LASERS AND FIBER OPTICS

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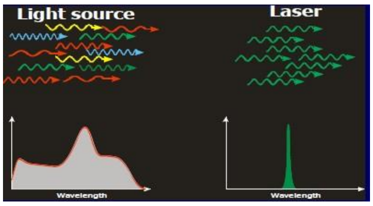
Part a: LASER

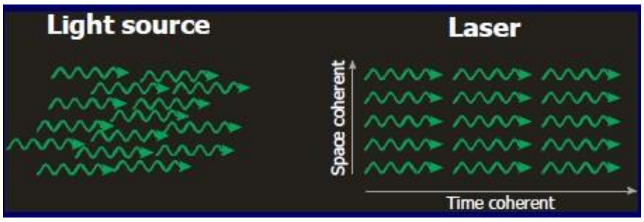
LASER is the acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

I. Basic Properties of Laser

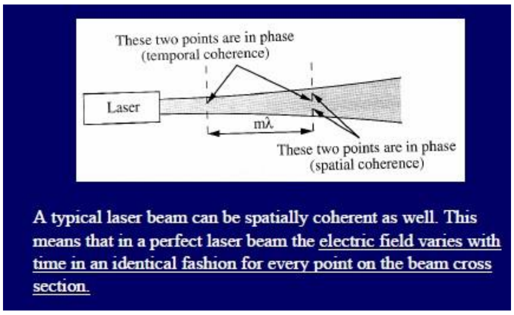
A laser is a device that produces a light beam with some **remarkable properties**, viz.

1. The light is nearly monochromatic.

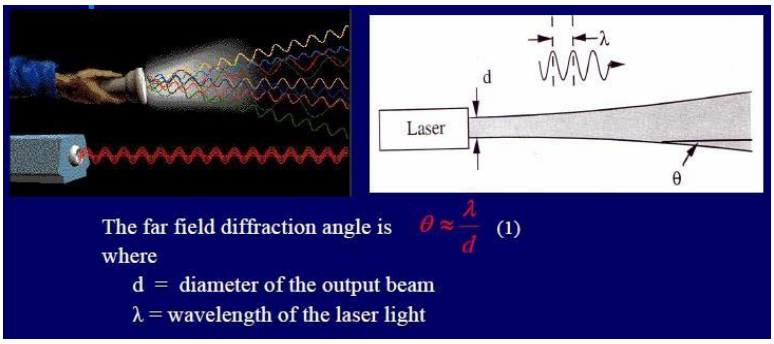




2. The light is coherent (temporal as well as spatial), with the waves all exactly in phase with one another.



3. A laser beam hardly diverges. Such a beam sent from the earth to a mirror left on the moon by the Apollo 11 expedition remained narrow enough to be detected on its return to the earth (total distance covered 1/3 of a million kilometers). A light beam produced by other means would have spread out too much for this to be done.
4. The beam is extremely intense (large energy density), more than the light from any other source.
5. Highly collimated beam.

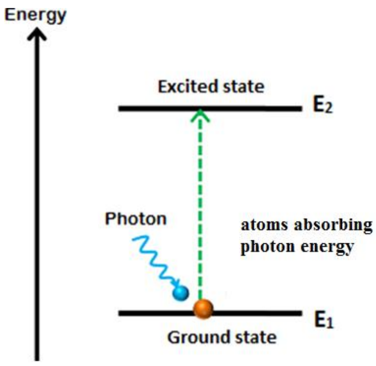


II. <u>Mechanism of Light Emission</u>

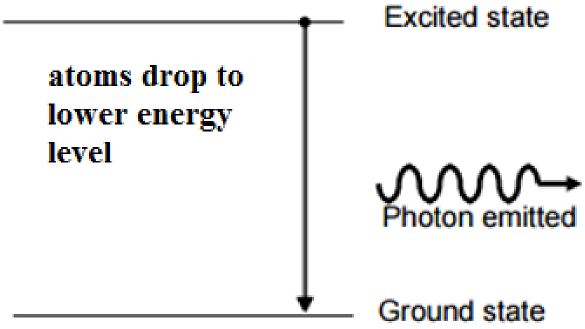
For atomic systems in thermal equilibrium with their surroundings, the emission of light is the result of **Absorption, and,** subsequently, **Spontaneous Emission** of energy. There is another process whereby the atom in an upper energy level can be triggered or stimulated to emit in phase with an incoming photon. This process is called **Stimulated Emission**. It is the most important process for laser action.

➢ Absorption

Every atom, according to the quantum theory, can reside only in certain discrete energy states or energy levels. Normally, the atoms are in the lowest energy state or ground state. When light from a powerful source like a flash lamp or a mercury arc with a photon of energy $h\nu = E_2 - E_1$ falls on a substance, the atoms in the ground state (E_1, say) can be excited to go to one of the higher levels (E_2, say). This process is called absorption.



- **Spontaneous emission**

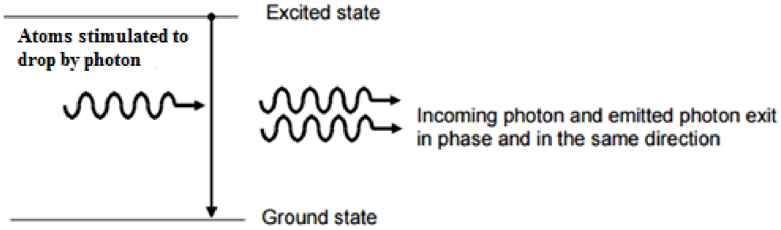


Consider an atom (or molecule) of the material staying initially in an excited state E_2. Since $E_2 > E_1$, the atom will tend to spontaneously decay to the ground state E_1 to attain the lowest energy state, and a photon of energy $h\nu = E_2 - E_1$ is released in a random direction as shown above. No external radiation is required to initiate the emission. This process is called “spontaneous emission”.

Note that when the released [equal to the energy difference E_2-E_1] is delivered in the form of an electromagnetic (E.M.) wave, the process called "radiative emission" which is one of the two possible ways. “Non-radiative” decay is occurred when the energy difference (E_2-E_1) is delivered in some form other than electromagnetic radiation (e.g. it may be transferred to the kinetic energy of the surrounding).

- **Stimulated emission**

Stimulated Emission requires the presence of external radiation when an incident photon of energy $h\nu = E_2 - E_1$ passes by an atom in an excited state E_2, it stimulates the atom to drop or decay to the lower state E_1. In this process, the atom releases a photon of the same energy, direction, phase and polarization as that of the photon passing by, the net effect is two identical photons (i.e. energy = 2hν) in the place of one, or an increase in the intensity of the incident beam. It is precisely this process of stimulated emission that makes possible the amplification of light in lasers**.**



The reason that the atom is stimulated to drop is that the incoming photon is an electromagnetic wave and its EM field will exert an oscillating force on the excited atom. If the incoming photon is of the correct frequency, this oscillating force will cause the excitedelectron to drop and both photons will exit with the same frequency, phase and direction.

Theory of Lasing

Atoms exist most of the time in one of a number of certain characteristic energy levels. In any group of atoms, thermal motion or agitation causes a constant motion of the atoms between low and high energy levels. In the absence of any applied electromagnetic radiation the distribution of the atoms in their various allowed states is governed by **Boltzman's law** which states that if an assemblage of atoms is in state of thermal equilibrium at an absolute temp. T, the number of atoms N_2 in one energy level E_2 is related to the number N_1 in another energy level E_1 by the equation

$$N_2 = N_1 e^{-(E_2 - E_1)/KT} \qquad (1)$$

Where $E_2 > E_1$, thus clearly $N_2 < N_1$. (K is Boltzmann's constant = 1.38×10^{-16} erg / K = 1.38×10^{-23} J/K and T is the absolute temperature in Kelvin).

At absolute zero all atoms will be in the ground state. As the temperature increases atoms move randomly from low to the higher energy states and back again. The atoms are raised tohigher energy states by chance and they return to the low energy state by their natural tendencyto seek the lowest energy level. When they return to the lower energy state electromagnetic radiation is emitted. This is spontaneous emission of radiation and because of its random nature, it is incoherent.

As indicated by the equation, the number of atoms decreases as the energy level increases. As the temp increases, more atoms will attain higher energy levels. However, the lower energy levels will be still more populated.

Einstein in 1917 first introduced the concept of stimulated or induced emission of radiation by atomic systems. He showed that in order to describe completely the interaction of matter and radiation, it is necessary to include that process in which an excited atom may be induced by the presence of radiation to emit a photon and decay to lower energy state.

An atom in level E_2 can decay to level E_1 by emission of photon. Let us call A_{21} the transition probability per unit time for spontaneous emission from level E_2 to level E_1. Then the number of spontaneous decays per second is N_2A_{21}, i.e. the number of spontaneous decays per second $= N_2A_{21}$.

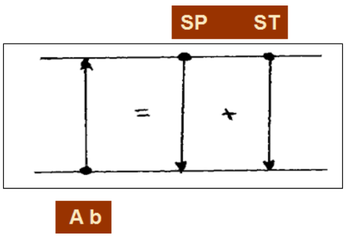
In addition to these spontaneous transitions, there will be induced or stimulated transitions. The total rate of these induced transitions between level 2 and level 1 is proportional to the density (U_ν) of radiation of frequency ν, where

$$\nu = (E_2-E_1)/h \quad , \qquad h \text{ being the Planck's constant.}$$

Let B_{21} and B_{12} denote the proportionality constants for stimulated emission and absorption. Then number of stimulated downward transition in stimulated emission per second = $N_2 B_{21} U_\nu$

Similarly, the number of stimulated upward transitions per second = $N_1 B_{12} U_\nu$

The proportionality constants A and B are known as the **Einstein A and B coefficients**. Under equilibrium conditions we have



$$N_2 A_{21} + N_2 B_{21} U\nu = N_1 B_{12} U\nu \qquad (2)$$

Solving for U_ν (density of the radiation) we obtain

$$U_\nu [N_1 B_{12} - N_2 B_{21}] = N_2A_{21}$$

or

$$U_\nu = \frac{N_2A_{21}}{N_1B_{12} - N_2B_{21}} = \frac{A_{21}}{B_{21}[\frac{B_{12}}{B_{21}}\frac{N_1}{N_2} - 1]}$$

Since,

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/KT} = e^{-h\nu/KT}$$

(From Boltzmann's Equation)

Therefore,

$$U_\nu = \frac{A_{21}}{B_{21}[\frac{B_{12}}{B_{21}}e^{h\nu-KT} - 1]} \tag{3}$$

According to Planck's formula of radiation

$$U_\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{[e^{h\nu-KT}-1]} \tag{4}$$

Comparing Eqns. (3) and (4)

$$\boldsymbol{B_{12} = B_{21}} \tag{5}$$

$$\boldsymbol{A_{21} = \frac{8\pi h\nu^3}{c^3}B_{21}} \tag{6}$$

Eqn. (5) and (6) are Einstein's relations.

Thus from atoms in equilibrium with thermal radiation

$$\frac{stimulated\ emission}{spontaneous\ emission} = \frac{N_2B_{21}U(\nu)}{N_2A_{21}} = \frac{B_{21}U(\nu)}{A_{21}}$$

$$= \frac{c^3}{8\pi h\nu^3}U(\nu)$$

$$= \frac{c^3}{8\pi h\nu^3}\frac{8\pi h\nu^3}{c^3}\frac{1}{\left[e^{h\nu/KT}-1\right]}$$

Thus, we get

$$\frac{\textbf{stimulated emission}}{\textbf{spontaneous emission}} = \frac{1}{[e^{\frac{hv}{KT}} - 1]} \tag{7}$$

Therefore, the rate of induced emission is extremely small in the visible region of the spectrum with ordinary optical source. In such sources, most of the radiation is emitted through spontaneous transitions. Since these transitions occur in a random manner, ordinary sources of visible radiation are incoherent.

On the other hand, in a laser the induced transitions become completely dominant. One result is that the emitted radiation is highly coherent. Another is that the spectral intensity at the operating frequency of the laser is much greater than the spectral intensities of ordinary light source.

III. Amplification in a Medium: Population Inversion and Active System

Consider an optical medium, through which radiation is passing, contains atoms in various energy levels E_1, E_2, E_3,….Let us take two energy levels E_1 & E_2, with population of N_1 and N_2, respectively, and where $E_2>E_1$. The rate of stimulated emission and absorption involving these two levels are proportional to N_2B_{21} & N_1B_{12} respectively. Since $B_{21}=B_{12}$, the rate of stimulated downward transitions will exceed that of the upward transitions when $N_2>N_1$, i.e. the population of the upper state is greater than that of the lower state. Such a condition is contrary to the thermal equilibrium distribution given by Boltzmann's law and, therefore, it is termed as **population inversion**. Thus, **the term population inversion describes an assembly ofatoms in which the majority of atoms are in energy levels above the ground state; normally theground state is occupied to the greatest extent.**

If a population inversion exists, then a light beam will increase in intensity i.e. it will be amplified as it passes through the medium. This is because the gain due to the induced emission exceeds the loss due to absorption.

A system in which population inversion has been achieved is called an **active system**.

- **Metastable State**

The atoms remain in the excited state for a very short period of time ~ 10^{-8} sec, after that they spontaneously release the excess energy. For stimulated emission to occur, the atoms should stay longer (typically ~ 10^{-4} sec) in the excited state to compensate for the loss in population due to spontaneous emission till the condition $N_2>N_1$ gets satisfied. Such relatively long-lived states with life time ~10^{-3} sec are called **metastable (temporarily stable) states** and their energy lie between upper excited state and the lower state.

The population of atoms in metastable state is greater than that in lower state, which leads to population inversion.

PUMPING

To attain and sustain population inversion, the atoms in the material must be continuously excited from lower energy level to higher energy level. This is done by continuous supply of energy to the medium. The process is known as **pumping**.

N.B.

By heating the material the state of population inversion cannot be achieved. By heating the material, the average energy of the atoms is increased (i.e. overall system is shifted to the higher energy level) without achieving the required condition for population inversion, i.e. $N_2 > N_1$. Therefore, to achieve the condition different methods are used.

- **OPTICAL PUMPING**

Here optical energy in the form of photon with right frequency is used to excite the atoms in the medium. For supplying optical energy, a discharge tube is employed to excite atoms from the ground state to a higher or excited state. Optical pumping is suitable for any medium which is transparent to light.

- **ELECTRICAL PUMPING**

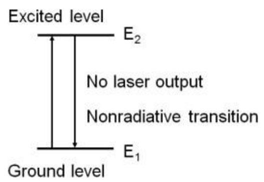
It is used for some mediums which can conduct electricity without affecting laser activity. Suitable for gas and semiconductor lasers. In gaseous medium, the gas is ionised by a pulse of high electric voltage, current flowing through the gas provides necessary energy to excite the atoms to uppermost level from where they decay to metastable level.

In semiconductor lasers charge carriers are excited.

As the atoms have a large number of energy levels, 2, 3 or 4 levels are eligible for a pumping process. ***The transition between two levels for which stimulated emission occurs is called lasing transition.***

N.B.

It is not possible to achieve population inversion with a 2-state (level) system. If the incoming radiation flux is made very large the probability of stimulated emission and absorption can be made to far exceed the rate of spontaneous emission. But in 2-state system, the best we can get is $N_1 = N_2$.



Suppose there are only 2 levels, a metastable state, corresponding to energy $h\nu$, above the ground state. The more photons with frequency ν we pump into the assembly of atoms, the more upward transitions there will be from the ground state to the metastable state. However, pumping will also stimulate downward transitions from metastable state to the ground state. i.e. population and depopulation processes take place simultaneously.

In other words, the incoming flood of photons is just as likely to cause an electron to drop (stimulated emission) as it is to cause an electron to rise (absorption). When half the atoms are in each state, the rate of stimulated emissions will be equal the rate of stimulated absorption, so the assembly can't have more than half its atoms in metastable state. In this situation laser amplification cannot occur.

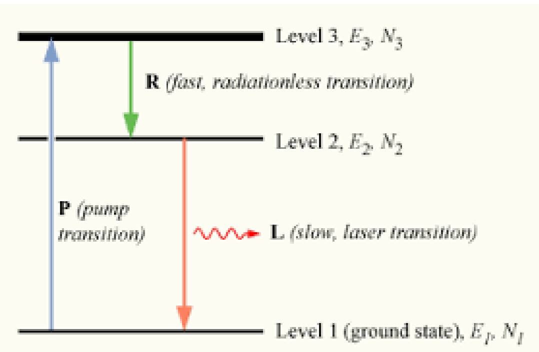
A population inversion is only possible when the stimulated absorptions are to a higher energy level than the metastable one from which the stimulated emission takes place, which prevents the pumping from depopulating the metastable state.

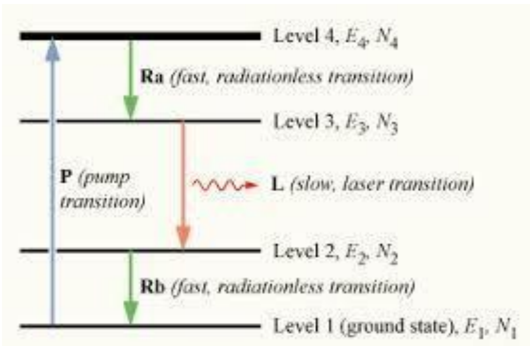
Lasers with different levels

N.B.

Pumping is a process of upward transition of atoms and molecules above the metastable state from the lowest state. Whereas, lasing involves both upward and downward transitions of atoms and molecules. Hence, the designation of pumping schemes as 3 or 4 level is technicallywrong.

Three-level and four-level lasers

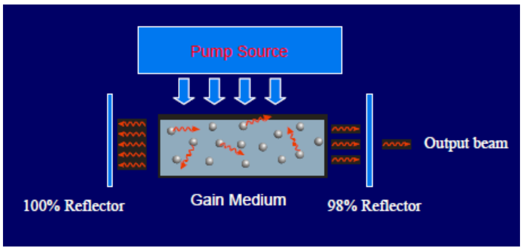




Advantages of four level lasers Compared to three level lasers

- The lasing threshold of a four level laser is lower.
- The efficiency is higher.
- Required pumping rate is lower.
- Continuous operation is possible in four level laser (e.g. He-Ne laser). Three level laser gives pulsed operation (e.g. Ruby laser)

Key mechanism to produce a laser: Optical Resonator



1. Pumping process prepares amplifying medium in suitable state.
2. Optical power increases on each pass through amplifying medium **(Optical resonator)**
3. If gain exceeds loss, device will oscillate, generating a *coherent* output.

Optical resonator

In laser, active medium is an amplifier, which is converted into an oscillator through the feedback mechanism established by an optical resonator. A pair of optically plane parallel mirrors, enclosing laser medium in between them, is known as an **optical resonant cavity**. One of the mirror is partially reflecting and the other is fully reflecting. The laser oscillation is initiated by photons spontaneously emitted by some of the excited atoms. The photons emitted along the optic axis of the resonant cavity travel through the medium and trigger stimulated emissions. They are reflected by the end mirror and reverse their path. The optical resonator selects the direction in which the light is to be amplified; the direction being the optical axis of the pair of mirrors. Thus, the optical cavity makes the laser beam directional. The photons, thus fed back into the medium, travel toward the opposite end mirror causing more stimulated emissions. It is again reflected back from that end. As the process repeats itself substantial light amplification takes place.

In order to make the stimulated emission dominate spontaneous emission, a high radiation density is required to be present in the active medium. The optical cavity builds up the photon density to a very high value through repeated reflection of photons and confines them within the medium.

Optical cavity selects and amplifies only certain frequencies causing the laser output to be highly monochromatic.

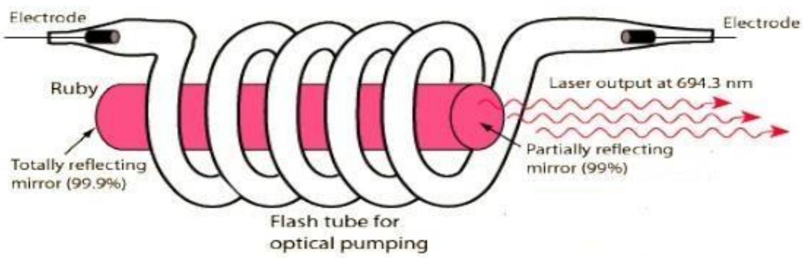
IV. Types of Lasers

- ***Solid-state lasers***
  - Ruby laser, Nd:YAG laser etc.
- ***Gas lasers***
  - Helium-Neon laser, CO_2 laser etc.
- ***Semiconductor diode lasers***
  - GaAs laser, InP laser etc.

Lasers work in continuous mode or in pulsed mode.

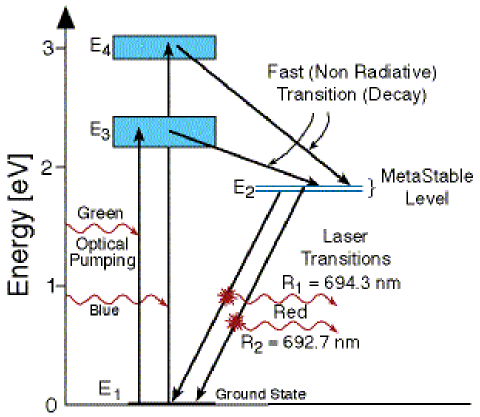
The Ruby Laser

Ruby belongs to the family of gems consisting of Al_2O_3 with various types of impurities. For example pink Ruby contains 0.05% Cr atoms. The construction of ruby laser is given below.



The ruby laser consists of a ruby rod made of chromium doped ruby material. At the opposite ends of this rod there are two silver polished mirrors. Whose one is fully polished and other is partially (~ 98%) polished. A spring is attached to the rod with fully polished end for adjustment of wave length of the laser light. Around the ruby rod a flash light is kept for the pump input. The whole assembly is kept in the glass tube. Around the neck of the glass tube the R.F source and switching control is designed in order to switch on and off the flash light for desired intervals.

When the R.F is switched on a flash of light is obtained around the ruby rod. This causes the Cr^{3+} ions within ruby rod to move from lower energy band E1 towards higher E3 and E4 bands by the green and blue components of the white light. The Cr^{3+} ions undergo non-radiative transitions from these energy levels to level E_2, which is a metastable state. Population inversion takes between E_2 and the ground state E_1, making these two levels suitable for lasing action. Transitions between the levels E_2 and E_1 result in emission of the laser light of wavelength 693.4 nm. The energy level diagram is given below.



Advantages of Ruby Laser

1. The ruby lasers are economical.
2. Since the ruby is in solid form therefore there is no chance of wasting material of active medium.
3. Construction and function of ruby laser is self-explanatory.

Disadvantages of Ruby Laser

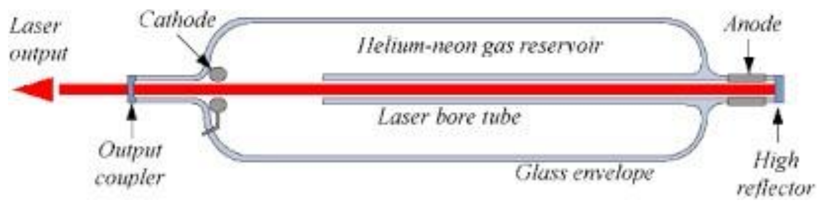
1. In ruby lasers no significant stimulated emission occurs, until at least half of the ground state electrons have been excited to the Meta stable state.
2. Efficiency of ruby laser is comparatively low.
3. Optical cavity of ruby laser is short as compared to other lasers, which may be considered a disadvantage.

Uses of Ruby Laser

Due to low output power they are used as toys for children, used in schools, colleges and universities for science programs and as decoration piece and artistic display.

The Helium-Neon (He-Ne) Laser

A helium-neon laser, usually called a He-Ne laser, is a type of small gas laser. It is a four-level laser. Its usual operation wavelength is 632.8 nm, in the red portion of the visible spectrum. It operates in Continuous Working (CW) mode.



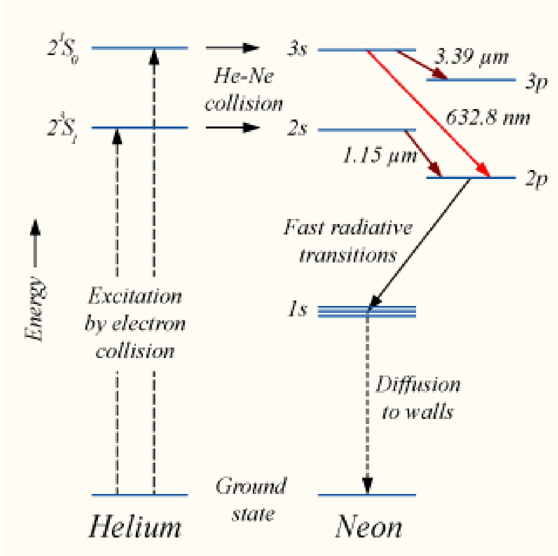
The basic construction of a He-Ne laser is shown above. The setup consists of a discharge tube of length 80 cm and bore diameter of 1.5cm. A mixture of helium and neon gases, in approximately a 10:1 ratio, contained at low pressure in a glass envelope. The energy or pumping of the laser is provided by a high voltage electrical discharge passed through the gas between the anode and cathode within the tube. The optical cavity of the laser usually consists of two concave mirrors or one plane and one concave mirror, one having very high (typically 99.9%) reflectance and the output coupler mirror allowing approximately 1% transmission.

In order to pump the ground state Ne atoms to the excited state, the ground state atoms of He are pumped to the 2^3S_1 and 2^1S_0 long-lived, metastable excited states by passing an electric discharge. The excited He atoms then collide with the ground state Ne atoms and transfer their energy to the Ne atoms exciting them into the 2s and 3s states. This is due to a coincidence of energy levels between the helium and neon atoms.

This process is given by the reaction equation:

$$He^* + Ne \rightarrow He + Ne^* + \Delta E$$

where (*) represents an excited state, and ΔE is the small energy difference between the energy states of the two atoms, of the order of 0.05 eV. The typical energy diagram is shown below.



The reason behind the above indirect transfer of energy to Ne is the small atomic cross-section of Ne which makes direct energy transfer a bit difficult to realize.

The number of neon atoms entering the excited states builds up as further collisions between helium and neon atoms occur, causing a population inversion between the neon 3s and 2s, and 3p and 2p states. Spontaneous emission between the 3s and 2p states results in emission of 632.8 nm wavelength light, the typical operating wavelength of a He-Ne laser.

After this, fast radiative decay occurs from the 2p to the 1s energy levels, which then decay to the ground state via collisions of the neon atoms with the container walls. Because of this last required step, the bore size of the laser cannot be made very large and the He-Ne laser is limited in size and power.

Typical power output for He-Ne lasers lie between 1 and 50 mW for continuous wave operations for inputs of ~ 5-10 W.

Advantages of He-Ne lasers

1. The biggest advantages of He-Ne laser is its continuous wave operation.
2. Compared to solid state lasers He-Ne laser is more directional and much more monochromatic.

Disadvantage of He-Ne lasers

1. Since this type of lasers use internal mirrors (i.e. with mirrors sealed inside the discharge tube), mirrors are very easily eroded by gas discharge and have to be replaced.

The Carbon Dioxide Laser

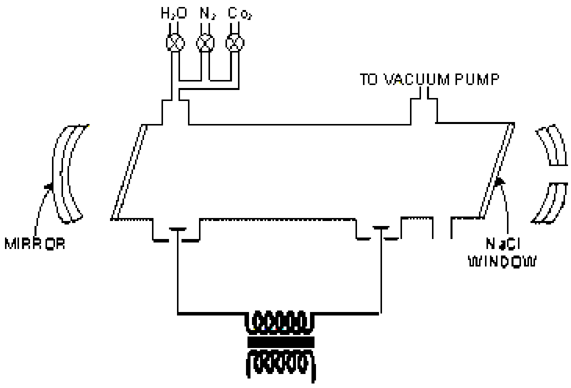
The carbon dioxide laser (CO_2 laser) is a type of molecular gas laser (invented by Kumar Patel of Bell Labs in 1964). It is the highest-power continuous wave lasers that are currently available. They are also quite efficient: the ratio of output power to pump power can be as large as 20%. The CO_2 laser produces a beam of infrared light with the principal wavelength bands centering around 9.4 and 10.6 µm.

Active medium

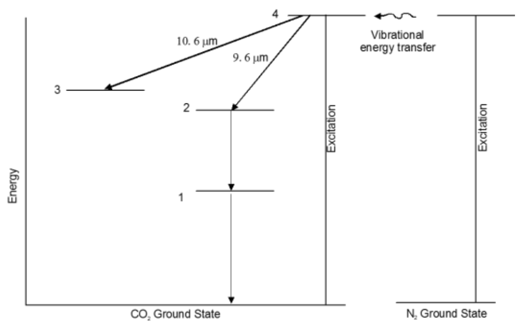
It consists of a mixture of CO_2, N_2 and helium or water vapor. The active centers are CO_2 molecules lasing on the transition between the rotational levels of vibrational bands of the electronic ground state.

Optical resonator

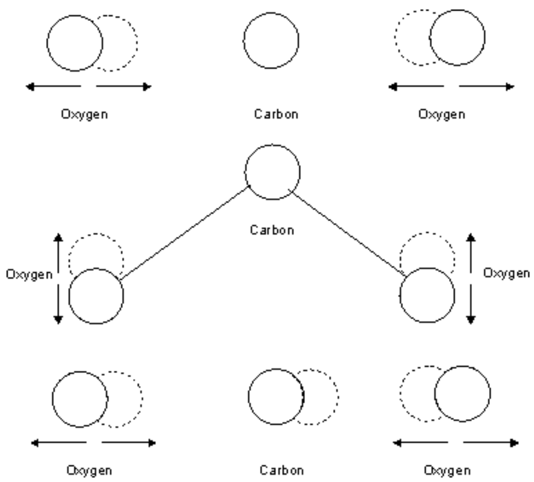
A pair of concave mirrors placed on either side of the discharge tube, one completely polished and the other partially polished, constitute the optical resonator. Population inversion is created by electric discharge of the mixture. A basic construction of carbon dioxide laser is shown alongside



The energy level diagram of vibrational – rotational energy levels with which the main physical processes take place in this laser is shown below.



As the electric discharge takes place in the tube, which contains a mixture of carbon dioxide, nitrogen and helium gases, the electrons striking nitrogen molecules impart sufficient energy to raise them to their first excited vibrational-rotational energy level. This energy level corresponds to one of the vibrational - rotational level of CO_2 molecules, designated as level 4. Due to collision with N_2 molecules, the CO_2 molecules are raised to level 4.



Different vibrational level of CO_2 molecule

The lifetime of CO_2 molecules in level 4 is quiet significant to serve as a metastable state. Hence, the desired population inversion of CO_2 molecules is established between levels 4 and 3, and between levels 4 and 2. The transition of CO_2 molecules between levels 4 and 3 produce lasers of wavelength 10.6 microns and that between levels 4 and 2 produce lasers of wavelength 9.6 microns.

The He molecules increase the population of level 4, and also help in emptying the lower laser levels. The molecules that arrive at the levels 3 and 2 decay to the ground state through collision induced transitions to the lower level 1, which in turn decays to the ground state.

The power output of a CO_2 laser increases linearly with length.

Advantages of CO_2 lasers

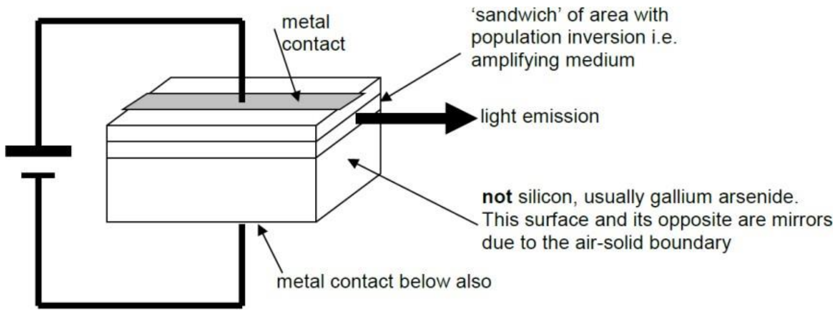
1. Compared to other gas lasers, CO_2 laser is much more efficient.
2. Output powers of several watts to several hundred watts may be obtained from CO_2 lasers.
3. The output wavelength of CO_2 laser falls in a band where atmospheric attenuation is very little. Hence it is suitable for open air communication and optical radar systems.

Disadvantage of CO_2 laser

1. Because CO_2 lasers operate in the infrared, special materials are necessary for their construction. Typically, the mirrors are silvered, while windows and lenses are made of either germanium or zinc selenide. For high power applications, gold mirrors and zinc selenide windows and lenses are preferred.

The Semiconductor (Diode) Lasers

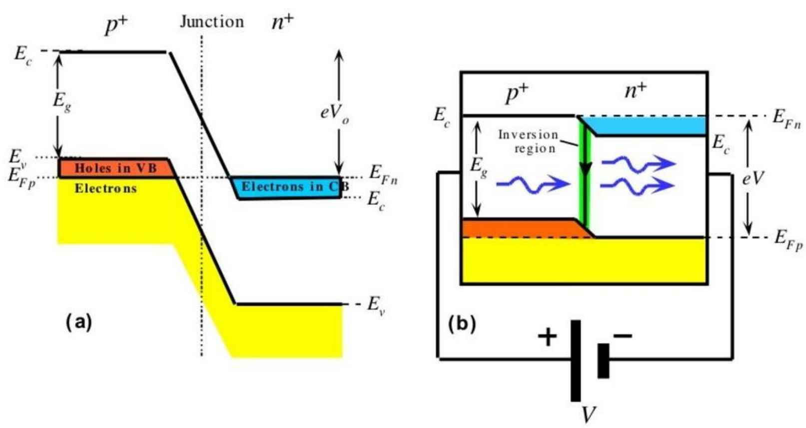
The basic structure of a standard 'edge emitting' semiconductor laser is shown below. The whole block shown below is a semiconductor chip with dimensions approximately 0.5mm × 0.5mm × 1mm, as shown below.



The mirrors are due to the semiconductor-air boundary at the edges of the chip. [This in fact gives 40% reflection only (at both sides).] This low reflectivity is still efficient for semiconductor laser because

1. The population inversion inside the semiconductor sandwich area is millions of times higher than in gas lasers [~10^{25} electrons/m^3].
2. The exponential increase in light intensity (i.e. 1 photon becoming two, becoming four etc.) occurs far more quickly because of the higher population inversion.
3. So the fact that we lose 60% of the light at each reflection is compensated for by having huge gains between the mirrors.

The energy bend diagram of a degenerately doped direct band gap semiconductor p-n junction is shown below.



In case of degenerate doping Fermi level (EFP) on P-side is in the valence band (VB) and EFN on the N-side is in the conduction band (CB). Energy levels up to the Fermi level are occupied by electrons. When there is no applied voltage the Fermi level is continuous across the diode (EFN = EFP). Band diagram with a sufficient forward bias will cause population inversion (as shown in the figure in the right side). Now there's a small region in the middle between the p-type and the n-type where we have a high concentration of electrons above holes. These electrons can be stimulated to drop and give away laser light.

The advantages of semiconductor lasers are

1. Cheaper
2. Smaller
3. More efficient
4. Easy for mass production.

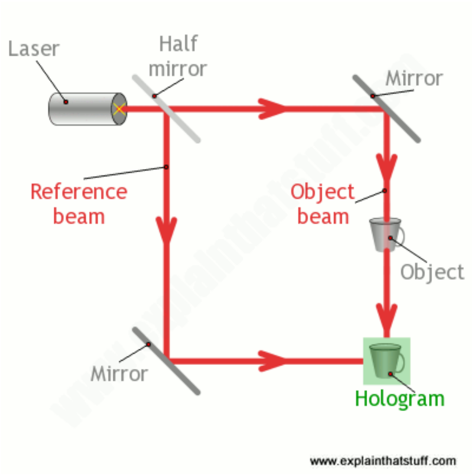
V. Applications of Laser

1. The narrow red beam of He-Ne laser is used in supermarkets to read bar codes.
2. Measuring distances
3. Red He-Ne laser have many industrial and scientific uses. They are widely used in laboratory demonstrations.
4. Laser is used in guided smart weapon.
5. Because of the high power levels available (combined with reasonable cost for the laser), CO_2 lasers are frequently used in industrial applications for cutting and welding, while lower power level lasers are used for engraving. They are also very useful in surgical procedures because water (which makes up most biological tissue) absorbs this frequency of light very well. Some examples of medical uses are laser surgery, skin resurfacing etc.
6. Semiconductor lasers are used in DVD and CD players, as Barcode readers, in telecommunications (via optical fibres), Image scanning etc.
7. Holography.

Holography

Holography is a technique that enables a light field, which is generally the product of a light source scattered off objects, to be recorded and later reconstructed when the original light field is no longer present, due to the absence of the original objects.

[Holography was invented in 1947 by Hungarian physicist Dennis Gabor (1900–1979), work for which he received the Nobel Prize in Physics in 1971.]



When the two laser beams reach the recording medium, their light waves, intersect and interfere with each other. It is this interference pattern that is imprinted on the recording medium. The pattern itself is seemingly random, as it represents the way in which the scene's light *interfered* with the original light source — but not the original light source itself. The interference pattern can be considered as an encoded version of the scene, requiring a particular key — the original light source — in order to view its contents.

If a laser, identical to the one used to record the hologram, is shined onto the developed film (hologram), it illuminates the hologram, it is diffracted by the hologram's surface pattern. This produces a light field identical to the one originally produced by the scene and scattered onto the hologram. The image this, therefore, known as a virtual image.

Part b: FIBER OPTICS

An **optical fiber** is essentially a waveguide for light. It transmits light pulses and can be used for analog or digital transmission of voice, computer data, video, etc.

Copper wires (or other metals) can carry the same types of signals with electrical pulses.

Advantages of optical fibers *vis-a-vis* metal wires

1. Optical fiber has **large bandwidth**, i.e. it can transmit more data per second.
2. It is of very **low loss**. This implies that longer distance communication is possible using the optical fibers.
3. Carries signal at a much **faster** rate.
4. **Immune** to **crosstalk**.
5. Since the data is carried as light, there is **no electrical hazard**.
6. Special applications like **medical imaging** and **quantum key distribution** are only possible with fiber because they use light and are made of dielectrics.

VI. BASIC WORKING PRINCIPLE OF FIBER OPTICS

Optical fibers work on the principle of **total internal reflection.**

The **angle of refraction** at the interface between two media is governed by **Snell's law**

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Where θ_1 is the angle of incidence in a medium with refractive index n_1, and θ_2 is the angle of incidence in a medium with refractive index n_2.

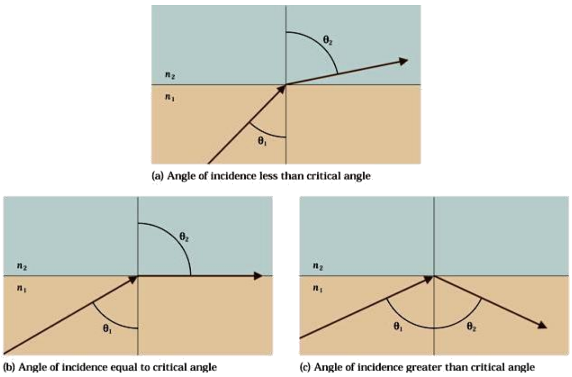


Fig. 1 Direction of light at the interface of two media

When a ray of light travel from a high to a low refractive index material, it will move away from the normal. i.e. the angle of incidence is smaller than the angle of refracted ray. The reverse is true for rays travelling from low to high index material. The relation between the incident and refracted angles are related in terms of propagation velocities in the media as

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} \qquad \text{where } v_1 = \frac{c}{n_1} \; and \; v_2 = \frac{c}{n_2}$$

(the above relation is valid provided the two materials involved are transparent and allow light propagation and v_i is the speed of light in medium *i*)

When θ_2, the angle of refraction, becomes 90° the refracted beam is not traveling through the n_2 material. Applying Snell's law of refraction,

$$\sin\theta_1 = \frac{n_2}{n_1}$$

The angle of *incidence* θ_1 for which θ_2 = 90° is called the critical angle θ_C.

From the above discussion following important conclusions can be drawn:

- The light can be restricted to the material with the higher index of refraction if the incidentangle is kept above the critical angle.
- A sandwich of high index material placed between two slabs of low index material will allow a beam of light to propagate in the high index material with relatively low loss.
- This concept is used in constructing fibers for fiber optic communication.

❖ Structure of an optical fiber

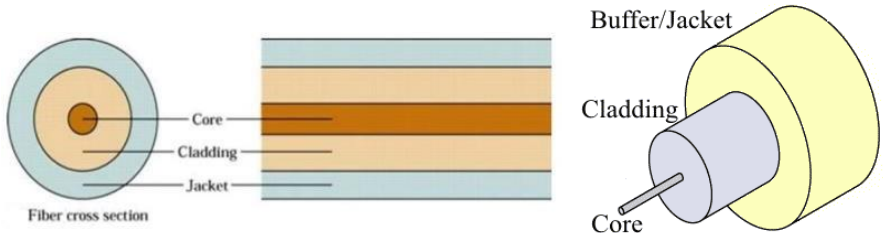


Fig. 2 Main parts of an optical fiber

A typical optical fiber consists of a core, a cladding, and a polymer jacket (buffer coating).

- **Core**
  - Glass or plastic with a higher index of refraction than the cladding
  - Carries the signal
- **Cladding**
  - Glass or plastic with a lower index of refraction than the core
- **Buffer**
  - Protects the fiber from damage and moisture (mechanical protection)
- **Jacket**
  - Holds one or more fibers in a cable

VII. Types of optical fiber

- The fibers in which the index of refraction changes radically between the core and the cladding are known as **step-index** fibers.
- In case of **Graded-index (GRIN)** fiber the index of refraction gradually decreases away from the center of the core eventually to meet the cladding.
- Graded-index fiber has less dispersion than a multimode step-index fiber.

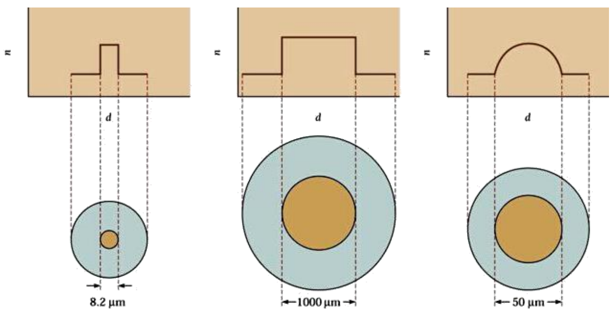


Fig. 3 Different types of optical fiber according to their refractive index profile

- **Modes in an optical fiber and fiber classifications in terms of number of modes they support**

In simple terms, modes in an optical fiber can be visualized as the possible number of allowed paths in the optical fiber. For a particular fiber the maximum number of modes it can support is constant.

In a fiber of fixed thickness, the modes that propagates at angles close to the critical angle are called higher order modes, and modes that propagate with angles larger than the critical angles are called lower order modes.

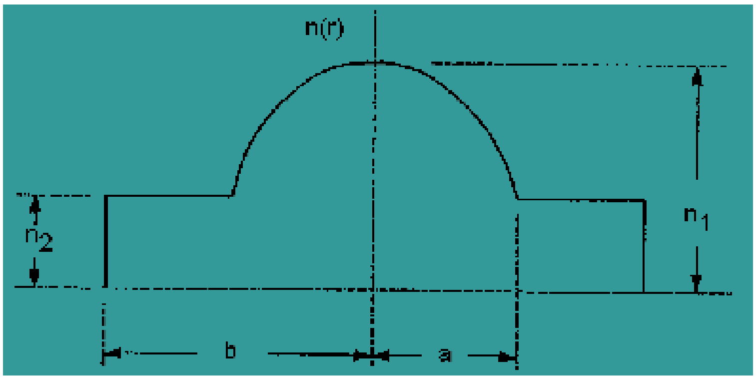
Depending on the number of modes that a fiber allows to propagate, the fibers are classified mainly into three categories, viz. (i) **single-mode step index** fiber, (ii) **multimode step index**fiber, and (iii) **multimode graded index** fiber. A comparative Table is given below.

Table 1: Comparison between single-mode step index, multimode step index and multimode graded index fibers

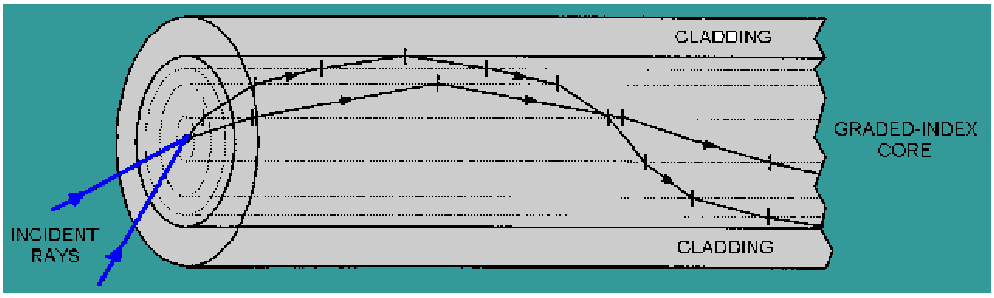
Single-mode step index fiber	**Multimode step index fiber**	**Multimode graded index fiber**
Allows only one mode to propagate.	Allows more than one mode to propagate	Allows more than one mode to propagate
Core diameter ~10 µm.	Core diameter ~50- 200 µm	Core diameter ~50- 100 µm
Low numerical aperture.	Numerical aperture varies between 0.2 and 0.29.	Low numerical aperture.
Very high band width.	Low band width.	Intermediate bandwidth.
Low attenuation and dispersion.	High dispersion loss affects the performance of such fiber.	Multimode graded-index fibers have less modal dispersion than multimode step-index fibers.
Generally laser is used as light source.	Generally LED is used as light source.	Laser and LED both can be used as light source.
Very expansive.	Less expansive.	Very expansive.
Can be used in long distance communication.	Used mainly in local area networks (LAN).	Used for transmitting information to the distance of a couple of kilometers.

Discussion on graded-index multimode fiber

- Let a multimode graded-index fiber has a core of radius equal to a. Unlike the step-index fibers, the value of the refractive index of the core (n_1) varies according to the radial distance (r). The value of n_1 decreases as the distance (r) from the center of the fiber increases.
- The value of n_1 decreases until it approaches the value of the refractive index of the cladding (n_2). The value of n_1 must be higher than the value of n_2 to allow for proper mode propagation. Like the step-index fiber, the value of n_2 is constant. The relative refractive index difference (Δ) is determined using the maximum value of n_1 and the value of n_2.



- The NA of a multimode graded-index fiber is at its maximum value at the fiber axis.



- The gradual decrease in the core's refractive index from the center of the fiber causes propagating modes to be refracted many times.
- Higher order modes compensate the larger distance travelled due to the higher speed compared to the lower order modes as a result of the varying refractive index.
- Multimode graded-index fibers have less INTERMODAL DISPERSION than multimode step-index fibers. Lower modal dispersion means that multimode graded-index fibers have higher bandwidth capabilities than multimode step-index fibers.

➢ Propagation of light through an optical fiber

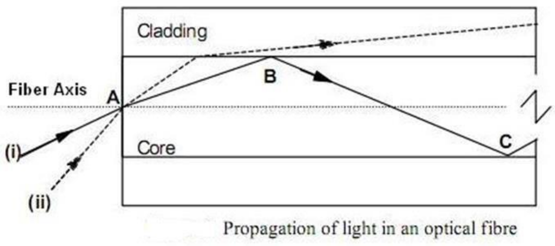


Fig. 4 Ray Diagram for light propagation through an optical fiber

To be guided through an optical fiber, a light ray must enter the core with an angle less than a particular angle called the **acceptance angle** of the fiber. A ray which enters the fiber with an angle greater than the acceptance angle will be lost in the cladding, as shown in Fig. 4 and 5.

The imaginary light cone with the acceptance angle as the vertex angle, is known as the **acceptance cone**.

Numerical aperture (NA) of the fiber is the light collecting efficiency of the fiber and is a measure of the amount of light rays can be accepted by the fiber.

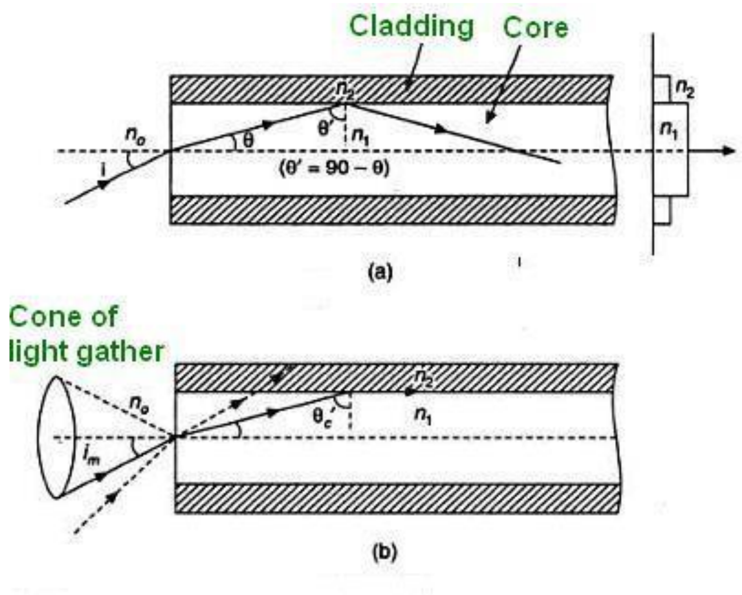


Fig. 5 Ray diagram for an optical fiber

From Fig. 5, we have

$$\theta' = (90^o - \theta)$$

$$n_0 \sin i = n_1 \sin \theta \qquad \text{for air, } n_0 = 1$$

So it may be totally reflected back to the core medium if θ' exceeds the critical angle $\theta'c$. Using Snell's laws at the core-cladding interface,

$$n_1 \sin \theta'_c = n_2 \sin 90^o$$

$$\sin\theta'_c = \frac{n_2}{n_1} \tag{2}$$

Therefore, for light to be propagated within the core of optical fiber as guided wave, the angle of incidence at core-cladding interface should be greater than θ'_c. As i increases, θ increases and so θ' decreases. Therefore, there is maximum value of angle of incidence beyond which it does not propagate rather it is refracted in to cladding medium. This maximum value of i, say i_m, is called the half of the maximum angle of acceptance and $n_0 \sin i_m$ is termed as the numerical aperture (NA).

$$NA = n_0.\sin i_m = n_1.\sin\theta = n_1.\sin(90^o - \theta'_c)$$

or $$NA = n_1 \cos\theta'_c = n_1\sqrt{1 - \sin^2\theta'_c} = n_1\sqrt{1 - \frac{n_2^2}{n_1^2}}$$ [using Eqn. 2]

or $$NA = \sqrt{n_1^2 - n_2^2} \tag{3}$$

The significance of NA is that light entering in the cone of semi vertical angle i_m only propagate through the fiber by total internal reflection. The higher the value of i_m or NA means more is the light collected for propagation in the fiber. Numerical aperture is thus considered as a lightgathering capacity of an optical fiber.

Numerical Aperture can also be defined as the sine of half of the angle of fiber's light acceptance angle (θ_a). Therefore, as per our discussion $\boldsymbol{\theta_a = 2\, i_m}$

The general expression relating acceptance angle θ_a and NA is given by

$$\theta_a = 2\sin^{-1}\frac{\sqrt{n_1^2 - n_2^2}}{n_0} \tag{4}$$

A parameter known as **Fractional refractive index** is defined as

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} = \frac{(NA)^2}{2n_1^2} \tag{5}$$

Hence, $$NA = n_1 \text{ x } (2\Delta)^{1/2} \tag{6}$$

Problem:

A fiber has the following characteristics: n_1 = 1.35 (core index) and Δ =2%. Find the N.A and the acceptance angle.

Ans: Given, core refractive index, $n_1 = 1.35$

and *fractional index change* $\Delta = 2\% = 0.02$

Using Eqn. 6 $NA = 1.35 \times (2 \times 0.02)^{1/2} = 0.27$

Using Eqn. 3 $i_m = \sin^{-1}(N.A) = \sin^{-1}(0.27) = 15.66°$

Acceptance angle = $2i_m = 31.33°$

VIII. NORMALIZED FREQUENCY OR 'CUT-OFF FREQUENCY' OR 'CUT-OFF PARAMETER' OR 'V- NUMBER' FOR FIBER

A dimensionless parameter that combines the key variables of the optical fiber isknown as normalized frequency or "V" number and is defined as

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{2\pi a}{\lambda}\, n_1(2\Delta)^{1/2} = \frac{2\pi a}{\lambda}(NA) \tag{7}$$

Where a is the fiber radius and λ is the operating wavelength.

The maximum number of modes, N_m, supported by a step index fiber is given by

$$Nm = 0.5\,V^2 \tag{8}$$

Thus, For V =10, N_m is 50. ***When the normalized frequency V is less than 2.405, the fiber can support only one mode***, which propagates along the axial length of the fiber, and the fiber becomes a single mode fiber. The wavelength at which the fiber becomes a single mode is called the **cut-off wavelength,** λ_c, of the fiber.

Dispersion and attenuation in optical fiber

When a signal pulse travels on an optical fiber it goes on broadening due to dispersion and its amplitude starts to reduce due to attenuation as shown in Fig. 6. As a result of these, after traversing certain distance the pulse shape is completely distorted not to resemble with the original pulse shape.

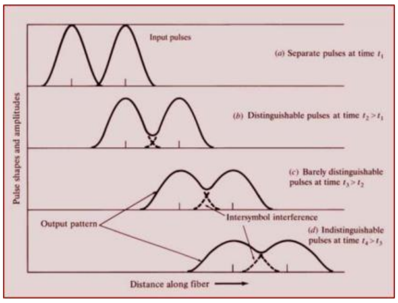


Fig. 6 Dispersion and attenuation of light signal propagating through an optical fiber

The spreading of light pulses as they propagate along the fiber is known as **dispersion**. It is tobe noted that

- Dispersion in fiber optics results from the fact that in multimode propagation, the signal travels faster in some modes than it would in others.
- Single-mode fibers are relatively free from dispersion except for *intra-modal dispersion.*
- Graded-index fibers reduce dispersion by taking advantage of higher-order modes.
- One form of intra-modal dispersion is called *material dispersion* because it depends upon the material of the core. Another form of dispersion is called *waveguide dispersion.*
- Dispersion increases with the bandwidth of the light source.

The loss of optical power as light travels down the optical fiber is called **attenuation**. It is defined as the ratio of the output optical power (P_0) to input optical power (P_i) from a fiber of length L. Mathematically,

$$P_0 = P_i e^{-\alpha L} \tag{9}$$

Where α is the fiber attenuation coefficient expressed in units of km^{-1}. Thus

$$\alpha = \frac{1}{L} ln \frac{P_i}{P_0}$$

In units of dB/km, α is defined by the equation

$$\alpha_{dB/km} = \frac{10}{L} log \frac{P_i}{P_0} \tag{10}$$

For an ideal fiber, $P_i = P_o$ and the attenuation would be zero.

- **Losses in optical fiber**

Losses in optical fiber result from attenuation in the material itself and from scattering, which causes some light to strike the cladding at less than the critical angle. Bending the optical fiber too sharply can also cause losses by causing some of the light to meet the cladding at less than the critical angle. It varies greatly depending upon the type of fiber

- Plastic fiber may have losses of several hundred dB per kilometer
- Graded-index multimode glass fiber has a loss of about 2–4 dB per kilometer
- Single-mode fiber has a loss of 0.4 dB/km or less

Major types of losses are

Materials loss

- **Due to impurities:** The material loss is due to the impurities (e.g. Fe, Ni, Co) present in glass used for making fibers. The Fig. 7 shows attenuation due to various molecules inside glass as a function of wavelength. It can be noted from the Fig. 7 that the material loss due to impurities reduces substantially beyond about 1200 nm wavelength.
- **Due to OH molecule:** In addition, the OH molecule diffuses in the material and causes absorption of light. The OH molecule has main absorption peak somewhere in the deep infra-red wavelength region. However, it shows substantial loss in the range of 1000 to 2000 nm.
- **Due to infra-red absorption:** Glass intrinsically is a good infra-red absorber. As we increase the wavelength the infra-red loss increases rapidly.

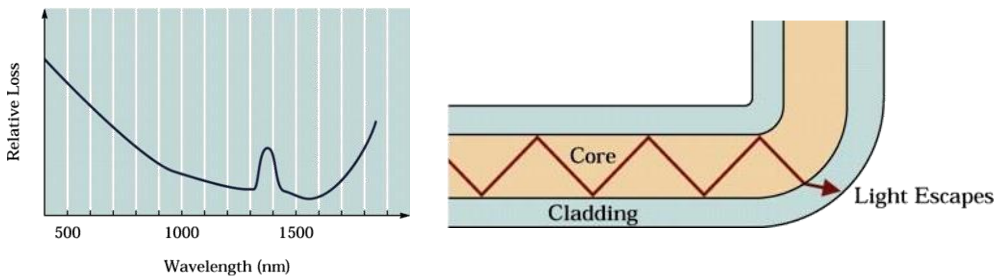


Fig. 7 Materials loss as a function of wavelength and bending loss in an optical fiber

Scattering loss

- The scattering loss results from the non-uniformity of the refractive index inside the core of the fiber. The refractive index of an optical fiber has fluctuation over spatial scales much smaller than the optical wavelength. These fluctuations act as scattering centers for the light passing through the fiber. The process is known as **Rayleigh scattering**. A very tiny fraction of light gets scattered and therefore contributes to the loss.
- The Rayleigh scattering is a very strong function of the wavelength. The scattering loss varies as λ^{-4}. This loss therefore rapidly reduces as the wavelength increases. For each doubling of the wavelength, the scattering loss reduces by a factor of 16. It is then clear that the scattering loss at 1550 nm is about factor of 16 lower than that at 800 nm.

IX. APPLICATIONS OF FIBER OPTICS

Optical fiber finds applications in the field of medical (endoscopes), defence and most notably in communication networks. A fiber optic communication network is shown in Fig. 8.

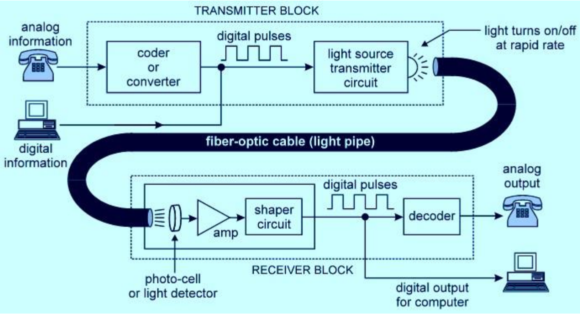


Fig. 8 Schematic of a fiber optic communication network.

- **Limitations of the Ray-model**

1. The ray model assumes that during total internal reflection the energy is confined to the core only. However, in reality, the optical energy spreads also in the cladding.
2. It does not speak of the discrete field patterns for propagation inside a fiber.
3. The ray model breaks down when the core size becomes comparable to the wavelength of light. It is, therefore, not quite justified for a SM fiber.

The limitations of the Ray model can be overcome in the wave model.

(All figures are taken from the freely available images in the internet)