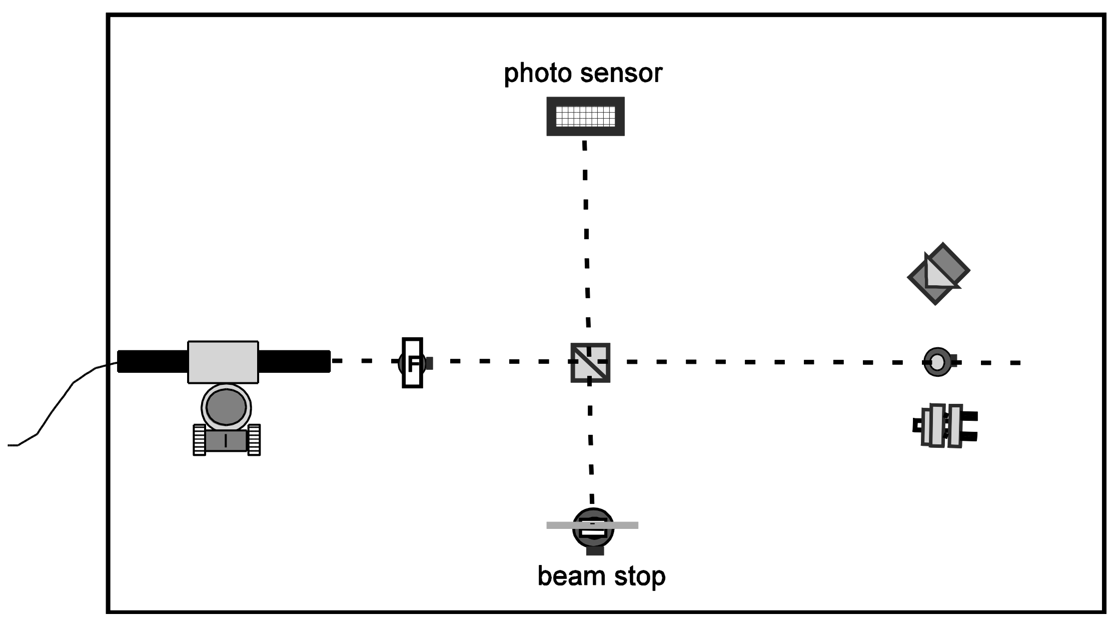
Experimental setup and procedure:



1. Mount the laser and filter.
2. Mount the beam splitter assembly.
3. Mount an index card into the dual filter holder and use it as a beam stop.
4. Measure the power of the beam after the beam splitter.
5. Estimate the errors.

(iii) Measurement of the laser power after reflection from the mirror and prism.

Experimental setup and procedure:



1. Modify the previous setup. Move the photo detector to the opposite side of the beam splitter.
2. Mount the mirror into a post holder and measure the reflection at normal incidence. Make sure you avoid or correct for reflections from the beam splitter.
3. Repeat the same procedure for the prism.

iv) Measurement of the reflection coefficient of the prism using small angle incidence.

Just repeat part i), but substitute the mirror with the prism.

Remarks:

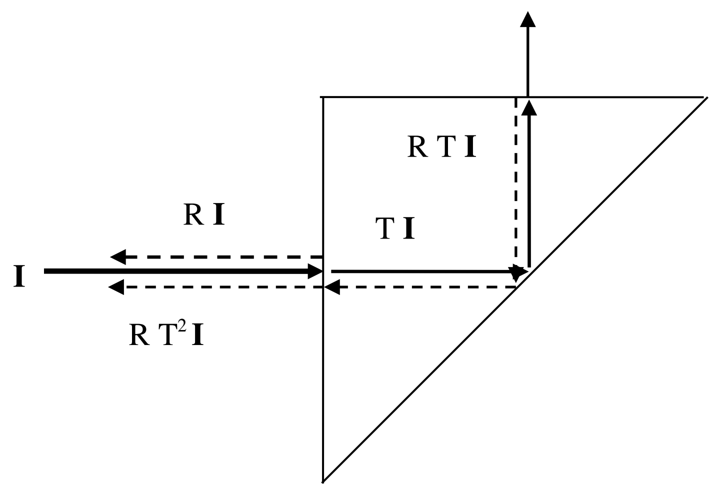
- When you align the mirror or the prism, the laser beam has to return onto itself. This might lead to fluctuating output as described in (1A, topic 9). Misalign the setup slightly to avoid this effect. How significant will this systematic error be?
- When working with the prism, make sure to orient it the way shown in the schematic. Why is this so crucial? What happens if you align it such that the longest side of the triangle is facing the laser beam?

Note:

Well, if your alignment was good, your results for R in part iii) should be almost twice as high as in part iv). And by calculating *n* you will see that the small angle method is much closer to the expected value. What is going on?

After careful consideration one can see that in the case of normal incidence power meter reads off not only the intensity of the beam reflected from the front surface of the glass, but also the intensity of the beams that undergo multiple reflections inside the prism (the figure below shows the first of such beams). Using coefficients of reflection R and transmission $T=1-R$ and summing an infinite geometrical series, you can derive the total reflected intensity:

$$I_R = RI(2-R) \approx 2RI$$



Note that your task is simplified by the fact that light is totally reflected from the longest side of the prism (why?).

And there's more to that experiment. Later in this course you will learn about the wave nature of light and interference. Strictly speaking, in our case not intensities, but rather the amplitudes of the electric field should be added with a corresponding phase shift (this is analogous to Fabry-Perot interferometer [Hecht, pp. 421-423, or Saleh&Teich section 9.1, and Project 4E). Still, our derivation is not that far from the truth, because adding intensities is roughly equivalent to averaging over a range of angles of incidence in our system. And as the alignment cannot be perfect (Fabry-Perot interferometer is sensitive to the lengths of the order of a wavelength), this averaging is required if we were to consider the interference picture.

Project 2: Polarization of Light

Introduction

The electric and magnetic fields of light waves are vector quantities. To give a full description of these fields, both their magnitude and direction must be specified. In non-absorbing media, the electric and magnetic fields are perpendicular to each other. Show that this follows from Maxwell's equations. In general, the electric field is used to specify the direction of polarization within the plane normal to the wave vector.

The phenomena of light scattering, dispersion, refraction and reflection can all be based on the microscopic picture of induced dipoles, excited in a medium by the incident light wave. As a result of the radiation properties of dipoles (no radiation is emitted along the direction of the dipole), certain directions of the E vector vanish when the wave is scattered, refracted, or reflected, i.e., the light wave is partially (or totally) polarized.

In general, light waves are elliptically polarized. The two in-plane components E_x and E_y (normal to the propagation direction z) are oscillating with a phase difference ϕ, and may have different magnitude. Depending on the phase difference, the light may have left-handed or right-handed polarization. The special case when $E_x = E_y$ and $\phi = \pm\pi/4$ corresponds to circular polarization.

Another effect involving polarization is double refraction or birefringence, i.e. when the refractive index of the material is anisotropic. Many classes of crystals and some plastics can exhibit birefringence. Light with a polarization perpendicular to the *optic axis* of the crystal would pass through the crystal according to Snell's law (ordinary ray). While light with a polarization not perpendicular to the optic axis (extraordinary ray) does not obey Snell's law. The beam rather splits up into two beams. There is a good description of this phenomenon in Section 8.4 of Hecht. You will use birefringent materials as a retarder. A retarder gives a phase-retardation between the ordinary and extraordinary waves.

You should read Sections 8.1 - 8.8 in Hecht or Saleh&Teich 6.1 - 6.6.

Before starting the experiments you will make three simple observations:

1. Observe the (hopefully blue) sky towards a point orthogonal to the sun's rays. How does the intensity change as you rotate a polarizing sheet about your line of sight?
2. Examine a printed page through a calcite crystal (available at the desk) by placing the crystal atop the page. Describe your observation. Now insert the polarizing sheet between the crystal and your eye. What happens as you rotate the polarizing sheet?
3. Take the polarizing sheets and cross them for minimal transmitted intensity. Now insert between them a few pieces of plastic sheet and mica that you find in your setup. What do you observe? What happens as you rotate one of the sheet polarizers? Explain your observed effects qualitatively in your write-up.

As you proceed with this project you will develop an explanation for all of these phenomena involving the interaction of polarized light with matter.

(2A) Malus's Law

Typically, light sources produce light that is not linearly polarized. Although the electric field has an instantaneously well-defined direction, its direction changes over all angles in the *x-y* plane (normal to the propagation direction *z*) in a time much shorter than the time constant of the measuring device. Over small time scales of many wave oscillations, the electric field is in general elliptically polarized, but over longer time scales the direction and the major axes of the ellipse of this polarization change randomly. But even these longer timescales are much shorter than our measurement times. Sometimes the misleading adjective "randomly polarized" is used to describe such a beam.

Light from such a source may be made polarized by passing it through a polarizing plastic film (polarizer). The plastic films are made of a polymer chain to which light-absorbing iodine is attached. The film is cast and then stretched so that the polymer chains align preferentially in one direction. Light parallel to the chains is absorbed, while light polarized perpendicular to the chains is transmitted. Why?

When light that has passed through a polarizer passes subsequently through an analyzer (a polarizer whose transmission axis is oriented at an angle relative to that of the first polarizer), the analyzer will transmit only the component of the electric vector which is parallel to the analyzer's transmission axis. Thus, the transmitted field E_t is the projection onto the transmission axis of the analyzer (i.e., $E_t = E_o \cos\theta$, where E_o is the amplitude of the total field and θ is the angle between the transmission axes of the polarizer and the analyzer. As a result, the light intensity transmitted through the polarizer/analyzer is proportional to

$$I(\theta) = I(0)\cos^2\theta .$$

This is known as the Malus's law.

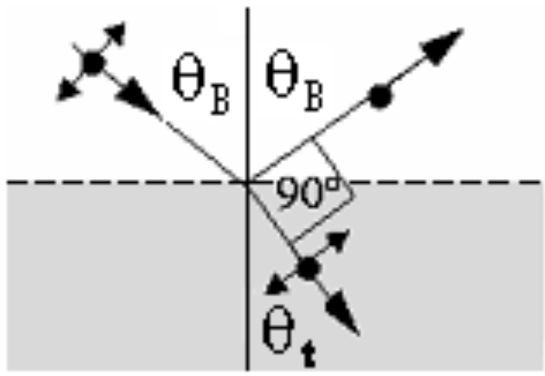
Objective. Your task in this experiment is the verification of the law of Malus and to determine the extinction ratio (the ratio between minimum and maximum intensities) of the polarizer pair.

Suggested experimental setup and procedure:

1. Mount the laser.
2. Place one polarizer in front of the laser. What happens to the transmitted power? Watch it over time. Is it very noisy? Let the laser warm up for some time - is the laser power still as noisy as when the laser was first turned on? Does the power change as you reorient the polarizer?
3. Insert a second polarizer (analyzer) after the first one. Measure the transmitted power as a function of the orientation of the analyzer. Plot out this relation. Repeat this for several orientations of the first polarizer. What effect should this have on your data? Is your data consistent with the law of Malus?

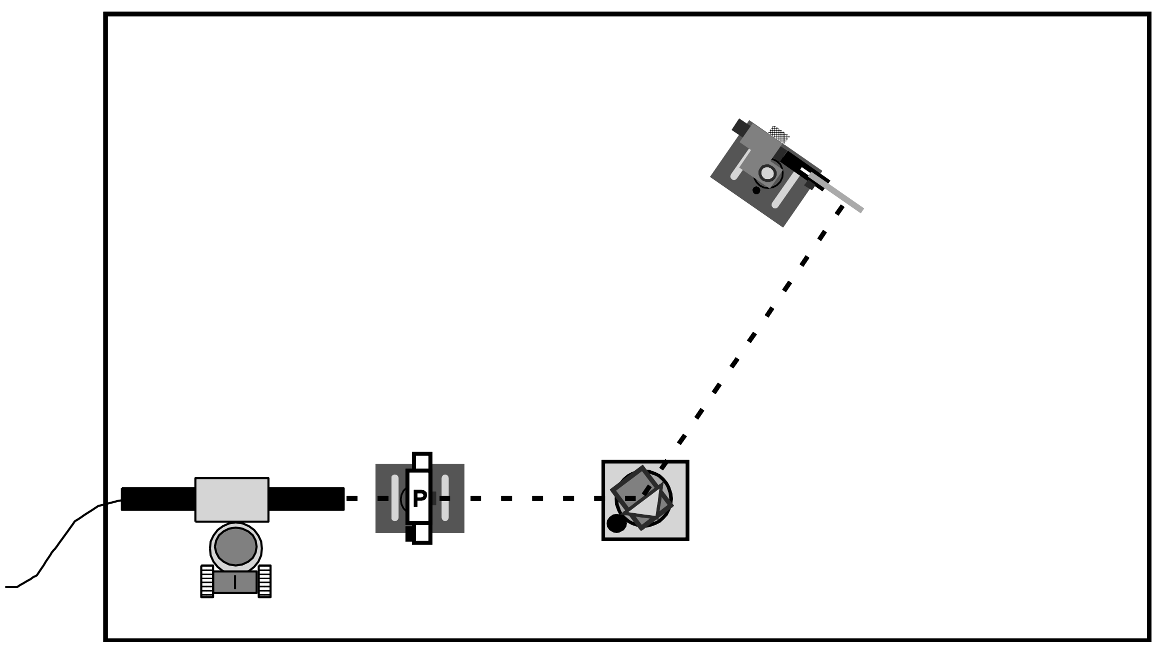
(2B) Measurement of the Index of Refraction by Brewster's Angle

Let's consider randomly polarized light incident upon an interface between two media of different indices of refraction. When the incidence angle $\theta_i = \theta_B$, where θ_B is the Brewster's angle, the reflected light will become completely polarized. For an air-glass interface, $\theta_B = \tan^{-1}(n)$, where n is the index of refraction of the glass. This is schematically shown in the figure below.



This effect will be further studied in (2C). But for now, let's use this effect to measure the index of refraction of the prism used in Project 1. Derive the fact that the angle between the reflected and the refracted ray is 90^0.

Objective. In this experiment, you will determine the index of refraction of the 90^o glass prism by measuring Brewster's angle. This will be the 5th method of measuring the index of refraction of the prism. How do the results of the 5 methods compare?



Suggested experimental setup and procedure:

1. Mount the laser.
2. Mount the polarizer in front of the laser.
3. Mount the 90º prism assembly onto a rotation stage and screw it to the breadboard. Be sure that the surfaces of the prism are clean.
4. Mount a target assembly and place it on the table.
5. Turn the laser on and adjust the polarizer to transmit light of linear polarization parallel to the table.
6. Determine Brewster's angle. Estimate errors!
7. After you have determined Brewster's angle, move the polarizer in front of the target. What is the intensity of the light transmitted through the polarizer? Explain.

Note:

You will be looking for a minima in the intensity signal. The most precise way to determine it is to plot intensity vs angle of the rotation prism and fit the plot to a parabola around the minimum.

(2C) Fresnel Reflection by a Dielectric

In this experiment you will study in some detail the reflection of light at an air/dielectric interface. You can picture the dielectric medium as consisting of many induced dipoles that are very closely spaced compared to the optical wavelength. The materials are typically transparent solids such as glass. The behavior of the radiating dipoles is responsible for the macroscopically observed reflected and transmitted light. Mathematically this case can be treated in the continuum limit (Maxwell's equations, energy conservation, continuity conditions of $\vec{H}$, $\vec{B}$, $\vec{E}$ and $\vec{D}$, and the dielectric constant ε). This analysis leads to Fresnel's formulae. If $E_{\|}$ is the light wave polarized in the plane of incidence and $E_{\perp}$ is the light wave polarized perpendicular to the plane, then the Fresnel's formulae describing reflection are given by:

$$\frac{E_{\|r}}{E_{\|i}} = \frac{n^2\cos\theta_i - \sqrt{n^2 - \sin^2\theta_i}}{n^2 co\theta_i + \sqrt{n^2 - \sin\theta_i}} = +\frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)}$$

and

$$\frac{E_{\perp r}}{E_{\perp i}} = \frac{\cos\theta_i - \sqrt{n^2 - \sin^2\theta_i}}{\cos\theta_i + \sqrt{n^2 - \sin^2\theta_i}} = -\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)},$$

where θ_i is the angle of incidence and θ_t is the angle of transmission (refraction). The power reflection coefficients are given by the squared modulus of the respective ratios:

$$R_{\parallel} = \left(\frac{E_{\parallel r}}{E_{\parallel i}} \right)^2$$

and

$$R_{\perp} = \left(\frac{E_{\perp r}}{E_{\perp i}} \right)^2 .$$

Again the permeability in the medium was set equal to that in vacuum. Notice that when $\theta_i + \theta_t =$ 90^{o}, $R_{\parallel} = 0$; this means that the reflected wave is polarized perpendicular to the plane of incidence. The particular angle of incidence for which this occurs is Brewster's angle θ_B, and $\theta_B = \tan^{-1}(n)$ for an air/glass interface.

<u>Objective.</u> You will verify Fresnel's law.

Suggested experimental setup and procedure:

1. First, you will measure the power reflection coefficients $R_{\parallel}$ and $R_{\perp}$. This setup is similar to that of (2B), except that instead of using a prism, you will use a blackened flat. Why was it blackened? Adjust the polarizer using Brewster's angle. Measure the power reflection coefficients $R_{\parallel}$ and $R_{\perp}$ as functions of θ_i. Make sure to cover angles from near normal incidence to greater than Brewster angle. Do the results agree with the above formulae?
2. Next, you will determine the orientation of the reflected polarization (the so-called azimuthal angle ψ) as a function of the incidence angle. Orient the polarizer so that the incidence polarization is at 45^{o} relative to the plane of incidence. Mount an analyzer on a rotation stage and put it in the reflected beam. The azimuthal angle ψ is the angle between the normal to the plane of incidence and the reflected polarization. Determine ψ of the reflected beam using the analyzer.
3. Since $\tan(\psi) = E_{\parallel} / E_{\perp}$, please compare results from parts 1 and 2. How do they differ and why? What must happen to the phase of $E_{\parallel}$ relative to $E_{\perp}$ upon reflection when you go through Brewster's angle? Show that this follows from the equations specified above. Why must this be so? Why could you see this change in part 2 but not in part 1?

(2D) Polarization of Light by Scattering

As you have observed at the beginning of this project, light scattered by the small particles (causing fluctuations of the dielectric properties) in the atmosphere is highly polarized at certain angles. Such scattering is called Rayleigh scattering in honor of Lord Rayleigh who first described such scattering mathematically (1871) or Tyndall scattering for John Tyndall who first studied it experimentally (1869). The wavelength dependence (λ^{-4}) of this scattering explains partly the blue color of the sky. The explanation for the polarization of the scattered light lies in the response of the electrons of the scattering particles to the incident light, i.e. the incidence light induces oscillating dipoles in the particles, which in turn radiate.

Objective. In this experiment you will investigate the amplitude and polarization of light scattered by small particles suspended in water. A qualitative comparison with the dipole model of the interaction of light with matter will be made.

Your observations will be qualitative in the sense that you will observe the main features and compare them with dipole radiation. The polarization however is seldom seen to be complete as this simple model indicates. The reasons are:

- For very small particle sizes the scattering is well described by the dipole model, i.e. it has the characteristics of a radiating dipole. However, when the particle size is increased, the scattering is confined to small angles in the forward and backward direction. This effect can be qualitatively understood by the finite size of the particles leading to diffraction patterns of small apertures. This effect was analyzed by Mie and is called Mie scattering.
- Multiple scattering occurs so that light reaching the detector has been scattered more than once.
- Anisotropies of the electronic response. In many molecules, the displacement of the electron in response to a field is not in the same direction as the applied field. In liquids and gases, the molecules are randomly oriented which tends to depolarize the scattered light.

Suggested experimental setup and procedure:

1. Place a vial filled with water and very little skim milk (should be almost clear) into the unpolarized laser beam. (You can tape it to a filter holder). Investigate the angular dependence of the scattered light qualitatively using your eyes. DO NOT LOOK INTO THE LASER BEAM!
2. Place a polarizer into the laser beam before the vial and observe the scattered light at a 90^o angle to the beam. Now rotate the polarizer.
3. What have you observed? Explain your observations!

(2E) Birefringence of Materials

Objectives. Birefringent materials can be used to control the passage of light through an optical system. In this experiment you will study, in some detail, birefringent materials. You will investigate the properties of a quarter-wave plate and use it to change the polarization of the laser. Finally, you will use a quarter-wave plate to examine the properties of another birefringent material and build an optical isolator.

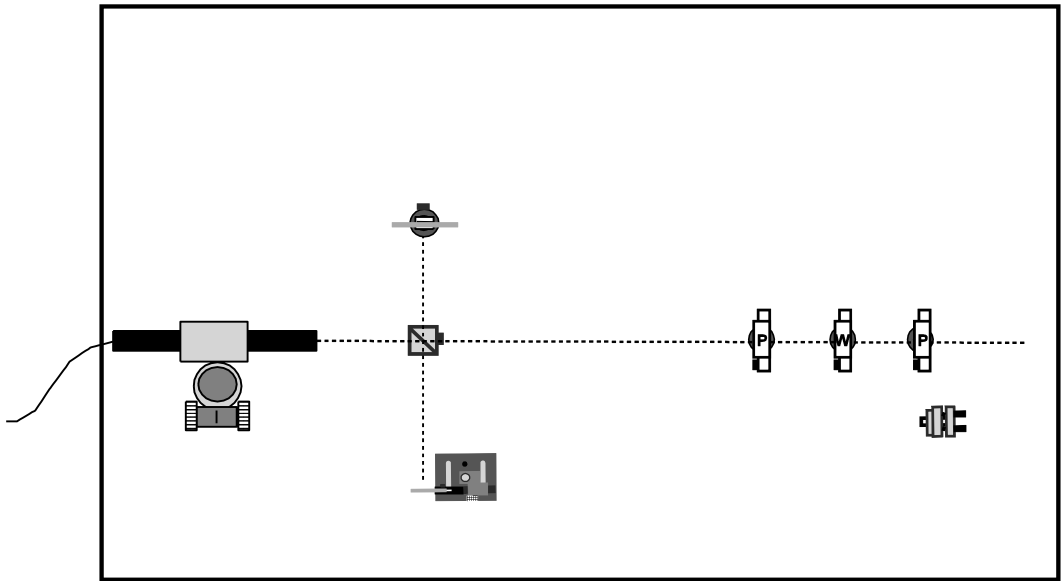
Suggested experimental setup and procedure for the quarter-wave plate experiment:

1. Here you will investigate the properties of a quarter-wave plate using two polarizers. Place

two polarizers about 30 cm in front of the laser. Place them far enough apart to have room for the quarter-wave plate between them.

2. Find the eigenstates of the quarter wave plate using the polarizers and the quarter-wave plate. These are the orientations of the plate that will keep the polarization unchanged, *i.e.*, they are the slow and fast axis, respectively. What does the experiment tell you about the orientation of the optic axis of the quarter-wave plate? Conduct a similar experiment by rotating one of the supplied plastic sheets instead of the quarter-wave plate.
3. Convert linearly polarized light into circularly polarized light. Orient the polarizer so that light is vertically polarized, and cross the analyzer with the polarizer. Place the quarter-wave plate between two crossed polarizers and orient it in such a way that the transmitted power is maximal (you might want to use the photo sensor). Now rotate the analyzer. What do you observe? Explain your findings and derive why this procedure leads to a circularly polarized beam.
4. Measure the retardation of an overhead transparency. (1) Orient the polarizer so that light is vertically polarized, and cross the analyzer with the polarizer. (2) Mount the transparency on a rotation stage, place the transparency between the polarizer and the analyzer, and find the eigenstates of the transparency. (3) Rotate the transparency by 45^{o} so that equal amount of the linearly polarized light will be incident onto the axes of the transparency. (4) Insert the quarter-wave plate between the transparency and the analyzer. (5) Rotate the axis of the quarter-wave plate by angle ψ from that of the transparency and rotate the axis of the analyzer by an angle ϑ from that of the quarter-wave plate so that you can achieve extinction after the analyzer. (6) Use the angle between the analyzer and the polarizer to calculate the relative phase shift φ between the eigenstates for the transparency. Show that this angle is given by $\tan\varphi = -\tan 2\vartheta / \sin 2\psi$, even when the transparency is rotated by an angle different to 45^{0}.
5. Observe the transparency between crossed polarizers observed at non-normal incidence, using a broad white light source (the cloudy sky, for example). Can you explain the fringe pattern observed around 40^{o} incidence angle? Interestingly, this pattern is related mathematically to the electronic structure of graphene, for whose discovery the Nobel prize was awarded in 2010.

Suggested experimental setup and procedure for the optical isolator experiment:



1. Here you will use a quarter-wave plate to optically isolate a part of an optical system. Adjust the quarter-wave plate by using the crossed polarizers to give circularly polarized light.
2. Replace the analyzer with a mirror. The mirror changes the handedness of the circularly polarized beam. Will the light reflected back through the quarter-wave plate be transmitted through the polarizer? Observe the reflection on the index card. Rotate the quarter wave plate or the polarizer. Describe and explain your observations.

Project 3: Geometrical Optics

Introduction

Although simple lenses have been used as magnifying glasses for centuries, the great technological advance which led to the invention of both the telescope and the microscope was the use of compound lenses by Dutch lens makers in the early 17th century. This coincided with the understanding of refraction by Snell and the publication of the definitive work on geometrical optics by Kepler.

In this experimental project you will learn how to use lenses. You will verify the thin-lens equation, study the different sizes and orientations of images, explore various types of lens combinations, and build a shadowgraphy system for visualization of small index of refraction changes. There is no attempt to give a detailed theoretical account here, and you are strongly advised to read Hecht § 5.1-5.4 and § 6.1-6.5 (or Saleh&Teich Chapter 1).

When studying simple lenses we are concerned with the "first order" properties of a lens, which for a "thin" lens can be specified by a single number: the focal length. For a so-called "thick lens", three numbers must be specified: the focal length and the positions of the two principal planes. Perfect imaging really only applies to rays near the lens axis. This is known as the "paraxial" or "first order" limit. Deviations from perfect imaging for extreme rays take the form of five types of aberration, known as Seidel aberrations. If we have light of different wavelengths we also have chromatic aberration. It is the task of the lens designer to balance conflicting requirements (e.g., minimize the number of lenses, maximize light gathering power, minimize fabrication difficulty, reduce aberrations, etc.) and come up with an optical design. The optimization procedure is done now with the help of computer programs. The resultant design for, say, an expensive camera zoom lens usually involves many elements and several types of glass. Without the ability to reduce internal reflections, such lenses would be quite useless. All these lenses have anti-reflective coatings (we will understand how that works later). From the price of a camera lens you can see how difficult it is to build a good lens system – the development of a special lens might cost as much as \$100,000 or even \$1M for the lens in the stepper in a micro-electronics fab.

Three factors go into the usefulness of an optical instrument: (1) magnification, (2) light gathering power (useful aperture), and (3) resolving power.

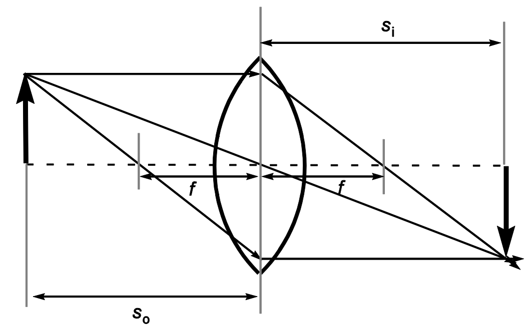
The first two can be described entirely by geometrical optics, i.e., by Snell's law. The third factor represents the ability of the instrument to perform its task: to resolve fine details. For example, with a telescope we might want to be able to distinguish the two partners in a double star; in a microscope, the fine detail inside a cell nucleus. One limit will be the failure of any realistic lens to form a perfect image as a result of lens aberrations. These aberrations can be described by geometrical optics and can in principle be reduced by making the aperture of the lens smaller, at the expense of light throughput. As the lens becomes smaller, the wave nature of the light can result in an angular spread ~ λ/D (where λ is the wavelength and D is the diameter of the aperture), which results in the blurring of the image. We will study these wave properties in greater detail later in this course. To reduce this effect we would like to make the lens aperture larger rather than smaller. The actual lens design is a trade off between the geometric optics limit and the diffraction limit.

Please note that specifications of your lenses (focal length, principal planes, etc.), and lens holders can be found in a Newport Catalog, available in the laboratory or on the web at http://www.newport.com.

(3A) The Thin Lens Equation

Objective: The thin-lens equation $\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i}$ will be verified experimentally, where f is the focal length, s_i is the image distance, and s_o is the object distance. You will measure object and image distances, and the focal length of the lens by several different methods. Use the obtained data to check the thin lens equation. Estimate the errors.

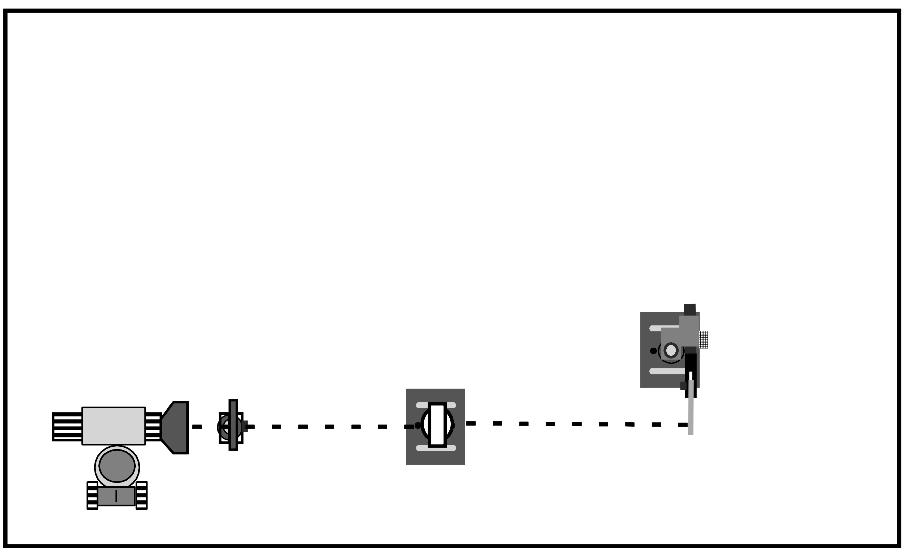
Note: The same sign convention as in Hecht is used.



Definition of lens parameters with principal rays

(i) Measurement of image and object distances by imaging an object.

Suggested experimental setup and procedure:

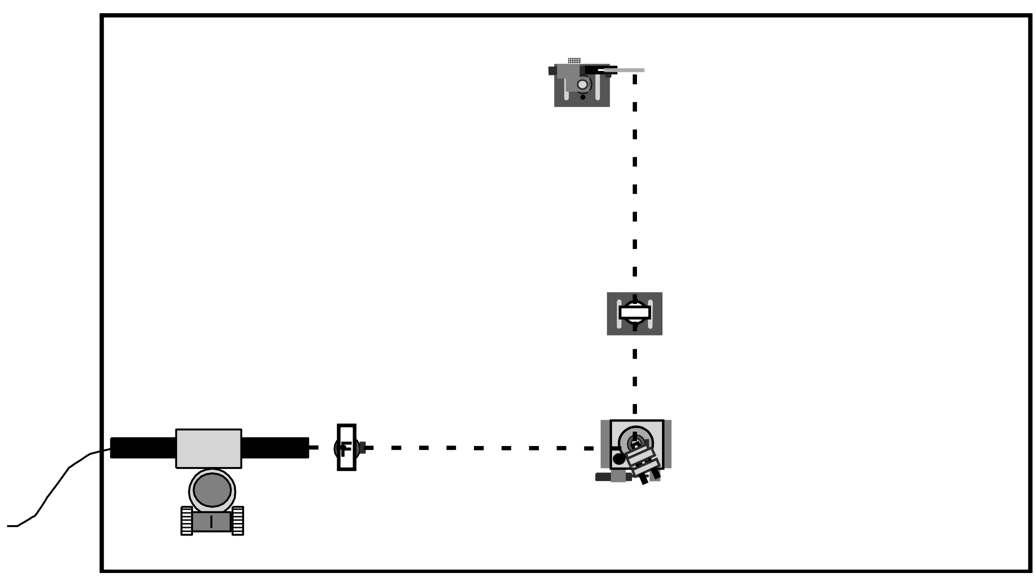


1. Mount a flashlight in the laser mount on the breadboard.
2. Use the arrow target slide as your object. Place a filter holder in front of the flashlight and place the slide into the holder.
3. Mount a 100-mm focal length plano-convex lens about 125 mm from the target. This is our first object distance. Which side of the plano-convex lens should face the target to minimize aberrations?
4. Use the beam stop to visualize the image. Turn the flashlight on and move the beam stop back and forth to get the sharpest image of the arrows. Compare the directions of the arrows of the image with that of the object.
5. Measure the object and image distance from a well-defined point at the center of the lens holder. Compare the size of the image with that of the object.
6. Redo the measurements for object distances 200, 400 and 600 mm.
7. Perform error analysis. Now, since you cannot be exactly sure where the lens was situated within the lens-holder, try to reduce the error in the focal length by assuming that there are small systematic errors in the measured values of s_O and s_I, and correcting them. These errors actually include the positions of the "principal planes", which represent the lens in thick lens theory. Use a computer code to find the best values for the systematic errors, by reducing the error in your value of the focal length.

(ii) Measurement of image and object distances with the help of a rotating mirror

Here we will locate the image using the "imaging requirement", that is all rays originating from a given point on an object (here a mirror) have to arrive at the same point in the image plane. To get rays at different angles, we will use a mirror mounted in a rotation stage.

Suggested experimental setup:

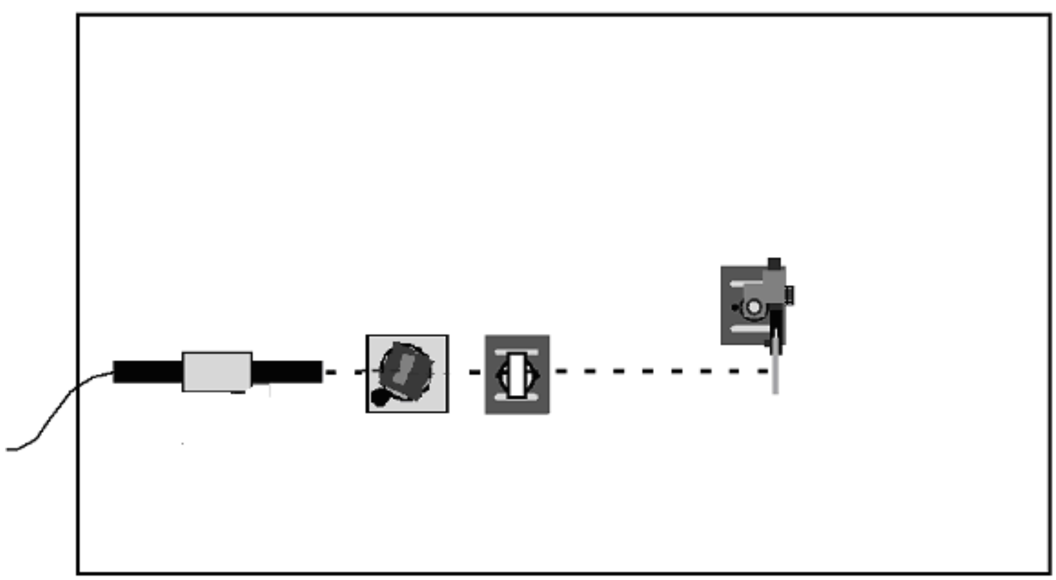


1. Mount the laser on the breadboard.
2. Place a ND-filter into a filter holder in front of the laser. Since the provided 0.5 ND filters only reduce the intensity by about 3, it is better to use two polarizers.
3. Mount the mirror on a rotation stage in front of the laser. Align the laser and mirror.
4. Place a 100-mm focal length plano-convex lens about 125 mm from the mirror. Align the lens such that the back reflection from the lens is centered on the beam spot at the mirror.
5. Use the target assembly as a beam stop. Make a small hole into an index card and mount it onto the target assembly. Align the hole with the beam so that the brightest part of the beam passes through the hole. This configuration can now be used to detect small motions of the beam.
6. Now you can conduct the experiment. Your goal is to locate the image of the mirror. Please describe your procedure of finding the image plane.
7. As in part (i), repeat the experiment for object (mirror) distances 200, 400 and 600 mm.
8. Perform error analysis. Please notice that if the axis of the rotation stage does not intercept the point of reflection of the laser at the mirror surface, a systematic error will be introduced to your measurements. In that case, please estimate the magnitude of this error.

(iii) Measurement of the focal length by translation of the laser

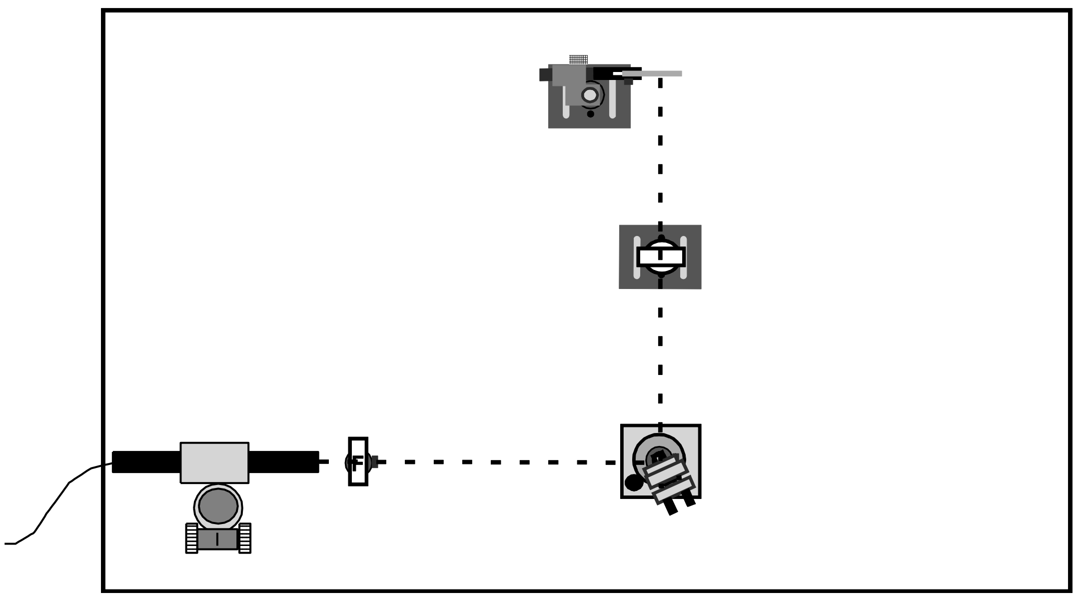
You will determine the focal length of the nominally 100-mm focal length lens. This will be achieved by translating the laser beam perpendicular to the optical axis to locate the focus of the lens.

Suggested experimental setup:



1. Mount the laser on the breadboard.
2. Mount a 100-mm focal length plano-convex lens in front of the laser.
3. Mount a glass slab on a rotation stage between them.
4. Translate the laser beam by rotating the glass slab (see (1D)) and move the screen along the optical axis until the laser spot does not move. Measure the distance from the middle of the lens to the screen; this value is a good approximation to the focal length. Repeat the measurement a few times to get an accurate result.
5. Now rotate the lens by 180º. Do you see a difference in your measurements between these two configurations? Explain why.

Sometimes an experiment requires not imaging but separating rotational from translational motion. Consider the following experimental setup:



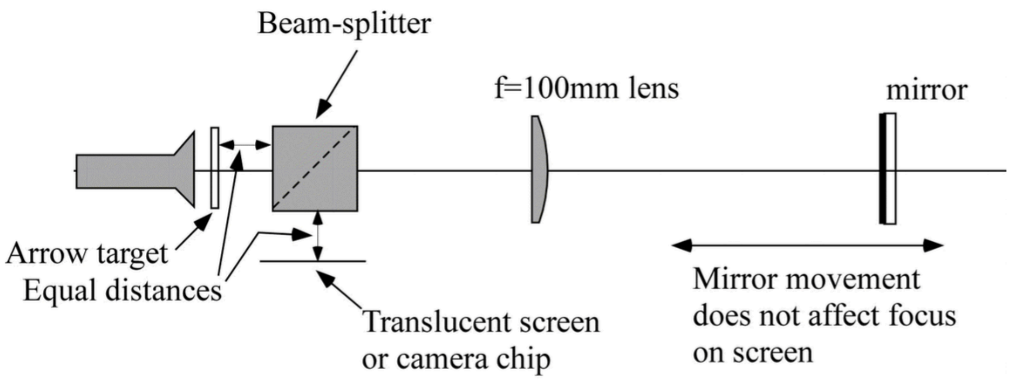
This setup is very similar to (3A) (ii), however, the rotation stage is also mounted on a translation stage. Again you will use the 100-mm focal length plano-convex lens.

The goal of this experiment is to adjust the above setup such that the laser spot at the index card (imaging plane) does not move when you translate the mirror (at any angle of the mirror such that it passes the lens). However, a rotation of the mirror leads to a motion of laser spot on the index card.

1. Find the suitable distances.
2. Construct a ray diagram.

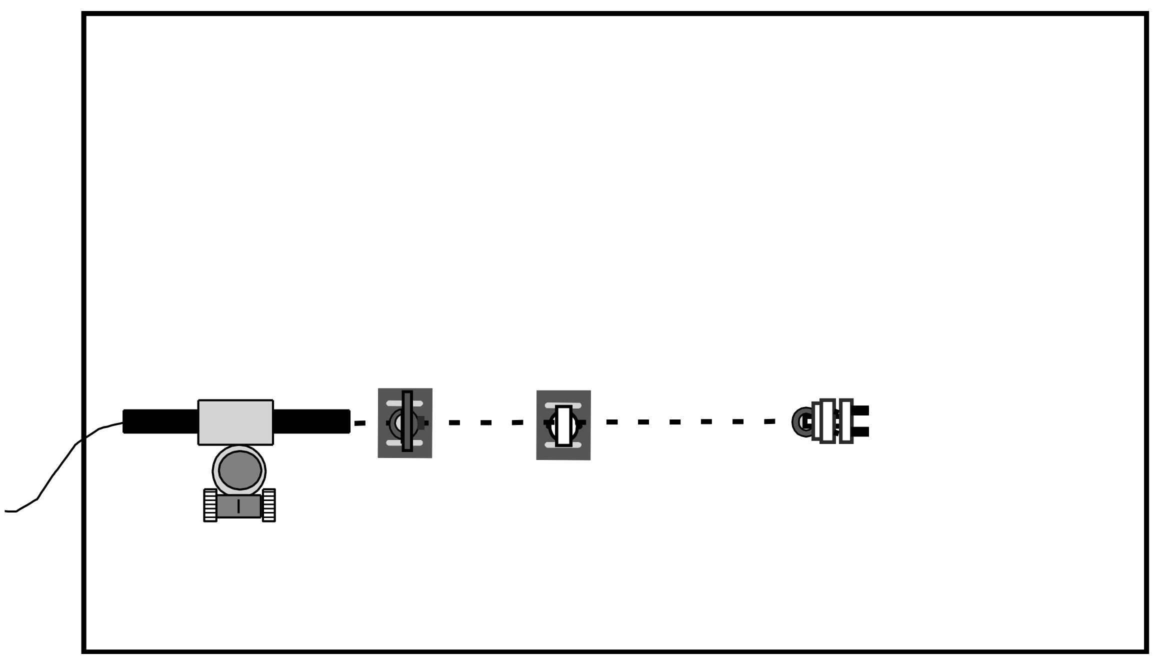
(iv) Measurement of the focal length by autocollimation.

You will use the method of autocollimation to measure the focal length of a nominally 100-mm focal length plano-convex lens. If a point light source is located at the focus of a lens, the rays passing through the lens will become collimated. If a mirror is used to reflect the beam back so that the beam retraces the same path through the lens, then a focused image of the source will appear at the source. The standard way in which the autocollimator is used is shown in the figure below. An object target is illuminated incoherently using the flashlight, and a lens used to create an image of this at infinity. You confirm this by using a beam-splitter (figure) and a screen or camera which is conjugate to the object slide when a plane mirror is placed in the parallel beam after the lens. When the setup is correctly aligned, the image sharpness is not affected by moving the mirror along the axis. The focal plane of a second lens (f>0) can then be found by putting it after the autocollimator lens, and finding the mirror plane which once again gives a sharp image on the screen or camera chip.



Autocollimator layout

Suggested experimental setup:



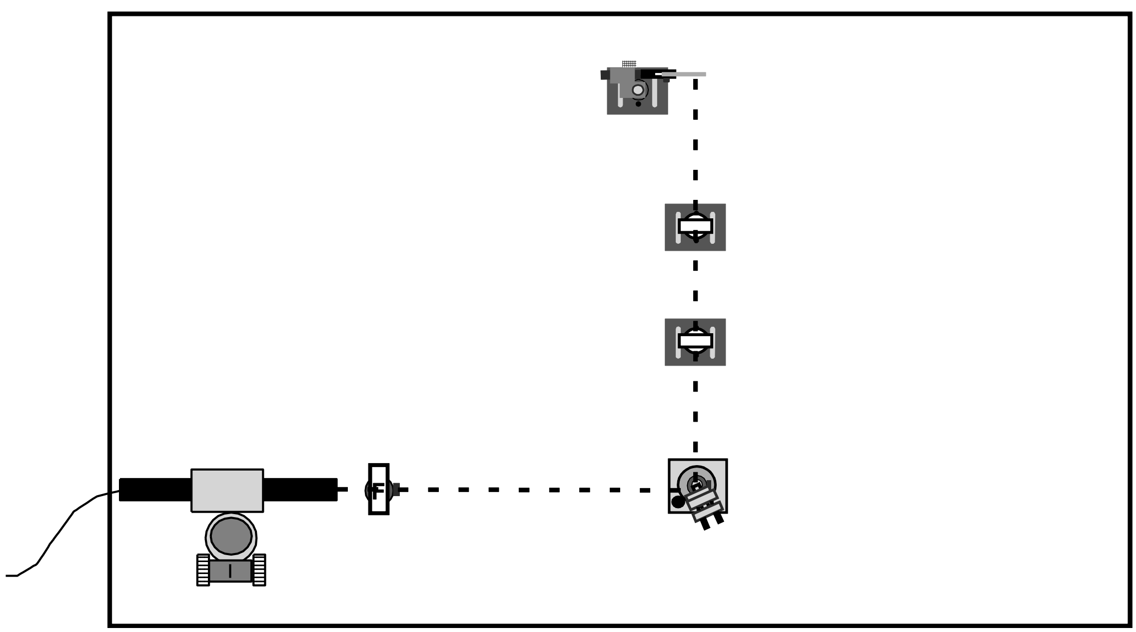
1. Mount and align the laser.
2. Set up a mirror in front of the laser and align the mirror. Be sure you have enough room for the lens.
3. Mount a 100-mm focal length plano-convex lens in front of the laser and align the lens.
4. Mount a pinhole in the filter holder and place it into the beam in front of the laser. The diffraction of the beam from this small hole will act as a point light source.
5. Autocollimate your system and measure the focal length. Compare with your earlier results.
6. Perform error analysis.

The summary for the whole experiment should contain the average value of the focal length obtained with the four different methods, weighted accordingly to their respective errors.

(3B) Negative lens

Objective: The focal length of a plano-concave lens with a nominal focal length of -25 mm is measured using the thin lens equation. Since the focal length is negative, we need an auxiliary positive lens of known focal length. [After all that work in part (3A), you surely should have one of known focal length.]

Suggested experimental setup:



1. The experimental design is similar to that of (3A) (ii).
2. Place the negative focal length lens with its concave side facing the mirror (Why?).

3. Use the mirror as your object. Measure the object distance.
4. Next, place the auxiliary lens more than 100 mm beyond the negative lens.
5. Find the image distance.
6. From the focal length of the auxiliary lens and the image distance, calculate the object distance for this lens. Then you can calculate the image distance of the negative focal length lens. By using the thin lens equation, the focal length of the negative lens can easily be calculated. Compare with the given value.
7. Perform error analysis.

(3C) Laser Beam Expanders and Telescopes

Often it is necessary to expand a narrow laser beam to fill a large aperture with (almost) parallel light. For example, expanded laser beams are required especially for a Michelson interferometer, where we want to illuminate a large area. The expansion of the initial laser beam can be accomplished by first diverging the beam with a short focal-length lens and then recollimating the beam with a second lens. This arrangement of lenses is analogous to that of an inverted telescope. It is inverted because the laser beam enters the telescope at the eyepiece and exits through the objective lens.

In this part of the project, you will demonstrate the design of two types of laser beam expanders: the Galilean and the Keplerian (or astronomical) telescopes.

(i) Measurement of the beam divergence of the laser with a razor blade

Beam expanders reduce the divergence of the laser beam. Before we build the expanders, you will learn how to measure the divergence of the laser beam used in the experiment. Assuming that the laser beam is Gaussian, the beam diameter of the laser varies as $D^2(z) = D_o^2 + [2\theta(z - z_o)]^2$, where the beam waist is located at $z = z_o$, D_o is the beam waist diameter, and θ is the far field half divergence angle of the beam. By measuring $D(z)$, θ can be determined. Note that for sufficiently large z from the beam waist, we can recover the geometrical optics prediction that the beam diameter increases linearly with z.

Suggested experimental setup:

1. Mount the laser on the breadboard.
2. Extend the beam path by using mirrors as much as possible.
3. To measure the beam diameter at a given distance from the laser, you can either use the razor blade technique or a camera that detects the beam spot. In the laser blade techniques, you will move a razor blade across the beam, while measuring the intensity of the light that is not blocked by the razor blade with a photodetector. Since the laser intensity fluctuates, you are advised to only make measurements at 3 razor positions (see below).
   - Mount the razor blade on a translation stage, and mount the photodetector behind it.

- Move the razor blade completely off the beam, measure total laser intensity.
- Now move in the razor blade until the laser intensity halves. The blade should be located at the center of the Gaussian beam. Record the micrometer reading.
- Move the razor blade to one side of the laser beam so that the intensity drops to a quarter. Record the micrometer reading.
- Repeat the measurement on the other side of the laser beam.
- From these 3 positions, you should be able to get a good estimate of the beam diameter.

When you use a camera to measure the size of the laser spot, you have to detect an image of the spot and fit a Gaussian to the intensity distribution. The rms width of the Gaussian is an estimate of the beam diameter.

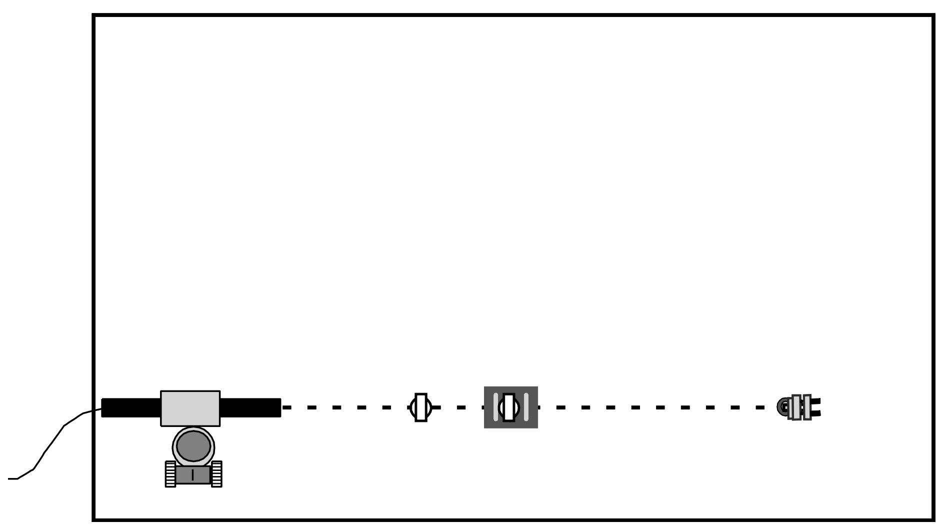
With either of these two methods, measure the beam diameter as a function of the distance from the laser (z). From these measurements determine θ.

Note: It is suggested that you make two sets of measurements: one far away from the laser to determine divergence, and another close to the laser to determine z_0 and D_0 (otherwise you will have to fit your data with 3 unknown parameters). The further complication here is that beam waist is located inside the laser. You can build a 4-f arrangement of lenses (ask your TA if you are not familiar with it) to obtain the waist outside of the laser cavity. Measure intensity profiles at about 5 points around the minimum and fit to a parabola, thereby extracting the beam waist. Afterwards measure the divergence far away.

(ii) Galilean beam expander

The Galilean beam expander consists of a diverging and a converging lens. We will be using -25 mm and 50 mm lenses to expand the laser beam. Measure the new beam divergence and convince yourself that the divergence is reduced by the right factor.

Suggested experimental setup:



1. Mount the laser on the breadboard.
2. Mount a -25 mm focal length plano-concave lens in front of the laser. Align the lens. Which side of the lens should be towards the laser?
3. Mount a 50 mm focal length plano-convex lens after the plano-concave lens so that their relevant principal planes are spaced at $f_1 + f_2$, and align this lens. You may use the 400 mm focal length plano-convex for observation of more dramatic effects of beam expansion. But for the final measurements, please use the 50 mm focal length plano-convex lens.
   - The sliding base shown above may not allow you to position the two lenses at this close proximity. In that case, you need to figure out another way to mount the second lens. Please ask your instructor for help if you cannot figure this out on your own.
   - In order to construct a correct Galilean beam expander, the spacing between the two lenses must be positioned rather accurately. This means that you cannot use the thin-lens approximation, but instead, you will have to find out where the principal planes are for each lens. You also need to know where a lens is positioned inside a lens holder.
   - The specifications for the lenses and lens holders may be found in a Newport Catalog, available in the laboratory or on the web at http://www.newport.com. The lenses are single, BK7, spherical lenses. In your lab report, please record this information, make drawings of lenses/lens holders, and indicate how you determine the exact distance between the two lenses.
4. Determine the beam divergence and waist as in part (3C)(i). Don't forget that the beam waist is now located at some distance after the second lens. Does the experiment agree with the theory?

Note:

You have been probably trying hard, but results are still not very good. In part it might be due to the difficulties in constructing a correct beam expander (you can try estimating the errors with ray matrices). But it is possible for you to verify a very basic relationship: conservation of the phase-space volume (Liouville's theorem). In the above case it states that no arrangement of lenses can change the phase-space volume of the beam, so that the product of beam waist and divergence stays constant.

(ii) Keplerian beam expander

By replacing the -25 mm lens with a positive focal length lens (+25 mm), we can transform the Galilean beam expander into a Keplerian beam expander. Repeat the steps described above.

(3D) Shadowgraphy

In this part of the lab, you will build a shadowgraphy system for visualization of small changes in the index of refraction of an object, which in our case is the flow out of the nozzle of an

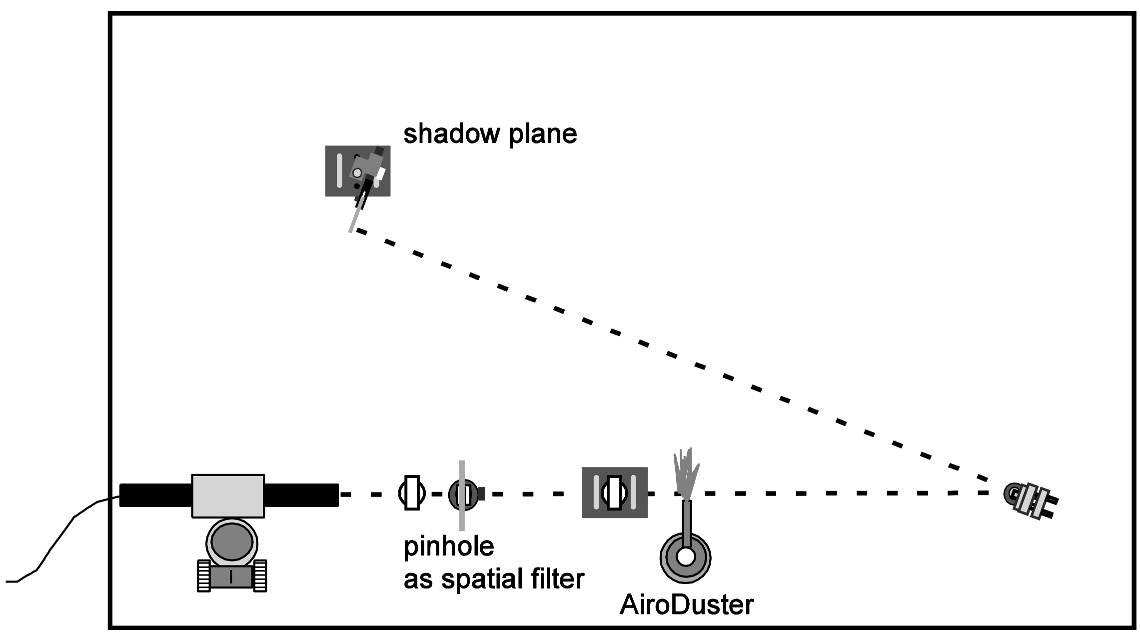
AiroDuster bottle. This lab is very qualitative and no quantitative results will be obtained. It is meant to introduce you to this very common method in flow visualization. In your lab report, please describe what was done in the lab and why.

Light bends when it travels in a medium of changing index of refraction. Shadowgraphy makes use of this effect by geometrically amplifying deviations after the light has left the volume of varying index of refraction. You can see this effect with your unaided eye. Place the nozzle of the AiroDuster bottle about 30 cm from your eye and hold it towards the room lights. Focus your eyes on the nozzle and let a small amount of gas out of the bottle. You will see the gas flowing out of the bottle.

Sometimes it is advantageous to use a parallel beam of light for flow visualization. This makes the deflection of the light rays more quantifiable. In the following experiment, you will investigate the sensitivity of the shadowgraph to changes in the index of refraction as you place a screen further and further away from the AiroDuster nozzle. Make notes of your qualitative observations. Please read also page 61 in "Exploring Laser Light" (available on the course website).

Another way to visualize small changes in the refractive index is the Schlieren system, which is widely used in wind-tunnels. In this case, an additional converging lens between the object and the screen produces an image of the object plane on the screen. Between the lens and the screen there is a plane in which the laser beam is focused to a spot. Without operating the AeroDuster, put a razor blade in this plane and adjust its position till it cuts the light intensity into two at all places on the screen (this is a very accurate method of locating the focal point, called the Foucault knife-edge test). Now operate the AeroDuster, and observe the changes. The advantage of this system is that it can be made quantitative quite easily.

Suggested experimental setup:



1. Set up the Keplerian beam expander.

2. Place a mirror at the far end of the table. We will use it to get a longer path length.
3. Choose a plane close to the expander to introduce the gas flow.
4. Place the target assembly into the light path. About 1.5 m from the AiroDuster is a good choice. Gently squeeze some air out of the AiroDuster. Describe what you observe at the target assembly.
5. Now move the screen (target assembly) closer and closer towards the AiroDuster. What happens?
6. Add the extra lens and the knife-edge to build the Schlieren system and repeat 4.
7. Give an explanation of the sensitivity change. Is the shadowgraph signal proportional to the index of refraction n or to its first or second derivative with respect to the lateral coordinates? (Plane perpendicular to the light beam.) Please give an explanation.

Using CCD Camera

You will use a CCD video camera to visualize the shadowgraph. This is the first step of digital imaging that you will learn in later projects.

1. First place the camera in the path of the beam. You might want to use a focusing lens for a better image quality.

Note that the CCD camera has a number of switches. Please turn off the AGC (automatic gain control). This makes sure that we can measure intensity variations from one image to the next. Next you have to adjust the light sensitivity of the camera by adjusting the shutter speed. The camera has a panel at the side that you can lift off. Below you find dip switches for the adjustment of AGC and shutter. For a fine adjustment of the intensity of the laser beam you may either use your neutral density filters or crossed polarizers. The camera is connected via a box (which has its own power supply) to the monitor “in” connection. You can connect the “out” connection to the computer and use a frame-grabber to record the pictures.

2. Now gently blow some air out of the AiroDuster. Watch this process on the TV monitor.
3. Now take the screen away. You are still imaging the same shadow plane however this time directly.
4. Make notes of what you have observed.

An alternative is to use the camera of your cell-phone!

Project 4: Interference

Introduction

In this project, you will observe phenomena that demonstrate the wave nature of light. In general what we call "interference" results when two or more waves that have a definite phase relationship for a sufficiently long time are combined. When there is a definite phase relationship, we say the beams are "coherent". In that case, the observed intensity is given by the superposition of the electric and magnetic fields of the wave. The observed intensity is proportional to the time average of the *square* of the combined fields.

The waves do not interfere with each other in the usual sense of the word. Two light beams interfere to create a fringe pattern without having any effect on each other. This is due to the fact that in vacuum the wave equation derived from Maxwell's equation is linear and so we can superimpose the individual waves. In dielectric materials this superposition principle no longer holds for waves of very large amplitude. The area of physics in which these nonlinear effects become important is known as nonlinear optics. The lasers used in this lab are much too weak to see any nonlinear effects.

We can have either constructive or destructive interference depending on the phase relationship between the individual waves. If we look at where the waves intersect a plane in space, we see a fringe pattern, which is an indication of how the relative phase depends on the point where the intensity is observed. In order for two waves to produce a stationary pattern, they must have the same frequency; otherwise the interference pattern changes in time. In the latter case, the time average becomes a simple sum of intensities.

Broadly speaking, there are two classes of interference effects. Two beams can be made from a single beam either by "division of wavefront" or by "division of amplitude" (see "Exploring Laser Light", page 111). An example of division of wavefront is the Lloyd's mirror experiment and for division of amplitude is the Michelson interferometer. Division of wavefront requires spatial coherence, that is, a definite phase relation between the wave amplitude at two separate points, while division by amplitude requires only coherence in time.

The project on interference is set up in 4 parts: thickness measurement by interference, Lloyd's mirror, the Michelson interferometer, and the Fabry-Perot interferometer.

As a preparation for the following projects, please read Chapter 9 in Hecht or Chapter 2 in Saleh&Teich.

(4A) Thickness Measurement by Interference

Often it is necessary to measure the thickness of a thin dielectric layer. In this experiment, you will be measuring the thickness of a cover glass by using fringes of equal inclination. For the case of a cover glass in air, the locations of the bright fringes are given by

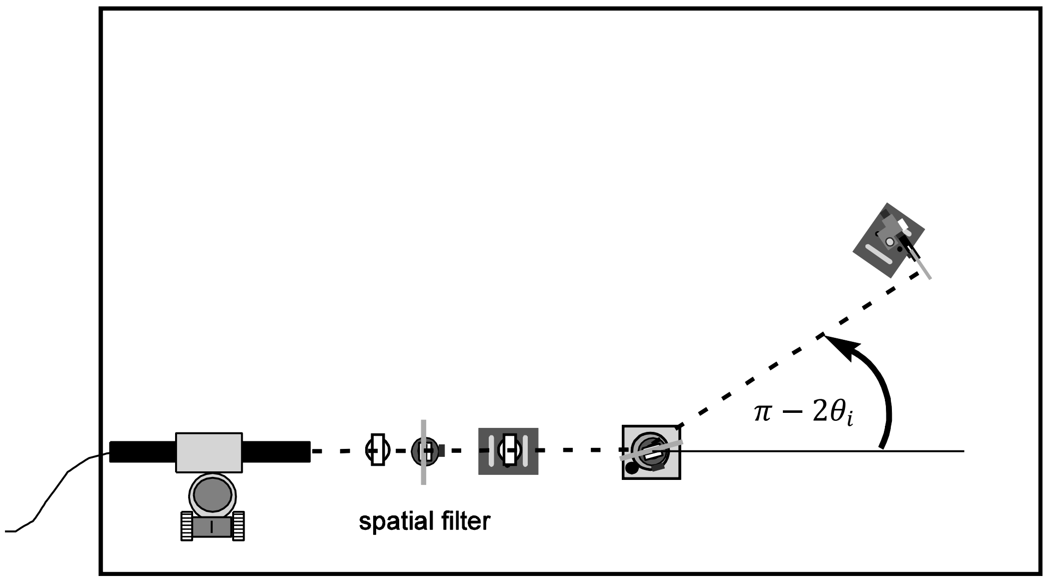
$$\cos\theta_t = \frac{(2m-1)\lambda_o}{4nd},$$

where *m* is the order of the fringe, *d* is the thickness of the layer, λ_o is the vacuum wavelength of the light, *n* is the index of refraction of the glass slide, and θ_t is the angle of the transmitted light within the glass slide with respect to the surface normal. The above formula can be rewritten in terms of the angle of incidence θ_i as

$$\sin^2\theta_i = n^2 - \left[\frac{(2m-1)\lambda_o}{4d}\right]^2 .$$

Please derive the above formula. You will be using the above formula to estimate the thickness of the slide cover glass.

Experimental setup and procedure:

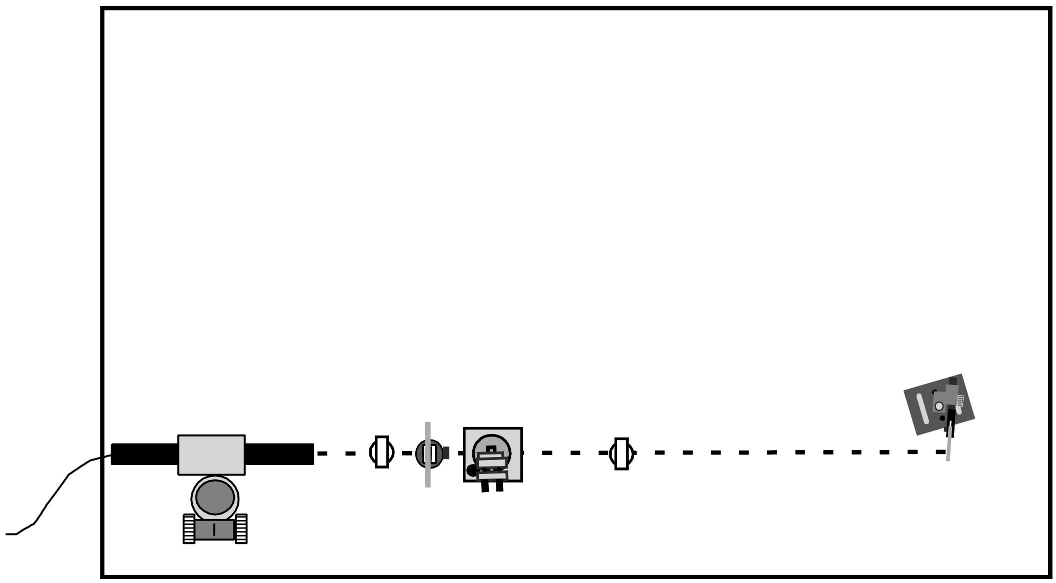


1. Mount the laser on the breadboard.
2. Build a beam expander with 25-mm and a 50-mm plano-convex lenses and clean up the beam with a spatial filter (the pinhole slide).
3. Mount a cover glass into the filter holder. With a little care you can clamp it into the alligator filter holder. Mount this assembly onto a rotation stage.
4. Observe the reflected spot with an index card. You will see interference fringes in the reflected spot (why?).
5. Rotate the cover glass, and measure θ_i when the dark fringe is centered on the reflected spot. Take all possible measurements of θ_i between 0^o and 90^o. Also take a digital image of the reflected spot with fringes and include it in your lab report.
6. Plot the data in a sensible way and show that the above formula holds. Calculate the thickness of the glass slide and compare with the value provided by the manufacturer. Perform error analysis!

(4B) Lloyd's mirror

This experiment is the classic method for obtaining interference fringes. It was first described in 1834. It is a simple method to measure the wavelength of light.

Experimental setup and procedure:



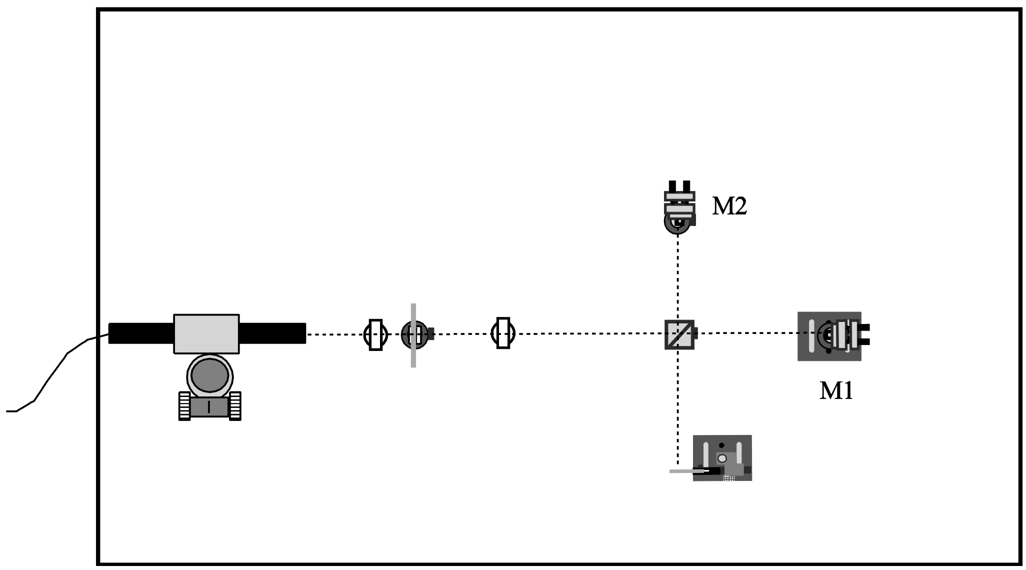
1. Mount the laser on the breadboard.
2. Build a point light source with a pinhole and a 25-mm plano-convex lens (similar to a spatial filter).
3. Mount a converging lens about 30 cm behind this setup. It will be used to image both the pinhole and the virtual pinhole produced by the mirror.
4. Mount a mirror on a translation stage (with the translation axis perpendicular to the optical axis) and place this mirror close to the pinhole. Align the mirror at a very shallow angle and translate the mirror so that half of the light glances over the mirror without reflection while the other half reflects off the mirror. As you will discover, to achieve this half and half condition, the mirror has to be very close to the pinhole.
5. You should now see two images of the pinhole after the second lens. By using the imaging condition, you can calculate the distance between the two light sources (not very accurate).
6. Remove the second lens carefully. In the region where the light from the "two" sources overlap you should see an interference pattern consisting of bright and dark vertical fringes. Do not confuse the sought-after uniform spaced fringes with fringes due to Fresnel diffraction from the edge of the mirror. Those fringes appear only close to the mirror and change strongly with the distance from it. Also take a digital image of the fringes and include it in your lab report.

7. By measuring the fringe spacing you can calculate the wavelength of light. Estimate the error (it might be large). Make sure that you observe the fringes in a suitable plane. How far is your observation plane away from the mirror? In your write-up explain why the observed fringe pattern is equivalent to the Young's double-slit experiment. How are the fringes modified by the phase-shift produced by reflection from the mirror?

(4C) Michelson Interferometer

In this experiment you will build a Michelson interferometer. You will use it to observe small displacements and refractive index changes. You will also use it to measure the frequency separation between the axial modes of the He-Ne laser. A modified version of a Michelson interferometer, known as the Twyman-Green interferometer, is often used for testing optical systems. It provides means to measure the amount of aberrations present in these optical systems.

Experimental setup and procedure:



1. Mount the laser about 30 cm from the long side of the table.
2. Set up a Keplerian beam expander filter using a +25-mm and a +400-mm focal-length lens, and clean up the beam with a spatial filter (the pinhole slide). Use narrow pinhole (50-100 microns) for better performance.
3. Mount a cube beamsplitter and align it by directing the retroreflections from the beamsplitter surface onto the pinhole.
4. Place a mirror on a sliding base (M1, test mirror). Mount it about 15 cm from the beamsplitter (see schematic) and align using the retroreflections of the pinhole.
5. Mount a second mirror (M2, reference mirror) in a post holder that is placed at a right angle, ~ 15 cm from the beam splitter. Align it using the retroreflections of the pinhole.

6. Place the target assembly opposite mirror M2.
7. Align the mirrors such that the two beams are brought into coincidence on the target assembly. Usually it is best to use only one mirror (M1) for adjustment.
8. Adjust the mirrors to minimize the number of fringes. Take a digital image of the fringes and include it in your lab report. Explain the observed fringe pattern. Make a schematic in your notebook.
9. Adjust the mirrors so that you see about five fringes.

   The curvature of the fringe pattern is caused by the interference of the plane reference wave front from M1 with the test wave front from M2. Any deviation from straight fringes is a result of the curvature in the wave front. This is partly due to the components under test, and partly due to the fact that the laser beam is not a planar wave. This departure, measured in number of fringes, is a measure for the departure of the test wavefront from the reference wavefront in number of wavelength of the laser light (*W*).
10. Move the second lens of the beam expander slowly towards the first. What do you observe? . Take a digital image of the fringes and include it in your lab report. You can also replace the +400-mm lens with a diverging lens. Explain your observations.
11. Place the AiroDuster nozzle into one arm of the interferometer. Blow and observe what happens. How is it different from shadowgraphy?
12. Insert your finger partly into one arm of the interferometer. Notice the variations in the fringes as a result of the hot air rising from your fingers.
13. Push the test mirror. What do you observe? Explain your observations.

(4D) Frequency separation between the axial modes of the He-Ne laser

In the next part of the experiment you will use the interferometer to measure the frequency spacing of the axial modes of the laser. Laser beams are generated in an optical resonator. In most lasers, unless special precautions are taken, the excited modes are standing waves that obey the condition $L = m\lambda/2$, where m = 1, 2, 3, ..., λ is the wavelength of light, and L is the distance between the mirrors. These modes are called the axial modes of the laser. The frequency separation of the axial modes is $\Delta\nu = c/2L$, where c is the speed of light in vacuum. The possible lasing frequencies are limited by linewidth of the atomic transitions of the lasing medium, in this case neon. The width of the transition is broadened by the Doppler effect as a result of the motion of the molecules of the He-Ne gas. In this way, a number of modes can be excited which are determined by the length of the laser. The closer the mirrors are spaced, the smaller the number of modes that can be excited. Neighboring laser modes alternate in polarization. This means that modes with equal polarization are spaced twice as far apart. In your laboratory laser (probably a 3-mode laser) most of the intensity is in a central mode, while the other modes have less intensity.

We can now use the Michelson interferometer to measure the spacing of the axial modes. Let’s consider a single mode. When we move one of the mirrors (say M1) away from the beam splitter you will see that the fringes move. For a parallel beam, the fringes would change from dark to bright. If x is the distance we move the mirror, the intensity variation is given in the case of a 50/50 beamsplitter by

$$I = I_o\left[1+\cos\left(\frac{4\pi x \nu_o}{c}\right)\right]$$

where ν_o is the frequency of the laser mode. Check this formula. If two modes are present in the beam with frequencies and intensities that are relatively close to one another, you will get a beating effect as x is varied. Please calculate the appropriate formula. Add up the two modes (actually there are four waves, two from each of the mirrors) and calculate the intensity *I(x)* for this situation. As a result you will find that the contrast of the fringe pattern will fade and come back at certain distances Δx and that the frequency mode spacing difference is given by $\Delta\nu = c/4\Delta x$.

Your objective in the next part of the experiment will be to verify this relation. The exact method is up to you and your partner. Estimate your errors.

Hint: You can measure the contrast of the fringe pattern (defined as $\frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}}$) at equally spaced intervals by means of a CCD camera (capture images and analyze with *Scion Image*), and then fit it to a cosine. The mode spacing difference can be extracted from the corresponding frequency.

It will be also helpful to think, how the wavelength of this cosine is related to the length of the laser cavity.

(4E) Fabry-Perot Interferometer

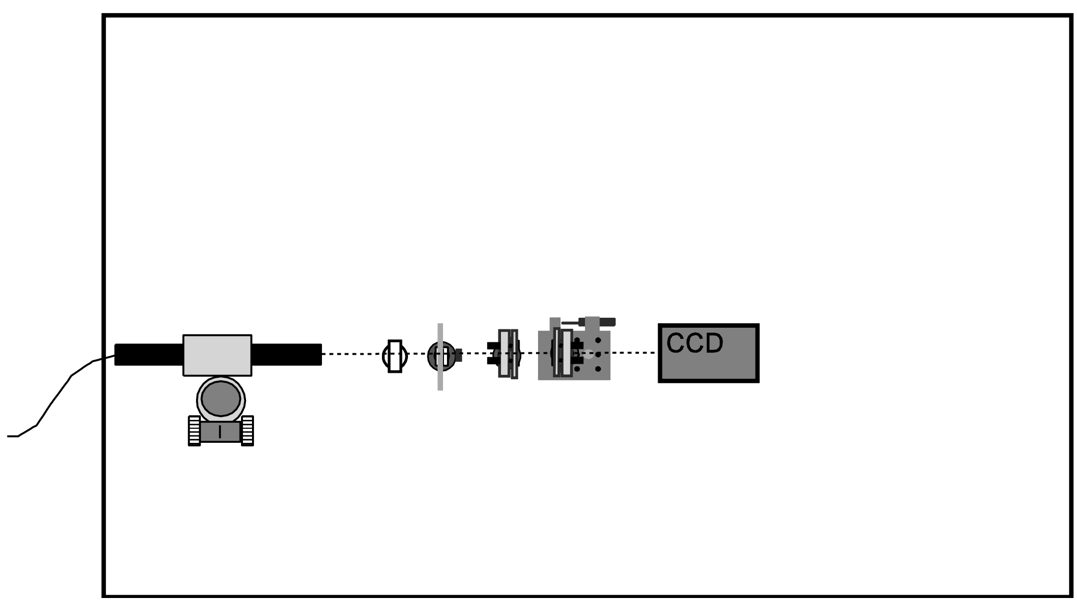
As a last example on interference you will set up a Fabry-Perot interferometer. This instrument is a spectroscopist's dream - it is capable of a wavelength resolution equal or better than the best spectrometers based on diffraction gratings. All this is accomplished by the use of an interferometer, or an "etalon" – two parallel, partially silvered glass surfaces. If the angle of the light wave normal (ray) is chosen correctly, multiple reflections from the surface will interfere constructively. Since the surfaces are only partially reflecting, some of the light escapes at each reflection. Light entering the interferometer at all other angles interferes destructively on adding up the multiple reflections and transmissions. This setup is often used as interference filter. Please familiarize yourself with "multiple reflections" (e.g. see Hecht Chapter 9). In the following experiment you will set up such an interferometer and investigate its properties.

Experimental setup and procedure:

1. Mount the laser. Make sure the beam is high enough for a mirror mounted on a translation stage.
2. Set up a spatial filter using a +25-mm lens and a pinhole. Use the smallest pinhole for better performance.
3. Mount the coated interference flat (golden appearance) in a post holder about 7cm behind the

lens.

4. Mount a second coated interference flat about 5cm from the first. You could mount it on a translation stage to adjust exactly to 5cm, but this would make the setup more sensitive to vibrations. Consider whether the exact distance matters and whether you should therefore use a translation stage.
5. Align both flats so that circular fringes appear in the transmitted wave. You will have to turn the lights off to see the fringes on an index card. After you align the fringes, use the CCD camera to view them, and take a digital image of the pattern. Describe the fringe pattern and compare it to the fringe pattern of the Michelson interferometer. Blow some air through the open space of the interferometer, what do you observe and why? Bend one of the posts holding the coated interference flats, what do you observe and why?
6. Introduce a polarizer at the laser. Describe the fringe pattern. Does it change when you rotate the polarizer? Investigate how the fringe pattern changes during warm-up of the laser.
7. Can you distinguish between the two laser lines? In the write-up, determine the free spectral range and the finesse of your interferometer. Do not forget to measure the reflection coefficient of the interferometer. From your calculation show whether you should have seen the laser lines or not.
8. To investigate the central region of your interference pattern, move the interferometer back to introduce a + 40 cm lens to make an expanded, less divergent beam.
9. Place a + 10 cm lens behind the interferometer.
10. Align the interferometer until you see a circular fringe pattern in the focal spot of the lens. Why do you have to look at the focal spot?



Project 5: Fresnel and Fraunhofer Diffraction, Fourier Optics

Introduction

So far we have ignored what happens to light when it passes an obstruction. You have already seen in the Lloyd's mirror experiment (as a disturbing effect) that light is diffracted as soon as it passes an obstruction. Diffraction cannot be explained within the context of "Geometrical Optics". As you might remember the Eikonal approximation of the wave equation leading to geometrical optics assumes a slow amplitude variation, which is not the true for light passing an obstruction. You should read Chapter 10 in Hecht or Chapter 4 of Saleh&Teich for a background in diffraction theory. There exist two limits in which diffraction is considered; in one case, the point of observation is assumed to be far away from the obstruction (Fraunhofer diffraction) and in the other limit the observation point is relatively near the obstruction (Fresnel diffraction).

In this lab we will investigate qualitatively both Fresnel and Fraunhofer diffraction and the Talbot effect. We will treat quantitatively Fraunhofer diffraction since the mathematical treatment is much simpler. In Fraunhofer diffraction where diffraction, is observed far from the aperture, the structure of the diffraction pattern does not change but merely expands with an increase in the distance of observation. In Fresnel diffraction where diffraction is observed near the aperture, the structure of the pattern can undergo dramatic changes with the distance of observation. This difference provides a method to differentiate Fraunhofer from Fresnel diffraction. Another way to produce a Fraunhofer diffraction pattern is by placing the diffracting obstacle at the front focal plane of a lens and observing the diffraction pattern in the back focal plane. We will investigate this setup in the following experiments. The lens captures the image at infinity and brings it to the front focal plane as a finite size image for observation with a CCD camera. You will conduct experiments on diffraction from a single slit, multiple slits, a circular aperture, a wire, opaque dots, and a diffraction grating.

In this project, the lab book does not provide you with an exemplary setup. You have to devise your own setup. You will capture images of diffraction, obtain a line profile, and compare experimental and theoretical profiles. The following programs can be useful: *Hauppauge WinTV GO* for the CCD camera, *Scion Image* for line profiles, and *Excel* for comparing profiles.

(5A) Diffraction from various apertures and objects.

The objective of the experiments is to measure the diffraction patterns from various apertures and objects under Fraunhofer limit. Here are the suggested steps:

Diffraction Measurements:

1. In order to achieve the best results, you will need to produce a clean, collimated beam. As you have done in earlier experiments, you should make a beam expander with a spatial filter (a pinhole). Make sure that you estimate the distance from each aperture where you expect

the Fraunhofer limit to be valid.

2. You may acquire diffraction images by directly projecting the diffraction pattern onto a CCD chip, or by using a lens together with a CCD camera as suggested above, whichever gives you the best image. Make sure to take measurements of all necessary distances.
3. The diffracting objects are all provided as slides:
   1) Single slit
   2) Multiple slits
   3) Circular aperture
   4) Wire
   5) Opaque dots

Line Profile with *Scion Image*:

1. Save the image in BITMAP or TIFF format. If your image was saved as JPEG, you can convert it to BITMAP using *Microsoft Internet Explorer*.
2. From the *Start* menu, select *Programs*, and then select *Scion Image*. Open the image file that you will analyze.
3. Select the rectangle tool in the *Tools* bar, and mark the region of interest with it. You can use the rectangle to include a number of horizontal lines that you wish to average over to get a better estimate of the line profile.
4. Under *Analyze*, choose *Plot Profile*. This will display the averaged intensity profile across the rectangle.
5. Make sure that the line profile plot window is selected. Then under *File*, Choose *Export*, and save the data. The line profile data will be saved as a column of intensity values.

Import data into *Excel*:

1. From the *Start* menu, select *Programs*, and then select *Microsoft Excel*. Read the line profile into *Excel*.
2. In the spreadsheet, create a column as pixel number and a column of the guessed intensity line profile using a correct theoretical equation.
3. Plot both the measured and the guessed line profile data. Vary the guessed parameter(s) to get the best agreement between the two curves.

For comparison, diffraction patterns (Fourier transforms) should be calculated by MATLAB, Mathematica, etc.

(5B) Diffraction Grating

· Hold a diffraction grating against a fluorescent lamp. Describe and explain your observation.

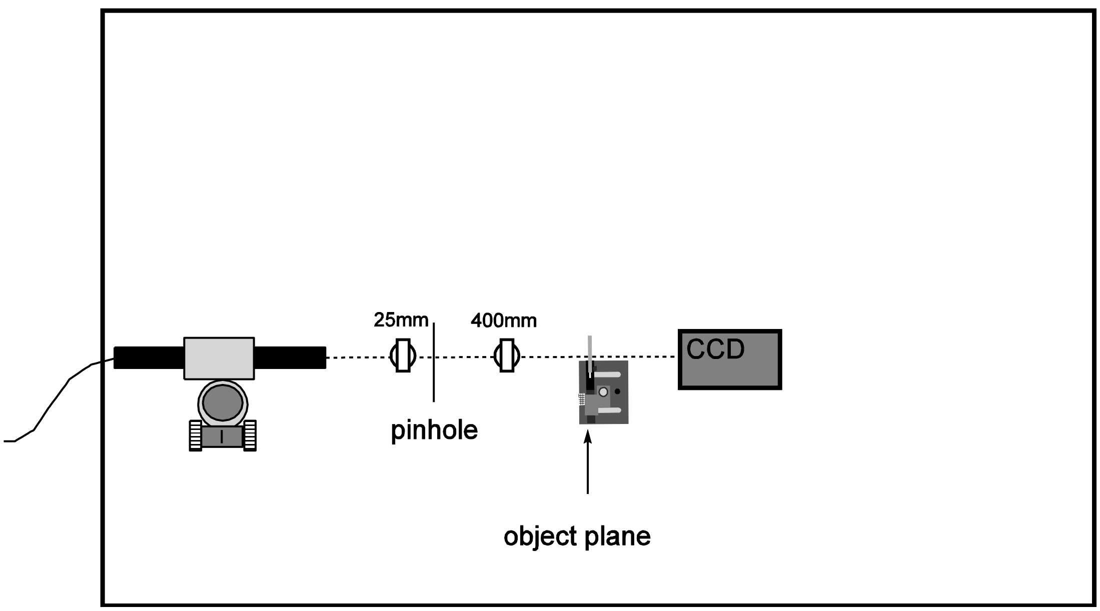
- Use the diffraction grating to measure the wavelength of the laser. Again it is your responsibility to devise the experiment. In the analysis, you can use the nominal grating frequency of 600 lines/mm.

(5C) The Talbot Effect

You will next perform a quick experiment to observe a very interesting effect that occurs in Fresnel propagation when a collimated beam passes through a rectangular mesh.

- Set up the mesh in the object plane as shown in the figure below.
- Next place a CCD camera right next to the mesh. Observe the Fresnel patterns as you move the camera away from the mesh. Take pictures of the various intricate patterns. At a certain point, you will see an image of the mesh appear. As you continue to move away you will see the whole process repeat itself, with images of the mesh appearing every d^2/λ. This behavior is known as the Talbot effect. It has numerous applications, including the copying of diffraction gratings. Note that in literature the formula for Talbot length has an additional factor of 2. Ask your professor about this.

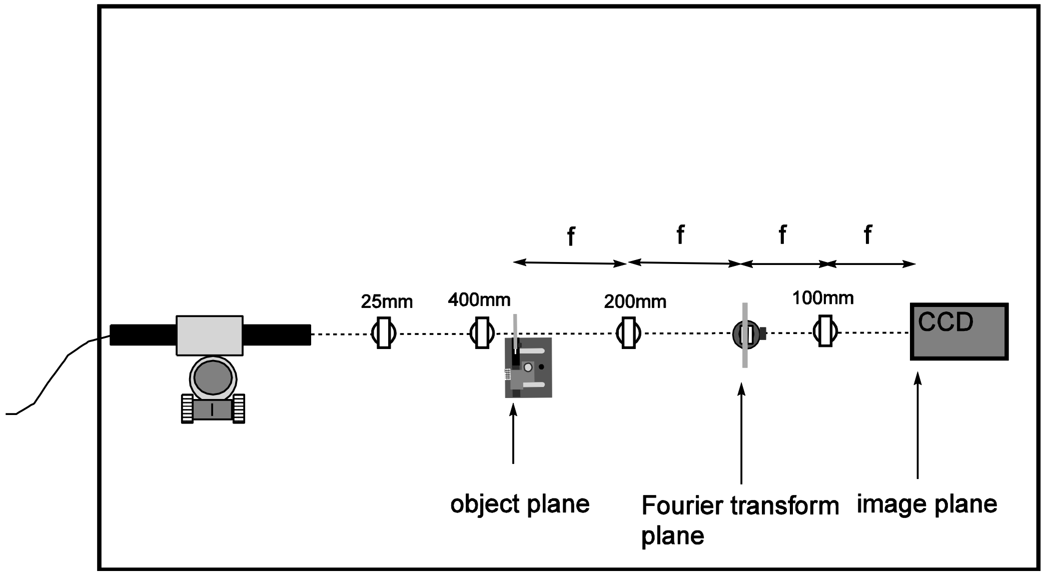
Experimental setup for Talbot effect:



(5D) Fourier Optics

In Fourier optics, one uses the Fourier transform properties of a lens to modify the spatial frequency content of an image, that is, to perform image processing. We observe that if we cut out all the high spatial frequencies, the reconstructed image becomes fuzzy and we lose resolution of fine detail. On the other hand, if we remove only the zero frequency ("DC") component, the image takes a rather strange appearance and, in many cases, the edges of the pattern are greatly enhanced. You should read Section 13.2 in Hecht (or Chapter 4 of Saleh&Teich). Describe all your experimental observations in your lab book. In your lab report, you should offer mathematical analyses for your observations, but not in excruciating detail.

A suggested experimental setup for an optical image processor is shown in the following figure.



The above setup is known as a canonical image processor. Make sure that you understand the function of each part of this setup and, in particular, the Fourier transform plane. In this experiment, you will look at the effects of various spatial filters on a variety of objects.

The four objects that you will be image processing are a sinusoidal grating, a wire mesh, a rectangular array of circles, and a half-tone image.

For each object:

1. Start out by looking at its Fourier transform and the unfiltered image with a CCD camera and capture them on the computer to be printed later.
2. Cover the object with an iris and vary the size of the iris. What do you observe? Explain your observations.
3. Now insert the following masks or filters at the Fourier transform plane. Take special care to ensure that the camera is at the image plane and that all the masks or filters are at the Fourier transform plane. Please try all of the available filters. For your report, you may choose two spatial filters that you think may illustrate an important filtering effect and take a picture of the filtered images. Please also provide theoretical explanations. Here are some of the available spatial filters:
   - Various widths of slits.
   - Various widths of lines.
   - Various sizes of opaque dots.
   - An edge.

(i) Sinusoidal grating

(ii) Wire mesh

How do you get an image of horizontal lines?

How do you double the frequency of the mesh in the image?

(iii) Rectangular array of circles

Employ the array theorem to explain the resulting diffraction pattern.

(iv) Half-tone images

Overlay the wire mesh with a half-tone picture. How do you make the wire mesh disappear in the image?

Project 6: A Project of Your Choice and Design

Examples that previous students have chosen are the following:

(6A) Width of different hair.

(6B) Change of refractive index with concentration of solution.

(6C) Optically active media and change of polarization plane with concentration of solutions (Corn syrup).

(6D) Holography using a digital camera and computational reconstruction.

(6E) Wavefront (Hartmann-Shack) sensor.