## OBJECTIVES

1) To understand the principle behind fiber optic communication
2) To gain knowledge about the structure of optical fibers and the ways of propagation of optical pulses through the fibers
3) To study the classification of optical fibers based on materials refractive index and the number of modes propagated through it.
4) To study the different process methods of optical fiber.
5) To study the applications of optical fibers in all fields of science and technology.

## REAL – LIFE APPLICATION

1) Optical communications
2) Networking
3) Submarine cables
4) Endoscopy

# UNIT V PHOTONICS AND FIBER OPTICS

**Introduction.**

LASER stands for Light amplification by stimulated emission of radiation.

Laser is a device which emits a powerful, monochromatic collimated beam of light. The emitted light waves are coherent in nature.

**Characteristics of Laser:**

1. **Directionality**

Ordinary light spreads in all directions and its angular spread is 1m/m. But it is found that laser is highly directional and is angular spread is 1mm/m. For example, the laser beam can be focused to very long distance with a few divergence or angular spread.

Divergence or angular spread is given by $\phi = \frac{r_2 - r_1}{d_2 - d_1}$

Where $d_1$ , $d_2$ are any two distances for the laser source emitted and $r_1$, $r_2$ are the radii of the beam spots at a distance $d_1$, and $d_2$ respectively as shown

2. **Intensity**:

Since an ordinary light spreads in all directions, the intensity reaching the target is very less. But in the case of laser, due to high directionality, the intensity of laser beam reaching the target is of high intense beam. For example, 1 mill watt power of He-Ne laser appears to be brighter than the sunlight.

3. **Monochromatic**:

Laser beam is highly monochromatic; the wavelength is single, whereas in ordinary light like mercury vapour lamp, many wavelengths of light are emitted.

4 **Coherence:**

It is an important characteristic of laser beam. In lasers the wave trains of same frequency are in phase, the radiation given out is in mutual agreement not only in phase but also in the direction of emission and polarization. Thus it is a coherent beam. Due to high coherence it results in an extremely high power.

2.1.3 Differences between ordinary light and Laser beam.

| S.No | Ordinary light | Laser beams |
|---|---|---|
| 1 | In ordinary light the angular spread is more. | In laser beam the angular spread is less. |
| 2 | They are not directional. | They are highly directional. |
| 3 | It is less intense | It is highly intense |
| 4 | It is not a coherent beam and is not in phase. | It is a coherent beam and is in phase |
| 5 | The radiation are polychromatic | The radiations are monochromatic |
| 6 | Example: Sun light, Mercury vapor lamp | He- Ne Laser, $Co_2$ laser |

**4 Principle of Spontaneous and Stimulated emission – Einstein's Quantum theory of radiation**

We know that, when light is absorbed by the atoms or molecules, then it goes from the lower energy level ($E_1$) to the higher energy level ($E_2$) and during the transition from higher energy level ($E_2$) to lower energy level ($E_1$) the light is emitted from the atoms or molecules.

Let us consider an atom exposed to light photons of energy $E_2 - E_1 = h\nu$, three distinct processes take place.

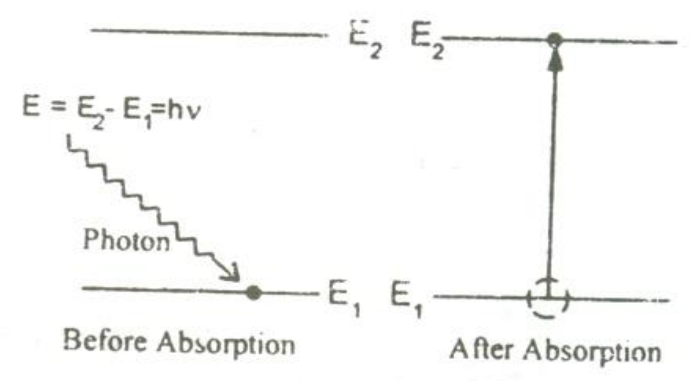
a. Absorption

b. Spontaneous emission

c. Stimulated Emission

**Absorption:**

An atom in the lower energy level or ground state energy level $E_1$ absorbs the incident photon radiation of energy $h\nu$ and goes to the higher energy level or excited level $E_2$ as shown in figure.




This process is called absorption

If there are many numbers of atoms in the ground state then each atom will absorb the energy from the incident photon and goes to the excited state. then,

The rate of absorption ($R_{12}$) is proportional to the following factors.

$R_{12}$ = Energy density of incident radiation $(\rho_v)$

= no of atoms in the ground state ($N_1$)

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

$$R_{12} = B_{12}\rho_v N_1 \longrightarrow \quad (1)$$

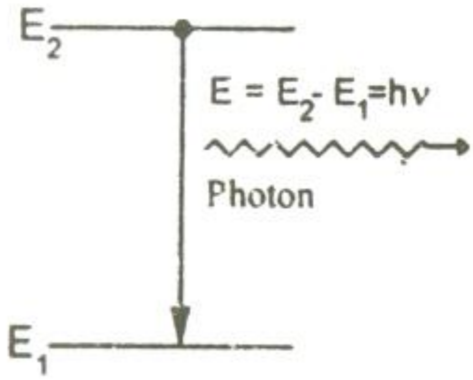
Where $B_{12}$ is a constant which gives the probability of absorption of absorption transition per unit time.

Normally, the atoms in the excited state will not stay there for a long period of time , rather it comes to ground state by emitting a photon of energy $E = h\nu$ . Such an emission takes place by one of the following two methods.

**Spontaneous emission:**

The atom in the excited state returns to the ground state by emitting a photon of energy $E = (E_2 - E_1) = h\nu$

Spontaneously without any external triggering as shown in the figure.




This process is known as spontaneous emission. Such an emission is random and is independent of incident radiation. If $N_1$ and $N_2$ are the numbers of atoms in the ground state ($E_1$) and excited state ($E_2$) respectively, then

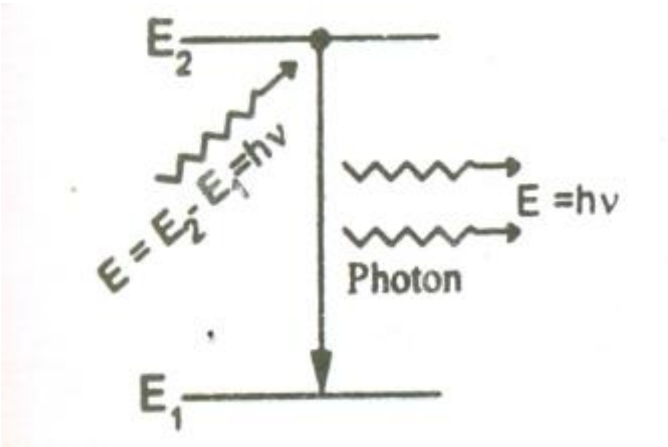
The rate of spontaneous emission is $R_{21}(SP) \propto N_1$

Or $$R_{21}(SP) = A_{21} N_2 \longrightarrow (2)$$

Where $A_{21}$ is a constant which gives the probability of spontaneous emission transitions per unit time.

**Stimulated Emission:**

The atom in the excited state can also return to the ground state by external triggering or inducement of photon thereby emitting a photon of energy equal to the energy of the incident photon, known as stimulated emission. Thus results in two photons of same energy, phase difference and of same directionality as shown.




Therefore, the rate of stimulated emission is given by

$$R_{21}(St) \propto \rho_v N_2$$

$$R_{21}(St) = B_{21}\rho_v N_2 \longrightarrow \quad (3)$$

Where $B_{21}$ is a constant which gives the probability of stimulated emission transitions per unit time.

**Einstein's theory**

Einstein's theory of absorption and emission of light by an atom is based on Planck's theory of radiation. Also under thermal equilibrium, the population of energy levels obeys the Boltzmann distribution law

Under thermal equilibrium

The rate of absorption = the rate of emission

$$\therefore B_{12}\rho_v N_1 = A_{21}N_2 + B_{21}\rho_v N_2$$

$$\rho_v \left[B_{12}N_1 - B_{21}N_2\right] = A_{21}N_2$$

$$\therefore \rho_v = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

Or $$\therefore \rho_v = \frac{A_{21}}{B_{12}\frac{N_1}{N_2} - B_{21}} \longrightarrow \quad (4)$$

We know from the Boltzmann distribution law

$$N_1 = N_0 e^{-E_1/K_B T}$$

Similarly $$N_2 = N_0 e^{-E_2/K_B T}$$

Where $K_B$ is the Boltzmann Constant,

T is the absolute temperature and

$N_0$ is the number of atoms at absolute zero.

At equilibrium, we can write the ratio of population levels as follows.

$$\frac{N_1}{N_2} = e^{\frac{(E_2 - E_1)}{K_B T}}$$

Since $(E_2 - E_1) = h\nu$, we have

$$\frac{N_1}{N_2} = e^{h\nu / K_B T} \longrightarrow \quad (5)$$

Substituting equation 5 in 4

$$\therefore \rho_v = \frac{A_{21}}{B_{12} e^{h\nu / K_B T} - B_{21}}$$

$$\rho_v = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left[\left( B_{12} / B_{21} \right) e^{h\nu / K_B T} - 1\right]} \longrightarrow \quad (6)$$

This equation has a very good agreement with Planck's energy distribution radiation law.

That is $$\rho_v = \frac{8\pi h \nu^3}{c^3} \cdot \frac{1}{e^{h\nu / K_B T} - 1} \longrightarrow \quad (7)$$

Therefore comparing equations (6) and (7) , we can write

$B_{12} = B_{21} = B$ and $$\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3} \longrightarrow \quad (8)$$

Taking $A_{21} = A$

The constants A and B are called as Einstein Coefficients, which accounts for spontaneous and stimulated emission probabilities.

## Ratio of magnitudes of Stimulated to Spontaneous emission rates

From equations (2) and (3) we have

$$\frac{R_{21}(St)}{R_{21}(Sp)} = \frac{B_{21} \rho_v N_2}{A_{21} N_2}$$

$$\frac{R_{21}(St)}{R_{21}(Sp)} = \frac{B_{21}}{A_{21}}\rho_v \longrightarrow \quad (9)$$

Rearranging equation (6) we have

$$\frac{B_{21}}{A_{21}}\rho_v = \frac{1}{\left[\left(\frac{B_{12}}{B_{21}}\right)e^{h\nu/K_BT} - 1\right]}$$

Since $B_{12} = B_{21}$ , we have

$$\frac{1}{\left[e^{h\nu/K_BT} - 1\right]} = \frac{B_{21}}{A_{21}}\rho_v \longrightarrow \quad (10)$$

Comparing (9) and (10) we get

$$\frac{R_{21}(St)}{R_{21}(Sp)} = \frac{1}{\left[e^{h\nu/K_BT} - 1\right]} = \frac{B_{21}}{A_{21}}\rho_v$$

In a simpler way the ratio can be written as

$$R = \frac{B_{21}}{A_{21}}\rho_v$$

Generally Spontaneous emission is more predominant in the optical region (Ordinary light). To increase the number of coherent photons stimulated emission should dominate over spontaneous emission. To achieve this, an artificial condition called ***Population Inversion is necessary.***

**Differences between Stimulated and spontaneous emission of radiation**

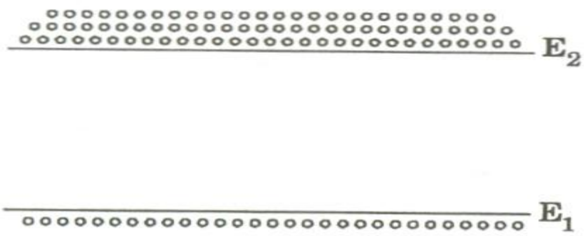
| S.no | Stimulated Emission | Spontaneous emission |
|---|---|---|
| 1. | An atom in the excited state is induced to return to the ground state , thereby resulting in two photons of same frequency and energy is called Stimulated emission | The atom in the excited state returns to the ground state thereby emitting a photon, without any external inducement is called Spontaneous emission. |
| 2. | The emitted photons move in the same direction and is highly directional | The emitted photons move in all directions and are random |
| 3. | The radiation is highly intense , monochromatic and coherent | The radiation is less intense and is incoherent. |
| 4. | The photons are in phase, there is a constant phase difference. | The photons are not in phase (i.e.) there is no phase relationship between them. |
| 5. | The rate of transition is given by $R_{21}(St) = B_{21}\rho_v N_2$ | The rate of transition is given by $R_{21}(SP) = A_{21}N_2$ |

**Population Inversion**:

Population Inversion creates a situation in which the number of atoms in higher energy state is more than that in the lower energy state.

Usually at thermal equilibrium, the number of atoms $N_2$ i.e., the population of atoms at higher energy state is much lesser than the population of the atoms at lower energy state $N_1$ that is $N_1 > N_2$ .


The Phenomenon of making $N_2 > N_1$ is known as Population Inversion.




**Conditions of Population inversion.**

1. There must be at least two energy levels $E_2 > E_1$.
2. There must be a source to supply the energy to the medium.
3. The atoms must be continuously raised to the excited state.

**Meta stable States**

An atom can be excited to a higher level by supplying energy to it. Normally, excited atoms have short life times and release their energy in a matter of nano seconds ($10^{-9}$) through spontaneous emission. It means atoms do not stay long to be stimulated. As a result, they undergo spontaneous emission and rapidly return to the ground level; thereby population inversion could not be established. In order to do so, the excited atoms are required to ***'wait'*** at the upper energy level till a large number of atoms accumulate at that level. In other words, it is necessary that excited state have a longer lifetime. A ***Meta stable state*** is such a state. Metastable can be readily obtained in a crystal system containing impurity atoms. These levels lie in the forbidden gap of the host crystal. There could be no population inversion and hence no laser action, if metastable states don't exist.

## Principle of Laser action

**Principle:** Due to stimulated emission the photons multiply in each step-giving rise to an intense beam of photons that are coherent and moving in the same direction. Hence the light is amplified by Stimulated Emission of the Radiation. Termed LASER.

**ACTIVE MEDIUM:**

A medium in which population inversion can be achieved is known as active medium.

**Active Center**: The material in which the atoms are raised to the excited state to achieve Population Inversion is called Active Center.

**PUMPING ACTION**:

The process to achieve the population inversion in the medium is called **Pumping action.**

It is essential requirement for producing a laser beam.

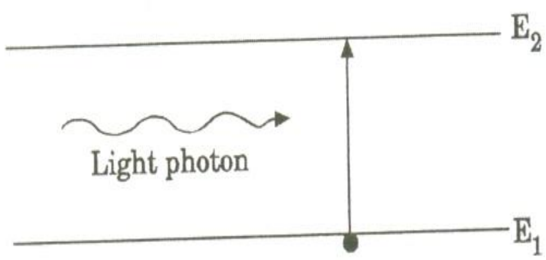
**Methods of pumping action:**

The methods commonly used for pumping action are:

1. Optical pumping (Excitation by Photons)
2. Electrical discharge method(Excitation by electrons)
3. Direct conversion
4. In elastic atom – atom collision between atoms

**a. Optical pumping**:

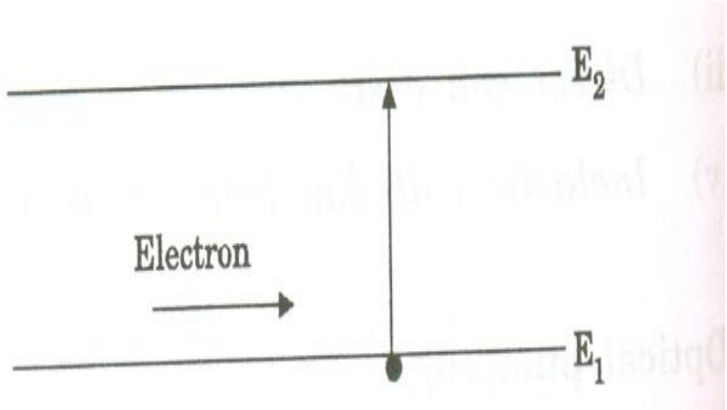
When the atoms are exposed to light radiations energy $h\nu$, atoms in the lower energy state absorb these radiations and they go to the excited state. This method is called Optical pumping. It is used in solid state lasers like ruby laser and Nd-YAG laser. In ruby laser, xenon flash lamp is used as pumping source.



**b. Electrical discharge method (Excitation by electrons)**

In this method, the electrons are produced in an electrical discharge tube. These electrons are accelerated to high velocities by a strong electrical field. These accelerated electrons collide with the gas atoms.

By the process, energy from the electrons is transferred to gas atoms. Some atoms gain energy and they go to the excited state. This results in population inversion. This method is called Electrical discharge method.




It is represented by the equation

$$A + e^* = A^* + e$$

Where A – gas atom in the ground state

$A^*$ = same gas atom in the excited state

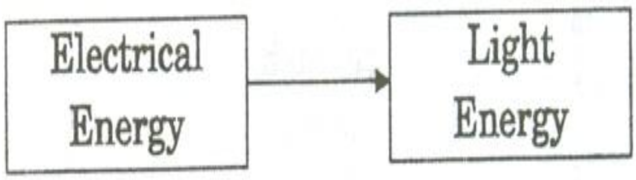
$e^*$ = Electrons with higher Kinetic energy

e – Same electron with lesser energy.

This method of pumping is used in gas lasers like argon and $CO_2$ Laser.

**C. Direct Conversion**

In this method, due to electrical energy applied in direct band gap semiconductor like Ga As, recombination of electrons and holes takes place. During the recombination process, the electrical energy is directly is converted into light energy.




**d. In elastic atom – atom collision**

In this method, a combination of two gases (Say A and B are used). The excited states of A and B nearly coincides in energy.

In the first step during the electrical discharge atoms of gas A are excited to their higher energy state $A^*$ (metastable state) due to collision with the electrons .

$$A + e^* = A^* + e$$

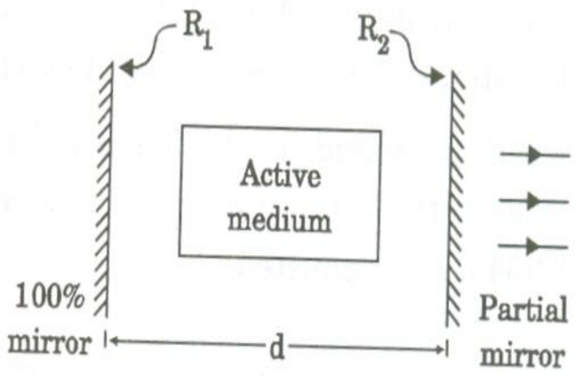
Now $A^*$ atoms at higher energy state collide with b atoms in the lower state. Due to inelastic atom - atom collision B atoms gain energy and they are excited to a higher state $B^*$ . Hence, A atoms lose energy and return to lower state.

$$A^* + B = A + B^*$$

**Optical resonator**

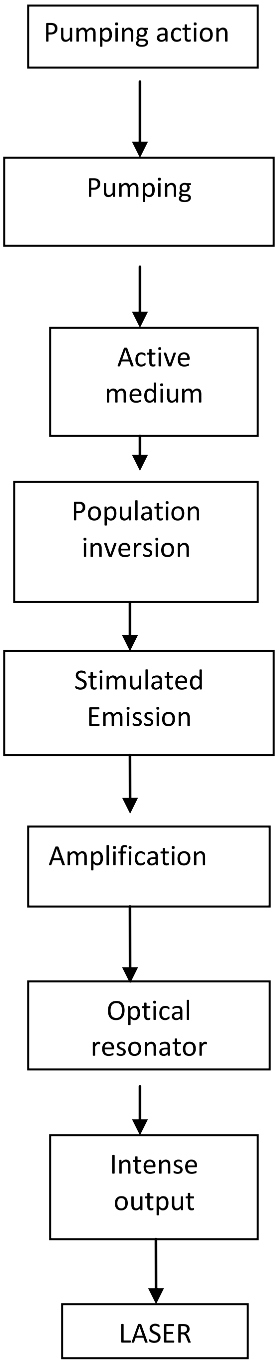
An optical resonator consists of a pair of reflecting surfaces in which one is fully reflecting ($R_1$) and the other is partially reflecting ($R_2$). The active material is placed in between these two reflecting surfaces.

The photons generated due to transitions between the energy states of active material are bounced back and forth between two reflecting surfaces.




This will induce more and more stimulated transition leading to laser action.

**Flow Chart of Laser action**




## 2.1.10 Types of Laser

Based on the type of active medium, Laser systems are broadly classified into the following categories.

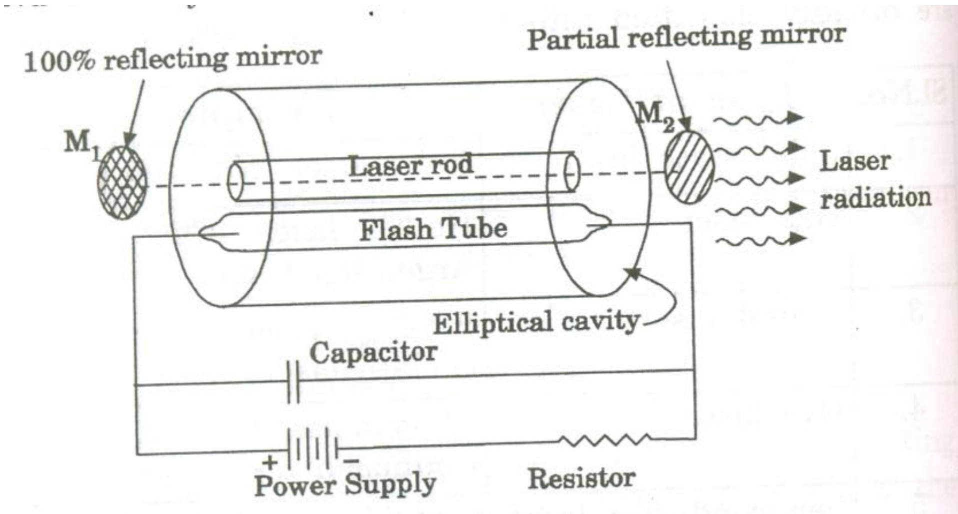
| S.NO | TYPE OF LASER | EXAMPLES |
|---|---|---|
| 1. | Solid State laser | Ruby Laser Nd:YAG laser |
| 2. | Gas laser | He-Ne Laser, $CO_2$ Laser, Argon – ion laser |
| 3. | Liquid Laser | $SeOCL_2$ Laser, Europium Chelate Laser |
| 4. | Dye laser | Rhodamine 6G laser, Coumarin dye laser |
| 5. | Semiconductor Laser | GaAs laser, GaAsP laser |

## 2.1.11 Nd: YAG laser

Nd: YAG laser is a neodymium based laser. Nd stands for Neodymium (rare earth element) and YAG stands for Yttrium Aluminum Garnet ( $Y_3Al_5\ O_{12}$) . It is a four level solid state laser.

**Principle:**

The active medium Nd: YAG rod is optically pumped by Krypton flash tubes. The Neodymium ions ($Nd^{3+}$) are raised to excited levels. During the transition from meta stable state to ground state, a laser beam of wavelength 1.064µm is emitted.




**Construction:**

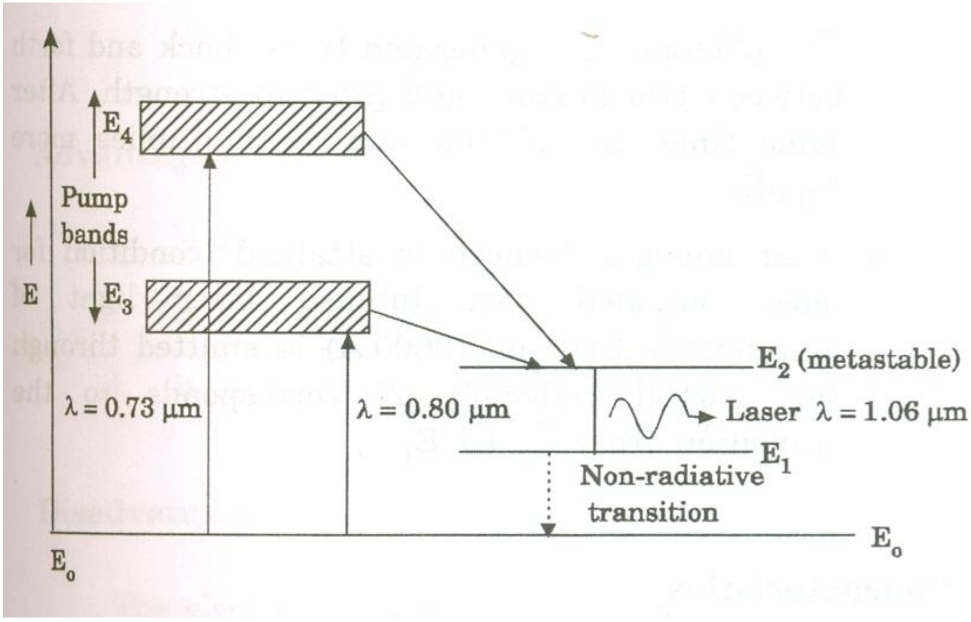
The construction of Nd: YAG laser is as shown in the figure 2.17. A small amount of Yttrium ions ($Y3^+$) is replaced by Neodymium ($Nd^{3+}$) in the active element of Nd: YAG crystal.

This active element is cut into a cylindrical rod. The ends of the cylindrical rod are highly polished and they are made optically flat and parallel. This cylindrical rod (laser rod) and a pumping source (flash tube) are placed inside a highly (reflecting) elliptical reflector cavity.

The optical resonator is formed by using two external reflecting mirrors. One mirror ($M_1$) is 100% reflecting while the other mirror ($M_2$) is partially reflecting.

**Working:**

Figure 2.18 shows the energy level diagram for Nd: YAG laser. These energy levels are those of Neodymium ($Nd^{3+}$) ions.




1. When the krypton flash lamp is switched on, by the absorption of light radiation of wavelength 0.73µm and 0.8µm, the Neodymium($Nd^{3+}$) atoms are raised from ground level $E_0$ to upper levels $E_3$ and $E_4$ (Pump bands).
2. The Neodymium ions atoms make a transition from these energy levels $E_2$ by non-radiative transition. $E_2$ is a metastable state.
3. The Neodymium ions are collected in the level $E_2$ and the population inversion is achieved between $E_2$ and $E_1$.
4. An ion makes a spontaneous transition from $E_2$ to $E_1$, emitting a photon of energy hγ. This emitted photon will trigger a chain of stimulated photons between $E_2$ and $E_1$.

5. The photons thus generated travel back and forth between two mirrors and grow in strength. After some time, the photon number multiplies more rapidly.
6. After enough strength is attained (condition for laser being satisfied), an intense laser light of wavelength 1.06μm is emitted through the partial reflector. It corresponds to the transition from $E_2$ to $E_1$.

**Characteristics:**

1. **Type:** It is a four level solid state laser.
2. **Active medium**: The active medium is Nd: YAG laser.
3. **Pumping method**: Optical pumping is employed for pumping action.
4. **Pumping source**: Xenon or Krypton flash tube is used as pumping source.
5. **Optical resonator**: Two ends of Nd: YAG rod is polished with silver (one end is fully silvered and the other is partially silvered) are used as optical resonator.
6. **Power output**: The power output is approximately 70 watt.
7. **Nature of output**: The nature of output is pulsed or continuous beam of light.
8. **Wavelength of the output**: The wavelength of the output beam is 1.06μm(infra-red)

**Advantages:**

1. It has high energy output.
2. It has very high repetition rate operation
3. It is much easy to achieve population inversion.

**Disadvantages:**

The electron energy level structure of $Nd^{3+}$ in YAG is complicated.

**Applications:**

1. It finds many applications in range finders and illuminators.
2. It is widely used in engineering applications such as resistor, trimming scribing, micro machining operations as well as welding, drilling etc.

3. It finds many medical applications such as endoscopy, urology, neurosurgery, ENT, gynecology, dermatology, dental surgery and general surgery.

## Molecular Gas laser

In a molecular gas laser, laser action is achieved by transitions between vibrational and rotational levels of molecules. Its construction is simple and the output of this laser is continuous.

In $CO_2$ molecular gas laser, transition takes place between the vibrational states of Carbon dioxide molecules.

## 2.1.13 CO2 Molecular gas laser

It was the first molecular gas laser developed by Indian born American scientist Prof.C.K.N.Pillai.

It is a four level laser and it operates at 10.6 μm in the far IR region. It is a very efficient laser.

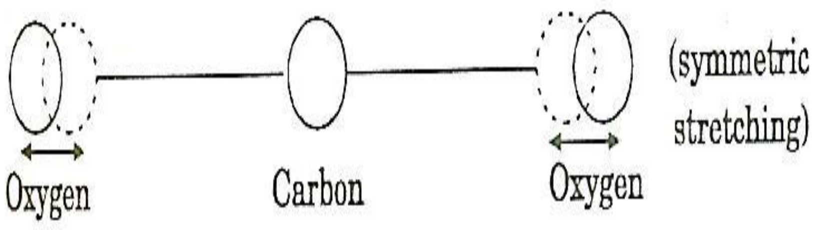
### Energy states of $CO_2$ molecules.

A carbon dioxide molecule has a carbon atom at the center with two oxygen atoms attached, one at both sides. Such a molecule exhibits three independent modes of vibrations. They are

a) Symmetric stretching mode.
b) Bending mode
c) Asymmetric stretching mode.

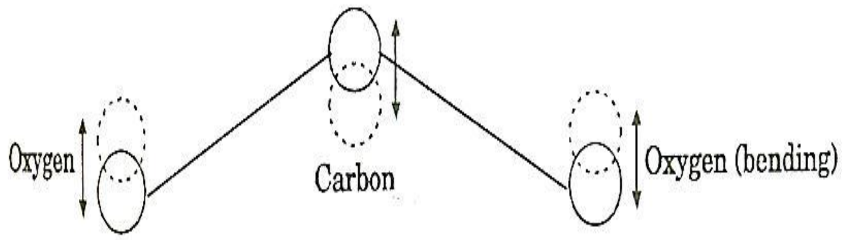
**a. Symmetric stretching mode**

In this mode of vibration, carbon atoms are at rest and both oxygen atoms vibrate simultaneously along the axis of the molecule departing or approaching the fixed carbon atoms.

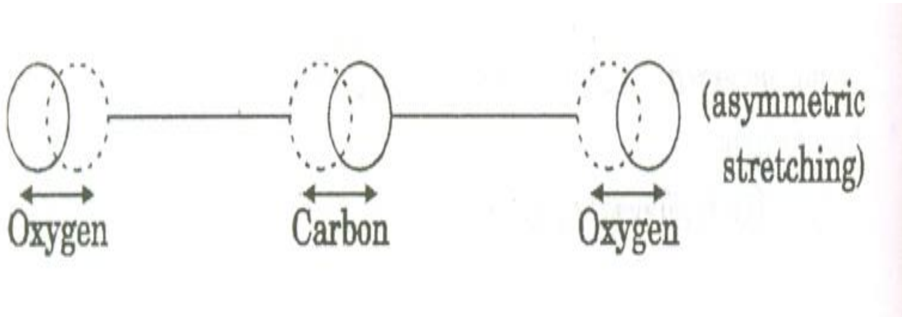



**b. Bending mode:**

In this mode of vibration, oxygen atoms and carbon atoms vibrate perpendicular to molecular axis.



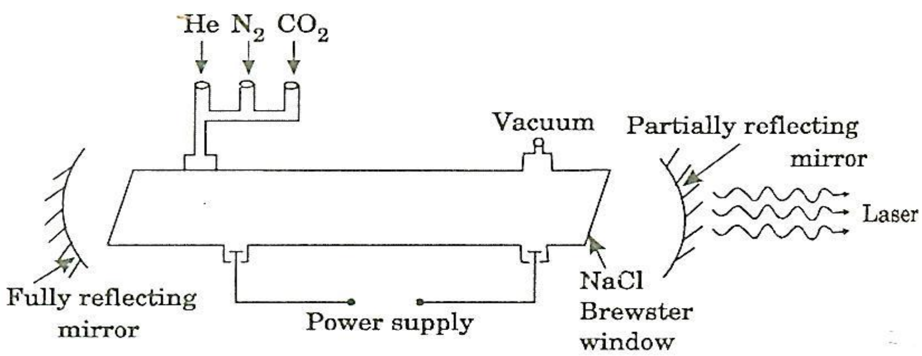

c. **Asymmetric stretching mode**:




In this mode of vibration, oxygen atoms and carbon atoms vibrate asymmetrically, i.e., oxygen atoms move in one direction while carbon atoms in the other direction.

**Principle:**

The active medium is a gas mixture of $CO_2$, N2 and He. The laser transition takes place between the vibrational states of $CO_2$ molecules.




**Construction**:

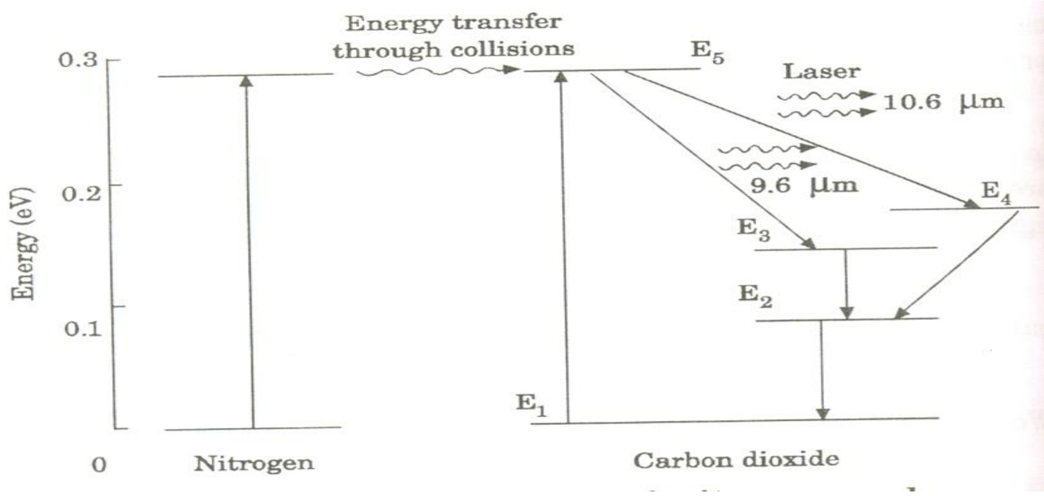
It consists of a quartz tube 5 m long and 2.5 cm in the diameter. This discharge tube is filled with gaseous mixture of $CO_2$ (active medium), helium and nitrogen with suitable partial pressures.

The terminals of the discharge tubes are connected to a D.C power supply. The ends of the discharge tube are fitted with NaCl Brewster windows so that the laser light generated will be polarized.

Two concave mirrors one fully reflecting and the other partially form an optical resonator.

**Working:**

Figure shows energy levels of nitrogen and carbon dioxide molecules.




When an electric discharge occurs in the gas, the electrons collide with nitrogen molecules and they are raised to excited states. This process is represented by the equation

$$N_2 + e^* = N_2^* + e$$

$N_2$ = Nitrogen molecule in ground state

$e^*$ = electron with kinetic energy

$N_2^*$ = nitrogen molecule in excited state

e= same electron with lesser energy

Now $N_2$ molecules in the excited state collide with $CO_2$ atoms in ground state and excite to higher electronic, vibrational and rotational levels.

This process is represented by the equation

$$N_2^* + CO_2 = CO_2^* + N_2$$

$N_2^*$ = Nitrogen molecule in excited state.

$CO_2$ = Carbon dioxide atoms in ground state

$CO_2^*$ = Carbon dioxide atoms in excited state

$N_2$ = Nitrogen molecule in ground state.

Since the excited level of nitrogen is very close to the $E_5$ level of $CO_2$ atom, population in $E_5$ level increases.

As soon as population inversion is reached, any of the spontaneously emitted photon will trigger laser action in the tube. There are two types of laser transition possible.

I. **Transition $E_5$ to $E_4$ :**

This will produce a laser beam of wavelength 10.6μm

II. **Transition $E_5$ to $E_3$**

This transition will produce a laser beam of wavelength 9.6μm. Normally 10.6μm transition is more intense than 9.6μm transition. The power output from this laser is 10kW.

**Characteristics:**

1. Type: It is a molecular gas laser.
2. Active medium: A mixture of $CO_2$ , $N_2$ and helium or water vapour is used as active medium
3. Pumping method: Electrical discharge method is used for Pumping action
4. Optical resonator: Two concave mirrors form a resonant cavity
5. Power output: The power output from this laser is about 10kW.
6. Nature of output: The nature of output may be continuous wave or pulsed wave.
7. Wavelength of output: The wavelength of output is 0.6μm and 10.6μm.

**Advantages:**

1. The construction of $CO_2$ laser is simple
2. The output of this laser is continuous.
3. It has high efficiency
4. It has very high output power.
5. The output power can be increased by extending the length of the gas tube.

**Disadvantages:**

1. The contamination of oxygen by carbon monoxide will have some effect on laser action
2. The operating temperature plays an important role in determining the output power of laser.
3. The corrosion may occur at the reflecting plates.
4. Accidental exposure may damage our eyes, since it is invisible (infra red region) to our eyes.

**Applications:**

1. High power $CO_2$ laser finds applications in material processing, welding, drilling, cutting soldering etc.
2. The low atmospheric attenuation (10.6μm makes $CO_2$ laser suitable for open air communication.
3. It is used for remote sensing
4. It is used for treatment of liver and lung diseases.
5. It is mostly used in neuro surgery and general surgery.
6. It is used to perform microsurgery and bloodless operations.

## Solid State diode lasers.

Laser action can also be produced semiconductors. The most compact of all the lasers in semiconductor diode laser. It is also called injection laser.

**Types of Semiconductor diode laser**

There are two types of semiconductor diode lasers

i. Homo junction laser
ii. Hetero- Junction laser.

**Homo – Junction laser:**

If a p-n junction is formed in a single crystalline material, then it is called as homo-junction laser.

Example: single crystal of gallium Arsenide (Ga-As)

**Hetero- Junction laser:**

If p-n junction is formed with different semiconducting materials, then it is known as Hetero- Junction laser. It is also called modern laser diode.

Example: Hetero- Junction laser can be formed between Ga-As and Ga-Al-As.

**Direct band gap Semiconductor**:

In this type, during the recombination of hole and electron, a photon of light is released.

Example: Ga-As

**In direct band gap Semiconductor**:

In this type, heat energy is produced during the recombination of hole and electron.

Example: Germanium and silicon

## 2.1.14 Semiconductor Diode laser:

**Definition:**

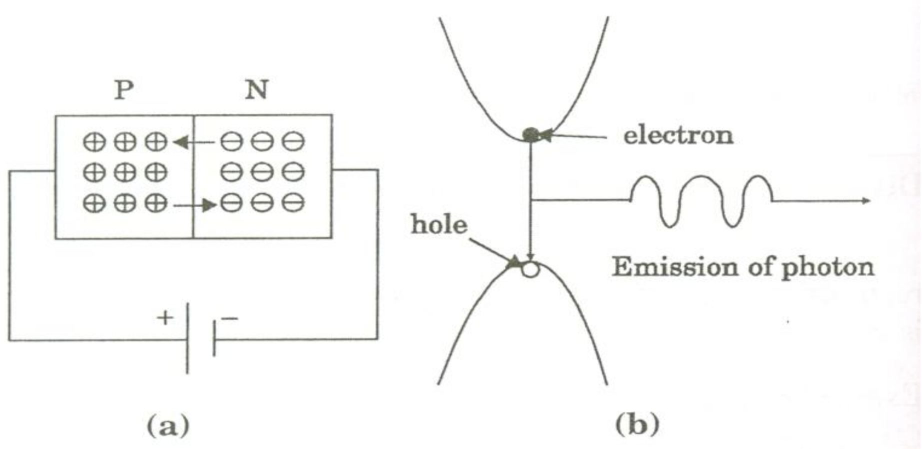
It is specifically fabricated p-n junction diode. This diode emits laser light when it is forward biased.

**Principle:**

When a p-n junction diode is forward biased, the electrons from n – region and the holes from the p- region cross the junction and recombine with each other.

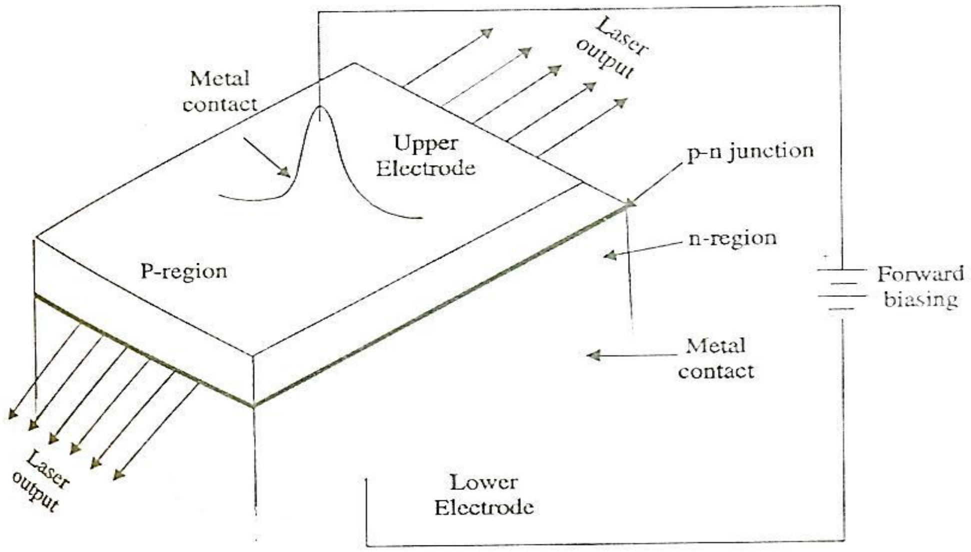
During the recombination process, the light radiation (photons) is released from a certain specified direct band gap semiconductors like Ga-As. This light radiation is known as recombination radiation.

The photon emitted during recombination stimulates other electrons and holes to recombine. As a result, stimulated emission takes place which produces laser.




**Construction:**

Figure shows the basic construction of semiconductor laser. The active medium is a p-n junction diode made from the single crystal of gallium arsenide. This crystal is cut in the form of a platter having thickness of 0.5μmm.



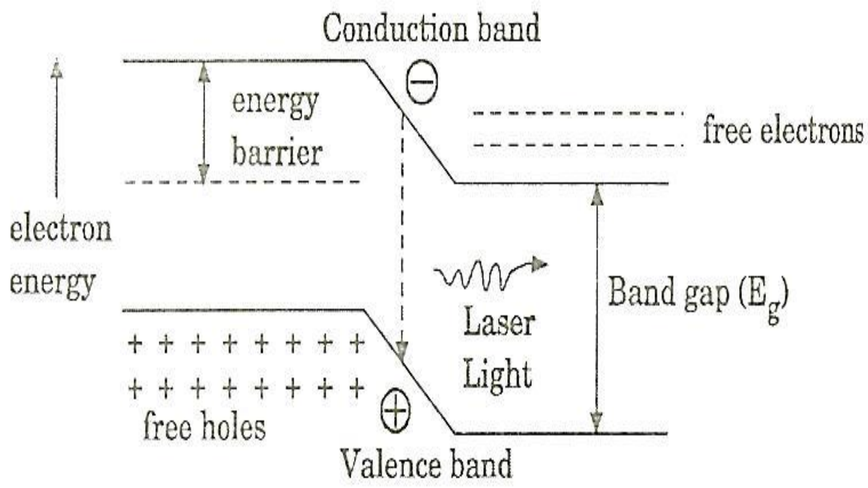
The platelet consists of two parts having an electron conductivity (n-type) and hole conductivity (p-type).

The photon emission is stimulated in a very thin layer of PN junction (in order of few microns). The electrical voltage is applied to the crystal through the electrode fixed on the upper surface.

The end faces of the junction diode are well polished and parallel to each other. They act as an optical resonator through which the emitted light comes out.

**Working:**

Figure shows the energy level diagram of semiconductor laser.




When the PN junction is forward biased with large applied voltage, the electrons and holes are injected into junction region in considerable concentration

The region around the junction contains a large amount of electrons in the conduction band and a large amount of holes in the valence band.

If the population density is high, a condition of population inversion is achieved. The electrons and holes recombine with each other and this recombination's produce radiation in the form of light.

When the forward – biased voltage is increased, more and more light photons are emitted and the light production instantly becomes stronger. These photons will trigger a chain of stimulated recombination resulting in the release of photons in phase.

The photons moving at the plane of the junction travels back and forth by reflection between two sides placed parallel and opposite to each other and grow in strength.

After gaining enough strength, it gives out the laser beam of wavelength 8400 $\overset{0}{A}$.

The wavelength of laser light is given by

$$E_g = h\nu = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E_g}$$

Where $E_g$ is the band gap energy in joule.

**Characteristics:**

1. **Type**: It is a solid state semiconductor laser.
2. **Active medium**: A PN junction diode made from single crystal of gallium arsenide is used as an active medium.
3. **Pumping method**: The direct conversion method is used for pumping action
4. **Power output:** The power output from this laser is 1mW.
5. **Nature of output:** The nature of output is continuous wave or pulsed output.
6. **Wavelength of Output:** gallium arsenide laser gives infrared radiation in the wavelength 8300 to 8500 $\overset{0}{A}$.

**Advantages:**

1. It is very small in dimension. The arrangement is simple and compact.
2. It exhibits high efficiency.
3. The laser output can be easily increased by controlling the junction current
4. It is operated with lesser power than ruby and $CO_2$ laser.
5. It requires very little auxiliary equipment
6. It can have a continuous wave output or pulsed output.

**Disadvantages:**

1. It is difficult to control the mode pattern and mode structure of laser.
2. The output is usually from 5 degree to 15 degree i.e., laser beam has large divergence.
3. The purity and monochromacity are power than other types of laser
4. Threshold current density is very large ($400 A/mm^2$).
5. It has poor coherence and poor stability.

**Application:**

1. It is widely used in fiber optic communication
2. It is used to heal the wounds by infrared radiation
3. It is also used as a pain killer
4. It is used in laser printers and CD writing and reading.

## 2.1.15 HETERO JUNCTION LASER

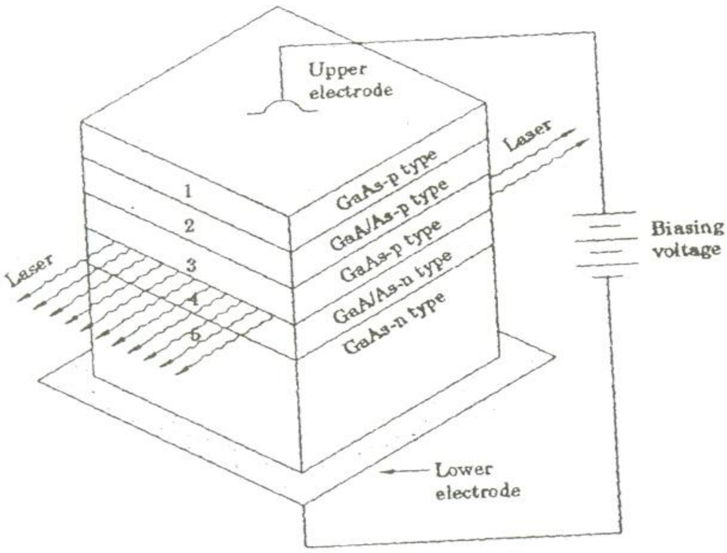
**A pn junction made up of the different materials in two regions ie., n type and p type is known ad hetrojunction.**

**Principle:**

When a PN junction diode is forward biased, the electrons from the n region and holes from the p region recombine with each other at the junction. During recombination process, light is released from certain specified direct band gap semiconductors.

**Construction:**

This laser consists of five layers as shown in the figure.



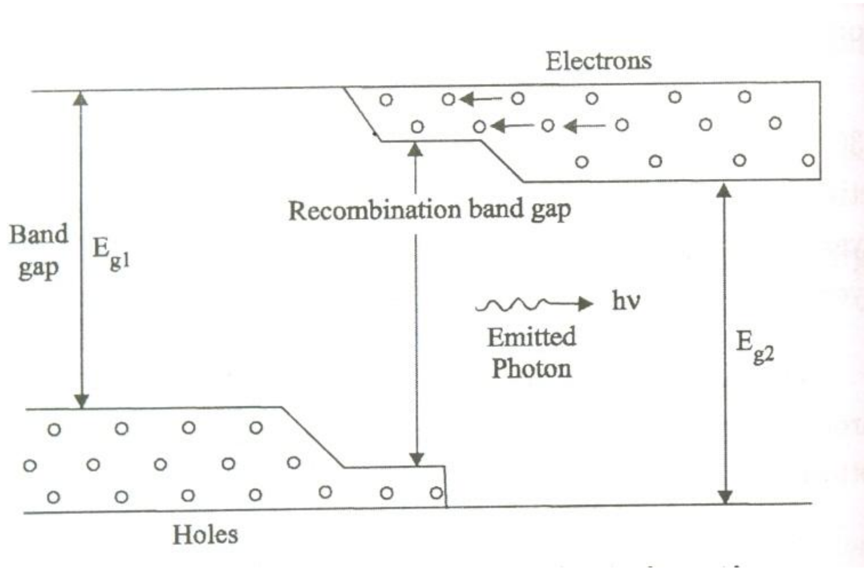

A layer of Ga-As p – type (3rd layer) will act as the active region. This layer is sand witched between two layers having wider band gap viz GaAlAs-p – type (2nd layer) and **GaAlAs**-n-type (4th layer).

The end faces of the junctions of 3rd and 4th layer are well polished and parallel to each other. They act as an optical resonator.

**Working:**

When the PN junction is forward biased, the electrons and holes are injected into the junction region. The region around the junction contains large amount of electrons in the conduction band and holes in the valence band.

Thus the population inversion is achieved. At this stage, some of the injected charge carriers recombines and produce radiation in the form of light.




When the forward biased voltage is increased, more and more light photons are emitted and the light intensity is more. These photons can trigger a chain of stimulated recombination's resulting in the release of photons in phase.

The photons moving at the plane of the junction travels back and forth by reflection between two sides and grow its strength. A coherent beam of laser having wavelength nearly 8000 $\overset{0}{A}$ emerge out from the junction region.

**Characteristics:**

| S.No | TITLE | | Description |
|---|---|---|---|
| 1. | Type | : | It is a heterojunction semiconductor laser |
| 2. | Active medium | : | PN junctions made from different layers. |
| 3. | Pumping method | : | Direct conversion method |
| 4. | Power output | : | The power output of laser beam is 1 mW |
| 5. | Nature of the Output | : | Continuous wave form |
| 6. | Wavelength of the output | : | Nearly 8000 $\overset{0}{A}$ |

**Advantages:**

1. It produces continuous wave output.
2. The power output is very high.

**Disadvantages:**

1. It is very difficult to grow different layers of PN junction.
2. The cost is very high.

**Applications:**

1. This type of laser is mostly used in optical applications
2. It is widely used in computers, especially on CD-ROMs.

**2.1.16 Comparison Chart of different types of Lasers**

| S.No | Characteristics | Nd-YAG laser | He-Ne laser | $CO_2$ Laser | Semiconductor laser |
|---|---|---|---|---|---|
| 1. | Type | Solid state laser | Gas laser | Molecular laser | Semiconductor laser |
| 2 | Active medium | Yttrium Aluminum garnet ( $Y_3 Al_5 O_{12}$) | Mixture of He and Ne in the ratio of 10:1 | Mixture of $CO_2$ ,$N_2$ and He gases | PN junction |
| 3 | Pumping method | Optical Pumping | Electrical pumping | Electrical Discharge method | Direct conversion |
| 4 | Optical resonator | Ends of the polished rods in silver | Pair of concave mirrors | Metallic mirror of gold or silicon coated with aluminum | End faces of the junction diode |
| 5 | Power output | $2 \times 10^4$ watt | 0.5- 50 mW | 10kW | 1 mW |
| 6 | Nature of power output | Pulsed | Continuous waveform | Continuous or pulsed | Pulsed or continuous wave form |
| 7 | Wavelength | 1.06µm | 6328 $\overset{0}{A}$ | 9.6µm and 10.6µm | 8300- 8500 $\overset{0}{A}$ |

## 3.1.1 Introduction: FIBER OPTICS

The development of lasers and optical fiber has brought about a revolution in the field of communication systems. Experiments on the propagation of information – carrying light waves through an open atmosphere were conducted. The atmospheric conditions like rain, fog etc affected the efficiency of communication through light waves.

To have efficient communication systems, the information carried by light waves should need a guiding medium through which it can be transmitted safely.

This guiding mechanism is optical fiber. The communication through optical fiber is known as light wave communication or optical communication.

A light beam acting as a carrier wave is capable of carrying more information than that of radio waves and microwaves due to its larger bandwidth.

Currently in most part of the world, fiber optics is used to transmit voice, video and digital data signals using light waves from one place to other place.

## 3.1.2 Optical fiber:

The optical fiber is a wave guide.

It is made up of transparent dielectrics ($SiO_2$), (glass or plastics).

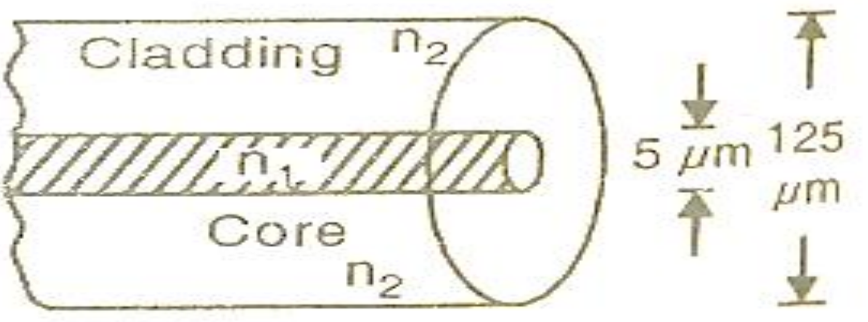
**3.2.1Fiber Construction**:

It consists of an inner cylinder made of glass or plastic called core. The core has high refractive index $n_1$.

This core is surrounded by cylindrical shell of glass or plastic called cladding.

The cladding has low refractive index $n_2$. This cladding is covered by a jacket which is made of polyurethane. It protects the layer from moisture and abrasion.

The light is transmitted through this fiber by total internal reflection. The fiber guides light waves to travel over longer distance without much loss of energy.

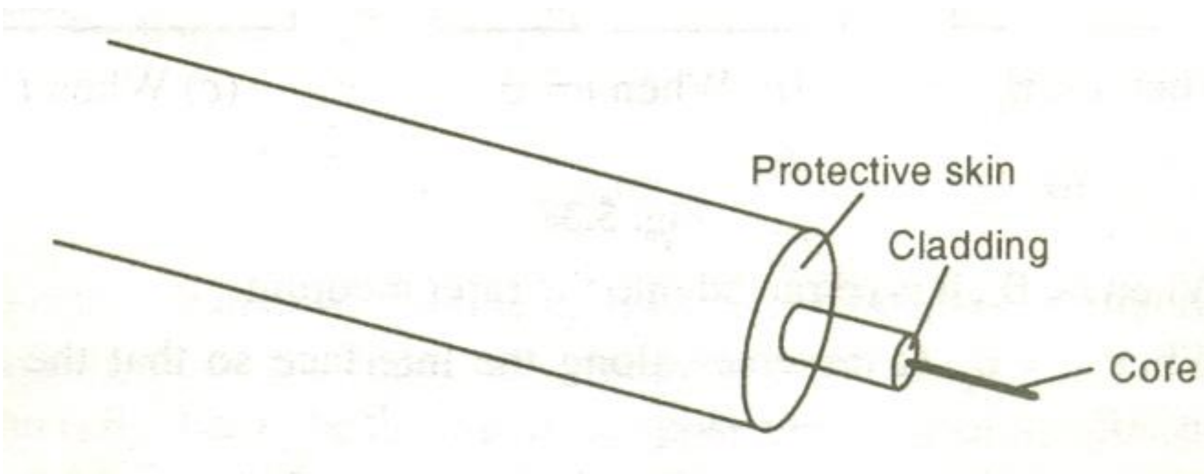



Core diameters range from 5 to 600μm while cladding diameters vary from 125 to 750μm.

Core transmits the light waves. The cladding keeps the light waves within the core by ***total internal reflection.***

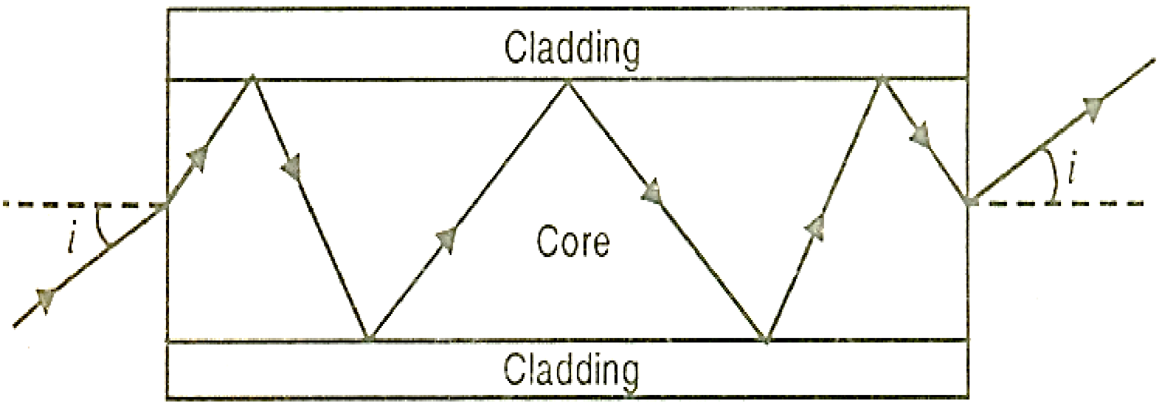
Refractive index:

The ***refractive index*** *or* ***index of refraction*** of a substance is a measure of the speed of light in that substance. It is expressed as a ratio of the speed of light in vacuum relative to that in the considered medium.




## 3.2.2 Principle of propagation of light in an optical fiber

The light launched inside the core at one end of the fiber propagates to the other end due to total internal reflection at the core and cladding interface.

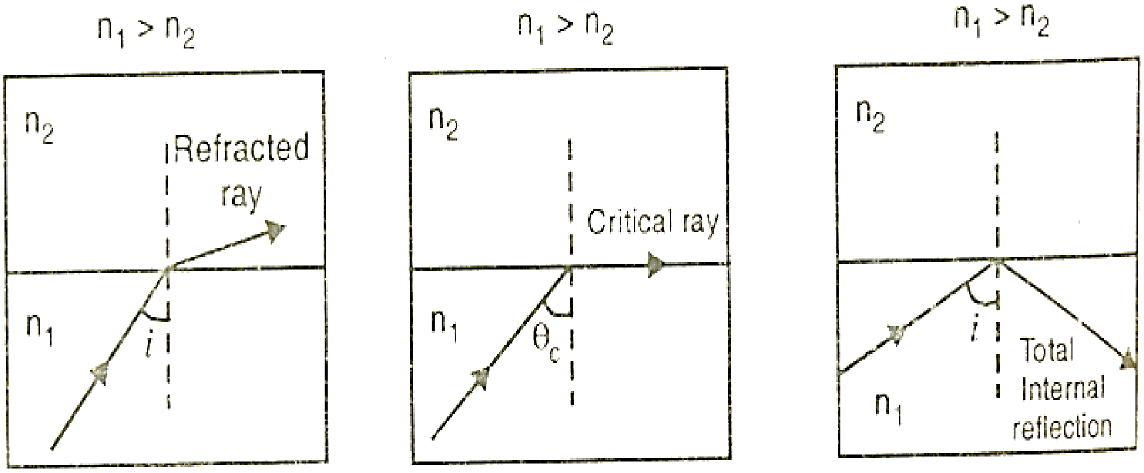



**Total internal reflection at the fiber wall can occur only if two conditions are Satisfied.**

1. The refractive index of the core material $n_1$ must be higher than that of the cladding $n_2$ surrounding it.
2. At the core – cladding interface, the angle of incidence ( between the ray and normal to the interface) must be greater than the critical angle defined as

$$Sin\theta_c = \frac{n_2}{n_1}$$

Let the light ray travel from core of refractive index $n_1$ to cladding of refractive index $n_2$ $n_1 > n_2$.




(a) When $i < \theta_c$ (b) When $i = \theta_c$ (c) When $i > \theta_c$

a) When $i < \theta_c$, it is refracted into rarer medium

b) When $i = \theta_c$, it traverses along the interface so that angle of refraction is $90^0$.

c) When $i > \theta_c$, it is totally reflected back into the denser medium itself.

When $i = \theta_c$ , then by Snell's law,

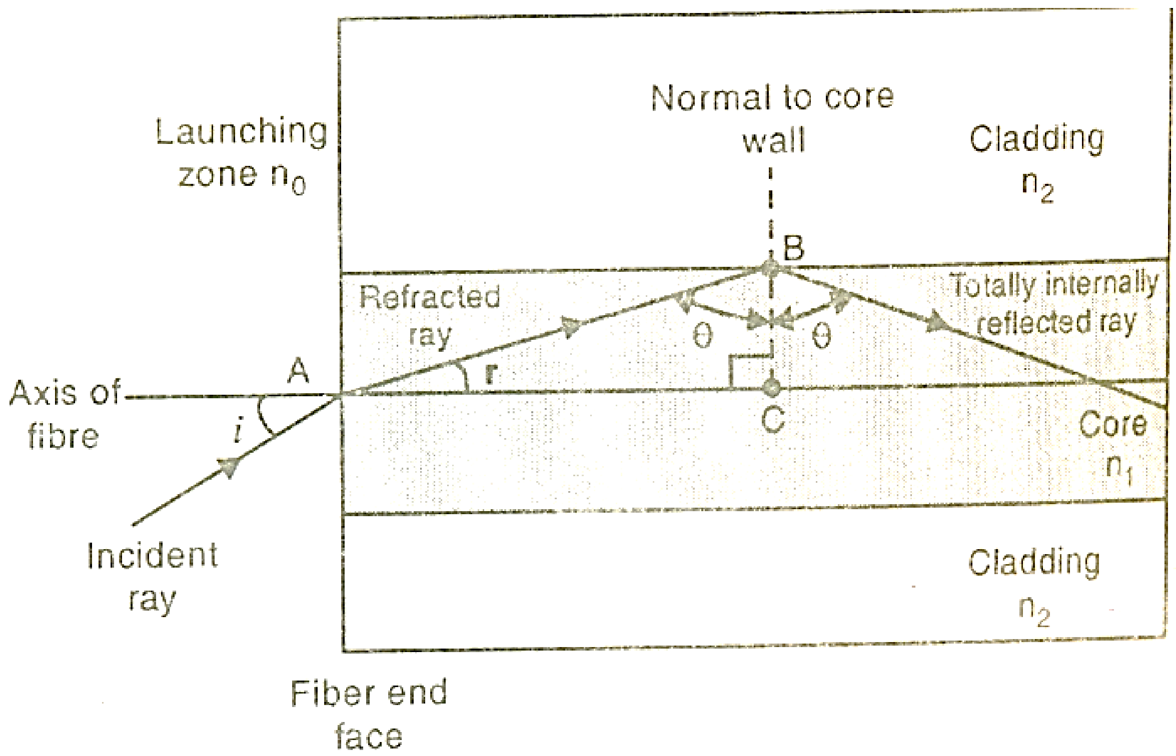
$$n_1 \sin \theta_c = n_2 \sin 90^0$$

$$\therefore \sin \theta_c = \frac{n_2}{n_1}$$

## 3.2.3 Propagation of light through fiber

Consider an optical fiber through which the light is being sent. The end at which light enters is called launching end. Let the refractive indices of the core and cladding be $n_1$ and $n_2$ respectively; $n_1 > n_2$. Let the refractive index of the medium from which the light is launched be $n_0$.

Let the light ray enter at an angle I to the axis of the fiber




The ray refracts at an angle r.

The ray strikes the core – cladding interface at an angle θ. If θ is greater than the critical angle $\theta_c$, the ray undergoes total internal reflection at the interface.

Let us now find out up to what maximum value of i at A total internal reflection at B is possible.

In triangle ABC, $r = 90 - \theta$ ⟶ (1)

From Snell's law $\frac{\sin i}{\sin r} = \frac{n_1}{n_0}$ ⟶ (2)

$$\sin i = \frac{n_1}{n_0}\sin r = \frac{n_1}{n_0}\sin r(90-\theta) = \frac{n_1}{n_0}\cos\theta$$

If θ is less than the critical angle $\theta_c$, the ray will be lost by refraction. Therefore, limiting value for containing the beam inside the core by total internal reflection is $\theta_c$. Let $i_m$ me the maximum possible angle of incidence at the fiber end face A for which $\theta = \theta_c$.

$$\sin i_m = \frac{n_1}{n_0}\cos\theta_c \quad \longrightarrow \quad (3)$$

But $\sin\theta_c = \frac{n_2}{n_1}$

$$\cos\theta_c = \sqrt{1-\sin^2\theta_c} = \sqrt{1-\frac{n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2-n_2^2}}{n_1}$$

$$\therefore \sin i_m = \frac{\sqrt{n_1^2-n_2^2}}{n_0}$$

Or $$i_m = \sin^{-1}\left(\frac{\sqrt{n_1^2-n_2^2}}{n_0}\right) \longrightarrow (4)$$

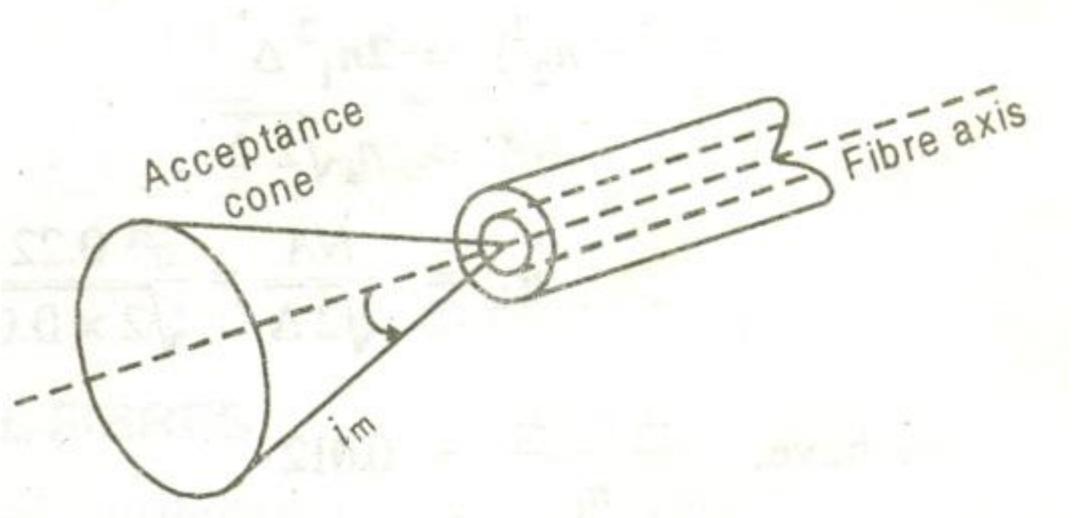
This angle $i_m$ is called the acceptance angle of the fiber.

**Definition**: Acceptance angle is defined as the maximum angle that a light ray can have relative to the axis of the fiber and propagate down the fiber.

Or the maximum angle at or below which the light can suffer Total Internal Reflection is called acceptance angle.

**Acceptance cone:**

An optical fiber accepts only those rays which are incident within a cone having a semi angle $i_m$.




The light rays contained within the cone having a full angle $2i_m$ are accepted and transmitted along the fiber. Therefore, the cone is called the acceptance cone.

Light incident at an angle beyond $i_m$ refracts through the cladding and the corresponding optical energy is lost. It is obvious that the larger the diameter of the core, the larger the acceptance angle.

**Numerical Aperture:**

**Definition:**

The numerical aperture (NA) is defined as the sine of the acceptance angle.

$$NA = \sin i_m$$

$$NA = \left( \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \right)$$

Numerical aperture determines the light gathering ability of the fiber. It is a measure of amount of light that can be accepted by a fiber. NA depends only on the refractive indices of the core and cladding materials. A large NA implies that a fiber will accept large amount of light from the source.

**Fractional Index change:**

It is the ratio of refractive index difference in core and cladding to the refractive index of the core.

$$\Delta = \frac{n_1 - n_2}{n_1}$$

**Relation between NA and $\Delta$**

$$n_1\Delta = n_1 - n_2$$

We know $NA = \sqrt{n_1^2 - n_2^2}$

NA = $\sqrt{(n_1 + n_2)(n_1 - n_2)}$

Substituting the value of $n_1 - n_2$ we have

$$NA = \sqrt{(n_1 + n_2)(n_1\Delta)}$$

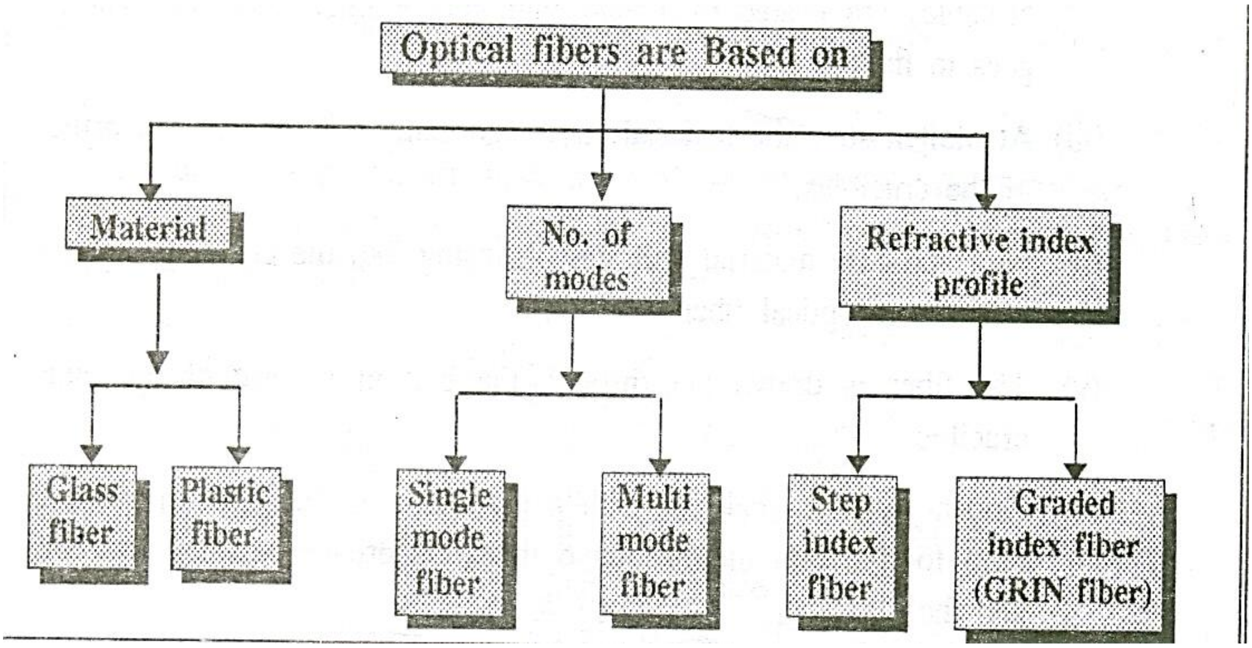
If $n_1 = n_2$, then $NA = \sqrt{2n_1^2\Delta}$

$$NA = n_1\sqrt{2\Delta}$$

## TYPES OF OPTICAL FIBERS

Optical fibers are classified into three major categories

i. The type of material used
ii. The number of modes
iii. The refractive index profile




Based on the type of the material used, they are classified into two types

1. **Glass fiber:**

   Example:

   Core: $SiO_2$ Cladding: $SiO_2$

   Core: $GeO_2$- $SiO_2$ Cladding: $SiO_2$

2. **Plastic fiber:**

   Example:

   Core: polymethyl methacrylate : Cladding: Co- Polymer

   Core: Polystyrene : Cladding: Methyl methacrylate

Based on the number of modes, they are classified as

1. Single mode fiber
2. Multimode fiber

Based on the refractive index profile, they are classified as

1. Step- index fiber
2. Graded index fiber

## MODES OF PROPAGATION:

Light propagates as electromagnetic waves through an optical fiber. All waves, having ray directions above the critical angle will be trapped within the fiber due to total internal reflection. However, all such waves do not propagate through the fiber. Only certain ray directions are allowed to propagate. The allowed directions correspond to the modes of the fiber.

In simple terms, modes can be visualized as the possible number of paths of light in an optical fiber. The paths are all zigzag paths excepting the axial direction. Accordingly, light rays travelling through a fiber are classified as axial rays or zigzag rays. As a ray gets repeatedly reflected at the walls of the fiber, phase shift occurs. Waves travelling along the certain zigzag paths will be in phase and intensified. Waves travelling along certain other paths will be out of phase and diminish due to destructive interference. The light rays path along which the waves are in phase inside the fiber are called modes. The number of modes that a fiber will support depends upon the ratio of d/λ where d is the diameter of the core and λ is the wavelength of the wave being transmitted.

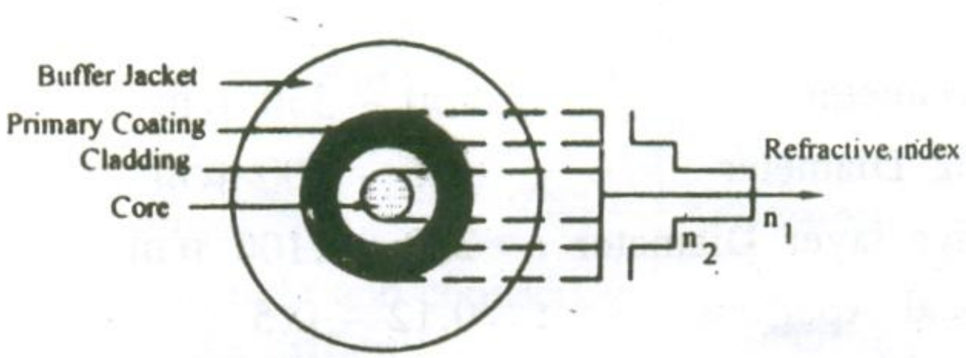
Modes are designated by an 'order' number 'm'. In a fiber of fixed thickness, the higher order modes propagate at smaller angles than the lower order modes.

***Axial ray that travels along the axis of the fiber is called zero order rays*.**

## SINGLE MODE FIBERS.

In general, the single mode fibers are step – index fibers. These types of fibers are made from doped silica. It has a very small core diameter so that it can allow only one mode of propagation and hence called single mode fibers.

The cladding diameter must be very large compared to the core diameter. Thus in the case of single mode fiber, the optical loss is very much reduced. The structure of a single mode fiber as shown.



**Structure:**

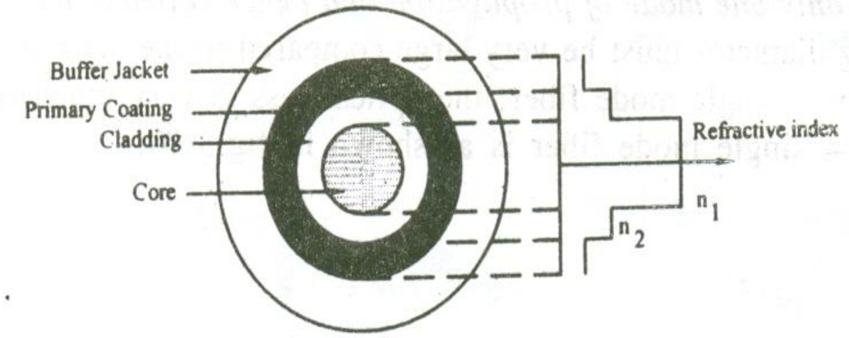
| | | |
|---|---|---|
| Core diameter | : | 5-10µm |
| Cladding diameter | : | Generally around 125µm |
| Protective layer | : | 250 to 1000µm |
| Numerical aperture | : | 0.08 to 0.10 |
| Band width | : | More than 50MHz km. |

**Application:**

Because of high bandwidth, they are used in long haul communication systems.

## MULTI- MODE FIBERS

The multi mode fibers are useful in manufacturing both for step – index and graded index fibers. The multi-mode fibers are made by multi-component glass compounds such as Glass – Clad Glass, Silica – Clad – Silica, doped silica etc. Here the core diameter is very large compared to single mode fibers, so that it can allow many modes to propagate through it and hence called as Multi mode fibers. The cladding diameter is also larger than the diameter of the single mode fibers. The structure of the multimode fiber is as shown in the figure.




**Structure:**

| | | |
|---|---|---|
| Core diameter | : | 50-350µm |
| Cladding diameter | : | 125µm - 500µm |
| Protective layer | : | 250 to 1100µm |
| Numerical aperture | : | 0.12 to 0.5 |
| Band width | : | Less than 50MHz km. |

The total number of modes possible for such an electromagnetic wave guide is

$$N = 4.9\left(\frac{d \times NA}{\lambda}\right)^2$$

Here d= core diameter

NA = numerical aperture

$\lambda$ = Optical wavelength.

**Application:**

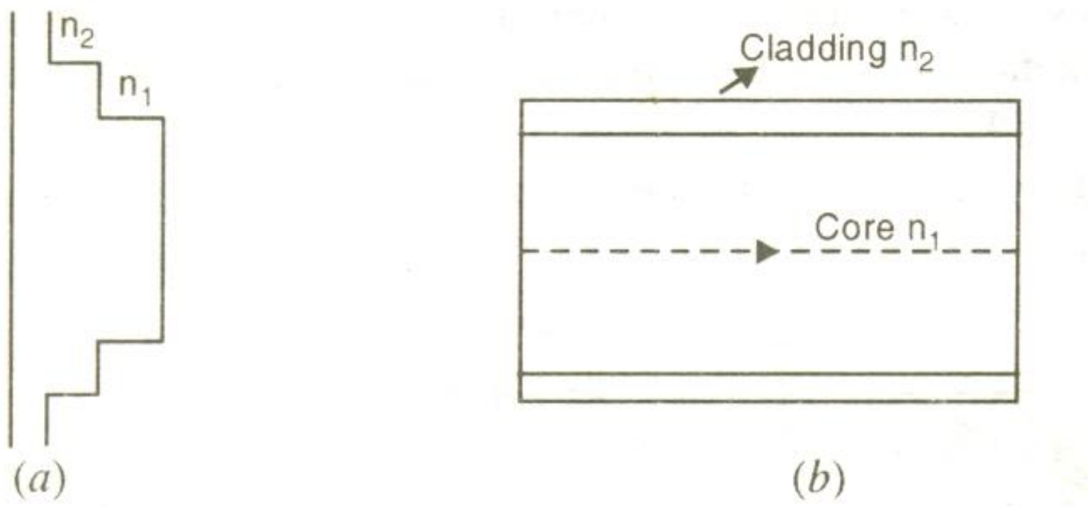
Because of its less band width it is very useful in short haul communication systems.

**DIFFERENCES BETWEEN SINGLE AND MULTIMODE FIBER**

| S.NO | SINGLE MODE FIBER | MULTIMODE FIBER |
|---|---|---|
| 1. | In single mode fiber only one mode can propagate through the fiber | In multimode it allows a large number of paths or modes for the light rays travelling through it. |
| 2. | It has smaller core diameter and the difference between the refractive index of the core and cladding is very small. | It has larger core diameter and refractive index difference is larger than the single mode fiber. |
| | **Advantages:** | **Disadvantages:** |
| 3. | No dispersion(i.e. there is no degradation of signal during propagation) | Dispersion is more due to degradation of signal owing to multimode. |
| 4. | Since the information transmission capacity is inversely proportional to dispersion $\left(T \propto \frac{1}{D}\right)$ the fiber can carry information to longer distances. | Information can be carried to shorter distances only. |
| | **Disadvantages:** | **Advantages:** |
| 5. | Launching of light and connecting of two fibers difficult. | Launching of light and also connecting of two fibers is easy. |
| 6. | Installation (fabrication) is difficult as it is more costly | Fabrication is easy and the installation cost is low. |

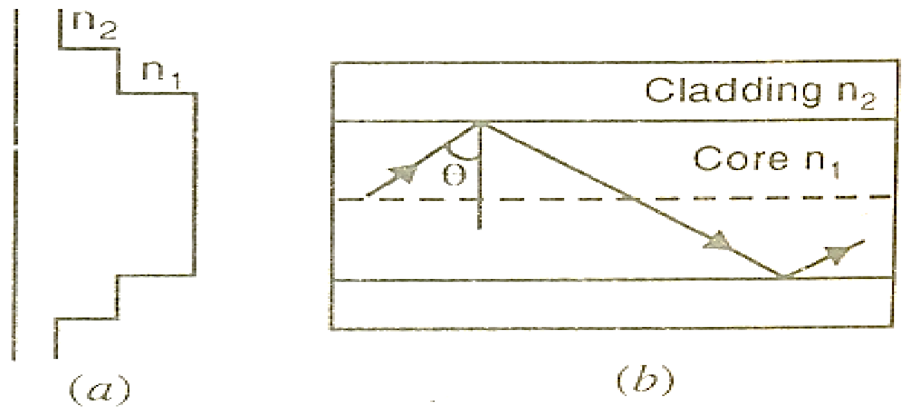
## 3.1.5 SINGLE MODE STEP INDEX FIBER

A single mode step index fiber consists of a very thin core of uniform refractive index surrounded by a cladding of refractive index lower than that of core. The refractive index abruptly changes at the core cladding boundary. Light travels along a side path, i.e., along the axis only. So zero order modes is supported by Single Mode Fiber.



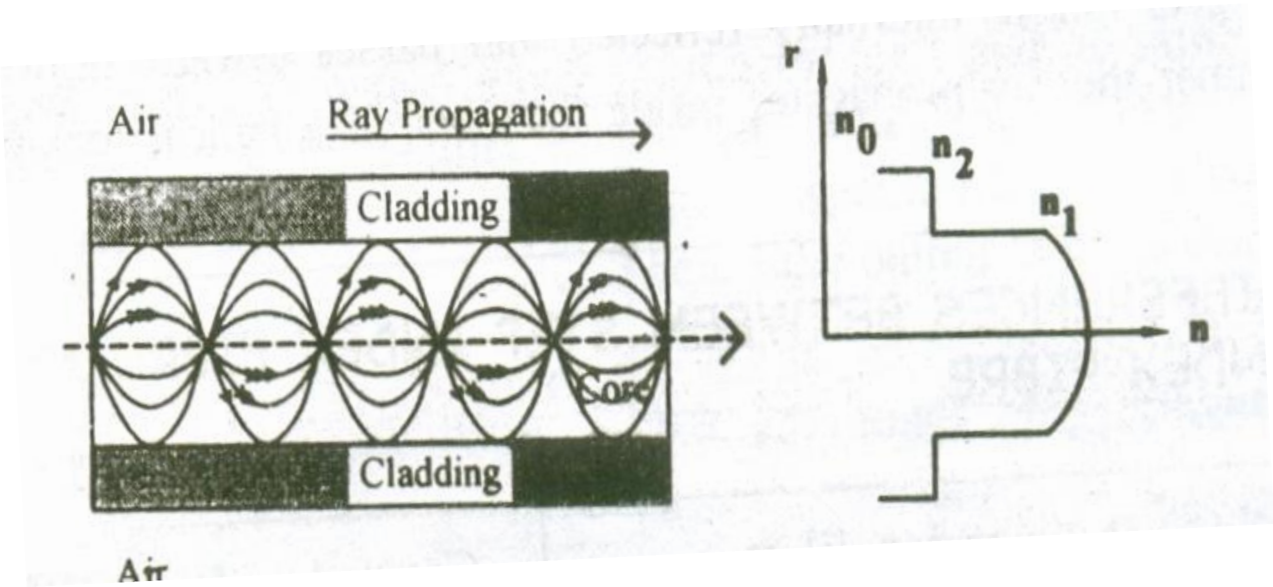

### 3.1.6 MULTIMODE STEP INDEX FIBER

A multimode step index fiber consists of a core of uniform refractive index surrounded by cladding of refractive index lower than that of the core. The refractive index abruptly changes at the core cladding boundary. The core is of large diameter. Light follows zigzag paths inside the fiber. Many such zigzag paths of propagation are permitted in Multi Mode Fiber. The Numerical Aperture of a Multi mode fiber is larger as the core diameter of the fiber is larger.




### 3.1.7 GRADED INDEX FIBER

GRIN fiber is one in which refractive index varies radially, decreasing continuously in a parabolic manner from the maximum value of $n_1$, at the center of the core to a constant value of $n_2$ at the core cladding interface.




In graded index fiber, light rays travel at different speeds in different parts of the fiber because the refractive index varies through out the fiber. Near the outer edge, the refractive index is lower. As a result, rays near the outer edge travel faster than the rays at the center of the core. Because of this, rays arrive at the end of the fiber at approximately the same time. In effect light rays arrive at the end of the fiber are continuously refocused as they travel down the fiber. All rays take the same amount of time in traversing the fiber. This leads to small pulse dispersion.

The pulse dispersion is given by $\Delta\tau = \tau_{max} - \tau_{min} = \frac{n_2 L}{2c}\Delta^2$

Here $\Delta = \frac{n_1 - n_2}{n_2}$

For a parabolic index fiber, the pulse dispersion is reduced by a factor of about 200 in comparison to step index fiber. It is because of this reason that first and second generation optical communication systems used near parabolic index fibers.

### 3.7.1 PROPAGATION OF LIGHT IN GRIN FIBER

Let $n_a$, $n_b$,$n_c$,$n_d$ etc be the refractive index of different layers in graded index fiber with $n_a > n_b > n_c > n_d$ etc. then the propagation of light through the graded index fiber is as shown in the figure.

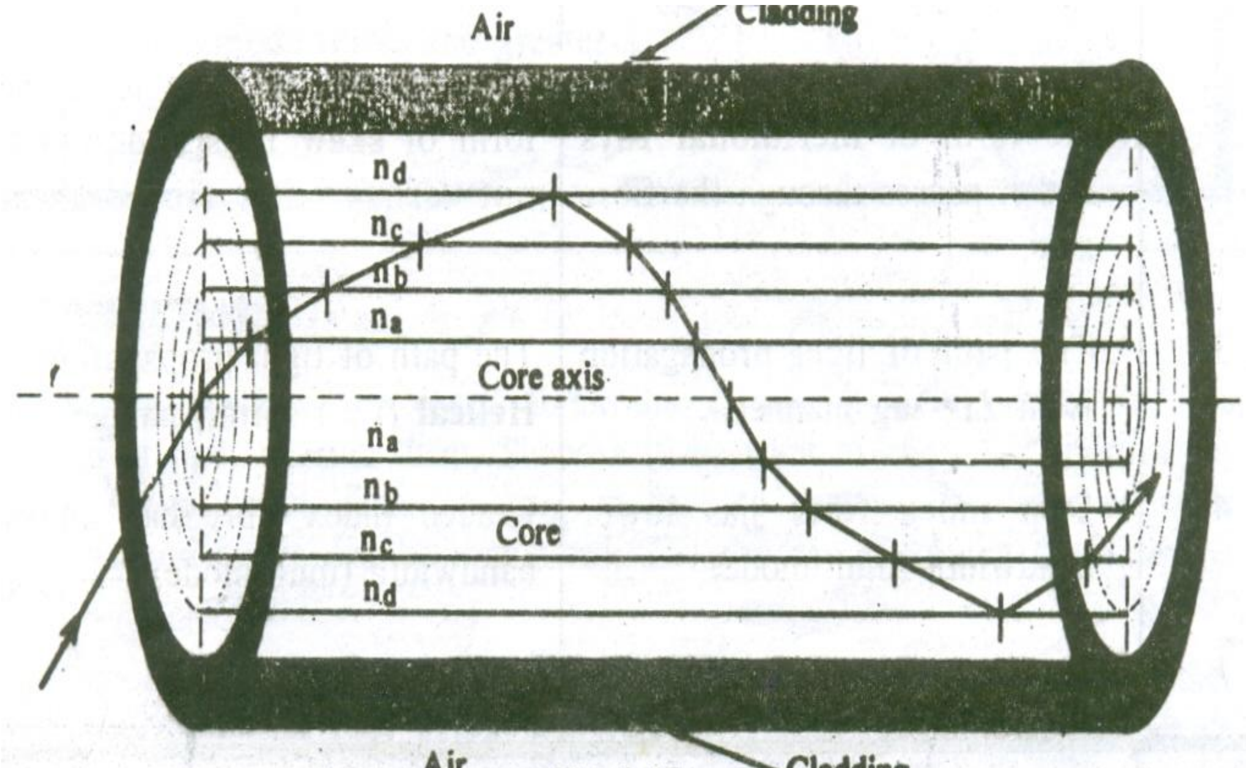



*Fig. 3.15*

Here, since $n_a > n_b$ the ray gets refracted. Similarly since $n_b > n_c$, the ray gets refracted and so on. In a similar manner, due to decrease in refractive index the ray gets gradually curved towards the upward direction and at one place , where in it satisfies the condition for total internal reflection,( $\phi > \phi_c$ ) it is totally internally reflected .

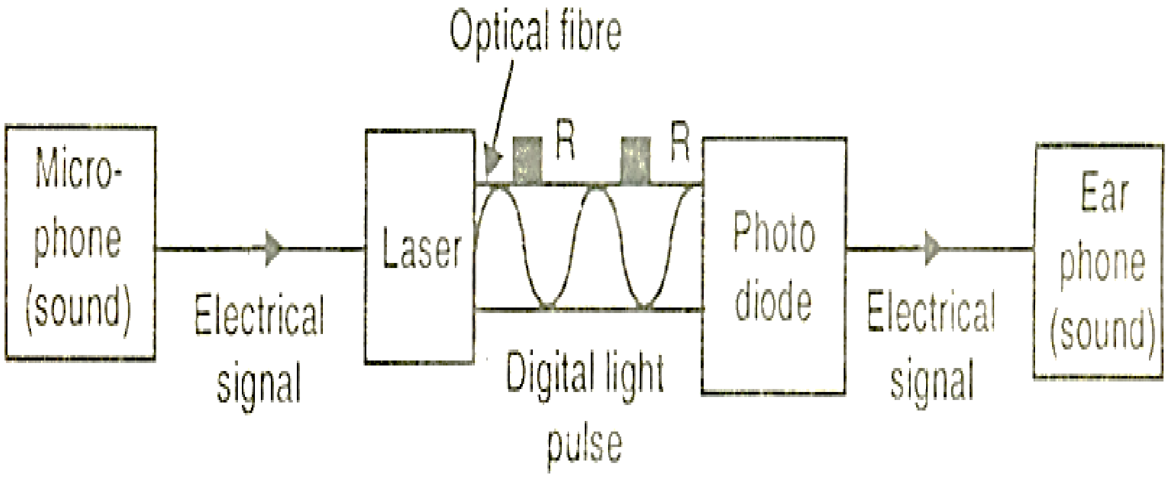
The reflected rays travels back towards the core axis and without crossing the fiber axis, it is refracted towards downwards direction and again gets totally internally reflected and passes towards upward direction. In this manner the ray propagates inside the fiber in a ***helical or spiral manner***

## 3.8 Difference between Step Index fiber and Graded Index fiber

| S. NO | STEP INDEX FIBER | GRADED INDEX FIBER |
|---|---|---|
| 1. | The refractive index of the core is uniform throughout and undergoes on abrupt change at the core cladding boundary | The refractive index of the core is made to vary gradually such that it is maximum at the center of the core. |
| 2. | The diameter of the core is about 50-200μm in the case of multimode fiber and 10μm in the case of single mode fiber | The diameter of the core is about 50μm in the case of multimode fiber |
| 3. | The path of light propagation is ***zig- zag*** in manner | The path of light is ***helical*** in manner |
| 3. | ***Attenuation is more*** for multimode step index fiber but for single mode it is very less.<br>*Explanation:*<br>When a ray travels through the longer distances there will be some difference in reflected angles. Hence high angle rays arrive later than low angle rays causing dispersion resulting in distorted output. | ***Attenuation is less.***<br>*Explanation:*<br>Here the light rays travel with different velocity inn different paths because of their variation in their refractive indices. At the outer edge it travels faster than near the center. But almost all the rays reach the exit at the same time due to helical path. Thus, there is no dispersion. |
| 4. | This fiber has ***lower bandwidth*** | This fiber has ***higher bandwidth*** |
| 5. | The light ray propagation is in the form of meridional rays and it passes through the fiber axis. | The light propagation is in the form of skew rays and it will not cross fiber axis. |
| 6. | **No of modes of Propagation:**<br>$N_{step} = 4.9\left(\frac{d \times NA}{\lambda}\right)^2 = \frac{V^2}{2}$<br>Where d= diameter of the fiber core<br>λ= wavelength<br>NA = Numerical Aperture<br>V- V-number is less than or equal to 2.405 for single mode fibers and greater than 2.405 for multimode fibers. | **No of modes of Propagation:**<br>$N_{Graded} = \frac{4.9\left(\frac{d \times NA}{\lambda}\right)^2}{2} = \frac{v^2}{4}$<br>Or $N_{graded} = \frac{N_{step}}{2}$ |

### 3.1.9 OPTICAL FIBER AS AN OPTICAL WAVEGUIDE

Optical fibers are used as dielectric waveguides for electromagnetic signals of optical frequencies. Figure shows the block diagram of transmission of sound along the optical fiber and conversion again to sound at the other end.




i. Sound is first converted into electrical signal by a microphone.
ii. The electrical signals modulate the intensity of light from laser.
iii. Then the information is carried along the fiber in a digital form.
   Boosters or repeaters are placed at a distance of about 50km of cable to make up the signal loses occurring due to scattering and absorption.
iv. At the receiving place, a photodiode converts the digital light pulses into corresponding electrical signals.
v. The electrical signals are then converted into sound by an earphone ( receiver)
   Time division multiplexing system is used to transmit many thousands of telephone cells through a single optical fiber with the use of digital pulses.

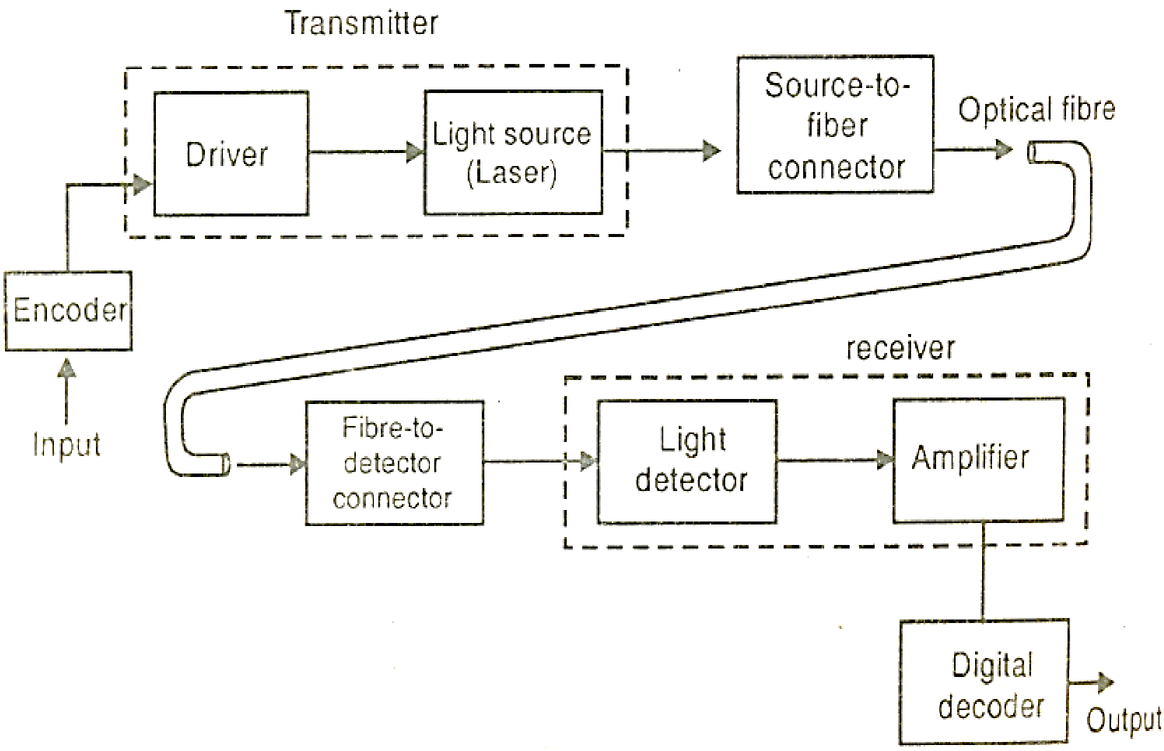
### 3.1.10 THE FIBER OPTIC COMMUNICATION SYSTEM

Figure shows the schematic diagram of a fiber optic communication system. The major components of an optical fiber communication system are

i. The optical transmitter
ii. The optical fiber
iii. The optical receiver

**PRINCIPLE:**

Basically, a fiber optic system converts an electrical signal to an infrared light signal. This signal is transmitted through an optical fiber. At the end of the optical fiber, it is reconverted into an electric signal




## Working:

1. Encoder encodes the information in the binary sequence zeros and ones.

   a. Encoder is an electric circuit where in the information is encoded into binary sequences of zeros and one. In the light wave transmitter each 'one' corresponds to an electrical pulse and 'zero' corresponds to an absence of a pulse. These electrical pulses are used to turn a light source on and off very rapidly. The driver converts the incoming electrical signal into a form that will operate with the light source.

2. These electrical pulses are used to turn a light source on and off rapidly.

3. The optical fiber acts as a wave guide and transmits the optical pulses towards the receiver, by the principle of total internal reflection.

4. The light detector receives the optical pulses and converts them into electrical pulses. These signals are amplified by the amplifier.

**5.** The amplified signals are decoded by the decoder.

**ADVANTAGES:**

1. Extremely wide bandwidth.

    a. Optical frequencies are very large ($10^{15}$ Hz) as compared to radio frequencies ($10^{6}$Hz) and microwave frequencies ($10^{10}$ Hz). The rate at which information can be transmitted is directly related to signal frequency. Therefore, a transmission system that operates at the frequency of light can theoretically transmit information at a higher rate than systems that operate at radio frequencies or microwave frequencies.

2. Lack of cross talk between parallel fibers.

    a. There is virtually no signal leakage from fibers. Hence, cross-talks between neighboring fibers are almost absent. This is quite frequent in conventional metallic system

3. Immunity to inductive interference

    a. Since optical fibers are not metallic, they do not pick up electromagnetic waves. The result is noise free transmission i.e., fiber optic cables are immune to interference caused by lighting or other electromagnetic equipment

4. Smaller diameter and light weight cable

    a. Optical fibers, because of their light weight and flexibility, can be handled more easily than copper cables.

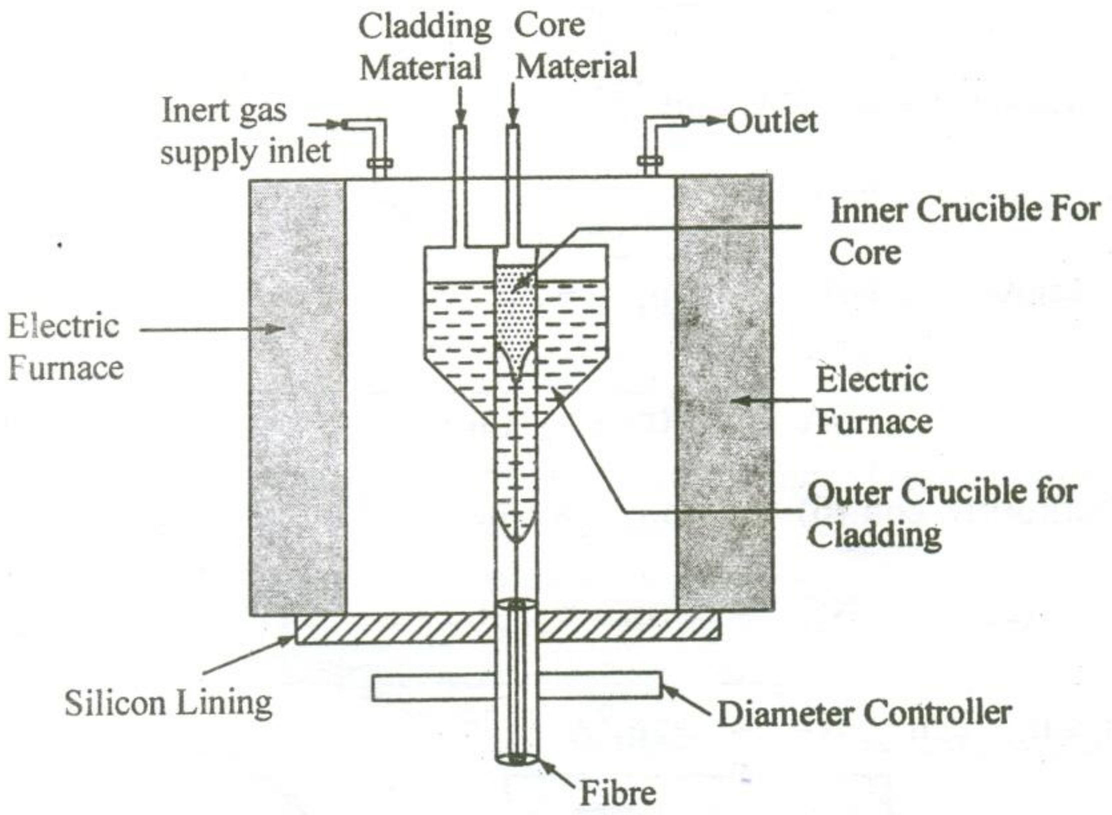
5. Signal security

a. The transmitted signal through the fibers does not radiate. Further the signal cannot be tapped from a fiber in an easy manner. Therefore, optical fiber communication provides a hundred percent signal security hence this system is highly suited to secure communications in defence communication networks.

6. Economical & Low loss per unit length.

## 3.1.11 Double Crucible Method

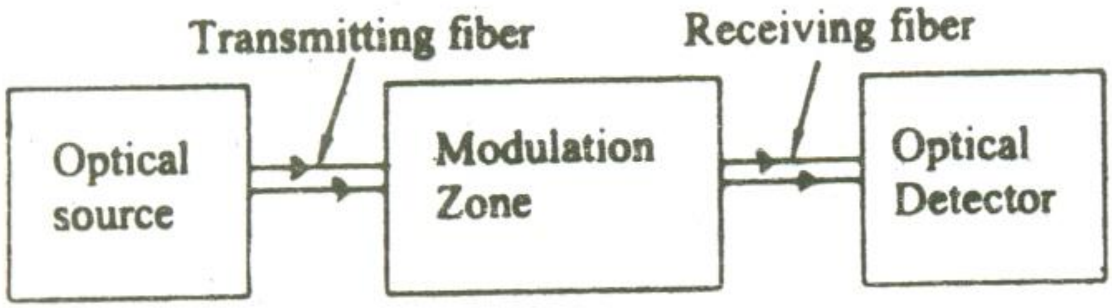
A method of fabricating an Optical Wave guide by melting the core and clad glasses in two suitably joined concentric crucibles and then drawing a fiber from the combined melted glass.




1. Highly purified glass powders of various refractive indices are fed into the inner crucible for the core in the outer crucible for cladding.
2. The electric furnace is switched on and the materials are heated to very high temperature.
3. The material goes to molten state and the material starts squeezing through the orifice of the crucible.
4. Now the core material will start diffusing into cladding material to form an optical fiber.
5. The fiber is drawn through the bottom surface of the crucible and dopant such as thallium with high rate of diffusion in silica is used to maintain the difference in refractive index.

## 3.1.12 FIBER OPTIC SENSORS

Optical sensor is a transducer which converts any form of signal into optical signal in the measurable form. Here optical fibers are used as a guiding media and hence called as wave guides. The block diagram of a sensor system is as follows.




The optical sources used here are LED/Laser. The optical signal produced by the optical source and is transmitted through the transmitting fiber in the modulation zone.

The optical signals are modulated based on any one of these properties, viz., Optical intensity, phase, polarization, Wavelength and spectral distribution. These modulated signals with any one of these properties are received by the receiving / fiber and is sent to the optical detector.

### 3.12.1. TYPES OF SENSORS

There are two types of sensors, viz.

i. Intrinsic sensors or Active sensors
ii. Extrinsic sensors or Passive sensors

### 3.12.2 INTRINSIC SENSORS OR ACTIVE SENSORS

In intrinsic sensors or active sensors the physical parameter to be sensed directly acts on the fiber itself to produce the changes in the transmission characteristics.

**Example:**

i. Temperature /Pressure Sensor( Phase and polarization sensor) and
ii. Liquid level sensor.

### 3.12.3 EXTRINSIC SENSORS

In extrinsic sensors or passive sensors, separate sensing element will be used and the fiber will act as a guiding media to the sensors.

**Examples:**

i. Displacement sensor

ii. Laser Doppler velocimeter sensor

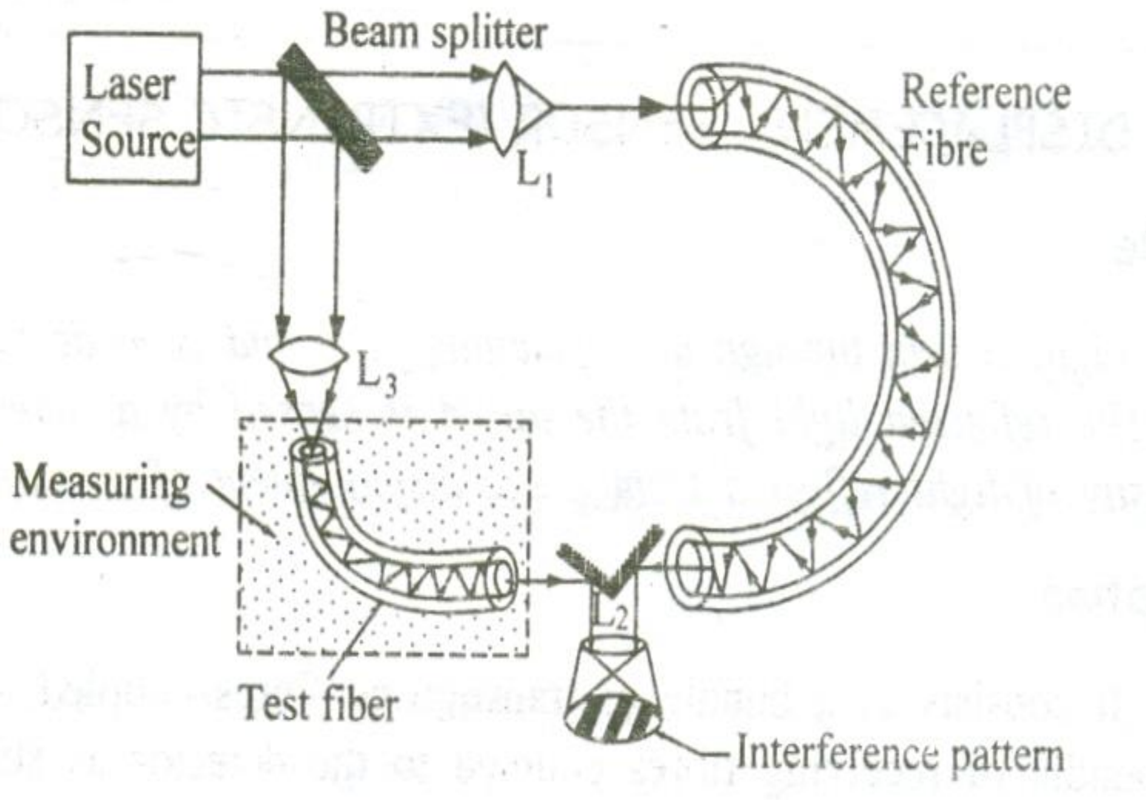
## TEMPERATURE SENSOR

**Principle:**

It is based on the principle of interference between the beams emerging out from the reference fiber and the fiber kept in the measuring environment.

**Description:**

It consists of a Laser source to emit light. A beam splitter, made of glass plate is inclined at an angle $45^0$ with respect to the direction of the laser beam.




**Two fibers viz,**

i. ***Reference fiber*** which is isolated from the environment

ii. ***Test fiber*** kept in the environment to be sensed, are placed as shown in the figure. Separate lens systems are provided to split and to collect the beam.

**Working:**

1. A monochromatic source of light is emitted from the laser source.
2. The beam splitter kept at an angle $45^0$ inclination divides the beam emerging from the laser source into two beams (i) main beam and (ii) splitted beam, exactly at right angles to each other.
3. The main beam passes through the lens $L_1$ and is focused onto the reference fiber which is isolated from the environment to be sensed.
4. The beam after passing through the reference fiber then falls on the Lens $L_2$.
5. The splitted beam passes through the Lens $L_3$ and is focused onto the test fiber kept in the environment to be sensed.
6. The splitted beam after passing through the test fiber is made to fall on lens $L_2$.
7. The two beams after passing through the fibers, produces a path difference due to change in parameters such as pressure, temperature etc in the environment.
8. Therefore a path difference is produced between two beams causing the interference pattern as shown in the figure.
9. Thus the change in pressure or temperature can be accurately measured with the help of the interference pattern obtained.

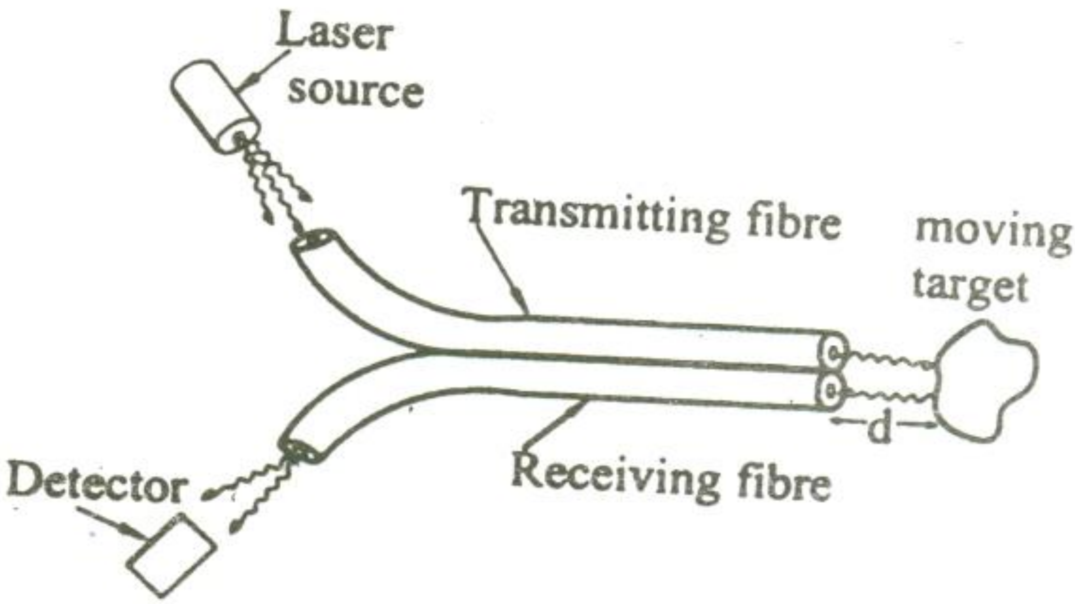
## DISPLACEMENT SENSOR (EXTRINSIC SENSOR)

**Principle:**

Light is sent through a transmitting fiber and is made to fall on a moving target. The reflected light from the target is sensed by a detector. With respect to intensity of light reflected from its displacement of the target is measured.

**Description:**

It consists of a bundle of transmitting fibers coupled to the laser source and a bundle of receiving fibers coupled to the detector as shown in the figure.




The axis of the transmitting fiber and the receiving fiber with respect to the moving target can be adjusted to increase the sensitivity of the sensor.

**Working:**

Light from the source is transmitted through the transmitting fiber and is made to fall on the moving target. The light reflected from the target is made to pas through the receiving fiber and the same is detected by the detector.

Based on the intensity of the light received, the displacement of the target can be measured, (i.e.) if the received intensity is more than we can say that the target is moving towards the sensor and if the intensity is less, we can say that the target is moving away from the sensor.

## MEDICAL ENDOSCOPE

Optical fibers are very much useful in medical field. Using low quality, large diameter and short length silica fibers we can design a fiber optic endoscope or fibroscope.

A medical endoscope is a tubular optical instrument, used to inspect or view the internal parts of human body which are not visible to the naked eye. The photograph of the internal parts can also be taken using this endoscope.

**Construction**

Figure shows the structure of endoscope. It has two fibers viz.,

1. Outer fiber($f_0$)

2. The inner fiber ($f_i$).

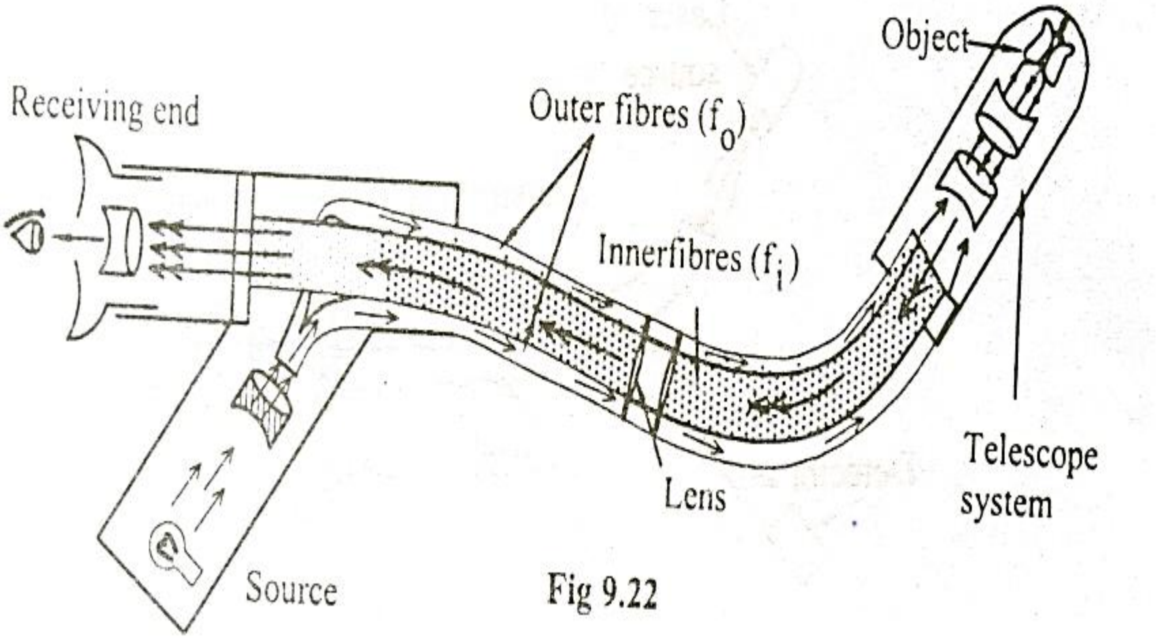



Fig 9.22

**Outer fiber:**

The outer fiber consists of many fibers bundled together without any particular order of arrangement and is called incoherent bundle. These fiber bundles as a whole are enclosed in a thin sleeve for protection. The outer fiber is used to illuminate or focus the light onto the inner parts of the body.

**Inner fiber:**

The inner fiber also consists of a bundle of fibers, but in perfect order. Therefore this arrangement is called coherent bundle. This fiber is used to collect the reflected light from the object. A tiny lens is fixed to one end of the bundle in order to effectively focus the light, reflected from the object. For a wider field of view and better image quality, a telescope system is added in the internal part of the telescope.

**Working:**

Light from the source is passed through the outer fiber ($f_0$). The light is illuminated on the internal part of the body. The reflected light from the object is brought to focus using the telescope to the inner fiber ($f_i$).

Here each fiber picks up a part of the picture from the body. Hence the picture will be collected bit by bit and is transmitted in an order by the array of fibers.

As a result, the whole picture is reproduced at the other end of the receiving fiber as shown in the figure. The output is properly amplified and can be viewed through the eye piece at the receiving end.

The cross sectional view is as shown in the figure.

In figure, we can see that along with input and output fibers, we have two more channels namely, (i) Instrumental Channel ($C_1$) and (ii) Irrigation channel ($C_2$) used for the following purposes.

**Instrumentation channel ($C_1$):**

It is used to insert or take the surgical instruments needed for operation.

**Irrigation channel ($C_2$):**

It is used to blow air or this is used to clear the blood in the operation region, so that the affected parts of the body can be clearly viewed.

## LOSSES IN OPTICAL FIBERS

When light propagates through an optical fiber, a small percentage of light is lost through different mechanisms. The loss of optical power is measured in terms of decibels per km for attenuation losses.

## ATTENUATION:

It is defined as the ratio of optical power output ($P_{out}$) from a fiber of length 'L' to the power output ($P_{in}$)

$$\text{Attenuation } (\alpha) = \frac{-10}{L} \log \frac{P_{in}}{P_{out}} \, dB/Km$$

Since attenuation plays a major role in determining the transmission distance, the following attenuation mechanisms are to be considered in designing an optical fiber.

**1. Absorption:**

Usually absorption of light occurs due to imperfections of the atomic structure such as missing molecules, ($OH^-$), hydroxyl ions, high density cluster of atoms etc., which absorbs light.

**2. Scattering:**

Scattering is also a wavelength dependent loss, which occurs inside the fibers. Since the glass is used in fabrication of fibers, the disordered structure of glass will make some variations in the refractive index inside the fiber. As a result, if light is passed through the atoms in the fiber, a portion of light is scattered (elastic scattering) .this type of scattering is called Raleigh scattering.

Raleigh scattering loss $\propto \frac{1}{\lambda^4}$

**3. Radiative loss:**

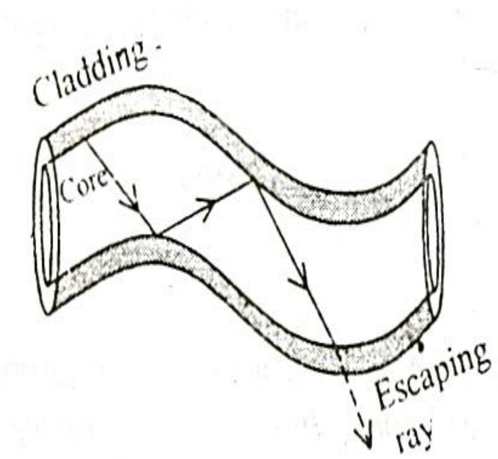
Radiative loss occurs in fibers due to bending of finite radius of curvature in optical fibers. The types of bends are

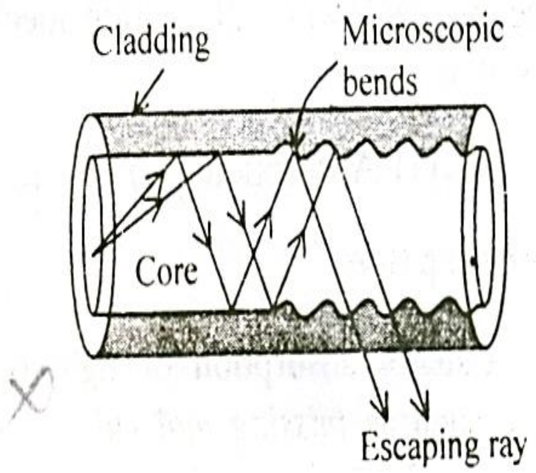
a. Macroscopic bends

b. Microscopic bends

**a. Macroscopic bends**:

If the radius of the core is large compared to fiber diameter, it may cause large-curvature at the position where the fiber cable turns at the corner. At these corners the light will not satisfy the condition for total internal reflection and hence it escapes out from the fiber. This is called as macroscopic / macro bending losses. Also note that this loss is negligible for small bends.




**b. Microscopic bends:**

Micro-bends losses are caused due to non-uniformities or micro bends inside the fiber as shown. This micro bends in fiber appears due to non uniform pressures created during the cabling of the fiber or even during the manufacturing itself. This lead to loss of light by leakage through the fiber.

**Remedy:**

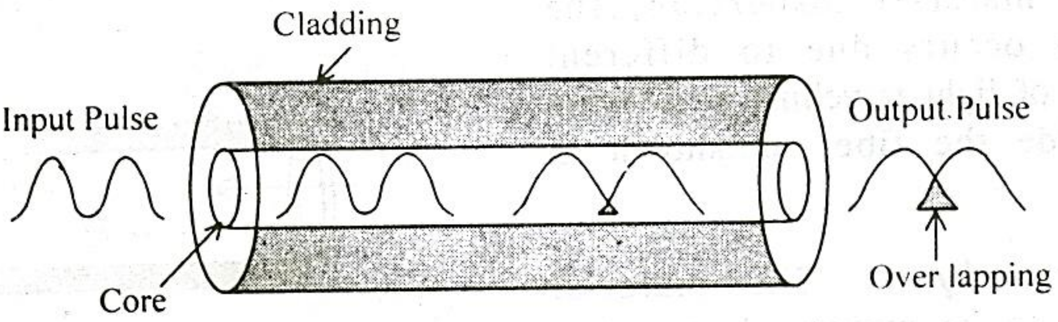
Micro-bend losses can be minimized by extruding (squeezing out) a compressible jacket over the fiber. In such cases, even when the external forces are applied, the jacket will be deformed but the fiber will tend to stay relatively straight and safe, without causing more loss.

## DISTORTION AND DISPERSION

The optical signal becomes increasingly distorted as it travels along a fiber. This distortion is due to dispersion effect.

**Dispersion:**

When an optical signal or pulse is sent into the fiber the pulse spreads /broadens as it propagates through the fiber. This phenomenon is called dispersion as shown in the figure.



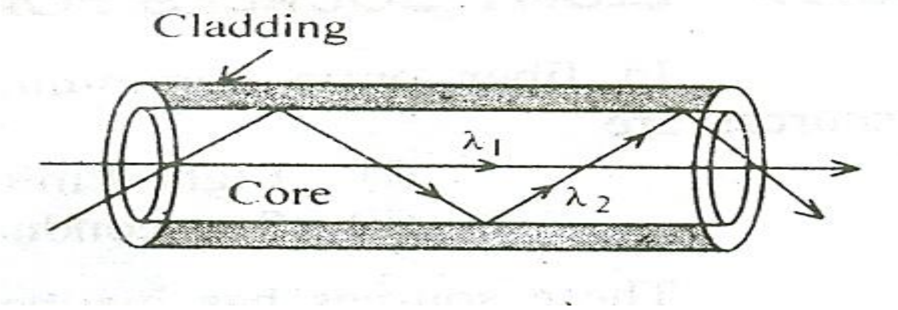

From figure we can see that the pulse received at the output is wider than the input pulse. Hence the output pulse is said to be distorted, due to dispersion effect.

The pulse broadening or dispersion will occur in three ways, viz.,

1. Inter-modal dispersion
2. Material dispersion or chromatic dispersion
3. Waveguide dispersion

**Intermodal dispersion**:

When more than one mode is propagating through the fiber, then the inter modal dispersion will occur. Since, many modes are propagating; they will have different wavelengths and will take different time to propagate through the fiber, which leads to intermodal dispersion.



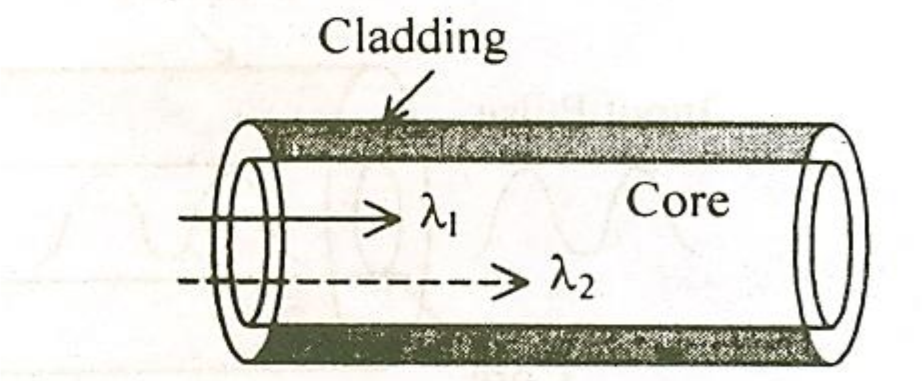

**Explanation:**

When a ray of light is launched into the fiber, the pulse is dispersed in all possible paths through the core, so called different modes.

Each mode will be different wavelength and has different velocity as shown in the figure. Hence, they reach the end of the fiber at different time. This results in the elongation or stretching of data in the pulse. Thus causes the distorted pulse. This is called intermodal dispersion.

**Material dispersion**:

In material dispersion, the dispersion occurs due to different wavelength travelling at different speed inside the fibers shown in the figure.




**Remedy:**

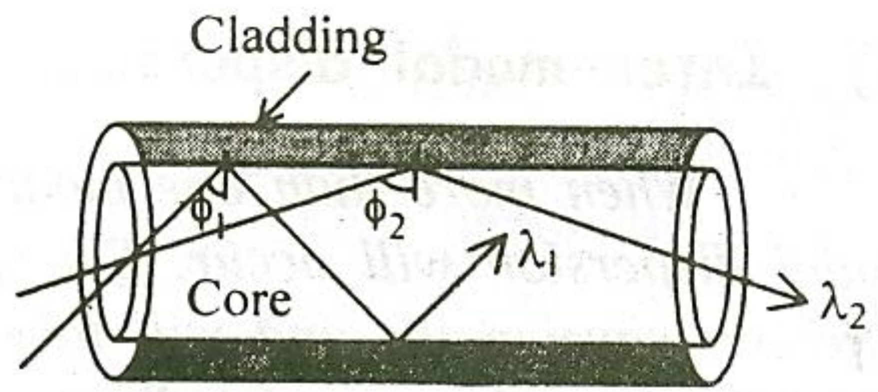
The material dispersion can be minimized at certain wavelengths say 870nm, 1300 nm and 1550 nm; these wavelengths are termed ***Zero Dispersion wavelengths(ZDW).***

Whether light wavelength is lesser than ***Zero Dispersion wavelengths*** , it travels slower and when it is higher than ZDW it travels faster. Thus the speed is altered and adjusted in such a way that all the waves passing through the fiber will move with constant speed and hence the material dispersion is minimized.

Note: this dispersion will not occur in single mode fibers

Wave guide dispersion:

The wave guide dispersion arises due to the guiding property of the fiber and due to their different angles at which they incident at the core-cladding interface of the fiber.




In general

Inter-modal dispersion > Material Dispersion> Waveguide dispersion

**DETECTOR:**

A ***detector*** is one which converts photons into electrons

A ***detector*** is one which converts light into either current or voltage.

**PRINCIPLE OF OPERATION of a Photo Detector**

A photodiode is a PN junction or PIN structure. When a Photon of sufficient energy strikes the diode, it excites an electron, thereby creating a ***free electron* and a *hole*.**

If the absorption occurs in the junction's depletion region, these carriers are swept from the junction by the built-in field of the depletion region. Thus holes move towards the anode, and electrons toward the cathode, and a ***photocurrent is produced***.

**Definition:**

It is a device which converts light signal to electrical wave forms.

Types of photo detectors:

There are three types of Photo-detectors

i. Photo emissive
ii. Photo conductive
iii. Photo voltaic

Photo voltaic devices:

We will study the three forms of devices.

i. PN junction photo detector
ii. PIN photo diode
iii. Avalanche photo diode(APD)

Figure explains the basic detection mechanism of PN junction diode photo detector. When reverse biased, the potential barrier between p and n regions increases. Therefore no current flows.

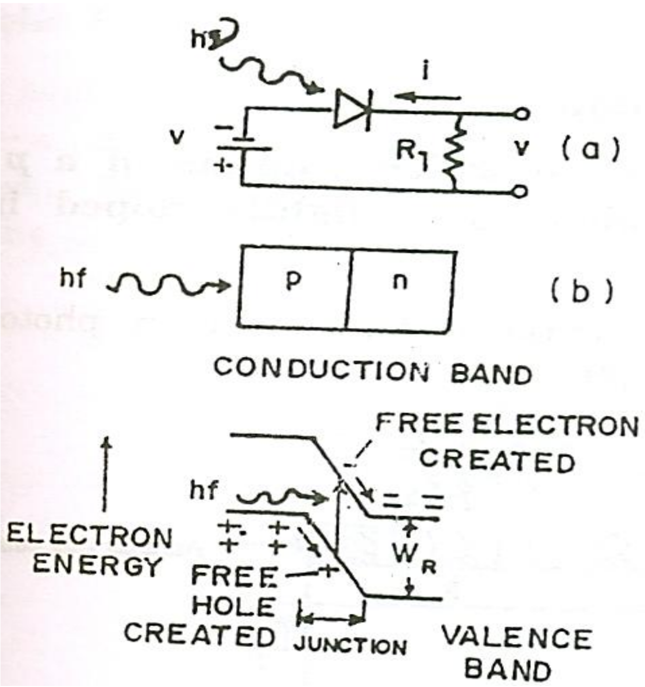



Figure shows an incident photons being absorbed in the junction after passing through the p layer. The light photons incident on the junction produce large number of electron – hole pairs. The electrons are attracted towards n region and holes are attracted towards p-region due to reverse bias of the diode. Thus the current passes through the external resistor.

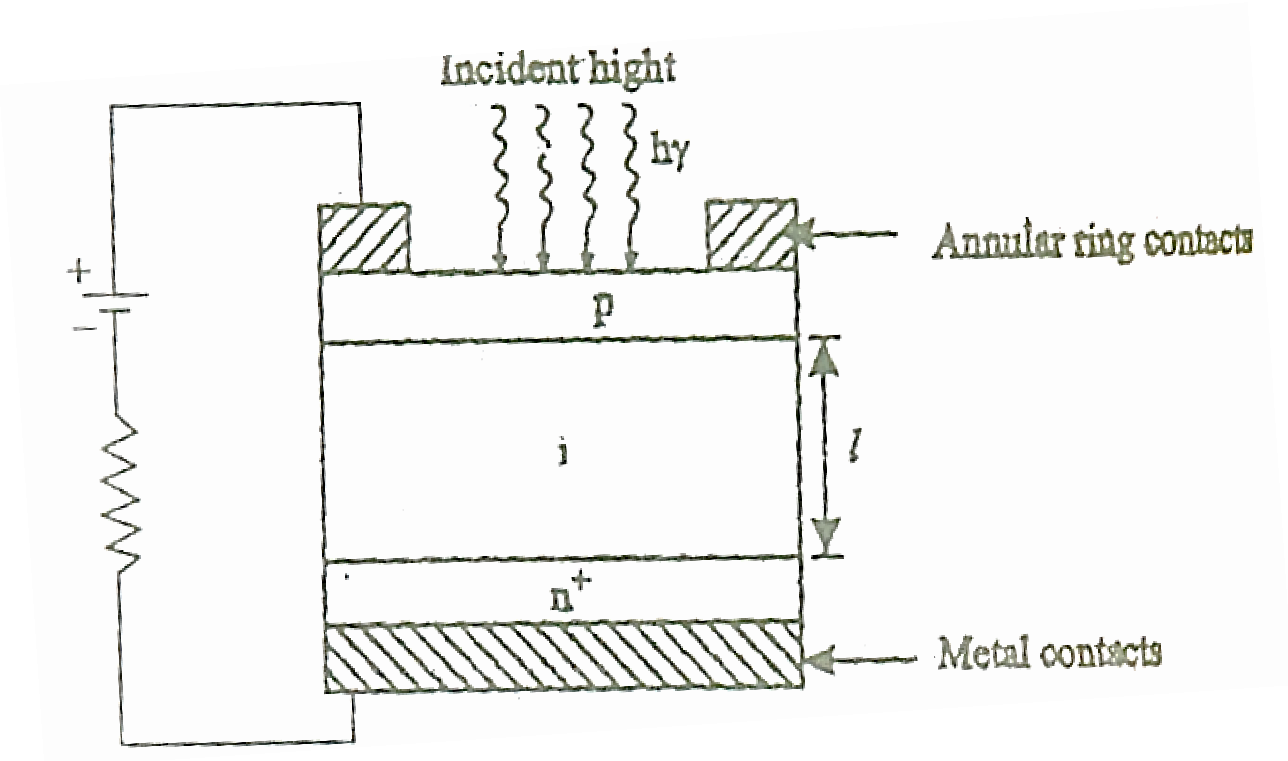
The current through the load depends upon on the intensity of the light incident on the diode.

The absorbed energy raises a bound electron across the band gap.

**PIN PHOTO DIODE:**

It is a device which consists of a p and n regions separated by a lightly doped intrinsic region.

The cross-sectional view of p-i-n photodiode is as shown.




A sufficiently large reverse bias is applied across the device. When an incident photon has energy greater than or equal to the band gap energy of the semiconductor material, an electron excites from valence band to conduction band.

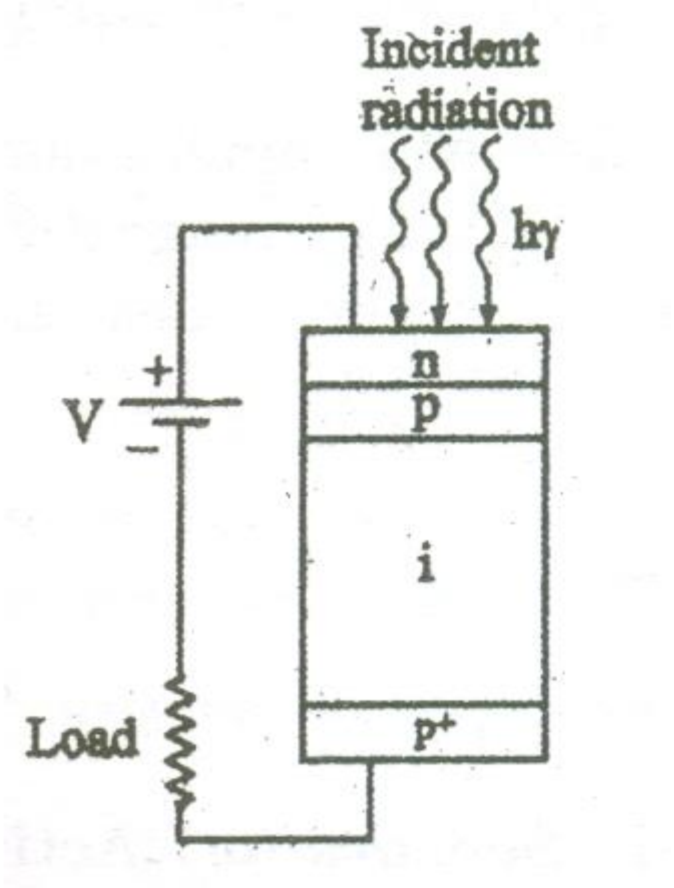
These carriers are mainly generated in the depletion region where most of the incident light is absorbed.

The high electric filed present in the depletion region causes the carriers to separate and be collected across the reverse biased junction. This gives rise to a current flow in the external circuit.

**Avalanche photo detector:**

An avalanche photodiode is more sophisticated than a p-i-n diode and it incorporates internal gain mechanism. So the photo-electric current is amplified within the detector.

This device is a reverse biased p-n junction that is operated at voltage close to the breakdown voltage.




The electron and hole pairs are generated in the depletion layer acquire sufficient energy from the field to liberate secondary electrons and holes with in the layer by impact ionization.

The secondary electron – hole pair drift in opposite directions and together with the primary carriers may produce new carriers. Thus, carrier multiplication and internal amplification occurs. This internal amplification process enhances the responsivity of the detectors.

## LIGHT EMITTING DIODES:

It is a semiconductor p-n junction diode which emits light when it is forward biased.

**Principle:**

The electrons injected into the p- region make a direct downward transition from the conduction band into valence band and they recombine with holes and emit photons of energy $E_g$.

We know that the forbidden gap energy is given by

$$E_g = h\nu \longrightarrow (1)$$

Where h = Planck's constant

$\nu$ = frequency of the emitted radiation

But we know $\nu = \frac{c}{\lambda} \longrightarrow (2)$

Substituting (2) in (1)

$$E_g = \frac{hc}{\lambda}$$

Hence, the wavelength of the emitted photon is given by relation

$$\lambda = \frac{hc}{E_g}$$

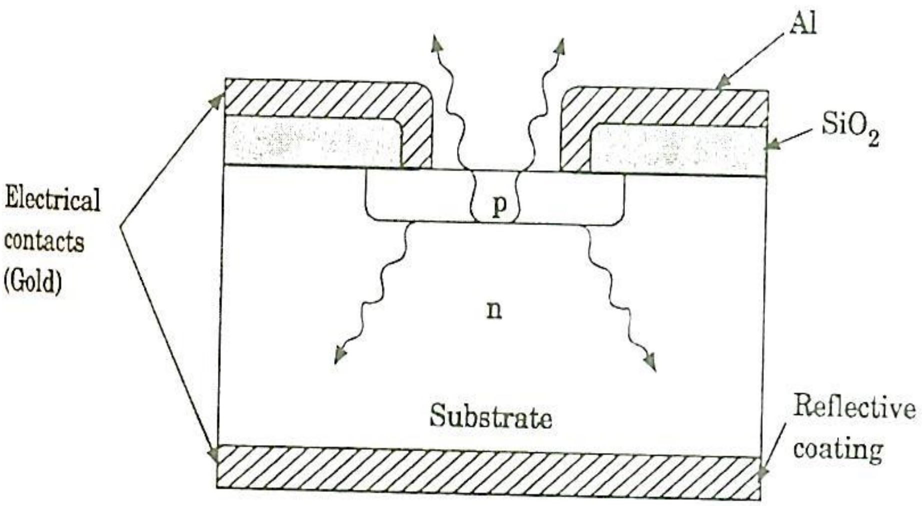
Therefore, the wavelength of the light emitted purely depends on the band gap energy.

**Construction:**

Figure shows crossectional view of a LED.

A n- type layer is grown on a substrate and a p- type layer is deposited on it by diffusion. Since carrier recombination takes place in the p-layer, it is deposited upper most.

For maximum light emission, a metal film anode is deposited at the outer edges of the p-layer. The bottom of the substrate is coated with metal (gold) film for reflecting most of the light surface of the device and also to provide connection with n- type layer.

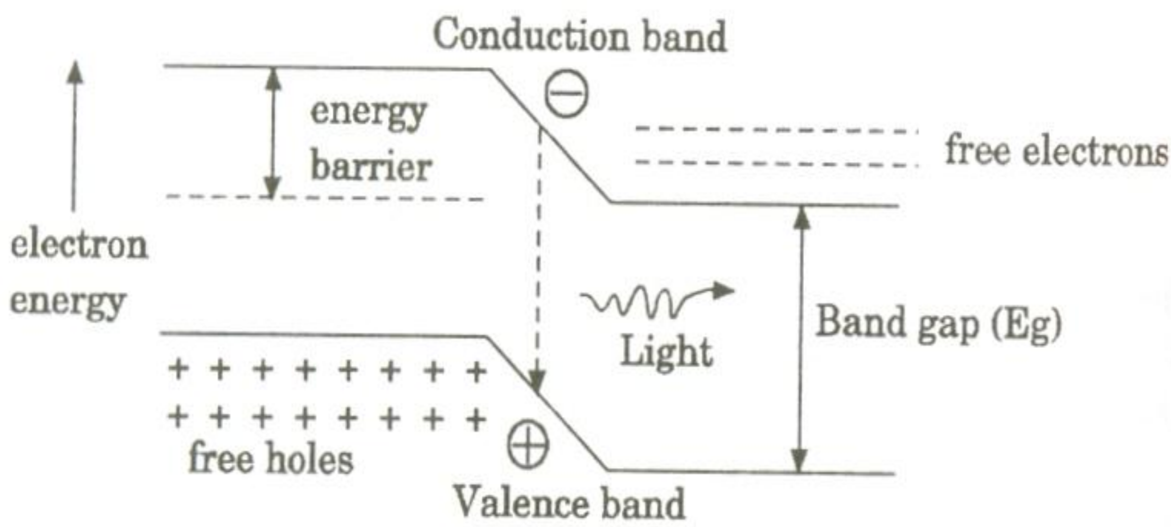



**Working:**

When the p –n junction diode is forward biased, the barrier width is reduced, raising the potential energy on the n-side and lowering that on the p-side.

The free electrons and holes have sufficient energy to move into the junction region. If a free electron meets a hole, it recombines with each other resulting in the release of a photon

Thus light radiation of the LED is caused by the recombination of holes and electrons that are injected into the junction by forward bias voltage.




**Advantages of LED:**

1. Light output is proportional to the current. Hence, the light intensity of LEDs can be controlled easily by varying the current flow.

2. LEDs are rugged and therefore withstand shocks and vibrations.
3. Varieties of LEDs are available which emit in different colours like red, green, yellow etc.
4. It has long life time and high degree of reliability.
5. It has low drive voltage and low noise.
6. It is easily interfaced to digital logic circuits.
7. It can be operated over a wide range of temperatures.

**Disadvantages of LED:**

1. It requires high power.
2. Its preparation cost is high.
3. LED is not suitable for large area display because of its high cost.
4. It cannot be used for illumination purposes.

**ANNA UNIVERSITY PART A QUESTIONS**

**1.** Give four applications of fiber optic sensors.
**2.** Explain the basic principles of fiber optic communication.
**3.** Distinguish between step index and graded index fiber
**4.** Define numerical aperture and acceptance angle
**5.** What is the principle used in PIN photo diode?
**6.** What is meant by injection luminescence?
**7.** Give any four examples for intrinsic and extrinsic sensor.
**8.** Mention the advantages of optical fiber communication systems.
**9.** What are the conditions of Total Internal reflection.

**ANNA UNIVERSITY PART B QUESTIONS**

**10.** Define numerical aperture and derive an expression for numerical aperture and angle of acceptance of fiber in terms of refractive index of core and fiber( Refer Page No 4-6)
**11.** Explain the propagation of light through optical fiber and the applications of optical fiber as waveguide and sensor.(Refer Page No 4- 6 & Page 15 & 19-22)
**12.** Describe in detail any one of the light source and detector used in fiber optic communication system( Refer Page No 28 -33)
**13.** What are different types of fiber optical sensors? Explain the working of any two sensors. ( Refer Page No 19-22)
**14.** Classify the optical fibers on the basis of materials, modes of propagation and refractive index difference.( Refer Page No 7 – 13 *Note: Need not give the difference in the answer*)

**15.** Describe how optical fiber is used in communication field. What are its advantages of it over the conventional methods?( Refer Page No 15 to 17)

**16.** Describe the construction and working of medical endoscope and give its application in medical field.( Refer Page No : 22 to 23)

**TWO MARK QUESTIONS AND ANSWERS**

1. Give four applications of fiber optic sensors.

a) Fiber optic sensors are used as optical displacement sensors, which is used to find the displacement of a target along with its position.
b) It is used as fluid level detector.
c) It is used to sense the pressure, temperature at any environment.
d) It is also used to measure the number of rotations of the fiber coil using the instrument called a gyroscope.

2. Explain the basic principle of fiber optic communication.

Total internal reflection is the principle of fiber optic communication.

**Principle:**

When light travels from a denser to rarer medium, at a particular angle of incidence called the critical angle, the ray emerges along the surface of separation. When the angle of incidence exceeds the critical angle, the incident ray is reflected in the same medium and this phenomenon is called the total internal reflection.

3. Give the application of fiber optical system.

a) It can be used for long distance communication in trunk lines.
b) A large no of telephone signals nearly 15000 can be passed through the optical fibers in a particular time without any interference.
c) It is used in computer networks especially in LAN.
d) It is also used as optical sensor.

4. Mention any four advantages of LED in electronic display.

a) Very small in size.
b) Different colours of display.
c) Works under a wide range of temperature.
d) It is a very wide range of operation.

5. Mention any four advantages of fiber optic sensors.

a) It has no external interference
b) It is used in remote sensing.

c) Safety of data transfer.
d) It is small in size.

6. Mention any two fiber optic sources.

a) Light emitting diode (LED) in LED we have two types 1.planar 2.dome shaped LED.
b) Laser diodes (LD). In laser diodes we have homojunction laser heterojunction laser injection laser diode etc.

7. What is meant by injection luminescence? Give examples.

When the majority careers are injected from P to N and N to P region, they become excess minority carriers. Then this excess minority carrier diffuses away from the junction and recombines with the majority carriers in P and N region and emits light. This phenomenon is known as injection luminescence.

8. What is meant by LED? Give its principle.

An LED is the abbreviation of light emitting diode. It is a semiconductor P N junction diode which converts electrical energy to light energy under forward biasing.

9. What is the principle used in PIN photodiode?

This diode works in reverse bias. Under reverse bias when light is made to fall on the neutral or intrinsic region electron hole pairs are generated. These electrons and holes are accelerated by the external electric field, which results in photo current. Thus light is converted into electrical signal.

10. Give any four examples of intrinsic sensor.

a) Pressure sensor
b) Liquid level sensor
c) Phase and polarization sensor.
d) Optical fiber flow sensor.

11. 10. Give any four examples of extrinsic sensor.

a) Displacement sensor
b) Laser Doppler velocimter sensor
c) Fluor optic temperature sensor
d) Current measurement sensor

12. State the applications of optical fibers in medical field.

a) Fiber optics endoscopes are used in medical diagnosis
b) It is used to visualize the inner organs of the body

c) Fibers as endoscopes are used in various medical fields such as cardioscopy, laparoscopy, cryoscopy etc.

13. What is meant by attenuation?

It is defined as the ratio of the optical power ($P_{out}$) from a fiber of length 'L' to the power input ($P_{in}$).

$$\text{Attenuation } = (\alpha) = \frac{-10}{L} \log \frac{P_{in}}{P_{out}} \, dB/Km$$

14. Mention the advantages of optical fiber communication over radio wave communication.

a) Optical communication can be made even in the absence of electricity

b) The optical signals are not affected by any electrical signals or lightening

c) Optical fiber communication is free from electromagnetic interference(EMI)

d) This type of communication is suitable to any environmental conditions

e) Easy maintenance, longer life, economical and high quality signal transmission are the additional features of optical fiber communication.

15. What are the losses that occur during optical fiber communication?

During the transmission of light through the optical fiber, three major losses will occur, viz., attenuation, distortion, and dispersion.

Attenuation is mainly caused due to absorption, scattering and radiation of light inside the fibers.

Distortion and dispersion occurs due to spreading of light and also due to manufacturing the defects.

16. What are the conditions of Total Internal reflection?

a) Light should travel from denser medium to rarer medium

b) The angle of incidence($\Phi$) on core should be greater than critical angle ($\Phi_c$)

$$\Phi > \Phi_c$$

c) The refractive index of the core ($n_1$) should be greater than the refractive index of the cladding ($n_2$).

$$n_1 > n_2$$