UNIT-II LASER AND FIBER OPTICS

LASER:

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 as 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 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.

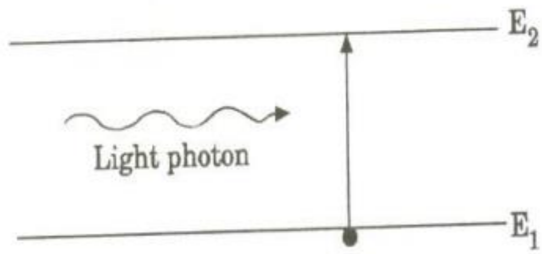
Methods of pumping action:

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:

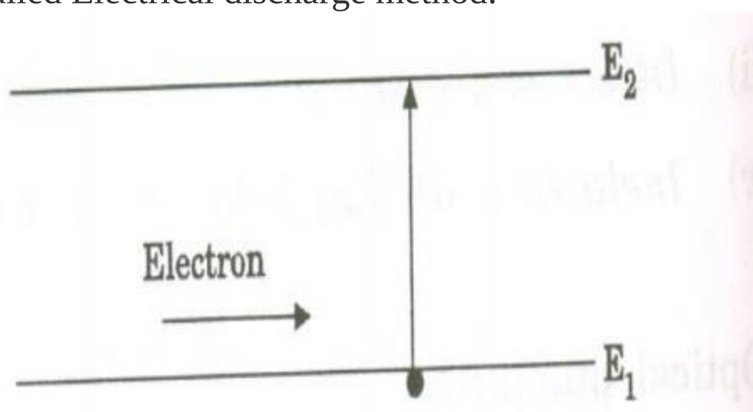
When the atoms are exposed to light radiations energy hv , atoms in the lower energy state absorb these radiations and they go to the excited state. This method is called Optical pumping. It is used in solid state lasers like ruby laser and Nd-YAG laser. In ruby laser, xenon flash lamp is used as pumping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

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

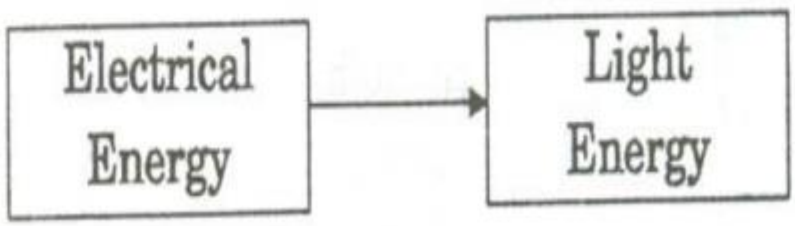
Where A – gas atom in the ground state

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 .

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

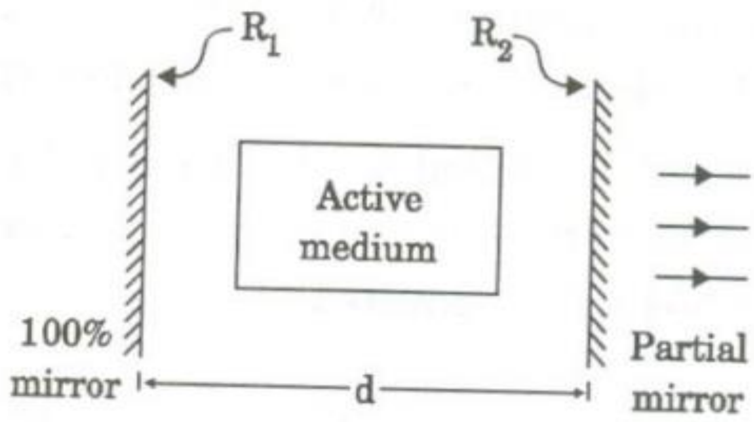
Now A* atoms at higher energy state collide with b atoms in the lower state. Due to inelastic atom - atom collision B atoms gain energy and they are excited to a higher state B* . Hence, A atoms lose energy and return to lower state.

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

Optical resonator

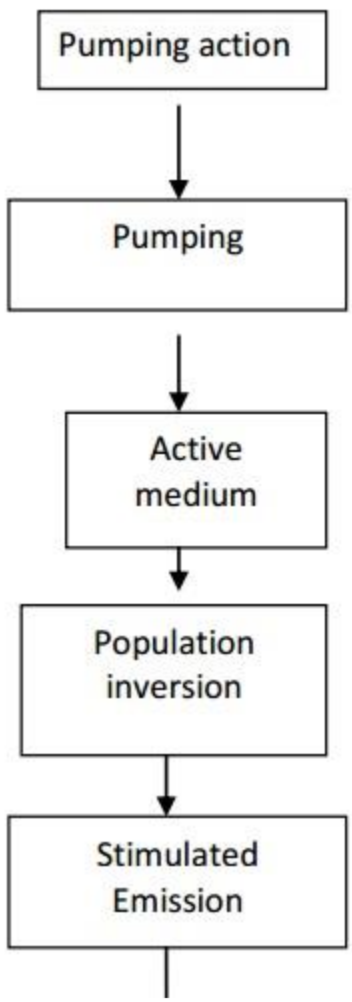
An optical resonator consists of a pair of reflecting surfaces in which one is fully reflecting (R1) and the other is partially reflecting (R2). The active material is placed in between these two reflecting surfaces.

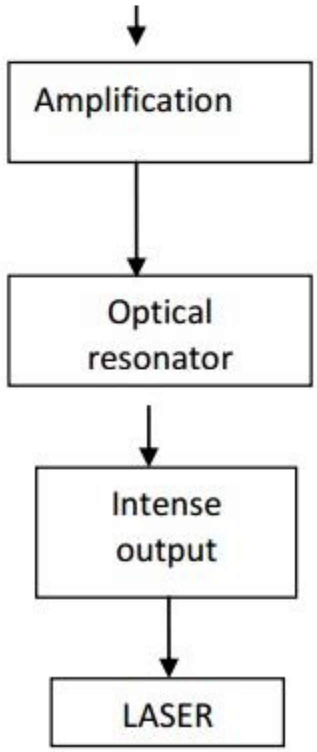
The photons generated due to transitions between the energy states of active material are bounced back and forth between two reflecting surfaces.



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

Flow Chart of Laser action





Types of Laser

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

TYPE OF LASER with 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: SeOCL2 Laser, Europium Chelate Laser
4. Dye laser: Rhodamine 6G laser, Coumarin dye laser
5. Semiconductor Laser: GaAs laser, GaAsP laser

Principle of Spontaneous and Stimulated emission – Einstein's Quantum theory of radiation / Einstein's A and B relation:

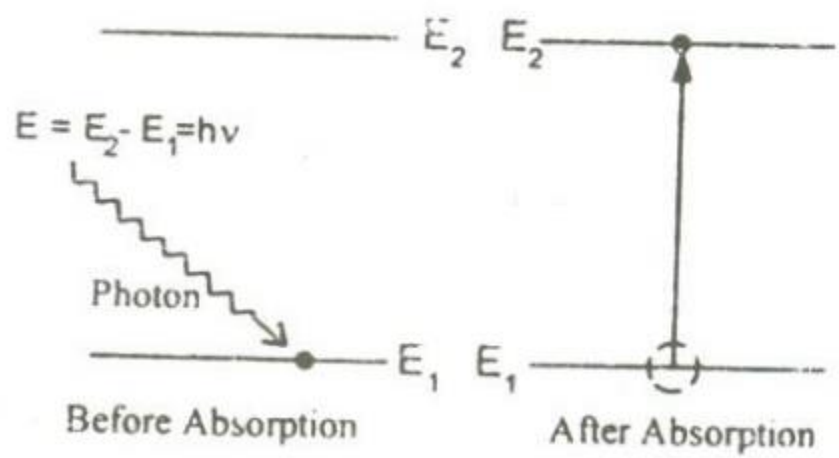
We know that, when light is absorbed by the atoms or molecules, then it goes from the lower energy level (E_1) to the higher energy level (E_2) and during the transition from higher energy level (E_2) to lower energy level (E_1) the light is emitted from the atoms or molecules.

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 (ρ_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 B12 is a constant which gives the probability of absorption of absorption transition per unit time.

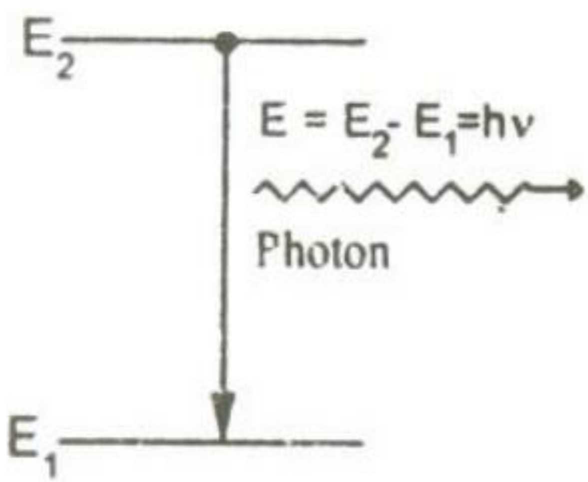
Normally, the atoms in the excited state will not stay there for a long period of time, rather it comes to ground state by emitting a photon of energy E=hν Such an emission takes place by one of the following two methods.

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

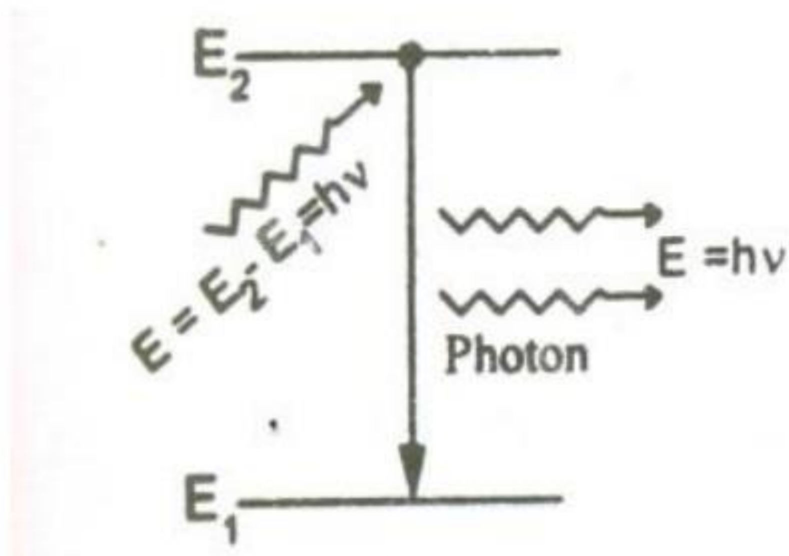
The rate of spontaneous emission is $R_{21}(SP) \propto N_1$

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

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 B21 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 $$\therefore \rho_v = \frac{A_{21}}{B_{12}\dfrac{N_1}{N_2} - B_{21}} \longrightarrow \qquad (4)$$

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 $(E_2 - E_1) = h\ddot{\nu}$, 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

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

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

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

Comparing (9) and (10) we get

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

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 $R_{21}(SP) = A_{21}N_2$

Stimulated Emission

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Spontaneous emission

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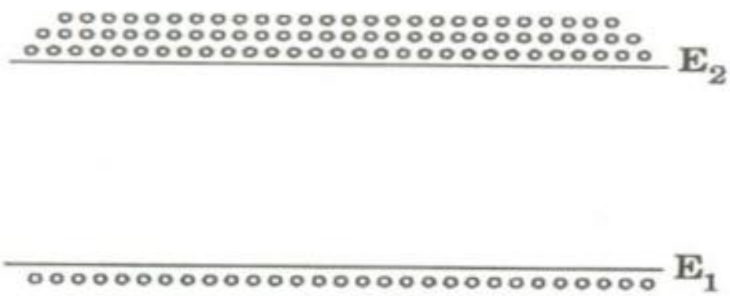
2. The emitted photons move in all directions and are random
3. The radiation is less intense and is incoherent.
4. The photons are not in phase (i.e.) there is no phase relationship between them.

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.

Semiconductor Diode laser:

Definition:

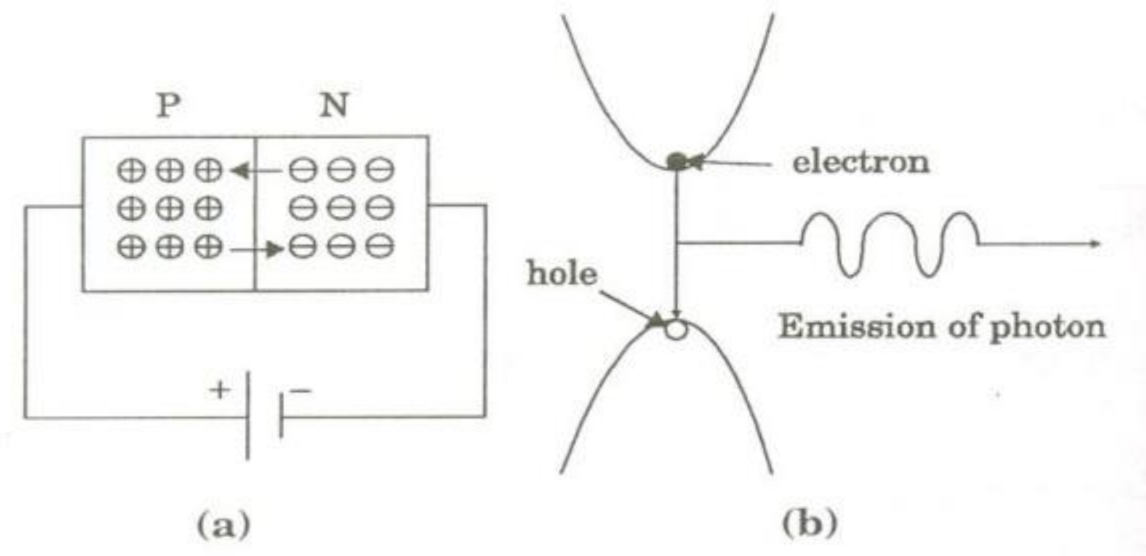
It is specifically fabricated p-n junction diode. This diode emits laser light when it is forward biased.

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.

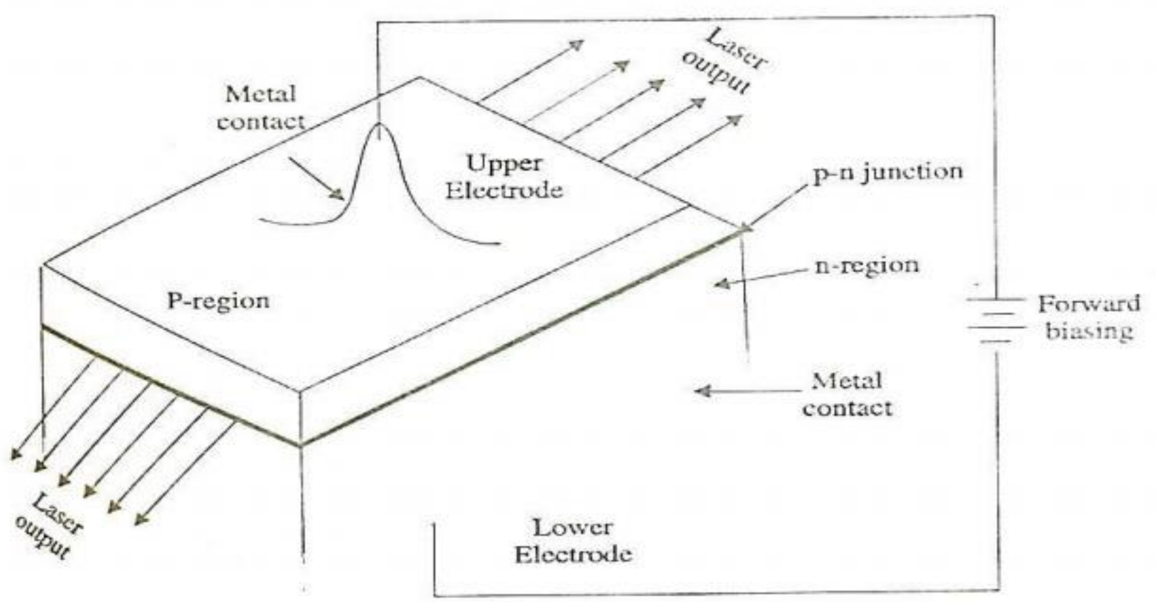
During the recombination process, the light radiation (photons) is released from a certain specified direct band gap semiconductors like Ga-As. This light radiation is known as recombination radiation.

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.



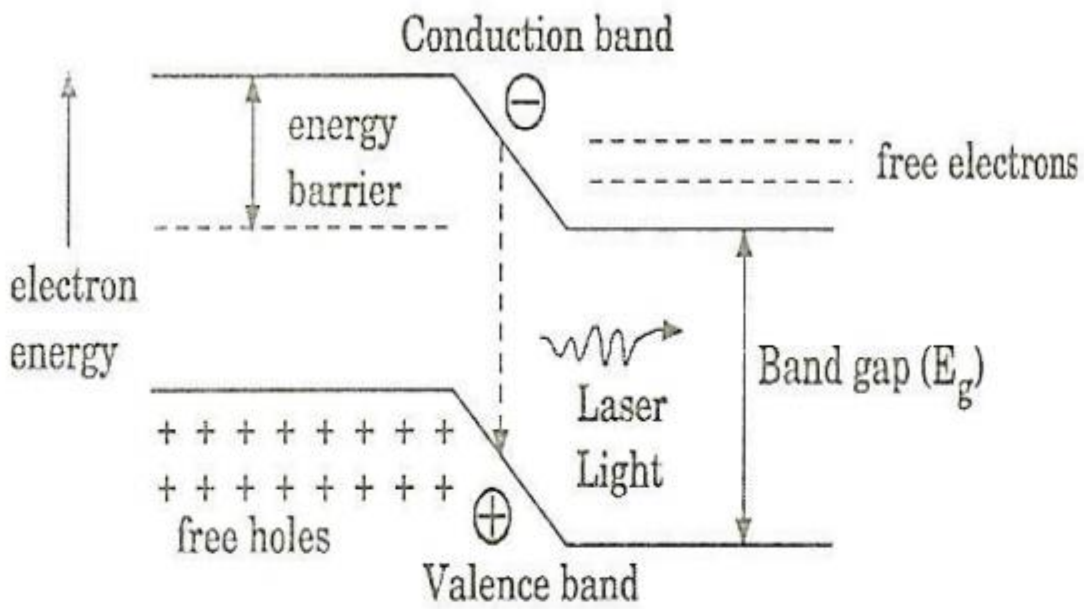
The platelet consists of two parts having an electron conductivity (n-type) and hole conductivity (p-type).

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 $8400^{o}A$. 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 $8500^{o}A$.

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 ($400A/mm^2$).
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.

HETERO JUNCTION LASER

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

Principle:

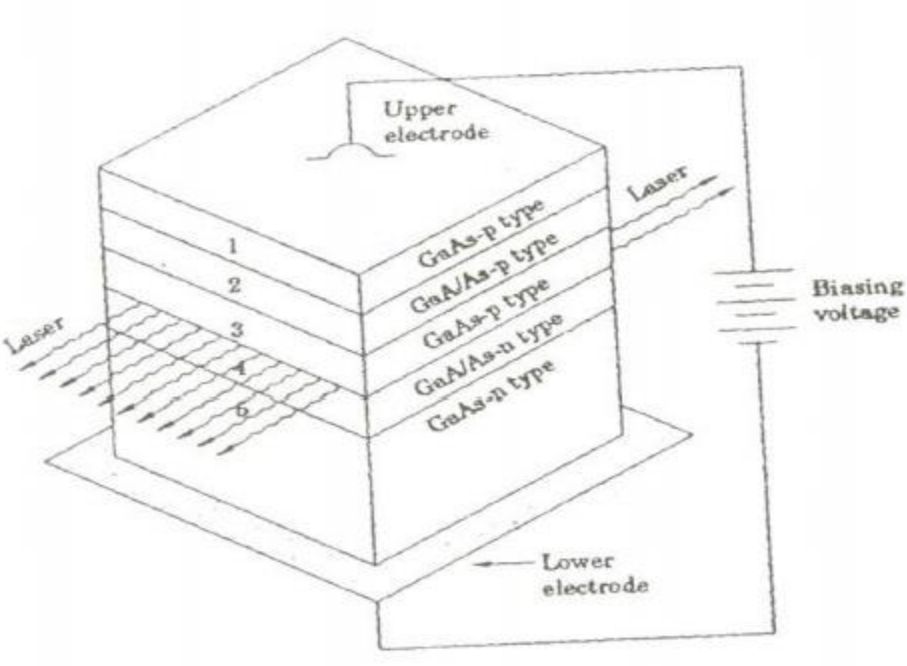
When a PN junction diode is forward biased, the electrons from the n region and holes from the p region recombine with each other at the junction. During recombination process, light is released from certain specified direct band gap semiconductors.

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 (4^{th} layer).

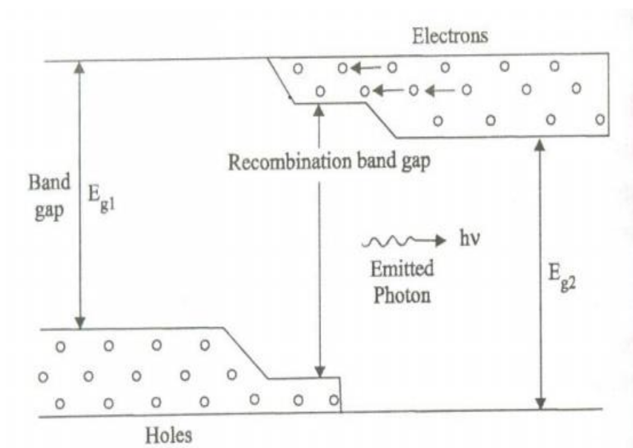
The end faces of the junctions of 3^{rd} and 4^{th} layer are well polished and parallel to each other. They act as an optical resonator.



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 ^{o}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 $\overset{0}{A}$

Description of heterojunction semiconductor laser

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^{o} 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.

FIBER OPTICS

Introduction:

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.

Optical fiber:

The optical fiber is a wave guide.
It is made up of transparent dielectrics (SiO_2), (glass or plastics).

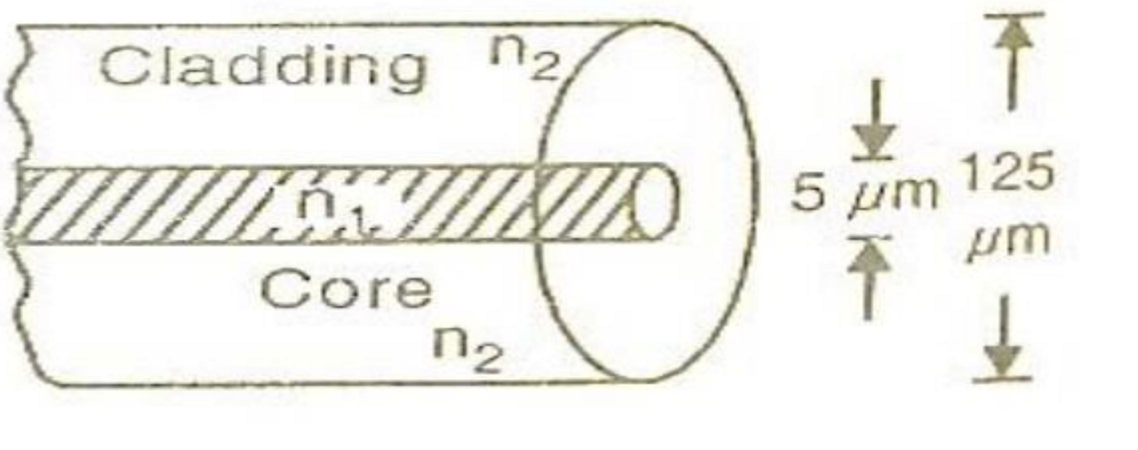
Fiber Construction:

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.

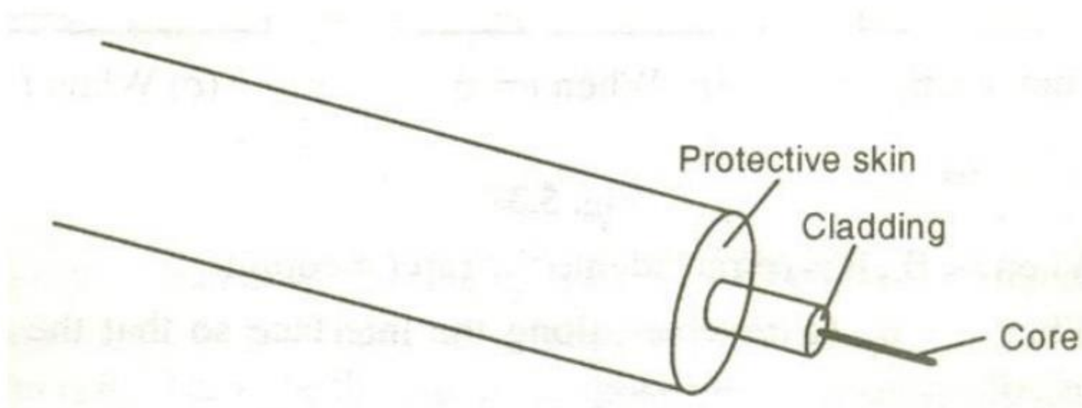
The light is transmitted through this fiber by total internal reflection. The fiber guides light waves to travel over longer distance without much loss of energy.



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.***

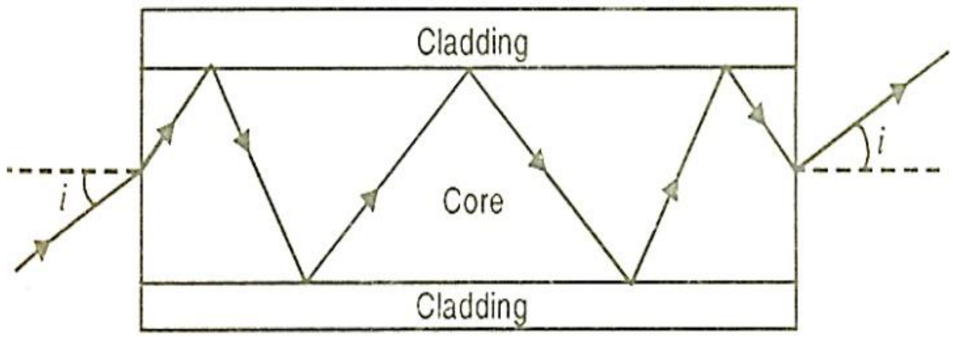
Refractive index:

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.



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.

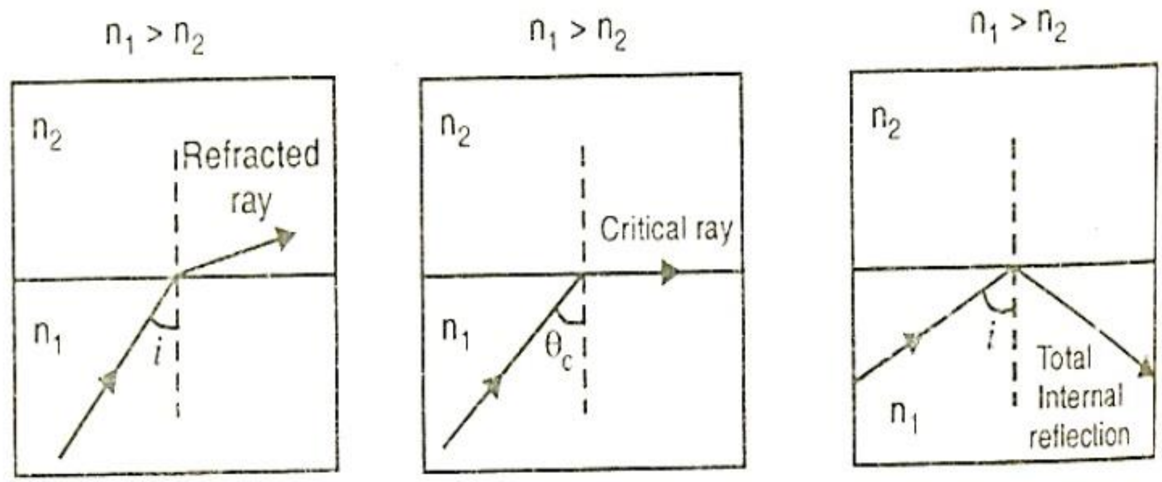


Total internal reflection at the fiber wall can occur only if two conditions are satisfied.

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 ie., $n_1 > n_2$.



(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,

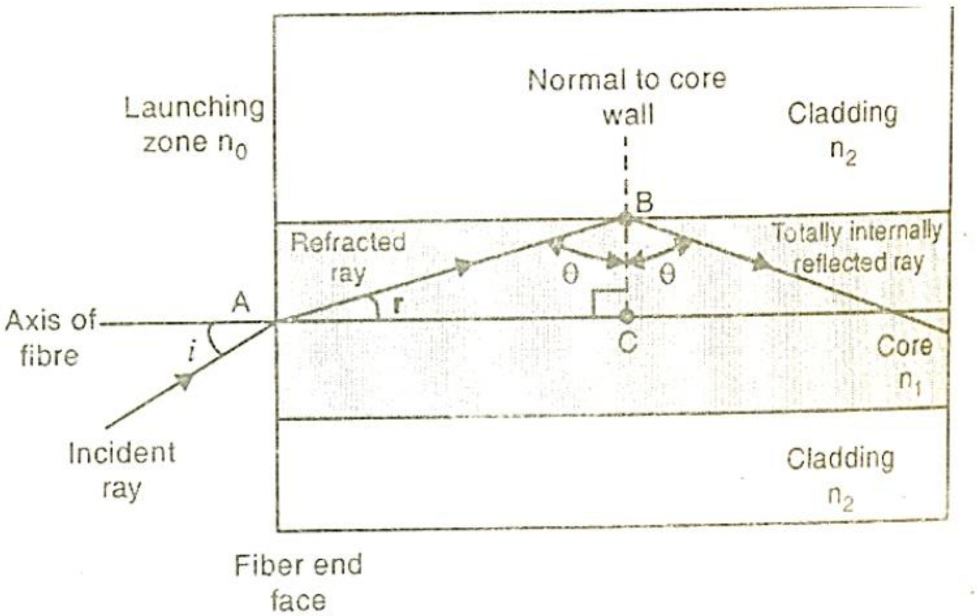
$$n_1 \sin\theta_c = n_2 \sin 90^0$$

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

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 θ_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.

$$\text{In triangle ABC, } r = 90 - \theta \longrightarrow (1)$$

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

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

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

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

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

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

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

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

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

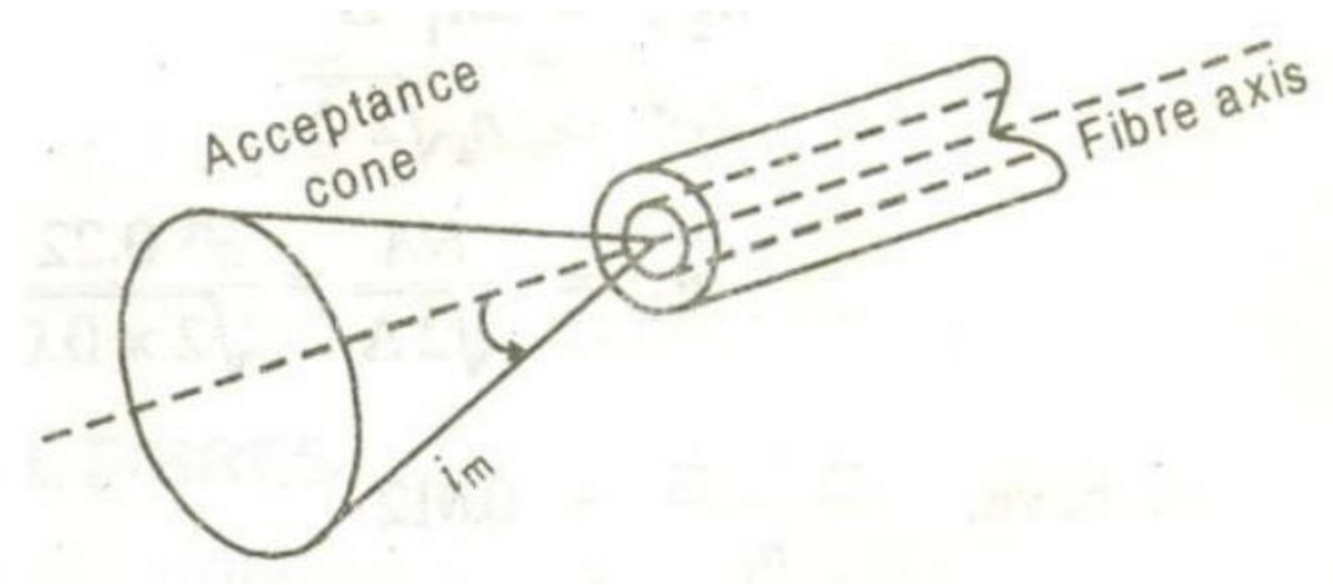
Definition: Acceptance angle is defined as the maximum angle that a light ray can have relative to the axis of the fiber and propagate down the fiber.

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 Δ

$$n_1\Delta = n_1 - n_2$$

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

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

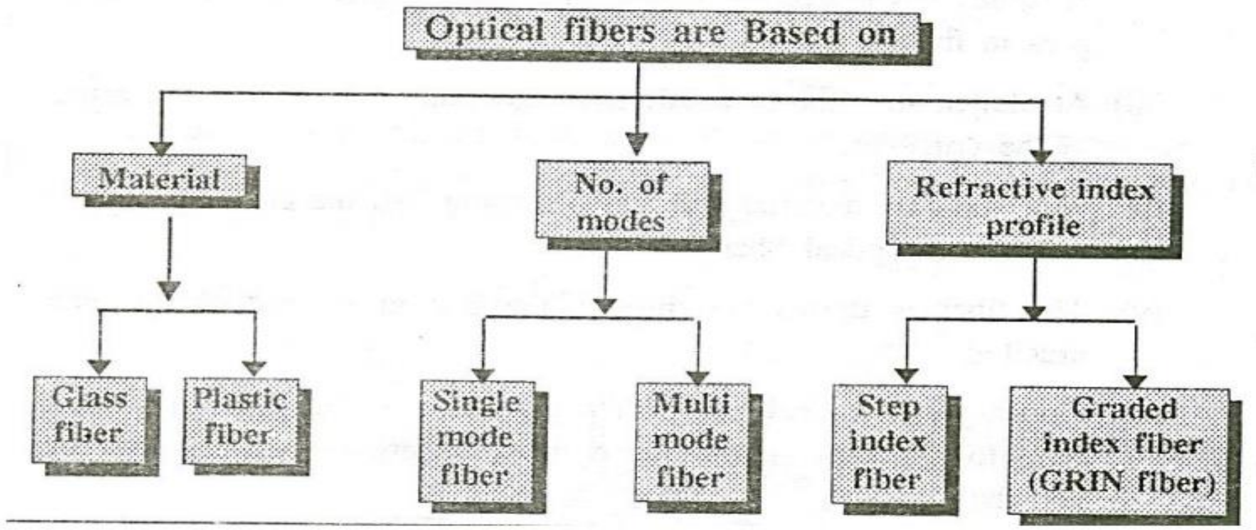
If $n_1 = n_2$, then $NA = \sqrt{2n_1^2\Delta}$

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

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



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

1. ***Glass fiber***: It is made up of mixture of silica glasses and metal oxides.
Example:
Core: SiO_2 Cladding: SiO_2
Core: GeO_2- SiO_2 Cladding: SiO_2

2. ***Plastic fiber:*** It is made up of plastics.
Example:
Core: Polymethyl Methacrylate: Cladding: Co- Polymer
Core: Polystyrene: Cladding: Methyl methacrylate

II. **Based on the number of modes, they are classified as**

1. Single mode fiber
2. Multimode fiber

MODES OF PROPAGATION:

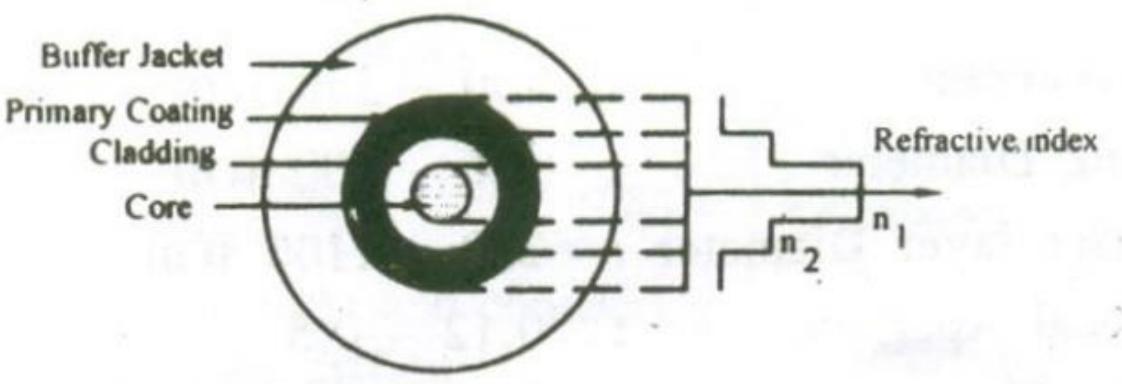
Light propagates as electromagnetic waves through an optical fiber. All waves, having ray directions above the critical angle will be trapped within the fiber due to total internal reflection. However, all such waves do not propagate through the fiber. Only certain ray directions are allowed to propagate. 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. ***Axial ray that travels along the axis of the fiber is called zero order rays***.

A. SINGLE MODE FIBERS:

1. It has a very small core diameter so that it can allow only one mode of propagation and hence called single mode fibers.
2. These types of fibers are made from doped silica.
3. In general, the single mode fibers are step – index fibers.
4. It has a small refractive index difference between core and cladding.
5. 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

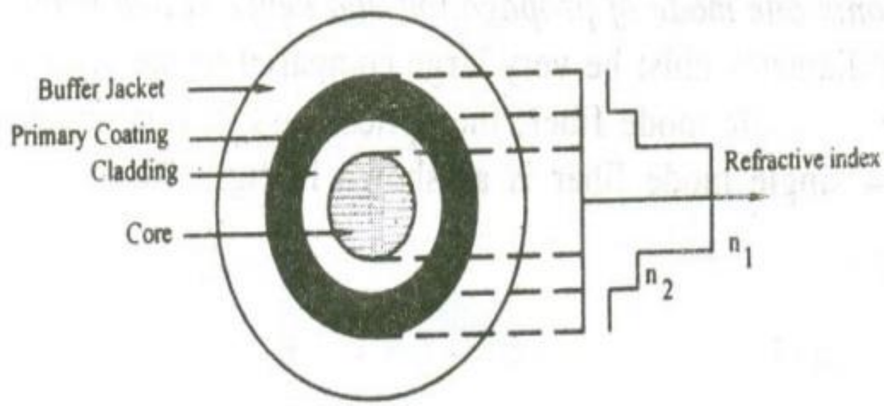
Band width: More than 50MHz.

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

B. MULTI- MODE FIBERS

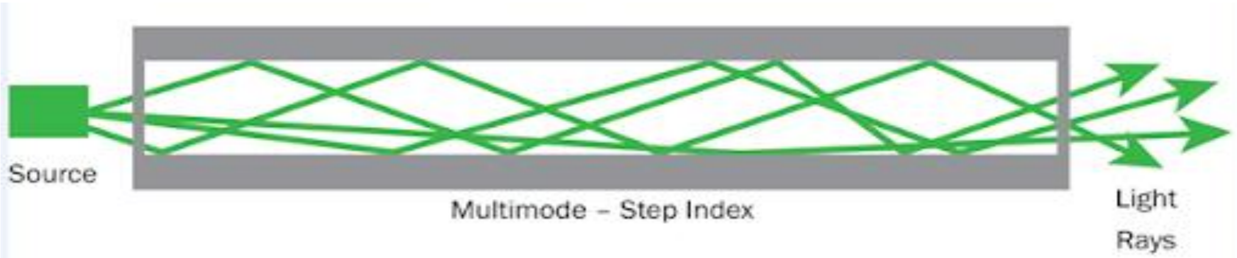
1. Here the core diameter is very large compared to single mode fibers, so that it can allow many modes to propagate through it and hence called as Multi mode fibers.
2. The cladding diameter is also larger than the diameter of the single mode fibers.
3. The multimode fibers are useful in manufacturing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

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

λ = 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.

III. <u>BASED ON REFRACTIVE INDEX PROFILE:</u>

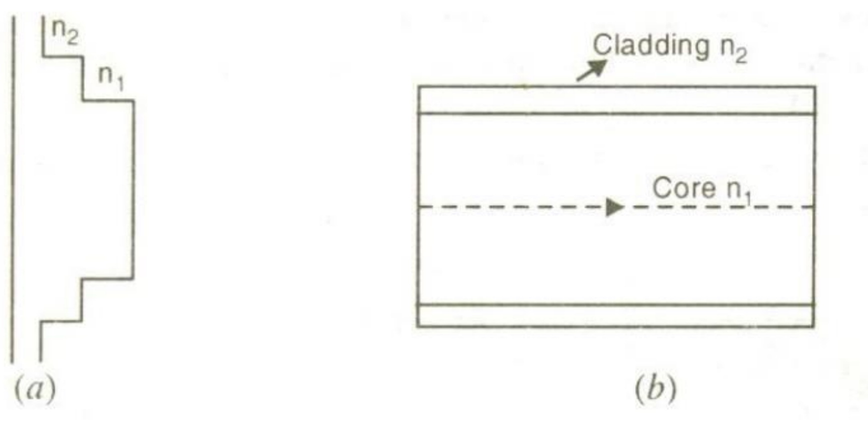
In optical fiber, cladding has uniform refractive index, but core either remains same or vary in a particular way.

1. Step- index fiber
2. Graded index fiber

<u>Refractive index profile:</u> Curve denoting variation of refractive index with respect to radial distance from axis of the fiber.

A. SINGLE MODE STEP INDEX FIBER

1. A single mode step index fiber consists of a very thin core of uniform refractive index surrounded by a cladding of same refractive index but lower than that of core.
2. 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.



Characteristics:

1. Thin core diameter
2. NA is small
3. Supports only one mode of light transmission
4. No signal loss
5. Higher bandwidth than multimode.

Advantages:

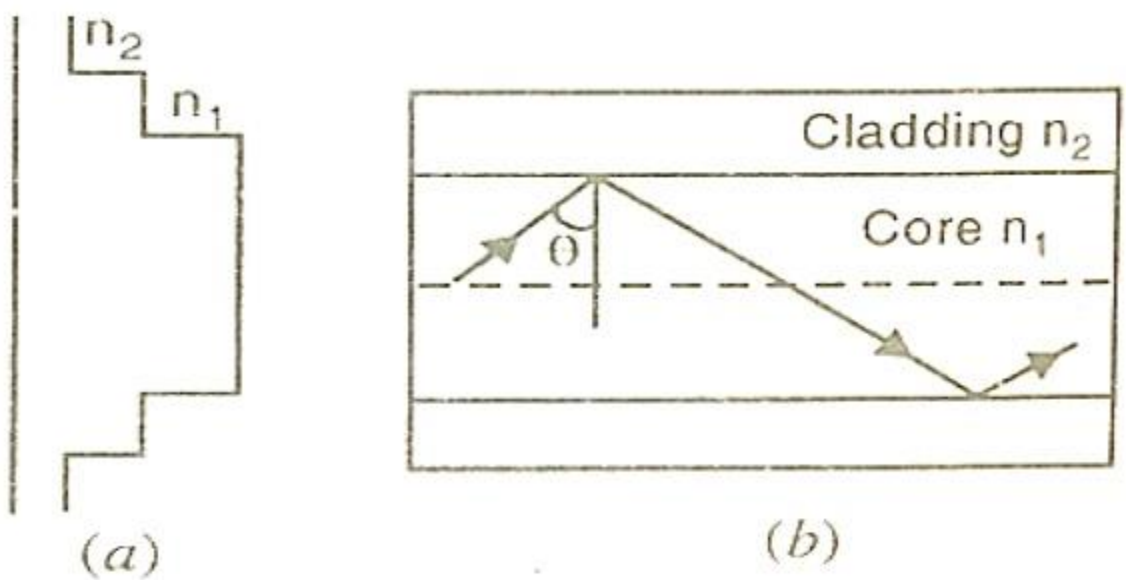
1. High rate of data transmission
2. No degradation of signal

Disadvantages:

1. Manufacturing and handling is very expensive.

B. MULTIMODE STEP INDEX FIBER

1. 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.
2. The refractive index abruptly changes at the core cladding boundary.
3. The core is of large diameter. Light follows zigzag paths inside the fiber. Many such zigzag paths of propagation are permitted in Multimode Fiber.
4. The Numerical Aperture of a Multimode fiber is larger as the core diameter of the fiber is larger.



Characteristics:

1. Large core diameter
2. Low bandwidth
3. Light is passed into multimode fiber using LED
4. Large NA and high attenuation.

Advantages:

1. Easier to operate since LED is used as source
2. Less expensive and require less complex circuitry
3. Easier to couple the fibers.

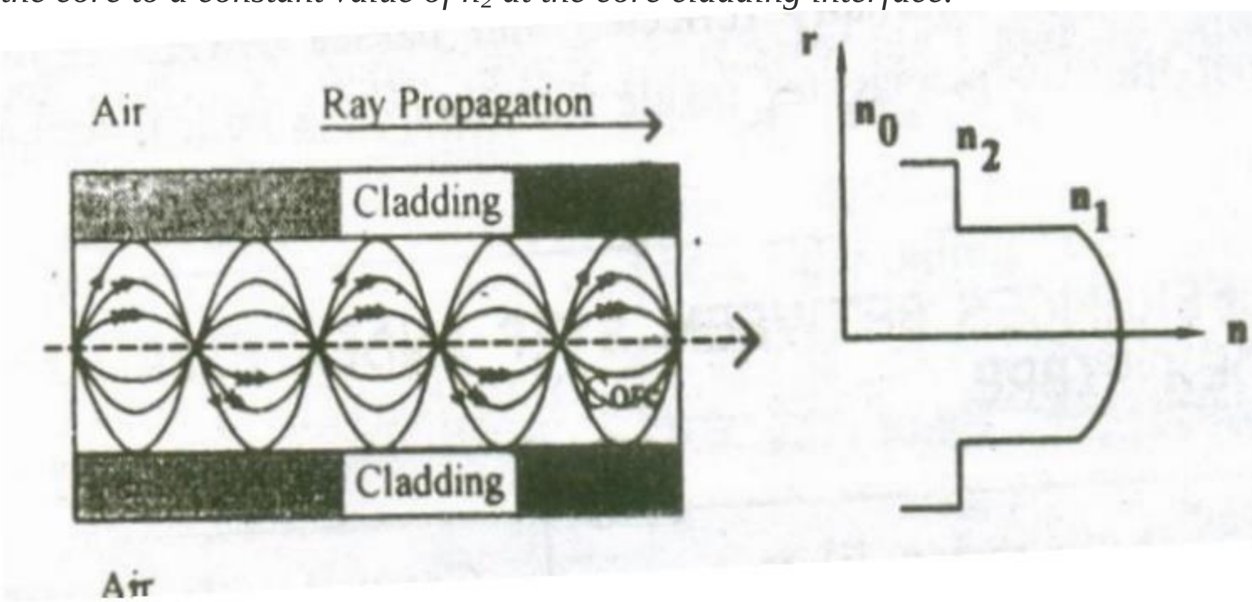
Disadvantages:

1. They suffer from internal dispersion loss
2. Low band width
3. Data transmission is less efficient.

Application: Data links requiring low bandwidth.

GRADED INDEX FIBER (GRIN)

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 throughout 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 $\Delta\tau = \tau_{\max} - \tau_{\min} = \frac{n_2 L}{2c}\Delta^2$

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

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.

Characteristics:

1. Small NA
2. Has intermediate bandwidth
3. Low attenuation
4. Light source –LED or LASER

Advantages:

1. High quality fiber, good bandwidth
2. Intermodal dispersion is reduced.

Disadvantages:

1. Most expensive of all types of fibers
2. Fabrication is difficult
3. Coupling of fibers and light source is difficult.

Application: Medium distance applications.

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.

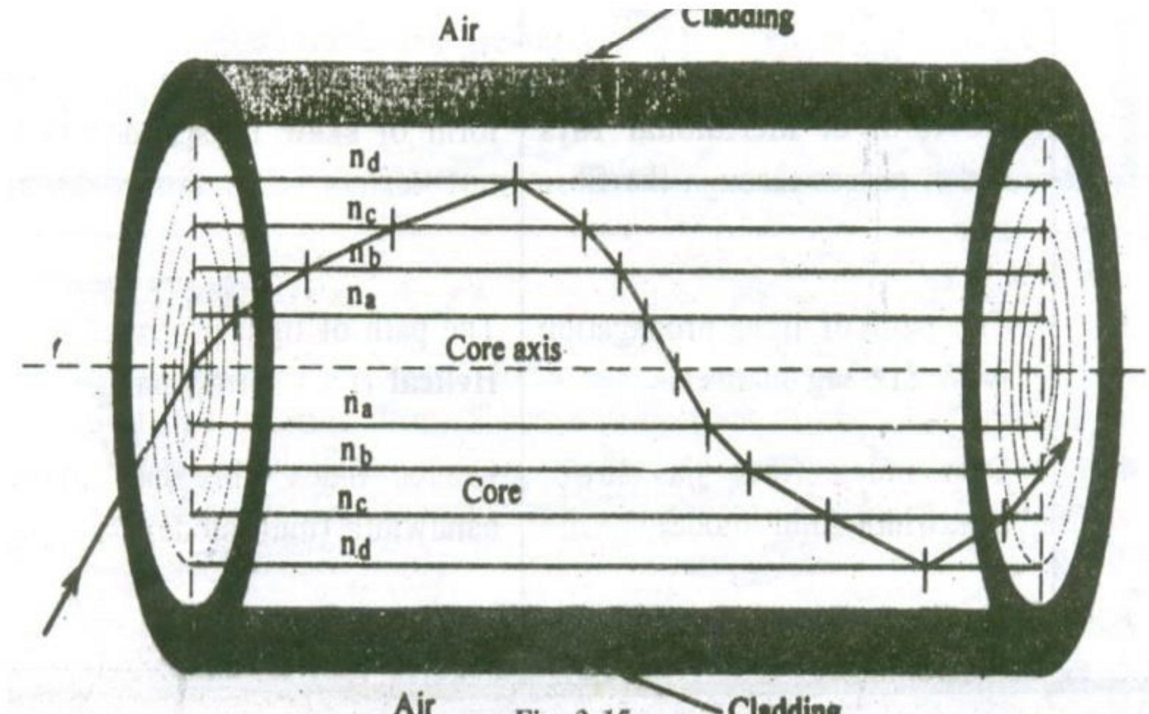


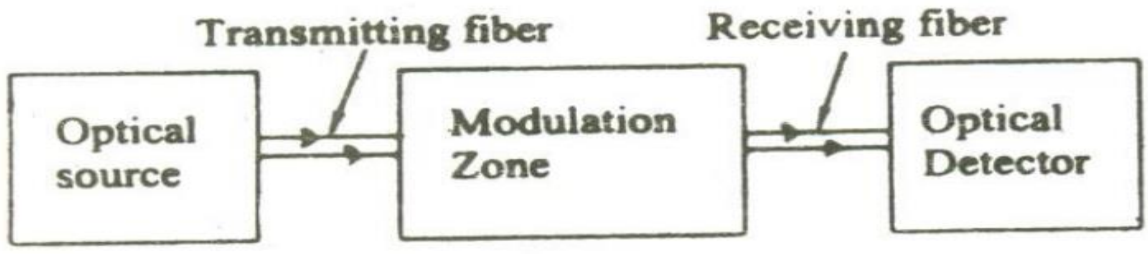
Fig. 3.15

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.***

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.

1. TYPES OF SENSORS

There are two types of sensors, viz.

i. Intrinsic sensors or Active sensors

ii. Extrinsic sensors or Passive sensors

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:

(a) Temperature /Pressure Sensor (Phase and polarization sensor) and
(b) Liquid level sensor.

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.

Example:

(a) Displacement sensor
(b) Laser Doppler velocimeter sensor

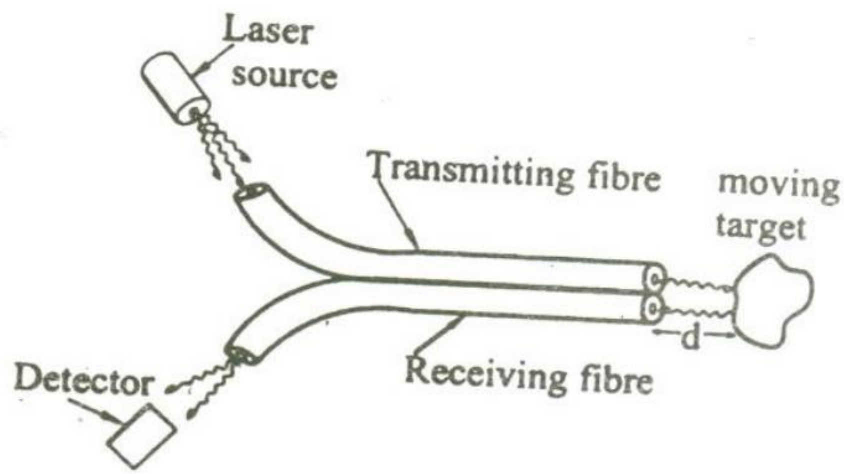
DISPLACEMENT SENSOR (EXTRINSIC SENSOR)

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 pass 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.

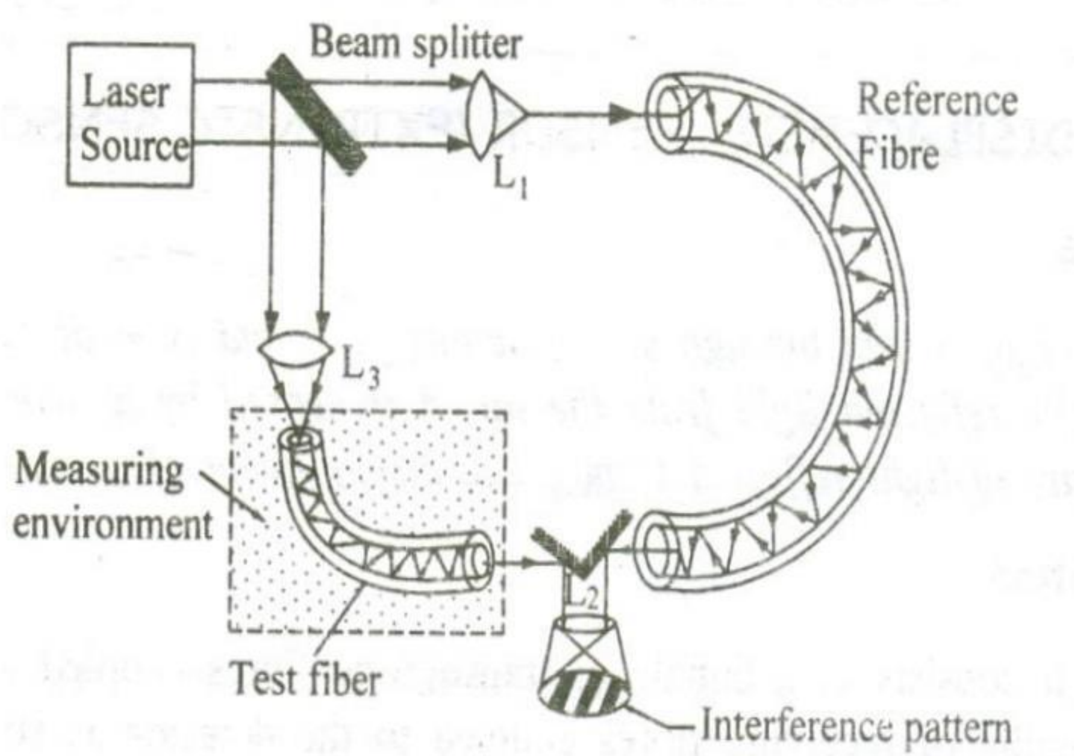
TEMPERATURE/PRESSURE SENSOR

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

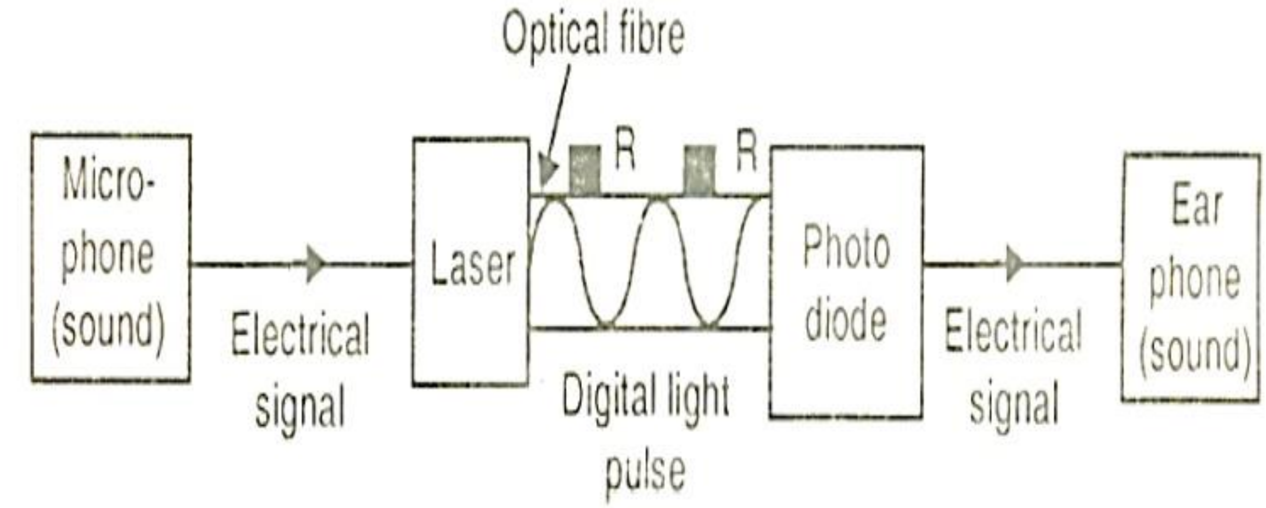
ii. ***Test fiber*** kept in the environment to be sensed, are placed as shown in the figure. Separate lens systems are provided to split and to collect the beam.

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 L1 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 L2.
5. The splitted beam passes through the Lens L3 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 L2.
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.

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.



1. Sound is first converted into electrical signal by a microphone.
2. The electrical signals modulate the intensity of light from laser.
3. Then the information is carried along the fiber in a digital form.
4. 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.
5. At the receiving place, a photodiode converts the digital light pulses into corresponding electrical signals.
6. 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.

THE FIBER OPTIC COMMUNICATION SYSTEM

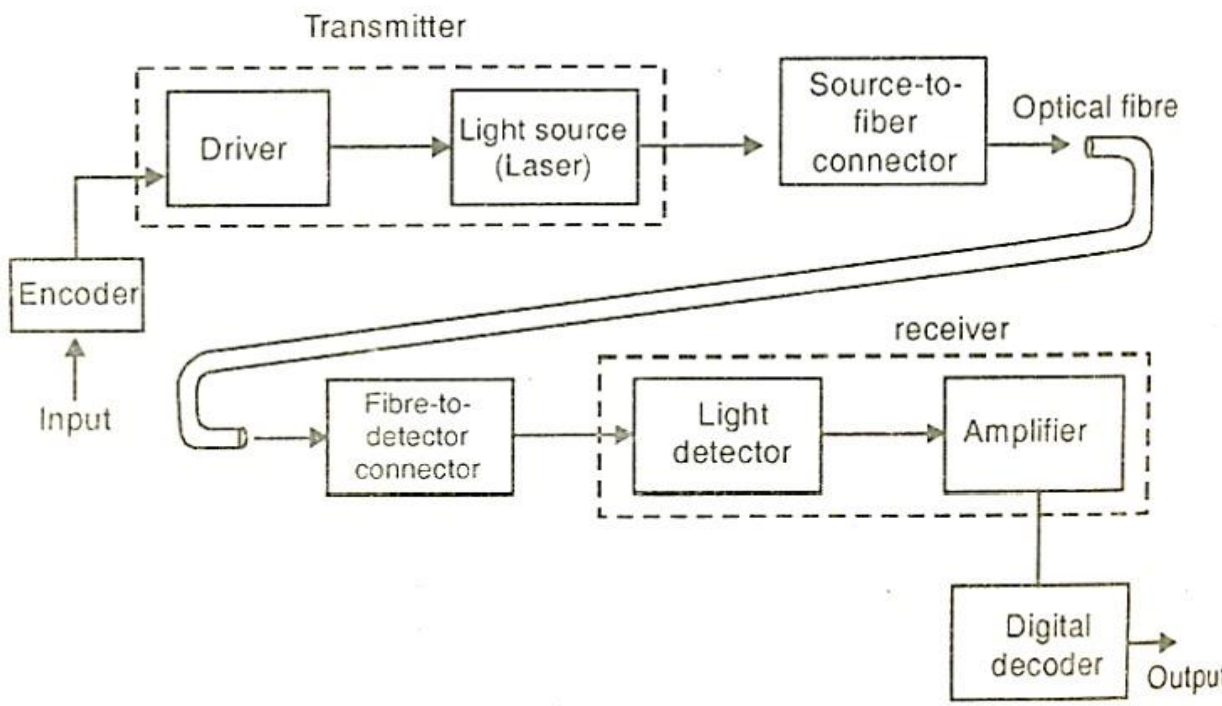
Figure shows the schematic diagram of a fiber optic communication system. The major components of an optical fiber communication system are

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.

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

2. The optical fiber acts as a wave guide and transmits the optical pulses towards the receiver, by the principle of total internal reflection.
3. The light detector receives the optical pulses and converts them into electrical pulses. These signals are amplified by the amplifier.

4. The amplified signals are decoded by the decoder.

ADVANTAGES:

1. Extremely wide bandwidth.

    Optical frequencies are very large (1015 Hz) as compared to radio frequencies (106Hz) and microwave frequencies (1010 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.

    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

    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

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

5. Signal security

    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.

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).

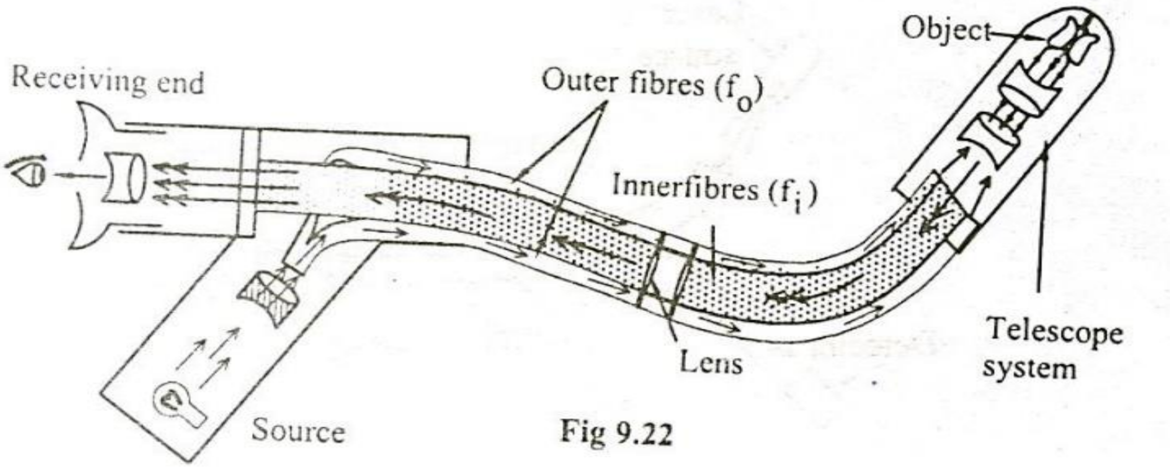


Fig 9.22

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 (f0). 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 (fi).

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 (C1) and (ii) Irrigation channel (C2) used for the following purposes.

Instrumentation channel (C1):

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

Irrigation channel (C2):

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.