LASER

- ***What is LASER?***

LASER is acronym for ***Light Amplification by Stimulated Emission of Radiation***.

Definition: LASER is device which can produce a highly intense, highly coherent, more directional and highly monochromatic beam.

In laser, the intensity of light is amplified by a process called stimulated emission.

Lasers are optical phenomena which find major application in various fields such as medicine, engineering, fiber optic communication, industries, etc. lasers are more powerful radiation than ordinary light radiation.

- ***State the characteristic of LASER:***

The following characteristics, distinguishes a laser beam from an ordinary light. They are:

1. Coherence
2. High intensity
3. High directionality
4. High monochromaticity

Laser light is highly powerful and capable of propagating over long distances and is not easily absorbed by water.

Coherence: The wave trains which are identical in phase and direction are called Coherence waves.

Since all the constituent photons of laser beam possess the same energy, momentum and propagate in same direction, the laser beam is said to be highly coherent.

High Intensity: Due to the coherent nature of laser, it has the ability to focus over a small area of 10^{-6} cm^2, i.e., extremely high concentration of its energy over a small area.

High Directionality: An ordinary source emits light in all possible direction. But, since laser travels as a parallel beam it can travel over a long distance without spreading.

The angular spread of a laser beam is 1mm/meter. This reveals the directionality of the laser beam.

High Monochromaticity: The light from a normal monochromatic source spread over a range of wavelength of the order of 1nm for laser. Hence, laser is highly monochromatic, i.e., it can emit light of single wavelength.

- ***<u>Einstein's Theory</u>***

Einstein explained the action of laser beam based on quantum theory of light. Production of laser light is a particular consequence of interaction of radiation with matter. Radiation interacts with matter under appropriate conditions and may lead to the transition of an atom or a molecule from one energy state to another. If the transition is from a higher state to a lower state, the system gives a part of its energy. But, if the transition is the reverse direction, then it absorbs the incident energy.

There are three possible ways through which interaction of radiation and matter can take place. Among the three types, one is absorption that is also known as induced absorption and the other two are emissions.

The emission of radiation can occur in two ways as suggested by Einstein. They are Spontaneous emission and Stimulated emission,

The interpretation of the interaction is done on the basis of ideas related to energy a level of the concerned system for which light is to be obtained.

All the three processes are described by considering an atom having only two energy-level E_1 and E_2.

a) Induced Absorption (Absorption)

Let the atom be initially in the lower state E_1. If a photon of energy *hv* is incident on the atom in the lower state, the atom absorbs the incident photon and gets excited to the higher energy state E_2. This process is called induced absorption as shown in fig. below.

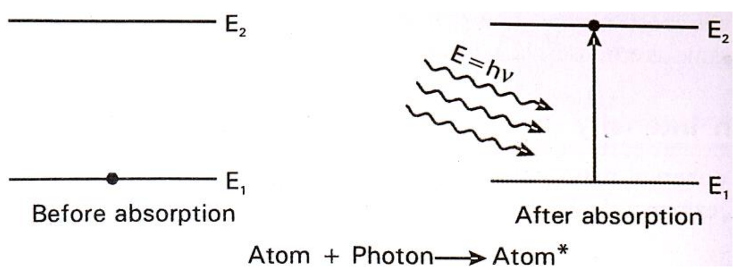


Fig. Induced absorption

The rate of absorption R_{12} is proportional to the population of the lower energy level N_1 and to the density of incident radiation ρ. Hence,

$$R_{12} \propto N_1\rho$$

Or

$$R_{12} = B_{12} N_1\rho \qquad \text{...... (1)}$$

Where, B_{12} is the proportionality constant known as probability of absorption of radiation per unit time.

b) Spontaneous Emission

It is a process in which there is an emission of photon whenever an atom transits from a higher energy state to a lower energy state without the aid of any external agency.

For this process to take place, the atom has to be in the excited state. Since, the higher energy level is an unstable one, the excited atom in the higher energy level E_2 spontaneously returns to the lower energy level E_1 with the emission of photon of energy $h\nu = E_2 - E_1$ as shown in figure below.

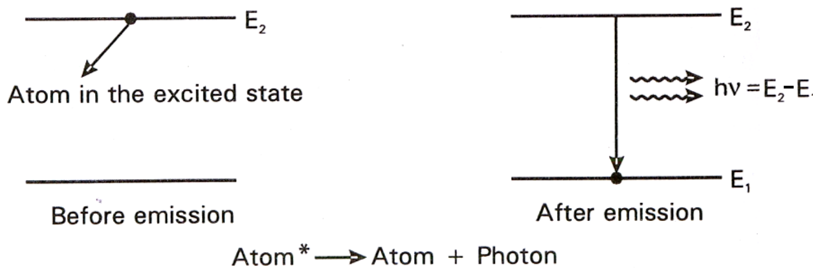


Fig. Spontaneous Emission

The rate of spontaneous emission of radiation R_{21} (sp) is proportional to the population N_2 at the higher energy level E_2.

i.e., $\qquad R_{21}(sp) \propto N_2$

$\therefore \qquad R_{21}(sp) = A_{21} N_2 \qquad$ ...... (2)

where A_{21} is the proportionality constant known as the probability of spontaneous emission per unit time.

c) *Stimulated Emission:*

It is a process in which there is an emission of a photon whenever an atom transits from a higher energy state to a lower energy under the influence of an external agency. i.e., an inducing photon.

For this process also, the atom should be already in the excited state. Let the photon having an energy $h\nu = E_2 - E_1$ interact with an atom in the excited state. Under such interaction, the incident photon stimulates the excited atom in the level E_2 to transits to the lower energy E_1, resulting in the emission of a photon of energy $h\nu = E_2 - E_1$ as shown in figure below.

Both the inducing photon and the emitted photon will have the same phase, energy and direction of movement. This kind of emission is responsible for laser action, i.e., the stimulated emission of radiation is principle used in laser action.

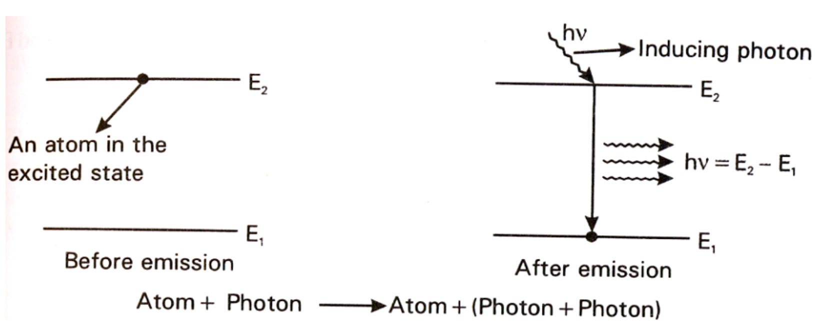


Fig. Stimulated Emission.

The rate of stimulated emission of radiation $R_{21}(st)$ is proportional to the population N_2 at the higher energy level E_2 and the density ρ of the inducing photon.

i.e., $R_{21}(st) \propto N_2\rho$

∴ $R_{21}(st) = B_{21}N_2\rho$ ...... (3)

Where, B_{21} is the proportionality constant known as the probability of stimulated emission of radiation per unit time. The coefficients B_{12}, A_{21} and B_{21}in the equations (1), (2) and (3) are called the Einstein's coefficients.

❖ ***Differentiate between Stimulated Emission and Spontaneous Emission.***

Sr. No.	Stimulated Emission	Spontaneous Emission
1	Emission of a light photon takes place through an inducement. i.e., by an external photon	Emission of a light photon takes place immediately without any inducement.
2	It is not a random process.	It is a random process.
3	The photons get multiplied through chain reaction.	The photons do not get multiplied through chain reaction.
4	It is a controllable process.	It is an uncontrollable process.
5	More intense.	Less intense.
6	Monochromatic radiation.	Polychromatic radiation.

❖ **<u>Relation between Einstein's Coefficient:</u>**

Einstein obtained a mathematical expression for the existence of two different kinds of processes-spontaneous emission and stimulated emission.

Since the transition between the atomic energy states is statistical process, it is not possible to predict which particular atom will make a transition from one state to another at a particular instant. But it is possible to calculate the rate of transmission between the states.

Let us assume at thermal equilibrium, the number of upward transitions is equal to the number of downward transitions per unit volume per second.

i.e. the rate of absorption = the rate of emission

$$B_{12}N_1\,\rho = A_{21}\,N_2 + B_{21}\,N_2\,\rho \qquad ....(1)$$

From the above equation,

$$(B_{12}N_1 - B_{21}\,N_2\,)\rho = A_{21}\,N_2 \qquad ....(2)$$

$$\rho = \frac{A_{21}\, N_2}{B_{12}\, N_1 - B_{21} N_2} \quad \text{...(3)}$$

$$\rho = \frac{A_{21}}{(B_{12}\frac{N_1}{N_2} - B_{21})} \quad \text{..(4)}$$

Under thermal equilibrium, the number of atoms N1 and N2 in the energy states E1 and E2 at a temperature T is given by Boltzmann distribution law. Hence we have

$$N_1 = N_0\ e^{(-E_1/K_B T)} \quad \text{...(5)}$$

$$N_2 = N_0\ e^{(-E_2/K_B T)} \quad \text{...(6)}$$

By taking the ratio of Equation (6) to equation (5), We get,

$$\frac{N_2}{N_1} = \frac{e^{(-E_2/K_B T)}}{e^{(-E_1/K_B T)}} = e^{-(E_2 - E1)/(K_B T)} \quad \text{....(7)}$$

Therefore,

$$\frac{N_2}{N_1} = e^{-(h\nu)\,/(K_B T)}$$

Or

$$\frac{N_1}{N_2} = e^{(h\nu)\,/(K_B T)} \quad \text{.....(8)}$$

Substituting equation (8) in equation (4), we get,

$$\rho = \frac{A_{21}}{(B_{12} e^{(h\nu)\,/(K_B T)} - B_{21})}$$

$$\rho = \frac{A_{21}/B_{21}}{(\frac{B_{12}}{B_{21}}) e^{(h\nu)\,/(K_B T)} - 1} \quad \text{....(9)}$$

But from Planck's Black Body radiation theory

$$\rho = \frac{8\pi h \nu^3/c^3}{e^{(h\nu)\,/(K_B T)} - 1} \quad \text{....(10)}$$

Hence comparing equations (9) and (10), we get

$$\frac{A_{21}}{B_{21}} = 8\pi h\nu^3/c^3 \text{ and } B_{12} = B_{21}$$

Take $B_{12} = B_{21} = B$ and $A_{21} = A$. The constants A and B are called Einstein's coefficients.

- **<u>Ratio of spontaneous and stimulated Emission rates:</u>**

The Ratio of stimulated and spontaneous emission rates can be written as:

$$\frac{R_{21(ST)}}{R_{21(SP)}} = \frac{B_{21}}{A_{21}}\rho \qquad (11)$$

But from equation (9), we know that

$$\frac{A_{21}}{B_{21}}\rho = \frac{1}{(\frac{B_{12}}{B_{21}})e^{(h\nu)/(K_B T)} - 1}$$

or

$$\frac{A_{21}}{B_{21}}\rho = \frac{1}{(e^{(h\nu)/(K_B T)} - 1)} \qquad (12)$$

Replacing the RHS of equation (11) with equation (12), we get

$$\frac{R_{21(ST)}}{R_{21(SP)}} = \frac{1}{(e^{(h\nu)/(K_B T)} - 1)}$$

or

$$\frac{R_{21(SP)}}{R_{21(ST)}} = (e^{(h\nu)/(K_B T)} - 1) \qquad ....(13)$$

Thus, when the energy of the incident photon is much greater than K_BT, the number of spontaneous emissions far exceeds the number of stimulated emissions. Hence, under this condition, I,e, $h\nu >> K_BT$, LASER action is not possible.

In order to achieve more stimulated emission, the population N2 of the excited state(Meta stable state) should be made larger than the population N1 of the lower (ground)state. This condition is called population inversion.

- ***Basic concept in LASER PHYSICS or Basic requirements to produce LASER:***

What is Population Inversion?

Population inversion is a state of achieving more number of atoms in the excited state compared to ground state.

i.e., $N_2 > N_1$

If this condition is satisfied, then there is a more chance of stimulated emission to take place. Hence, population inversion is an essential condition for producing laser.

Population inversion can be achieved by a process called pumping.

What is pumping and Describe different types of Pumping.

Pumping is the mechanism of exciting atoms from the lower energy state to a higher energy state by supplying energy from an external source.

The most commonly used pumping mechanisms are described below.

Optical Pumping: In this type of pumping atoms are excited (i.e., population is inversion achieved) by means of an external optical source.

This type of pumping technique is adopted in solid state lasers such as ruby laser and Nd:YAG laser.

Electrical Pumping (Direct Electron Excitation)

In this type of pumping the electrons are accelerated to a high velocity by a strong electric field. These moving electrons collide with the neutral gas atoms and ionize the medium.

Thus, due to ionization they get raised to a higher energy level.

This technique of pumping is adopted in gas laser such as CO_2 laser.

Direct Conversion: In this type of pumping, a direct conversion of electric energy into light takes place. This technique of pumping is adopted in semiconductor laser.

In addition to the above three, the other type of pumping are inelastic collision between atoms and chemical methods which are respectively, adopted in He-Ne gas laser and in dye and chemical lasers.

Lasing: The process which leads to emission of stimulated photons after establishing the population inversion is referred to as lasing.

Life Time: The limited time for which a particle or an atom remains in the excited state is known as life time.

Metastable State: Metastable states are the energy levels in an atomic system where the life time of atom is very large (of the order of 10^{-3} to 10^{-2} second). This property helps in achieving the population inversion.

Active Medium: A medium in which population inversion is achieved for laser action is called active medium. The medium can be solid, liquid, gas and plasma.

Based on the active medium and method of pumping, the lasers are classified into;

1. Solid state laser
2. Liquid lasers
3. Gaseous lasers
4. Dye casters
5. Semiconductor laser

Optical Resonator: It is a pair of reflecting surfaces (mirrors) of which one is a perfect reflector and the other is a partial reflector.

It is used for amplification of photons thereby producing an intense and highly coherent output.

Principle of Laser:

Laser is based on the principle of stimulated emission of radiation which night amplification. For stimulated emission of radiation to take place, the population of atoms in higher energy level should be greater than the lower energy level, i.e., $N_2 > N_1$. This can be achieved by pumping. Light amplification is achieved by photon multiplication within an optical resonator cavity.

Initially, the state of population inversion has to be achieved in the active medium which is within a resonator cavity. Then, a spontaneously emitted photon by one of the excited atom stimulates another atom it encounters in its path to release a second photon. Thus, these two photons which are coherent in nature stimulate other two atoms to produce another two photons. Hence, there will be four coherent photons. Thus, the photon number gets multiplied just like a chain reaction thereby producing an amplified light by stimulated emission of radiation resulting in a highly intense beam called laser.

Basic Laser system Components

A basic laser system has three important components. They are;

1. The active medium
2. The pumping source
3. The optical resonator

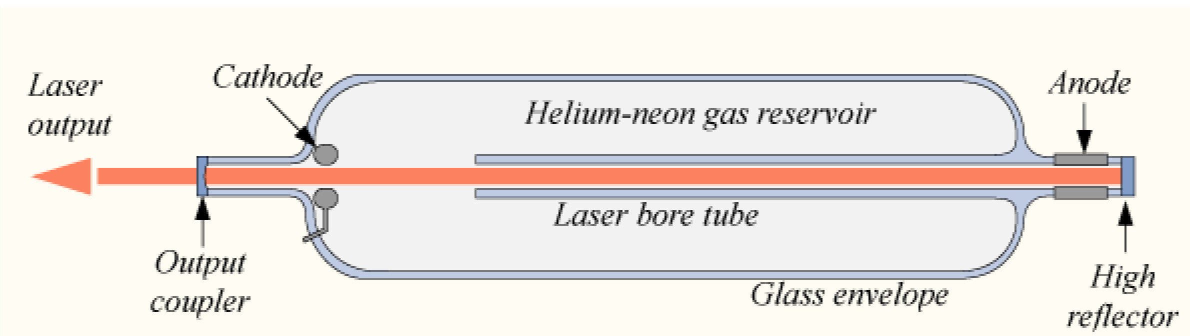
helium–neon laser or **He-Ne laser**

A **helium–neon laser** or **He-Ne laser**, is a type of gas laser whose gain medium consists of a mixture of 10:1 ratio of helium and neon at a total pressure of about 1 torr inside of a small electrical discharge. The best-known and most widely used He-Ne laser operates at a wavelength of 632.8 nm, in the red part of the visible spectrum.

Construction and operation:

The gain medium of the laser, as suggested by its name, is a mixture of helium and neon gases, in approximately a 10:1 ratio, contained at low pressure in a glass envelope. The gas mixture is mostly helium, so that helium atoms can be excited. The excited helium atoms collide with neon atoms, exciting some of them to the state that radiates 632.8 nm. Without helium, the neon atoms would be excited mostly to lower excited states, responsible for non-laser lines.

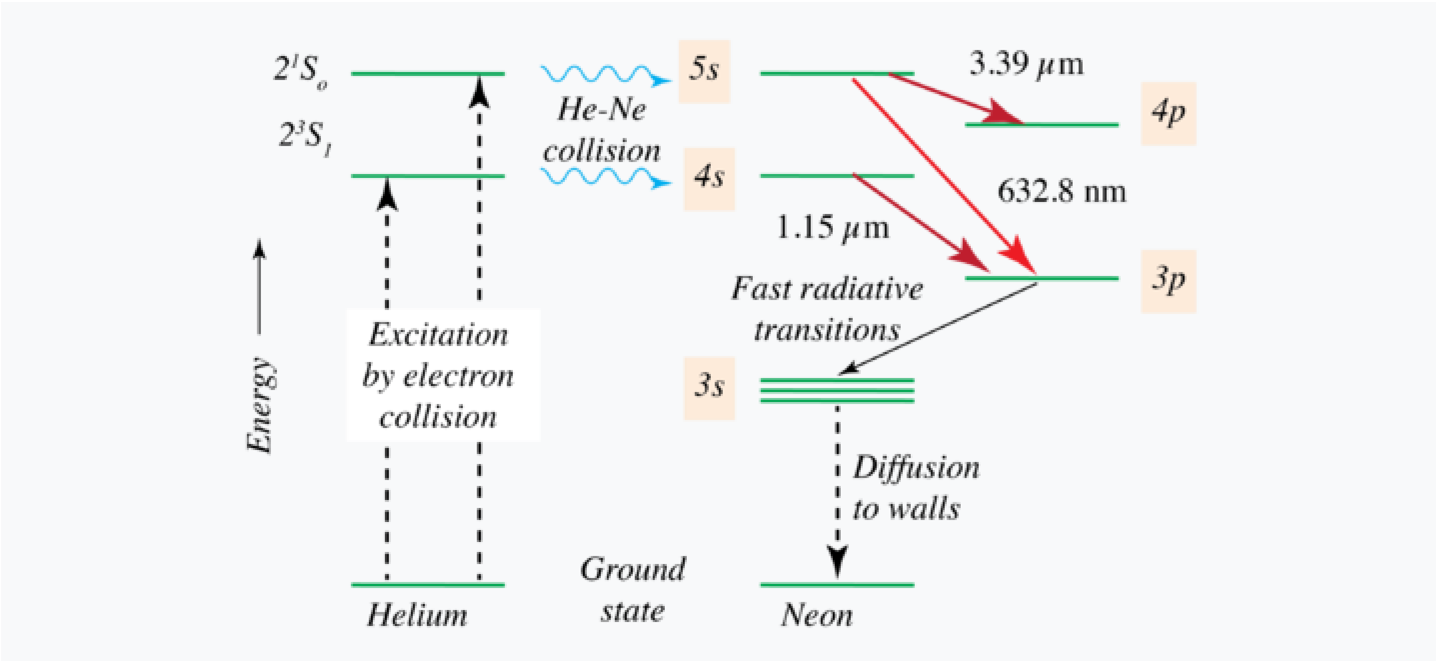
A neon laser with no helium can be constructed, but it is much more difficult without this means of energy coupling. Therefore, a He-Ne laser that has lost enough of its helium (e.g., due to diffusion through the seals or glass) will lose its laser functionality because the pumping efficiency will be too low. The energy or pump source of the laser is provided by a high-voltage electrical discharge passed through the gas between electrodes (anode and cathode) within the tube. A DC current of 3 to 20 mA is typically required for CW operation. 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.



Schematic diagram of a helium–neon laser

Commercial He-Ne lasers are relatively small devices, among gas lasers, having cavity lengths usually ranging from 15 to 50 cm (but sometimes up to about 1 meter to achieve the highest powers), and optical output power levels ranging from 0.5 to 50 mW.

The red He-Ne laser wavelength of 633 nm has an actual vacuum wavelength of 632.991 nm, or about 632.816 nm in air. The wavelengths of the stimulated emission modes lie within about 0.001 nm above or below this value, and the wavelengths of those modes shift within this range due to thermal expansion and contraction of the cavity. Frequency-stabilized versions enable the wavelength of a single mode to be specified to within 1 part in 10^8 by the technique of comparing the powers of two longitudinal modes in opposite polarizations. Absolute stabilization of the laser's frequency (or wavelength) as fine as 2.5 parts in 10^{11} can be obtained through use of an iodine absorption cell.



Applications:

Red He-Ne lasers have enormous industrial and scientific uses. They are widely used in laboratory demonstrations in the field of optics because of their relatively low cost and ease of operation compared to other visible lasers producing beams of similar quality in terms of spatial coherence (a single-mode Gaussian beam) and long coherence length (however, since about 1990 semiconductor lasers have offered a lower-cost alternative for many such applications).

❖ ***Describe the construction and working of Nd: YAG LASER with a suitable energy-level diagram.***

Active medium: This is a four-level solid state laser system. Yittrium Aluminium Garnet ($Y_3Al_5O_{12}$), commonly known as YAG, doped with neodymium ions Nd^{3+} is the active medium. The active medium is taken in the form of a crystal and is drawn into a rod. The neodymium ions Nd^{3+} are the active centers.

Resonator Cavity: the end faces of the Nd: YAG rod are ground polished and silvered to act as the optical resonator mirrors, or the optical cavity can be formed by using two external reflecting mirrors M_1 and M_2.

Optical Pumping: A xenon flash lamp or krypton flash lamp is used as a pumping source.

Construction: The schematic diagram of a Nd: YAG laser is shown in figure below.

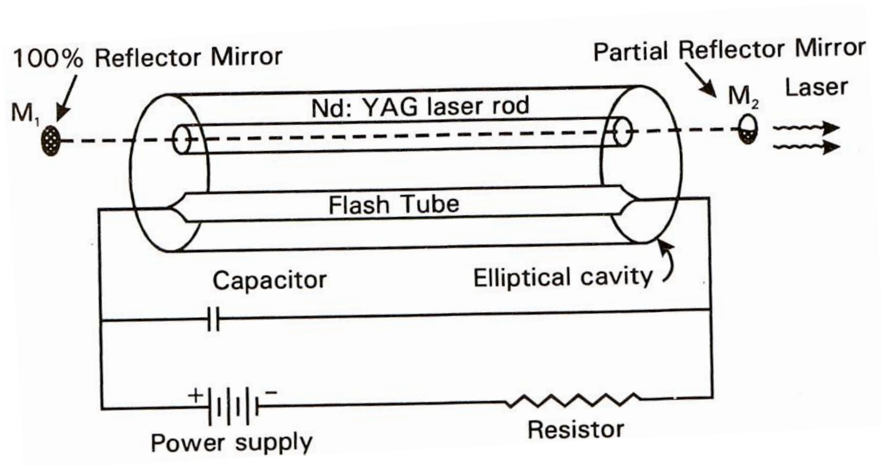


Figure. Nd: YAG LASER

A Nd: YAG rod and krypton flash lamp are enclosed inside an ellipsoidal reflector. In order to make the entire flash radiation to focus on the laser rod, the Nd: YAG rod is placed at one focal axis and the flash lamp at the other focal axis of the ellipsoidal reflector.

Working: The flash lamp is switched on. The optical pumping excites the Nd^{3+} ions from the ground energy state E_0 to the higher energy level E_3 and E_4 by absorbing radiations of wavelength 0.80 µm and 0.73 µm, respectively. The energy-level diagram is shown in figure below. The excited Nd^{3+} ions then make a transition from these energy levels. The transition from the energy level E_4 to E_2 is a non-radiative transition. The E_2 is the Metastable state. Upon continuous excitation, population inversion of Nd^{3+} ions is achieved at the Metastable state E_2.

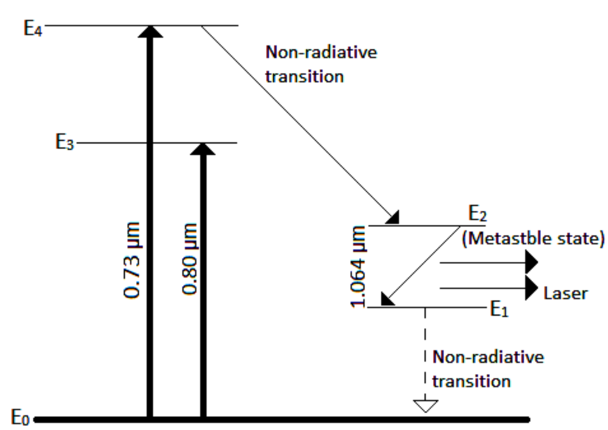


Fig. Energy level diagram

Any of the spontaneously emitted photon will make the excited Nd^{3+} ions to undergo a transition between $E_2 \rightarrow E_1$ state. Thus, during this transition the stimulated photon is generated.

The photons travelling parallel to the resonator axis experience multiple reflections at the mirrors. As a result, the transition $E_2 \rightarrow E_1$ yields an intense and coherent laser beam of wavelength 1.064 μm. These lasers give beam continuously. The Nd^{3+} ions then make a transition between $E_1 \rightarrow E_0$, which is a non-radiative transition.

Only a part of energy emitted by the flash lamp is used to excite the Nd^{3+} ions, while the rest heats up the crystal. Thus, the system can be cooled by either air or water circulation.

Applications:

1. These lasers are widely used for cutting, welding and surface hardening of the industrial products.
2. These lasers are used in military as range finder and as target destinations.
3. These lasers are used in medical field for cataract surgery, to treat gastrointestinal bleeding and gall bladder surgery.
4. It is used in long haul communication.
5. It is used in the study of inertial confinement fusion.

- ***Give the applications of LASER:***
-

Some of the applications of laser in various fields are listed below.

a) In Industry:

In industries, lasers are applied to a larger extent for the following processes:

1. For welding and melting.
2. For cutting and drilling holes.
3. To test the quality of materials.
4. For the heat treatment of metallic and non-metallic materials.

b) In Medicine:

1. Used for the treatment of detached retinas.
2. Used in performing micro and bloodless surgery.
3. Used for treatment of human and animal cancers and skin tumors.

c) Military applications:

1. The laser beam can serve as war weapon, i.e., A powerful laser beam can be used to destroy in a few seconds, the big size objects like aero planes, missiles etc., by pointing the laser beam onto them. For this reason, it can be even called as death ray.
2. The laser beam can be used to determine precisely the distance, velocity and direction as well as the size and form of distance object by means of the reflected signal. It is known as LIDAR.

d) Science and Engineering applications:

1. It is used in fiber optic communication.
2. Communication between planets is possible with laser.
3. It is used in holography.
4. It is used in underwater communication between submarines, as they are not easily absorbed by water.
5. It is used to accelerate some chemical reactions.
6. It is used to create new chemical compounds by destroying atomic bonds between molecules.

It is used to drill minute holes in cell walls without damaging the cell itself.

❖ ***Answer in short***

1. **What is laser?**

   Laser is a device which can produce a highly intense, highly coherent, more directional and highly monochromatic beam.
2. **What is population inversion?**

   It is a state of achieving more number of atoms in the excited state compared to the ground state, i.e., $N_2 > N_1$
3. **Name the three processes that occur when light interacts with matter.**

   The three processes that occur when light interacts with matter are:
   a. Stimulated absorption
   b. Spontaneous emission
   c. Stimulated emission
4. **Give the differences between stimulated and spontaneous emission of radiation.**

Sr. No.	**Stimulated emission**	**Spontaneous emission**
1	Emission of a light proton takes place through an inducement, i.e., by an external photon.	Emission of light proton takes place immediately without any inducement.
2	It is not a random process.	It is a random process.
3	The photons get multiplied through reaction.	The photons don't get multiplied chain through chain reaction.
4	It is a controllable process.	It is an uncontrollable process.
5	More intense.	Less intense.
6	Monochromatic radiation.	Polychromatic reaction.

5. **What is an active medium?**

   A medium in which population inversion is achieved for laser action is called an active medium.
6. **What is a metastable state?**

The Metastable states are the energy levels in an atomic system where the life time of atoms is very large. This property helps in achieving the population inversion.

7. **What is an optical resonator?**

   It is a pair of reflecting surfaces (mirrors), of which one is being a perfect reflector and the other being the partial reflector.

   It is used for amplification of photons, thereby producing an intense and highly coherent output.

8. **What is active medium in a Nd: YAG laser?**

   Yttrium Aluminium Garnet doped with Nd^{+3} ions is the active medium in Nd: YAG laser.

9. **Mention the applications of laser in communication.**

   I. Laser is used in communications between satellites and rockets and between planets, i.e., inter-planetary communications.
   II. Laser is used as light source for optical fiber communications.
   III. Laser light is used for under water communication between submarines as it is not absorbed by water.

10. **State the applications of laser in military.**

   I. ***Death Ray:*** since laser beam is very energetic, it can destroy object like aircrafts, missiles, etc. for this reason it is known as **death ray or way weapon.**
   II. **LIDAR(Light Detection And Ranging):** laser beam can exactly determine size. Form, distance, velocity and direction of distant object (enemy plane, missile, etc.) by receiving the reflected laser beam as in RADAR (Radio Detection and Ranging).
   III. ***Laser gun:*** in a laser gun a powerful convergent laser beam is focused onto a target.

11. **What are the advantages and disadvantages of laser surgery?**

   Highly sterile, localized and definite, No side effect, Painless and bloodless surgery, Short period of surgical time, Efficient healing.

Disadvantage of laser surgery: Highly expensive

❖ ***Example:***

Find the ratio of population of the two energy state in a laser. The transition between which is responsible for the emission of photons of wavelength $698.3*10^{-9}$ m. Assume the temperature to be 300 K.

Given; T = 300 K; $\lambda = 698.3*10^{-9}$ m; N_2/N_1 = ?

Let ΔE be the energy difference between the two energy states.

$$\therefore \ \frac{N_2}{N_1} = e^{\left(\frac{-\Delta E}{K_B T}\right)}$$

Where, $\Delta E = hc / \lambda$

Hence, $\frac{N_2}{N_1} = e^{-\left(\frac{6.625\times10^{-34}\times3\times10^{8}}{698.3\times10^{-9}\times1.38\times10^{-23}\times300}\right)}$

$= e^{-\left(\frac{1.9875\times10^{-25}}{2.89096\times10^{-27}}\right)} \qquad = e^{-68.748}$

$\boldsymbol{\frac{N_2}{N_1} = 1.3892 \times 10^{-30}}$.

Best of Luck

FIBER OPTICS

❖ *Introduction:*

The term **Communication** may be defined as transfer of information from one point to another. For the information to be transmitted over a distance, a communication system is usually required.

Within a communication system the Information transfer is made possible by **modulating or superimposing the information** on to an Electro-magnetic wave which act as a **carrier** for information signal. This modulated carrier is then transmitted to the required destination where it is received & the original information signal is obtained by demodulation.

❖ *Fiber Optics System:*

Communication system that uses ***Light as a carrier*** of information from a source to a destination through a guided fiber cable (Glass or Plastic) are called Fiber optics system.

The information carrying capacity of communication system is directly proportional to its bandwidth, i.e. the wider the Bandwidth, the greater is its information carrying capacity. Light frequencies used in fiber optics system are between 10,000 to 400,000 GHz to obtain higher information carrying capacity.

Because of high information carrying capacity & low attenuation, now-a-days Fibers are finding wide application in Telecommunication, Local area networks, sensors, computer networks etc.

❖ *The Primary Advantages of Fiber-optics Communication Compared to metallic Cable (Electrical) communication*

1. ***Extremely Wide (Large) Bandwidth:*** The bandwidth available with single glass fiber is more than 100 GHz. With such a large bandwidth, it is possible to transmit thousands of voice conversations or dozens of video signals over the same fiber simultaneously. Irrespective of whether the information is voice, data or video or a combination of these, it can be transmitted easily over the optical fibers. Whereas, only a very less number (40-50) of independent signals alone can be sent through metallic cables.
2. ***Immunity to Electrostatic Interference:*** As optical fiber being made of either glass or plastic (non conductors of electricity) external electrical noise and lighting do not affect the energy in a fiber cable. The result is noise free transmission. However, this is not true for metallic cables made of metals, as they are good conductors of electricity.
3. ***Elimination of Cross Talk:*** Fiber systems are immune to cross talk between cables caused by magnetic induction. Whereas, in a metallic cable cross talk results from the electromagnetic coupling between two adjacent wires.
4. ***Lighter Weight and Smaller Size:*** Fibers are very smaller in size. This size reduction makes fibers the ideal transmission medium for ships, aircraft and high rise buildings where bulky copper cables occupy to much space. Reduction in size results in reduction in weight also.

5. ***Lower Cost:*** The material used in fibers is silica glass or silicon dioxide which is one of the most abundant materials on earth, resulting in lower cost. Optical-fiber costs are continuing to decline. The costs of many systems are declining with the use of fiber and that trend is accelerating.
6. ***Security:*** Fiber cables are most secured than metallic cables. Due to its immunity to electromagnetic coupling and radiation, optical fiber can be used in most secure environments. Although it can be intercepted or trapped, it is very difficult to do so because at the receiving user's end an alarm would be sounded.
7. ***Greater Safety:*** In many wired systems, (metallic cables) the potential hazard of short circuits requires precautionary designs. Whereas, the dielectric number of optical fibers eliminates the spark hazard.
8. ***Corrosion:*** Fiber cables are more resistive to environmental extremes. They operate over large temperature variation than their metallic counterparts, and are less affected by corrosive liquids and gases.
9. ***Longer Life Span and Ease of Maintenance:*** A longer life span of 20 to 30 years is predated for the fiber optic cables as compared to 12 to 15 years for the conventional cables.

❖ **Fiber cable Construction**

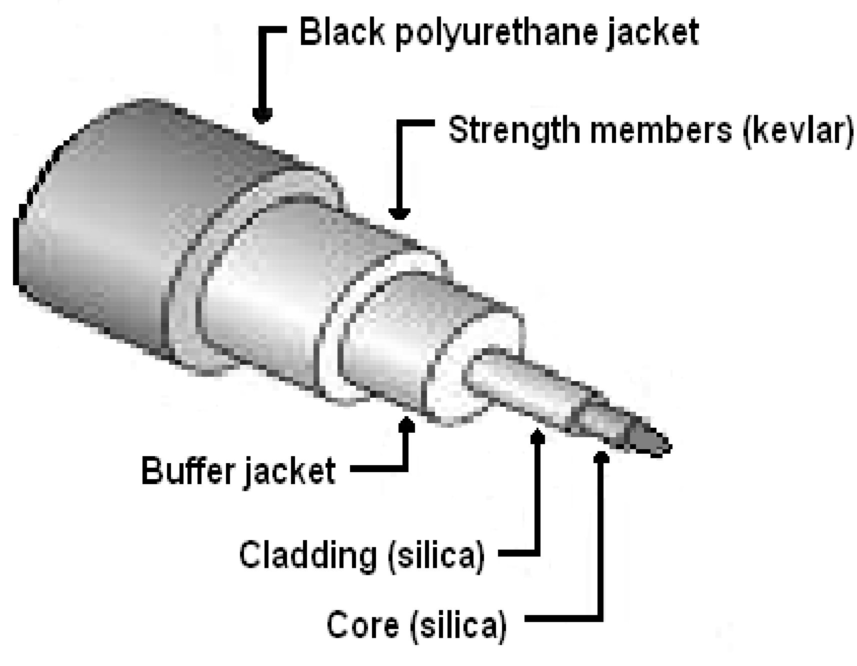


Fig:- Fiber Optic Cable

❖ There are different cable designs available today. Depending on the configuration, the cable may include a core, a cladding, a protective tube, a polyurethane compound and one or more protective jackets.

- The fiber cable consists of a core at the centre and a cladding outside the core. The core is generally a cylindrical dielectric glass with a refractive index n_1 and the cladding is the second cover made of glass with a lower refractive index n_2 than the core refractive index.

- The cladding in turn is covered by a buffer jacket. This buffer jacket provides protection for the fiber from external mechanical influences that could cause fiber breakage or excessive optical attenuation.

- ***Surrounding he buffer jacket there is a layer of strength membranes called Kevlar (a yarn type material) which increases the tensile strength of the cable.*** Again, an outer protective tube is filled with polyurethane, which prevents moisture from coming into contact with the fiber.

- **<u>Basic principle-Total Internal Reflection</u>**

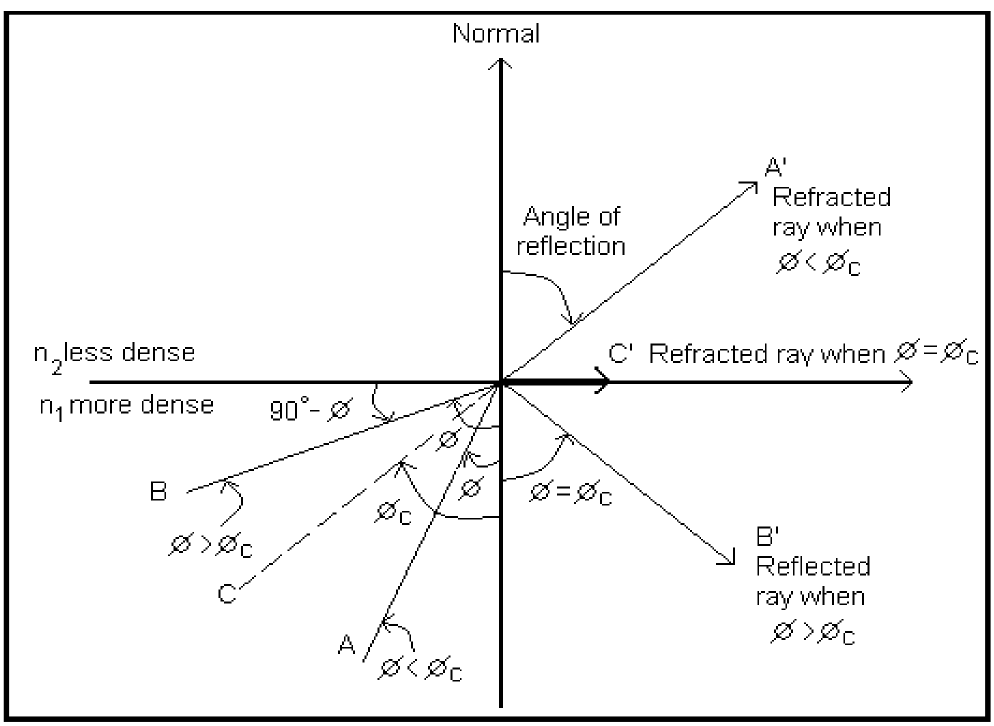
  - Total internal reflection within fiber wall can occur only if two conditions are satisfied.

1. Refractive index of the core $n_1 > n_2$ (refractive index of the cladding)

2. The light must approach the wall with an angle of incidence Φ that is greater than the critical angle Φ_c given by

$$\sin \Phi_c = n_2 / n_1$$

(When $\Phi = \Phi_c$ then Snell's Law, $n_1 \sin \Phi_c = n_2 \sin 90^\circ$ or $\sin \Phi_c = n_2 / n_1$). ***Critical angle Φ_c is defined as the value of the incident angle at which the angle of refraction is 90º.***



1 When the angle of incidence Φ is less than the critical angle Φ_c, refraction occurs rather than total internal reflection, with the subsequent loss of the light ray into the cladding (Ray AA').

2 When the angle of incidence Φ is greater than the critical angle Φ_c, total internal reflection occurs & is reflected at the same angle to the normal (Ray BB').

When the angle of incidence Φ is equal to the critical angle Φ_c, the refracted ray emerges parallel to the interface between the core & the cladding, i.e. the angle of reflection is 90º (RayCC').

❖ Acceptance Angle and Numerical Aperture

- ***Definition: Acceptance angle of the fiber Φ_{max} is defined as the maximum value of the angle of incidence at the entrance (air-fiber interface) end of the fiber, at which the angle of incidence at the core-cladding interface is equal to critical angle of the core medium***

$\sin\Phi_{max} = \sqrt{n_1^2 - n_2^2}$

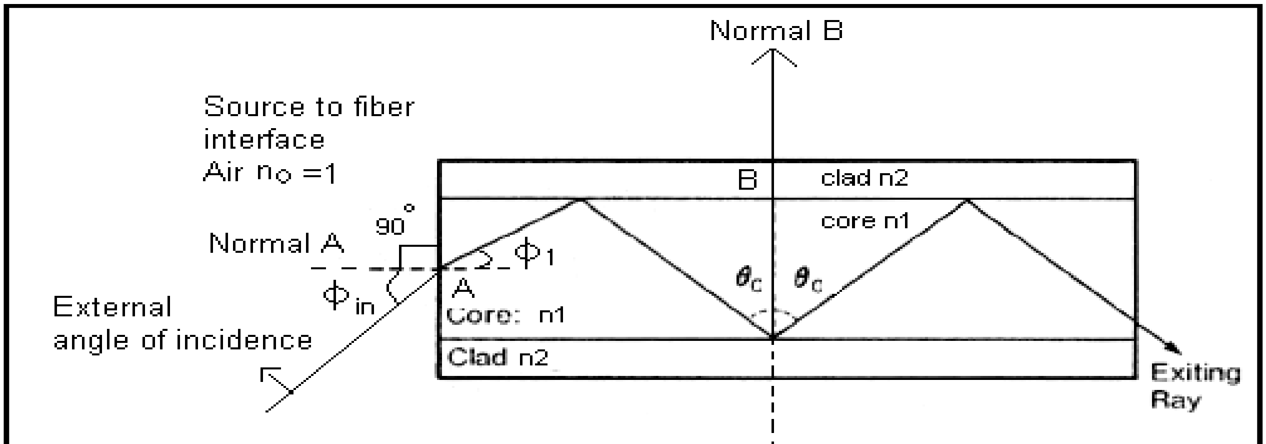


Fig 6.3: (a) Ray propogation into & down an optical fiber

- In order for a ray of light to propagate down the cable (i.e. for total internal reflection is to take place), it must strike the internal core/cladding interface at the angle that is greater than the critical angle Φ_c.

- Applying Snell's law to the external angle of incidence yields, the following relation

$$\mathbf{n_0 \sin\Phi_{in} = n_1 \sin\Phi_1.} \qquad (1)$$

$$\mathbf{But\ \Phi_1 = 90º - \Phi_c}$$

(2) Therefore substituting eq^n (2) in (1) we get,

$$\mathbf{n_0 \sin\Phi_{in} = n_1 \sin(90º - \Phi_c)}$$

$$\mathbf{n_0 \sin\Phi_{in} = n_1 \cos\Phi_c} \qquad (3)$$

- If we consider the point B in fig.6.3a, the critical angle value for Φ_c is

$\sin \Phi_c = n_2 / n_1$ (from snell's law)………(4)

- Expressing the term $\cos\Phi_c$,in eq^n(3), in terms of $\sin\Phi_c$,

$n_0 \sin\Phi_{in} = n_1(1-\sin^2\Phi_c)^{1/2}$ ……………..(5)

(using $\cos^2\theta=1-\sin^2\theta$)

- substituting for $\sin \Phi_c$ from equation (4)

$n_0 \sin\Phi_{in}= n_1[1-(n_2/n_1)^2]^{1/2}$

$n_0 \sin\Phi_{in}= n_1 (n^2_1-n^2_2/n_1^2)^{1/2}$ or

$n_0 \sin\Phi_{in}= n_1/ n_1 (n^2_1-n^2_2)^{1/2}$.................(6)

- Because light rays generally enter the fiber from an air medium, n_0=1. Therefore, the maximum value of $\sin\Phi_{in}$ is given as

$\sin\Phi_{in\ (max)} = (n^2_1-n^2_2)^{1/2}$

Or

$\Phi_{in\ (max)} = \sin^{-1} (n^2_1-n^2_2)^{1/2}$ ……….(7)

Thus Φ_{in} is called the acceptance angle or acceptance cone half-angle.

- Because light rays generally enter the fiber from an air medium, n_0=1. Therefore, the maximum value of $\sin\Phi_{in}$ is given as

$\sin\Phi_{in\ (max)} = (n^2_1-n^2_2)^{1/2}$

Or

$\boldsymbol{\Phi_{in\ (max)} = \sin^{-1} (n^2_1-n^2_2)^{1/2}}$ **……….(7)**

Thus Φ_{in} is called the acceptance angle or acceptance cone half-angle.

- Acceptance angle of the fiber is the maximum angle with which a light ray can enter into the fiber & still be totally Internal reflected.
- A cone of light incident at the entrance end of the fiber will be guided through the fiber, provided, the semi-vertical angle of the core is less than or equal to $\Phi_{in\ (max)}$ fig.6.3b.

Numerical Aperture

- Numerical aperture (NA) is a figure of merit that is used to describe the light gathering or light collecting ability of an optical fiber. The larger the magnitude of NA, the greater the amount of light accepted by the fiber from the external light source.
- NA is mathematically defined as the sine of the acceptance cone half-angle.

$NA = \sin\Phi_{in\ (max)}$ Or $NA = (n^2_1-n^2_2)^{1/2}$

- The NA can also be expressed in terms of normalized refractive index difference or relative refractive index(Δ). It is defined as the ratio of refractive index between core & cladding to the refractive index of core.

$\Delta= n^2_1-n^2_2 /2n^2_1 = n_1-n_2/n_1$

Therefore $\boldsymbol{NA= n_1 (2\Delta)^{1/2}}$

Solution:

$$NA = (n_1^2 - n_2^2)^{1/2} = [(n_1+n_2)(n_1-n_2)]^{1/2}$$

$$= [(n_1+n_2)n_1\Delta]^{1/2} \qquad [\text{Because } (n_1-n_2/n_1)=\Delta]$$

$$= (2n_1^2\Delta)^{1/2} \text{ if } n_1=n_2 \qquad \text{Therefore } NA = n_1 (2\Delta)^{1/2}$$

Types of Optical Fibers

- The optical fibers can be classified into different types based on

1. Materials of which the fibers are made
2. The mode of propagation &
3. The refractive index (index profile).

- **Fiber materials**

a) High content silica glass
b) Multicomponent silica glass &
c) Plastic.

Basic requirements to be satisfied by a materials to obtain highest quality of optical fibers .

1. It must be possible to make long, thin flexible fibers from the material.
2. Physically compatible materials having slightly different refractive indices for the core & cladding must be available.
3. The material must be transparent at the particular optical wavelength to guide the light efficiently.

Types of optical fibers based on material:

- There are three types of optical fibers based on material type of make. In all the three types, the core as well as the cladding can be made either glass or plastic.

1. Plastic core with plastic cladding.

Eg. A polystyrene core & methyl methacrylate cladding.

2. Glass core with plastic cladding (Also called PCS fiber, plastic-clad-silica).

These fibers are less affected by radiation and hence more suitable for military application.

3. Glass core with glass cladding (Also called SCS fiber, silica-clad-silica).

Eg. Sio_2 core,P_2o_5- sio_2 cladding.

Propagation (Transmission) of light through an Optical fiber:

- Light can be propagated down an optical fiber by either reflection or refraction.
- Mode of Propagation:

In fiber optics terminology, the word mode simply means path. That is, it defines the number of paths being taken by the light to propagate down the cable. There are two modes of propagation

1. **SingleMode fiber(SM Fiber) (monomode or fundamental fiber).**
2. **Multimode fiber.(MM fiber)**

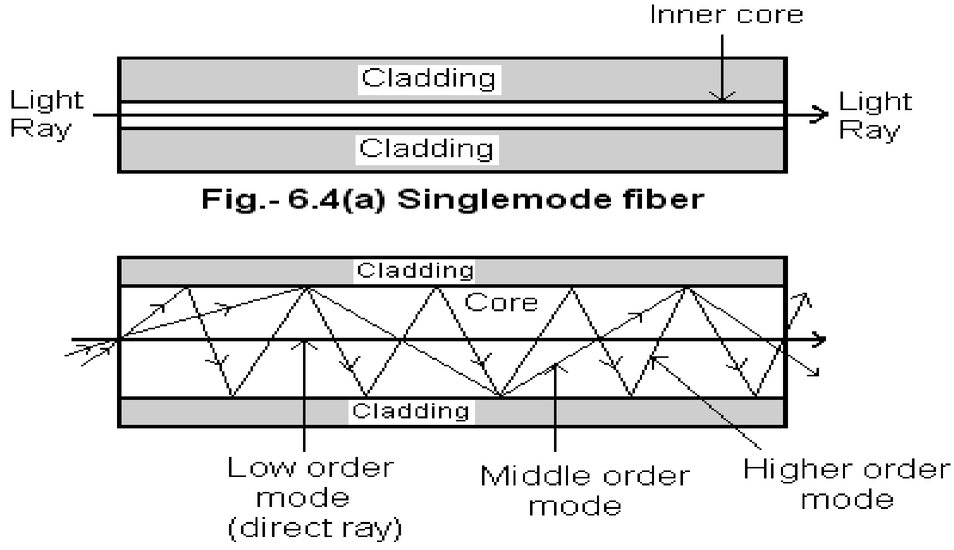


Fig.- 6.4(a) Singlemode fiber

Fig.- 6.4(b) Multimode fiber

Fig.- 6.4 Modes of Propagation

Index Profile

- In any optical fiber, the whole material of the cladding has a uniform refractive index value. But, the refractive Index of the core material may either remain constant or subjected to variation in a particular way.
- The curve which represent the variation of refractive index (along the vertical axis) with respect to the radial distance (along the horizontal axis) from the axis of the fiber is called the refractive index profile.
- There are two basic types of index profiles.

1. Step-index fiber
2. Graded-index fiber

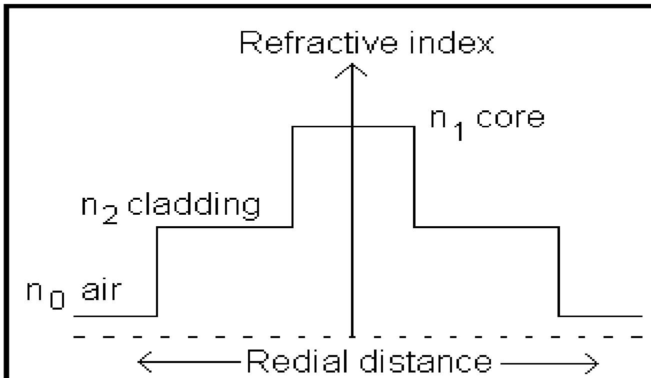


Fig.- 6.5(a) Step index fiber

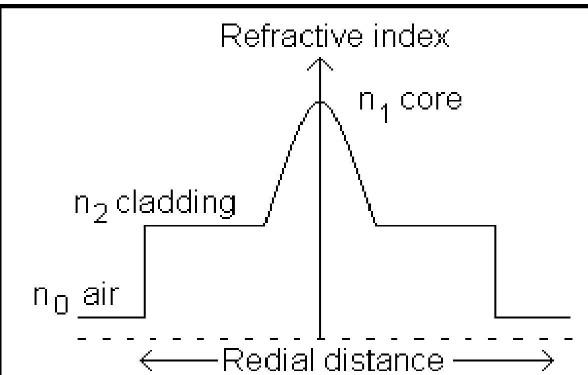


Fig.- 6.5(b) Graded index fiber

Fiber configurations:

■ There are 3 types of optical fiber configurations (combining the mode & index profile).

1. Single mode step-index fiber. (SMSI fiber)
2. Multimode step-index fiber. (MMSI fiber)
3. Multimode graded index fiber.

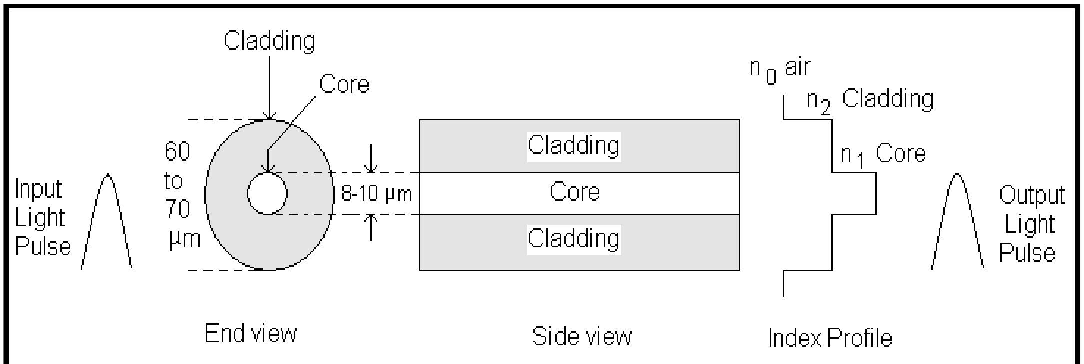


Fig.- 6.6 Singlemode step index fiber

(Including Typical Dimensions, Index profile & Pulse Dispersion Effects)

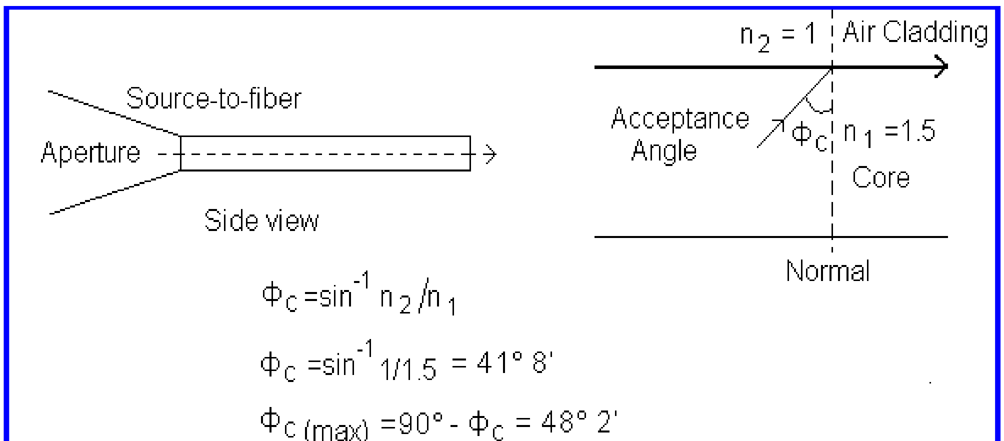
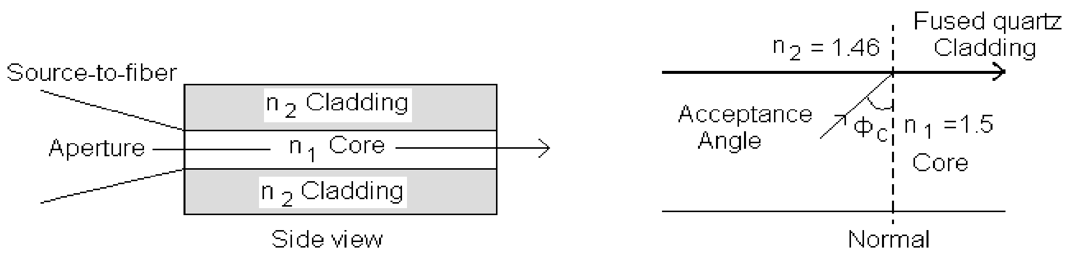


Fig.- 6.6(a) Singlemode Step index fiber with air cladding



$\Phi_C = \sin^{-1} 1.46/1.5 = 76°\ 7'$

$\Phi_{C\ (max)} = 13°\ 13'$

Fig.- 6.6(b) Singlemode Step index fiber with glass cladding

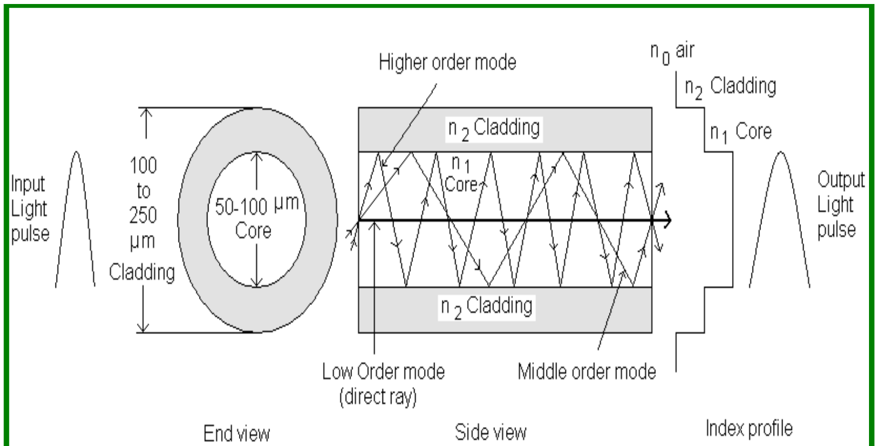
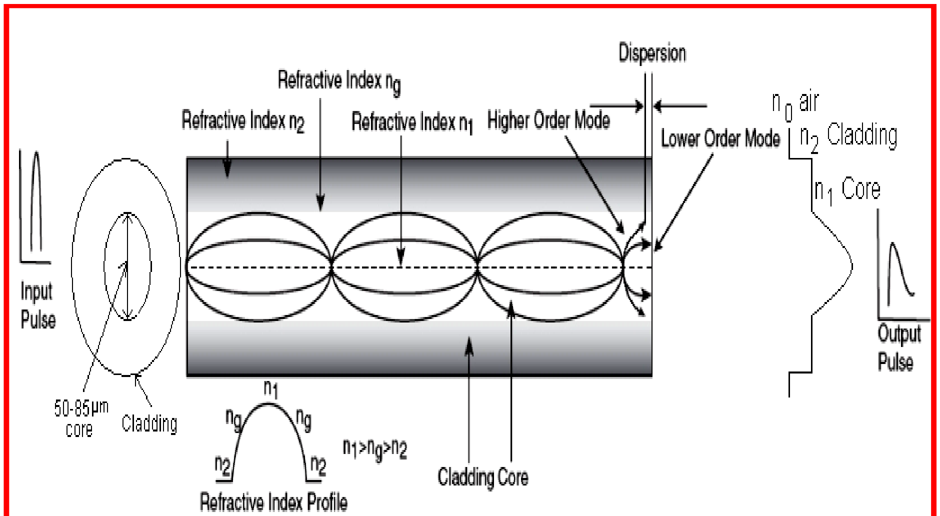


Fig.- 6.8 Multimode step index fiber



Multimode graded index fiber

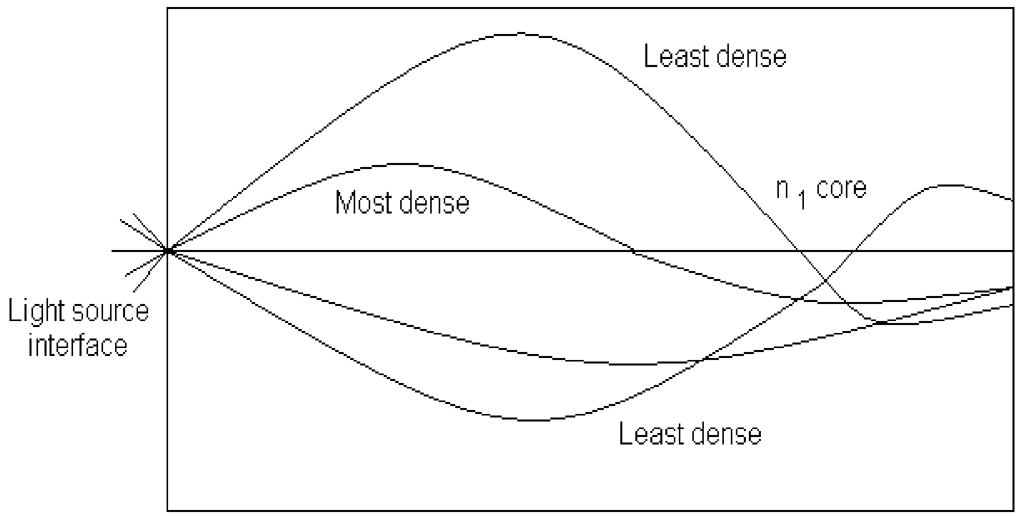


Fig.- 6.10

<u>Difference Between Singlemode and Multimode fiber</u>

❖ **<u>Singlemode fiber</u>**

- Light can propagate in only one mode.
- The fiber core diameter is very small and also the difference of refractive indices of the core and cladding is very small.
- Since the light propagates in a single mode, no dispersion occurs.
- Launching of light into the fiber & Coupling process is not easy.
- Used in long haul communication.
- Since, the fabrication is difficult, the production cost is high.

❖ **<u>Multimode fiber</u>**

- Light can propagate through the fiber with a large No. of modes.
- The fiber core diameter is large & also, the difference in refractive indices of the core cladding is also large.
- Due to multimode propagation & materials scattering, there is signal degradation.
- Launching of light into fiber & coupling process are easy.
- Used in LAN (local area network)
- Since the fabrication is easy, the production cost is low.

<u>Difference between step index fiber & graded index fiber:</u>

❖ **<u>Step index fiber</u>**

- Refractive index of the core cladding is uniform
- Since there is abrupt change in the refractive index at the core & cladding interface, the refractive index profile takes the shape of the step. Hence called step index fiber.
- Pulse dispersion is more in single mode step index fiber.

- Attenuation is less for single mode step index fiber & more for multimode step index fiber.
- SMSI fibers are expensive & difficult to manufacture. But MMSI are inexpensive & simple to make it.
- The bandwidth for SMSI fiber is more than MMSI fiber.
- NA is very less for SMSI but more for MMSI.

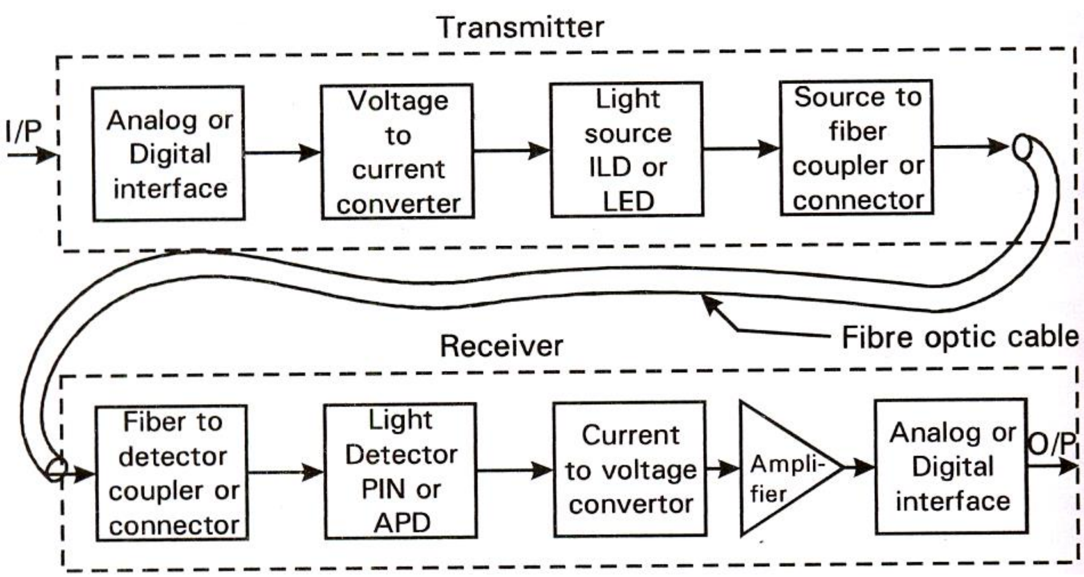
❖ **Graded index fiber**

- Refractive index of the core is not uniform. But, the refractive index of the cladding is uniform.
- In this fiber, the refractive index of the core is Max. at the Centre & decreases gradually with distance towards the outer edge. Hence called Graded index fiber.
- Pulse dispersion is reduced by a factor of 200 in comparison to step index.
- Attenuation is less.
- Graded index fibers are easy to manufacture.
- Multimode graded index fiber has a higher bandwidth.
- NA is high.

Fiber Optics Communication link

- The important components of fiber optic communication link are

1. Transmitter
2. Fiber optic cable
3. Receiver



Examples

1. **An optical fiber core and its cladding have refractive indexes of 1.545 and 1.495 respectively. Calculate the critical angle ϕ_c, acceptance angle $\phi_{in(max)}$ and Numerical aperture.**
   Given, n1 = 1.545, n2 = 1.495, ϕ_c =?, $\phi_{in(max)}$ = ?, NA = ?

   - Critical angle $\varphi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

$$\varphi_c = \sin^{-1}\left(\frac{1.495}{1.545}\right)$$
$$\varphi_c = \sin^{-1}(0.9676)$$
$$\boldsymbol{\varphi_c = 75°\,23'.}$$

- Acceptance angle $\varphi_{in(max)} = \sin^{-1}\sqrt{n_1^2 - n_2^2}$

$$\varphi_{in(max)} = \sqrt{1.545^2 - 1.495^2}$$
$$= \sin^{-1}\sqrt{0.152}$$
$$\boldsymbol{\varphi_{in(max)} = 22°56'.}$$

- Numerical aperture $NA = \sin\varphi_{in(max)} = \sin 22°56'$

∴ ***NA = 0.3896***

2. A silica optical fiber has a core of refractive index 1.55 and a cladding of refractive index of 1.47. Determine (a) the critical angle at the core cladding interface (b) the numerical aperture for the fiber and (c) the acceptance angle in air for the fiber.

Given, n1 = 1.55; n2 = 1.47; ϕ_c =?; $\phi_{in(max)}$ = ?; NA = ?

(a). the critical angle is $\varphi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.47}{1.55}\right)$

$$\varphi_c = \sin^{-1}(0.94838)$$

∴ $$\boldsymbol{\varphi_c = 71°30'.}$$

(b). The numerical aperture for the fiber is

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.55^2 - 1.47^2} = \sqrt{0.2416}$$

NA = 0.4915

(c). The acceptance angle in air for the fiber is

$$\varphi_{in(max)} = \sin^{-1}(NA) = \sin^{-1}(0.4915)$$
$$\boldsymbol{\varphi_{in(max)} = 29°26'.}$$

3. An optical fiber has a numerical aperture of 0.20 and a cladding refractive index of 1.55. Determine the acceptance for the fiber in water which has a refractive index 1.33.

Given, n_2 = 1.55; NA = 0.20; n_0= 1.33; n_1 = ?; NA in water = ?; $\phi_{in(max)}$ = ?
When fiber is in air n_0 = 1

∴ $$NA = \sqrt{n_1^2 - n_2^2}$$

Or $$NA^2 = n_1^2 - n_2^2$$

∴ $$n_1^2 = n_2^2 + NA^2$$

Or $$n_1 = \sqrt{n_2^2 + NA^2}$$
$$= \sqrt{1.55^2 + 0.20^2}$$
$$\boldsymbol{n_1 = 1.5628}.$$

When fiber is in water $n_0 = 1.33$

Therefore, numerical aperture when fiber is in water is

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} = \frac{\sqrt{0.03984}}{1.33} = \frac{0.19960}{1.33}$$

∴ $$\boldsymbol{NA = 0.1500}.$$

Hence acceptance angle is

$$\varphi_{in(max)} = \sin^{-1}(NA)$$
$$= \sin^{-1}(0.1500)$$
$$\boldsymbol{\varphi_{in(max)} = 8°37'}.$$

4. Calculate the refractive indices of the core and cladding material of a fiber. (Given, NA = 0.22 and relative refractive index difference Δ = 0.012)

$$NA = n_1\sqrt{2\Delta}$$
$$n_1 = \frac{NA}{\sqrt{2\Delta}}$$
$$= \frac{0.22}{0.1549} = 1.420$$

The refractive index of the core is **1.420**

To find n_2:

Formula - 1	Formula – 2
$NA = \sqrt{n_1^2 - n_2^2}$ $NA^2 = n_1^2 - n_2^2$ ∴ $n_2^2 = n_1^2 - NA^2$ Or $n_2 = \sqrt{n_1^2 - NA^2}$ $= \sqrt{1.968}$ $\boldsymbol{n_2 = 1.402}.$	$\frac{n_1 - n_2}{n_1} = \Delta$ $\therefore n_2 = n_1(1 - \Delta)$ $= 1.42\ (1 - 0.012)$ $= 1.42 \times 0.988$ $\therefore\ \boldsymbol{n_2 = 1.402}$

The refractive index of the cladding is **1.402**

❖ ***Answer in Short***

1. **Define fiber optic system.**
   A communication system that uses light as the carrier of information from a source to a destination through a guided fiber cable is called fiber optic system.
2. **What is the relationship between information capacity and bandwidth?**
   The information carrying capacity of a communication system is directly proportional to its bandwidth, i.e., wider the bandwidth, the greater is its information carrying capacity.

3. **Highlight the advantages of fiber optic communication over metallic cable communication.**

   The fiber optic communication system

   1) Has extremely wide bandwidth.
   2) Are immune to electrostatic interference.
   3) Are light in weight and also small in size.
   4) Are more secured, greater safety and there is no cross talk interference.

4. **What is a Kevlar?**

   Kevlar is a yarn type material having high tensile strength. This Kevlar is used in fiber construction to provide additional strength to the cable.

5. **What is the purpose of cladding in optical fiber?**

   Cladding helps in retaining the light within the core because of its lower refractive index than core. In addition, provides mechanical strength, reduces scattering loss and also protects the core from absorbing surface contaminants with which it could come into contact.

6. **Give the conditions to be satisfied for total internal reflection.**

   1) The refractive index n_1 of the core must always be greater than the refractive index n_2 of the cladding, i.e., $n_1 > n_2$.
   2) The light must approach the wall of the fiber with an angle of incidence ϕ that is greater than the critical angle ϕ_c, i.e., $\phi > \phi_c$.

7. **Define acceptance angle.**

   It is defined as the maximum value of the angle at the entrance (air/fiber interface) end of the fiber, at which the angle of incidence at the core-cladding interface is equal to critical angle of the core medium.

8. **Can a light propagate through a fiber cable with the angle of incidence at the entrance end greater than acceptance angle?**

   No, only when the light enters at an angle less than the acceptance angle it can propagate through the cable by undergoing total internal reflection.

9. **Define index profile.**

   The curve which represents the variation of refractive index along the vertical axis with respect to the radial distance along the horizontal axis from the axis of the fiber is called refractive index profile.

10. **What are the basic requirements that must be satisfied in selecting a fiber material?**

    a) It must be possible to make a long thin flexible wire.
    b) The material must be physically compatible having slightly different refractive indices for the core and cladding.
    c) It must be transparent at a particular optical wavelength in order to guide the light more efficiently.

11. **What are the important components in a fiber optic communication system?**

The important components of a fiber optic communication system are

a) Transmitter
b) Fiber optic cable and
c) Receiver.

…Best of Luck…