

UNIT-II

Optical fiber transmission media

* optical fiber types :-

→ The types of optical fiber depends on the refractive index, materials used, and mode of propagation of light.

* The classification based on the refractive index is as follows,

* Step index fiber

* Graded index fiber

* Step index fiber :-

→ The optical fiber in general, with a core of constant refractive index n_1 and a cladding of slightly lower refractive index n_2 is known as "step index fiber". Because its refractive index makes a step change at the core-cladding interface.

→ The general refractive index profile for a step index fiber can be given as,

$$n(r) = \begin{cases} n_1 & r < a \text{ (core)} \\ n_2 & r \geq a \text{ (cladding)} \end{cases}$$

→ which illustrates two types of step index fibers.

They are,

* Single mode step index fiber

* multimode step index fiber

* Graded index fiber :-

→ Graded index fibers do not have a constant refractive index in the core but a decreasing core index $n(r)$ with radial distance from a maximum value of n_1 at the axis to a constant value n_2 .

beyond the core radius in the cladding. This index variation can be given as,

$$n(r) = \begin{cases} n_1 \left[1 - 2\Delta \left(\frac{r}{a} \right)^\alpha \right]^{1/2} & r < a \text{ (core)} \\ n_2 \left(1 - 2\Delta \right)^{1/2} = n_2 & r \geq a \text{ (cladding)} \end{cases}$$

where,

$\Delta \rightarrow$ is the relative index difference

$\alpha \rightarrow$ profile parameter which gives the characteristics refractive index profile of the fiber core.

\Rightarrow The number of modes in a graded-index fiber is,

$$M = \frac{\alpha}{\alpha+2} a^2 k^2 n_1^2 \Delta$$

where,

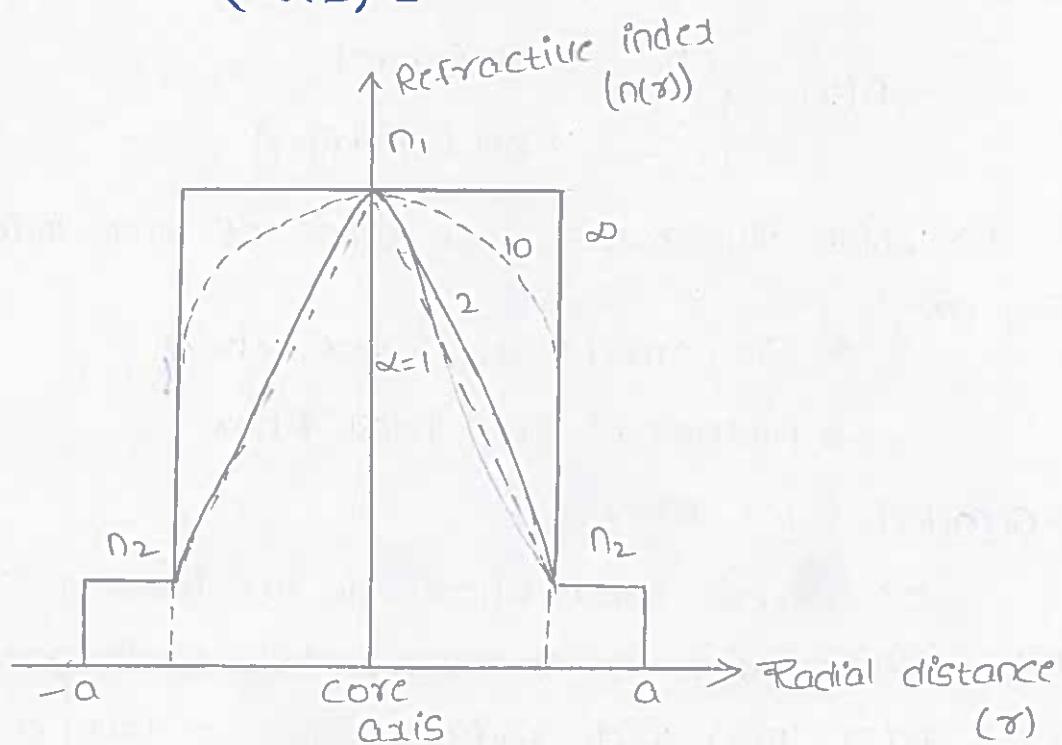
$a \rightarrow$ Index profile

$k \rightarrow$ Free space propagation constant = $\frac{2\pi}{\lambda}$

$n_1 \rightarrow$ Refractive index of core

$\Delta \rightarrow$ Refractive index difference = $\frac{n_1 - n_2}{n_1}$

$$\therefore M = \left(\frac{\alpha}{\alpha+2} \right) \frac{a^2}{2}$$



* Light propagation:-

- When the wavelength of light is much smaller than the object which encounters the wave fronts appear as straight lines to this object (or) opening.
- In this case, the light can be represented as a plane wave and its direction of travel can be indicated by a light ray which is drawn perpendicular to the phase front.
- Hence, the large scale effects like reflection and the refraction can be analyzed by ray tracing. This approach of optics is known as ray optics.
- The light ray propagation in a fiber can be analysed by two methods,

- * Ray theory approach
- * mode theory approach.

* Ray theory transmission :-

- Ray theory is the one dimensional approach and indicates the direction of propagation. The ray theory is applicable only for multimode fibers.
- It has the accurate value when the ratio between the core radius to the wavelength is large
- The ray theory is otherwise (using ray) known as tracing approach (or) geometrical optics method.
- The analysis using ray approach is very easy when we compare it with the electromagnetic wave analysis (or) modal analysis

Ray types :-

The light ray which is passing through the fiber is classified into two types,

They are,

* Meridional rays

* Skew rays.

* meridional rays :-

Meridional rays consists of core axis which is also known as the fiber symmetry axis. meridional ray passes through the fiber axis. meridional rays are of two types namely bounded rays and unbounded rays.

Bounded rays are the meridional rays that are trapped in the core which propagate along the fiber axis and unbounded rays are the light rays refracted out of the fiber core.

i, Analysis of meridional rays :-

meridional rays having the following parameters,

- Refractive index
- Total internal reflection
- Acceptance angle
- Numerical aperture.

ii, Skew rays :-

There exists another category of rays called as skew rays. The skew rays travel through the fiber without passing through the fiber axis.

Skew rays are used to smoothen, the non-uniform input given to the fiber and produce a more uniform output. Anyways, the amount of smoothing will depends on the number of reflections encountered by the skew rays.

* Refractive index :-

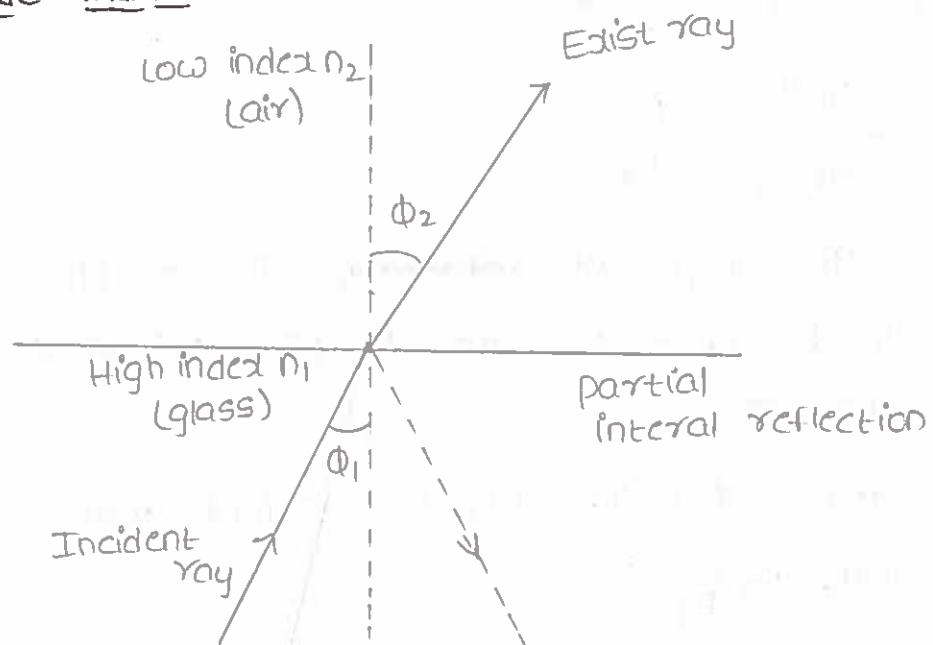


fig:- Light rays incident on high to low refractive index interface.

→ Refractive index is defined as the ratio between the speed of light in vacuum to the speed of light in material. It is denoted by " μ " (or) "n"

$$\mu \text{ (or) } n = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in medium}}$$

→ When the ray is incident on the interface between two dielectrics of differing refractive indices, part of the ray is reflected into the first medium and the rest is reflected into the second medium.

→ Let us take n_1 is the index profile of first medium and n_2 is the index profile of second medium. The condition for the refraction is n_1 must be greater than n_2 .

→ The refraction will occur at the interfaces due to the difference in the speed of light in two materials

→ The incident angle and the reflected angle is related by using Snell's law of refraction. According to Snell's law.

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1}$$

When the angle of refraction is 90° the refracted ray will become parallel to the interface between two materials

Therefore, when $\phi_2 = 90^\circ$, the incident angle = critical angle

$$\sin \phi_1 = n_2/n_1$$

$$\sin \phi_c = n_2/n_1$$

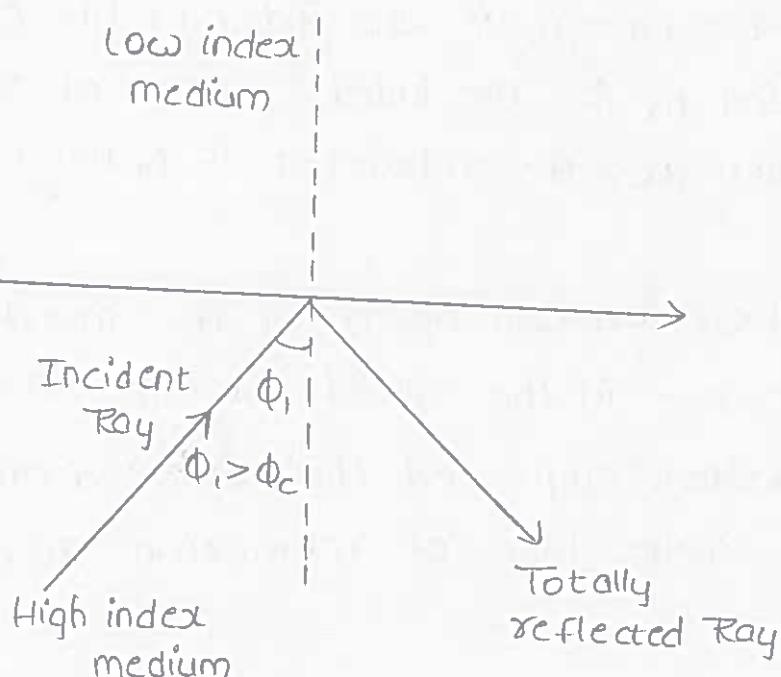
The critical angle (ϕ_c) = $\sin^{-1}(n_2/n_1)$

* Total internal reflection :-

Total internal reflection is defined as the complete reflection of light into the same medium without any transmission of light.

→ Conditions for the total internal reflection are,

- 1, Light should travel from higher refractive index material to lower refraction index material
- 2, Incident angle should be greater than the critical angle.



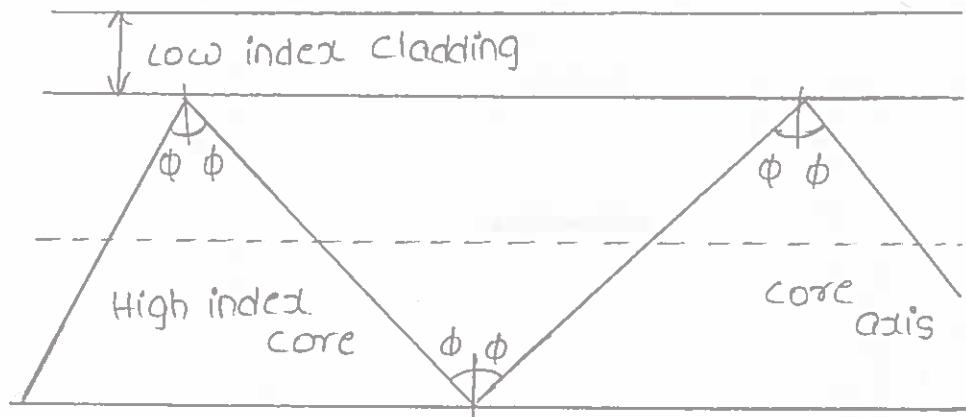


Fig :- Transmission of a light ray in a perfect optical fiber.

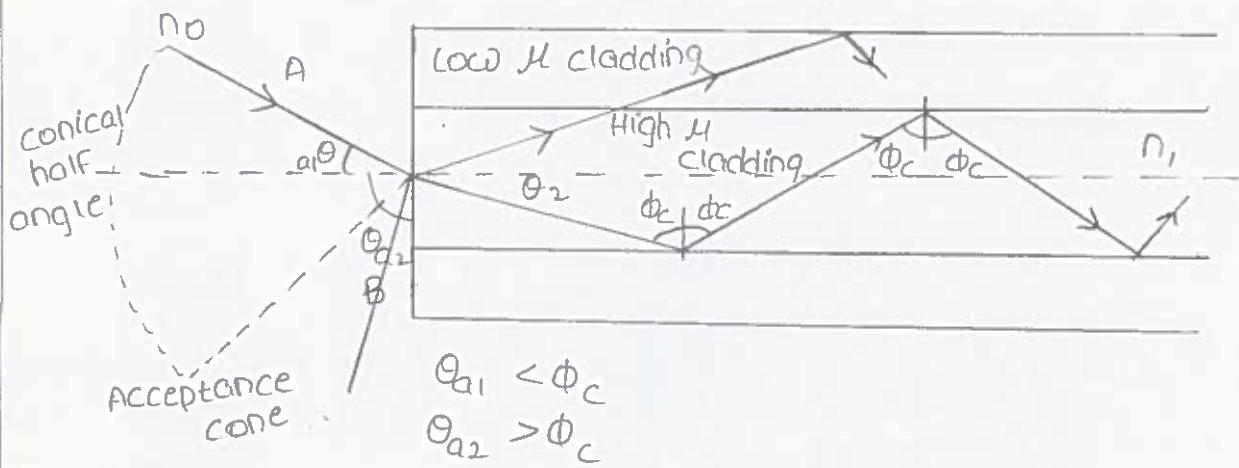
* In a fiber, when the light ray is incident at the core cladding interface, total internal reflection will occur. Since the angle of the incident at the core cladding boundary is greater than the critical angle, the light gets totally reflected back to the core.

* Acceptance angle :-

→ Acceptance angle is the maximum angle to the fiber axis at which light may enter the fiber axis in order to be propagated.

→ Let us consider two rays are launched into the fiber. The first ray named as "A" which, makes an angle θ_c within the core cladding interface. This ray making an angle θ_a to the fiber axis and it gets refracted at the air core interface and this refracted ray is getting propagated into fiber.

The second ray "B" which is launched to fiber at angle greater than θ_a . This ray B gets refracted into the cladding and gets lost by radiation. θ_a must be less than the critical angle at the fiber core.



According to Snell's law of refraction at the core air interface

$$\Rightarrow n_0 \sin \theta_{a1} = n_1 \sin \theta_2 \rightarrow ①$$

$n_0 \rightarrow$ air refractive index = 1

$\theta_{a1} \rightarrow$ Acceptance angle at air core interface
incident angle at air core interface

$n_1 \rightarrow$ Refractive index of core

$\theta_2 \rightarrow$ Refracted angle at air core interface

At core cladding interface, total internal reflection takes place. The angle of incident at the core cladding surface is denoted by ϕ .

$$n_0 \sin \theta_{a1} = n_1 \sin (90 - \phi)$$

$$n_0 \sin \theta_{a1} = n_1 \cos \phi \rightarrow ②$$

$$\sin \theta_{a1} = n_1 \cos \phi [n_0 = 1]$$

$$\sin \theta_{a1} = n_1 \sqrt{1 - \sin^2 \phi} \quad (\because \sin^2 \theta + \cos^2 \theta = 1)$$

IF $\phi = \phi_c$, then $\theta_{a1} = \theta_a$

$$\sin \theta_a = n_1 \sqrt{1 - \sin^2 \phi_c}$$

$$\sin \theta_a = n_1 \sqrt{1 - \frac{n_2^2}{n_1^2}} \quad (\because \phi_c = \sin^{-1} \left(\frac{n_2}{n_1} \right))$$

$$\sin \theta_a = n_1 \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}$$

$$\sin \theta_a = n_1 \ln_1 (\sqrt{n_1^2 - n_2^2})$$

$$\theta_a = \sin^{-1} \sqrt{n_1^2 - n_2^2}$$

* Numerical aperture :-

Numerical aperture gives the measure of light gathering capacity of the fiber. It is the referred as figure of merit of the fiber. Numerical aperture is given by,

$$NA = \sqrt{n_1^2 - n_2^2} = n_0 \sin \theta_a$$

most probably, the light is launched to the fiber from the air medium

$$\therefore n_0 = 1$$

$$NA = \sin \theta_a = \sqrt{n_1^2 - n_2^2}$$

The relative refractive index difference is given by

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

The relative,

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

$$NA = \sin \theta_a = \sqrt{n_1^2 - n_2^2}$$

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

$$NA = \sin \theta_a = \sqrt{2n_1(n_1 - n_2)} \quad (\because n_1 \approx n_2)$$

$$\begin{aligned} NA &= \sin \theta_a = \sqrt{2n_1(n_1 \Delta)} \\ &= \sqrt{2n_1^2 \Delta} = n_1 \sqrt{2\Delta} \end{aligned} \quad (\because \Delta \approx \frac{n_1 - n_2}{n_1})$$

Then the maximum acceptance angle is said to be a numerical aperture and it is given by,

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

$$\theta_a = \sin^{-1}(n_1 \sqrt{2\Delta})$$

$$\theta_a = \sin^{-1}(NA)$$

* Optical fiber configurations :-

The manufacturing process involved in producing quality fibers and fiber fabrication methods.

While selecting the fiber materials for making optical fibers, a few essential requirements cannot be overlooked. They are,

- 1, The material selected should be ideal for making long, thin, flexible and reliable fibers.
- 2, For the fiber to guide light efficiently the basic material must be transparent at particular wavelength.
- 3, The material which is selected for the core and cladding should have different refractive index.

* Materials which are satisfying the above requirements is plastics and glasses. Majority of the fibers are made of glass consisting either silicon (SiO_2) or a silicate. Glass fibers are used for the long distance communication. In contrast to glass fibers, plastic fibers are used for the short distance communication. In the glass fibers itself there are a few varieties namely,

- Glass fiber
- Halide glass fibers
- Actinic glass fibers
- Chalcogenide glass fibers
- Plastic clad glass fibers

* Glass optical Fibers :-

Glass obtained from fusing mixtures of metal oxides sulphide (or) selcnides is a randomly connected molecular network which heated upto serval 100°C glass remains as a hard solid. When the temperature increases further, glass gradually begins to soften until at very high temperature, it becomes a viscous liquid. The term melting temperature is used in glass manufacture.

Melting temperature in a glass refers to, an extended temperature range in which the glass becomes fluid enough to free itself and emerge as bubbles. The glass fibers are made up of silica (SiO_2) which has a refractive index of 1.458 at 850nm. For achieving two different refractive indexes dopants are added to the basic raw materials. To achieve high refractive index core GeO_2 , P_2O_5 are added and to achieve low refractive index cladd B_2O_3 is added. Some of the fiber compositions of core and cladd are given by,

Core	cladding
$\text{GeO}_2 - \text{SiO}_2$	SiO_2
$\text{P}_2\text{O}_5 - \text{SiO}_2$	SiO_2
SiO_2	$\text{B}_2\text{O}_3 - \text{SiO}_2$
$\text{GeO}_2 - \text{B}_2\text{O}_3 - \text{SiO}_2$	$\text{B}_2\text{O}_3 - \text{SiO}_2$

A raw material for silica is sand. Glass composed of pure silica is referred as silica glass, fused silica (or) vitreous silica. Properties of silica are,

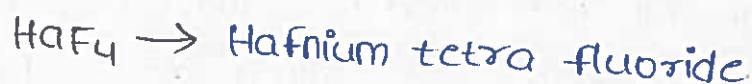
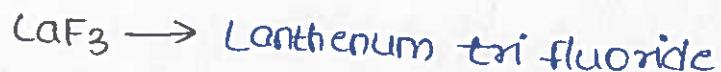
- 1, Resistance to deformation at temperature 1000°C
- 2, High resistance to breakage from thermal shock because of its low thermal expansion.

3, Good chemical durability
4, High transparency both in visible and IR region.
* Its high melting point is disadvantageous, if the glass is prepared from molten state, but this is avoided practically in vapour deposition technique method of manufacturing.

* Halide Glass optical fibers :-

* Fluoride glasses have extremely low transmission losses at mid IR wavelengths. Fluoride glasses belongs to a general family of Halide glasses in which the anions are from elements in group VII of the periodic table, namely fluorine, chlorine, bromine and iodine. Fluoride glass is a heavy metal which uses ZrF_4 as major component and glass network former.

→ ZBLAN is one of the popular fluoride glass that forms the core of glass fiber and have high refractive index. ZBLAN consists of ZrF_4 , BaF_2 , LaF_3 and NaF . To obtain low refractive index cladding ZrF_4 is replaced by HfF_4 .



* These fibers having minimum losses of 0.01 to 0.001 dB/km. Fabrication of these types of fiber is very difficult. First, ultra pure materials must be used to reach this low loss level. Secondly, fluoride glass is prone to diversities.

* Active glass optical fibers :-

→ When rare elements [atomic number 51 to 71] are added to the glass gives the material a new optical and magnetic properties. These new properties allow the material to perform amplification, attenuation and phase retardation on the light passing through it. Doping can be done both for silica and halide glasses. Erbium and neodymium are two commonly used materials for fiber lasers.

→ The rare-earth elements ionic concentration is low to avoid clustering effects. By studying the absorption and fluorescence spectra of these materials, one can use optical source at which emit an absorption wavelength, excite electrons ^{higher} ~~lower~~ energy levels in the rare-earth dopants. While dropping this excited electrons lower energy levels at fluorescence wavelength they emit light in a narrow optical spectrum.

* Chalgenide glass optical fibers :-

For some applications like optical switches and fiber lasers, non linear properties should be achieved. This characteristic is exploited by chalgenide glass fibers. These types of glasses contain at least one chalcogen element (S, Se (or) Te) and typically one another element such as P, I, Cl, Br, Cd, Si (or) Tl. As_2S_3 is one of the mostly used material among the various chalgenide glasses. Losses in these glasses typically range around 1 dB/m.

Se → Selenium

Te → Tellurium

Tl \rightarrow Taliun

* plastic optical fibers :-

→ plastic clad glass fibers :-

* For long distance communication where very low losses are achievable, optical fibers constructed with glass cores and glass claddings are very important. For short distance communication where higher losses are tolerable, less expensive plastic clad silica fibers can be used. These fibers are composed of silica cores with lower refractive index being a polymer material. These fibers are also often referred to as PCF fibers. High purity natural quartz is a common material source for the silica core. Similarly common cladding material is a silicone resin having a refractive index of 1.405 at 850nm.

→ Another popular plastic cladding material is perfluorinated ethylene propylene. The low refractive index 1.338 of these material results in fibers with potentially large numerical apertures. This is used for only step fibers. The large difference between the core and clad refractive index will yield high numerical aperture.

* plastic fibers :-

For short distance all plastic multimode step index fibers are good candidates. The toughness and durability of plastic allow these fibers to be handled easily is an advantage while they exhibit greater optical signal attenuation. This type of fiber is having numerical aperture 0.6 and large acceptance angle of upto 70°. Also mechanical flexibility of plastic

allows these fibers to have large cores with typical diameter ranging from 110 to 1400 microns.

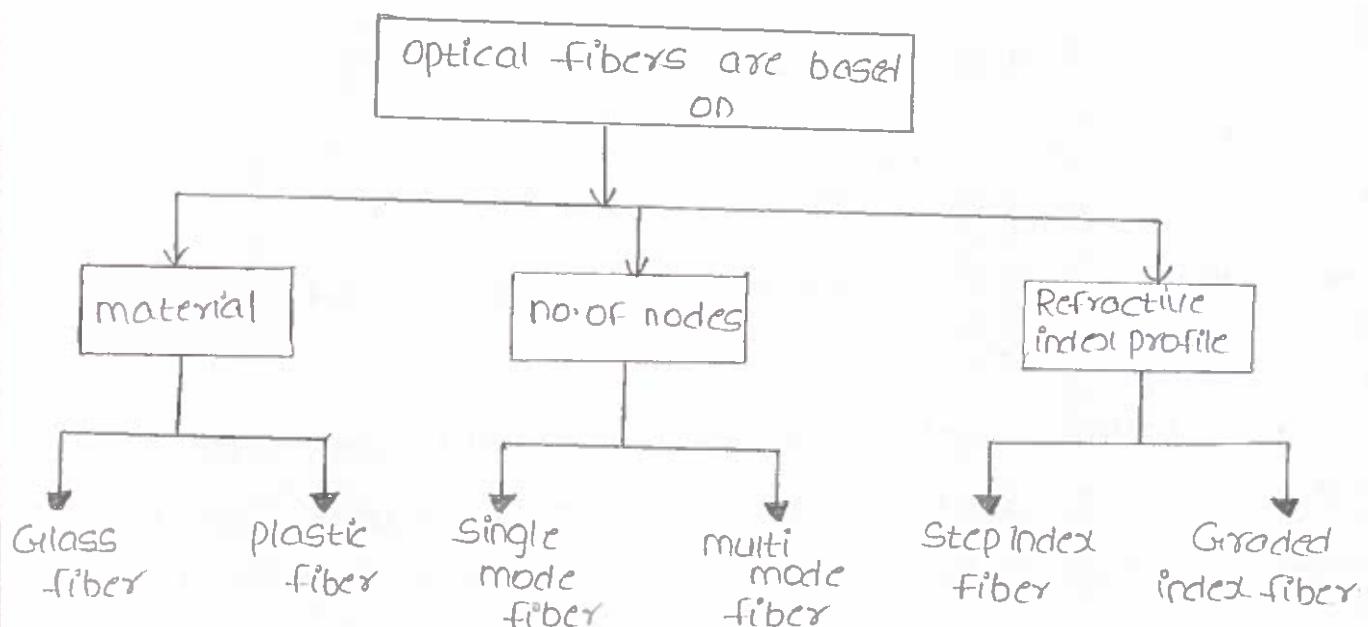
* Optical fiber classification :-

- Optical fiber falls into three basic classifications,
- * Step index multimode
 - * Graded index multimode
 - * Single mode.

→ A mode is essentially a path that light can follow down the fiber.

→ Step-index fiber has a core with one index of refraction, and a cladding with a second index.

→ A graded index fiber has a varying core index of refraction, and a constant cladding index.



* Losses in optical fiber cables :-

Attenuation :-

Transmission loss (or) Attenuation is one of the important characteristics of fiber. This characteristic is taking major role in determining the maximum distance between the transmitter and receiver without

using repeaters. The basic attenuation mechanisms are,

1. Absorption loss
2. Scattering loss
3. Radiative loss

→ The unit of attenuation is expressed in terms of logarithmic unit of the decibel. The decibel is defined as the ratio of the input optical power P_i to the output optical power P_o .

$$\text{Number of decibels (dB)} = 10 \log_{10} \frac{P_i}{P_o}$$

→ When the light travels along the fiber, its power decreases exponentially with distance. Let us take the power at origin is $P(0)$. and the power at the distance ' z ' is $P(z)$ then $P(z)$ is expressed,

$$P(z) = P(0) e^{-\alpha_p z}$$

$$\text{Where, } \alpha_p = \frac{1}{z} \ln \left[\frac{P(0)}{P(z)} \right]$$

→ α_p is the fiber attenuation co-efficient, which is having the unit of km^{-1} .

→ Sometimes attenuation can be expressed in terms of nepers. If P_1 and P_2 are two power levels, with $P_2 > P_1$, then the power ratio in nepers is given as the natural logarithmic unit.

→ Power ratio in nepers = $\frac{1}{2} \ln \frac{P_2}{P_1}$ is given by,

$$N = \frac{1}{2} \ln \frac{P_2}{P_1}$$

$$N = \frac{1}{2} \log_e \left| \frac{P_2}{P_1} \right|$$

Where,

$N \rightarrow$ Attenuation in nepers.

Relationship between Neper and decibel

$$\log_e x = \log_{10} x \times \log_{e} 10$$

$$\log_e 10 = 2.3026$$

$$\log_e x = 2.3026 \log_{10} x$$

$$\frac{1}{2} \log_e \left| \frac{P_2}{P_1} \right| = \frac{1}{2} \times 2.3026 \log_{10} \left| \frac{P_2}{P_1} \right|$$

$$N = \frac{1}{2} \times 2.3026 \log_{10} \left| \frac{P_2}{P_1} \right|$$

$$2N = 2.3026 \log_{10} \left| \frac{P_2}{P_1} \right| \rightarrow ①$$

We know that,

$$\text{Attenuation in decibel } D = 10 \log_{10} \left| \frac{P_2}{P_1} \right|$$

$$\frac{D}{10} = \log_{10} \left| \frac{P_2}{P_1} \right| \rightarrow ②$$

from eq'n ①,

$$\log_{10} \left| \frac{P_2}{P_1} \right| = \frac{2N}{2.3026} \rightarrow ③$$

from eq'n ② and ③,

$$\frac{D}{10} = \frac{2N}{2.3026}$$

$$D = \frac{10 \times 2}{2.3026} N$$

$$D = 8.686 N$$

\therefore Attenuation in decibel = $8.686 \times$ attenuation in Neper
(or)

$$\text{Attenuation in Neper} = \frac{1}{8.686} \times \text{attenuation in decibel}$$

For simplicity attenuation is expressed always in terms of decibel/km.

$$\therefore \alpha(\text{dB/km}) = \frac{10}{z} \log \left| \frac{P(0)}{P(z)} \right|$$

$$\alpha(\text{dB/km}) = 4.343 d \text{p km}^{-1}$$

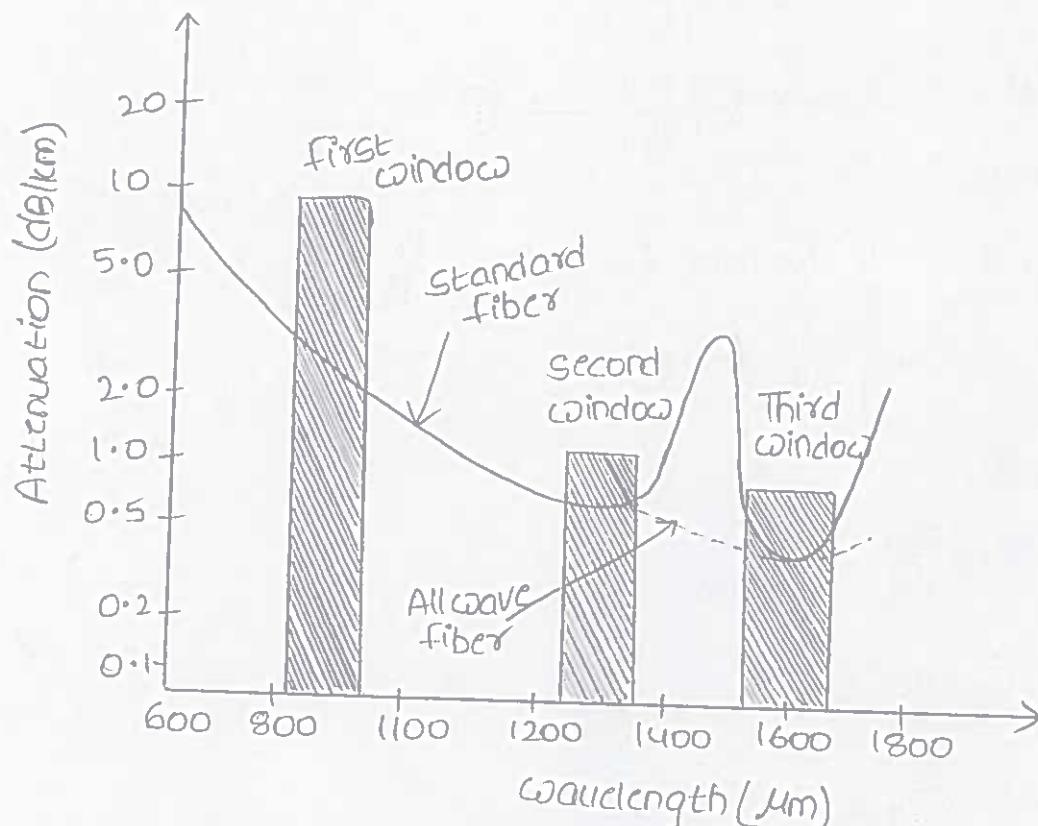
In optical communication attenuation is defined terms of km length

$$\alpha(\text{dB}) = \frac{10}{L} \log \left| \frac{P_i}{P_o} \right|$$

where,

$\alpha(\text{dB}) \rightarrow$ Attenuation per unit length

$L \rightarrow$ Fiber length.



*Absorption :-

Absorption is caused by three mechanisms,

1. Absorption by atomic defects in the fiber materials
2. Intrinsic absorption by the basic constituent atoms of the fiber material.
3. Extrinsic absorption by impurity atoms in the fiber material.

→ Absorption by atomic defects :-

These type of absorption is caused by atomic defects like missing molecules, clusters of atoms, imperfection of the atomic structure of the fiber material. This type of absorption having very small value,

the value is mostly negligible when comparing with intrinsic and extrinsic absorption.

* Intrinsic absorption:-

The intrinsic absorption is of two types,

1. Intrinsic absorption due to electronic absorption bands in ultra violet region.
2. Intrinsic absorption due to atomic vibration bands in infrared region.

* The optical communication wavelength range in terms of μm is $0.8\mu\text{m}$ to $1.7\mu\text{m}$. In silica fibers, intrinsic absorption will occur above $1.5\mu\text{m}$. The photons of light energy are converted into random mechanical vibration infrared absorption. Maximum IR peak value at $0.8\mu\text{m}$ and minimum peak value at $3.2, 3.8$ and $4.4\mu\text{m}$.

→ In the visible region losses at $1.5\mu\text{m}$ are lesser than 0.5 dB/km . The optical loss is determined by calculating the presence of OH ions and the inherent infrared absorption of the constituent material. The inherent absorption will occur because of the interaction between the vibrating bond and the EM field of the optical signal.

→ The Empirical expression for the infrared absorption for $\text{GeO}_2 - \text{SiO}_2$ glass is given by,

$$\alpha_{\text{IR}} = 7.81 \times 10^6 \times e\left(-\frac{48.48}{\lambda}\right)$$

→ Intrinsic absorption also depends upon the electronic absorption bands in the ultraviolet region. Ultraviolet absorption decays exponentially with increasing wavelength at $0.8\mu\text{m}$. The ultra violet absorption have the value of 0.3 dB/km .

Extrinsic absorption by impurity atoms :-

→ Extrinsic absorption is due to transition metal ions such as iron, chromium, cobalt, copper, manganese and nickel. This type of absorption is more pronounced in direct melt methods because in that type of fabrication method, the dopants are added directly to the silica.

→ In the case of vapour axial deposition the impurity level ranges from 1 to 5 parts per million.

Scattering losses :-

Scattering losses having two types,

1. Linear scattering loss

i, Rayleigh scattering

ii, Mie scattering.

2. Non-linear scattering loss

i, Stimulated Brillouin scattering

ii, Stimulated Raman scattering.

* Linear scattering losses :-

→ Linear scattering transfers linearly the optical power in one propagating mode to a different mode. This losses will occur as a leaky mode (or) as radiation mode. This mode does not continue to propagate within the fiber core but it is radiated from the fiber. Since there is no change in frequency of the signal, it is said to be linear scattering. Scattering loss will be more in multimode fibers due to higher dopant concentration and greater compositional fluctuations.

1, Rayleigh Scattering :-

→ This loss occurs in the ultra violet region. Its tail extends upto infrared region. It arises from the microscopic inhomogeneities present in the material of fiber. Inhomogeneities may arise from the density fluctuations, reflective fluctuations and compositional variations.

For, SiO_2 fiber, Rayleigh loss is given by,

$$\alpha_{\text{scat}} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F m^{-1}$$

where,

n → Refractive index of silica

p → photoelastic co-efficient of silica

β_c → Isothermal compressibility.

T_F → Fictive temperature at which solidification of glass takes place (or) simply annealing temperature

* The transmission loss due to Rayleigh scattering

$$\alpha_{\text{Trans-scatt}} = \exp(-\alpha_{\text{scat}} L)$$

where,

L → length of fiber

* At high wavelength Rayleigh scattering loss will be reduced. It is an elastic scattering because there is no change in frequency.

2, Mic scattering :-

Mic scattering arises due to imperfect structure of wave guide, irregularities in the core-cladding interface, core-cladding refractive index difference along the fiber and diameter fluctuations.

By achieving high relative refractive index difference and doing perfect fabrication Mic scattering get reduced.

Non-linear scattering losses :-

→ Non-linear scattering losses will occur at high power levels. The transferring of power from one mode to another mode takes place either in forward (or) reverse direction. This is an inelastic scattering resulting due to shift in the frequency when the refractive index of the medium depends on the optical intensity of the signal, then these non linear scatterings are occurred.

I, Stimulated Brillouin scattering :-

Stimulated Brillouin Scattering is a loss mechanism due to thermal molecular vibrations within the fiber. This type of scattering line contains upper side band and lower side band along with the incident light frequency. The threshold optical power from Brillouin scattering is proportional to $d^2 \lambda^2 \alpha_B$ and is given by,

$$P_B = 4.4 \times 10^{-3} \lambda^2 d^2 \alpha_B \Delta V \text{ watts}$$

where,

d → Fiber core diameter

λ → Operating wavelength

α_B → Brillouin scattering loss co-efficient

ΔV → Source band width.

In stimulated Brillouin scattering an incident light will produce scattered photon as well as phonon of acoustic frequency.

2. Stimulated Raman Scattering:

The scattered light consist of a scattered phonon and a high frequency optical phonon. In contrast to Brillouin scattering Raman scattering is having three orders of high magnitude. The threshold optical power for Raman scattering is proportional to $d^2 \lambda \alpha_R$ and is given as,

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_R \text{ Watts}$$

where,

$d \rightarrow$ core diameter

$\lambda \rightarrow$ operating wavelength

$\alpha_R \rightarrow$ Raman scattering loss co-efficient

* Bending losses (or) Radiative losses

Whenever the bends and curves will be in the path of optical ray radiative losses will occur. These are two types of bending losses,

1, Macroscopic bending losses

2, microscopic bending losses

Macroscopic bending losses (or) Large Radius losses:-

These occur when the radius of curvature of bend is greater than the fiber diameter. When the radius of curvature of bend decreases (or) curvature of fiber increases, the loss increases exponentially upto a critical radius of curvature.

For multimode fiber, the critical radius of curvature of bend,

$$R_c = \frac{3n_1^2 \lambda}{4\pi(n_1^2 - n_2^2)^{3/2}}$$

The attenuation co-efficient by the macrobends

$$\alpha_b = A \exp(-BR_c)$$

for single mode fiber,

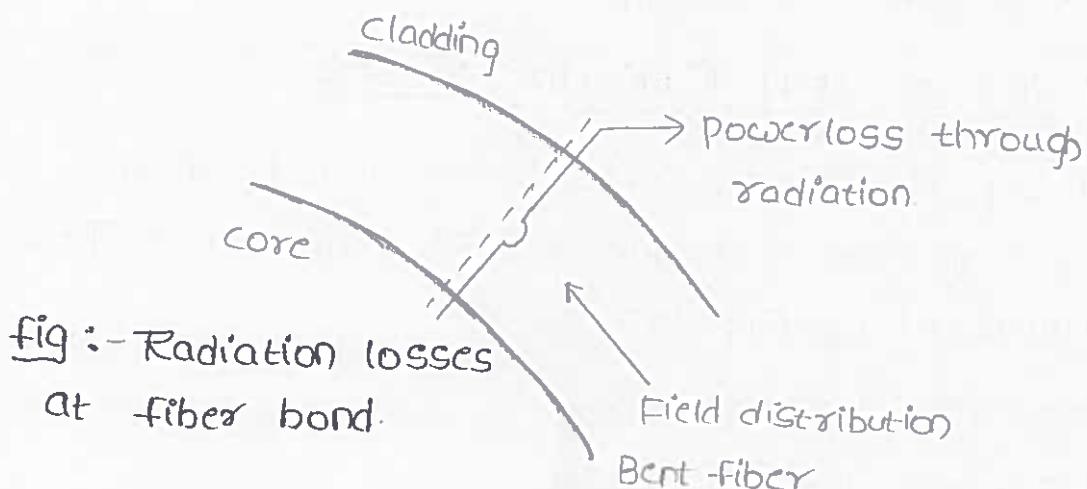
$$R_c = \frac{20\lambda}{(n_1 - n_2)^{3/2}} \left(2.748 - 0.996 \frac{\lambda}{\lambda_c} \right)^{-3}$$

where,

$\lambda_c \rightarrow$ cutoff wavelength

$$R_c \rightarrow \frac{2\pi a n_i \sqrt{2\Delta}}{2.405}$$

$$R_c = \frac{2\pi a (\text{NA})}{2.405}$$



* minimization of this type of losses is done by,

1, Fibers with large relative refractive index difference.

2, operating at the shortest wavelength possible.

Microbending (mode coupling losses) :-

microbending introduces from the fiber when it is incorporated into cables. This type of bending introduces slight surface imperfections which can cause mode coupling between adjacent modes (or) coupling of energy between the guided modes and the leaky modes in the fiber which in turn creates a radiative loss.

The losses due to non uniform pressure during cabling is referred as cabling (or) packaging losses.

The loss depends on the fiber deformation, length of fiber and the optical power distribution. Microbending losses proportional to the number of modes propagating through the fiber and inversely proportional to wavelength.

Light source:-

→ The requirement of an semiconductor material for the active layer of optical source must have a direct band gap (DBG). Both energy and momentum must be conserved for electron transitions to (or) from the conduction band with the absorption (or) emission of photon. Though photon has considerable energy its momentum $h\nu/c$ is very small.

Semiconductors are classified as direct band (or) indirect band gap materials depending upon the shape of bandgap as a function of momentum k .

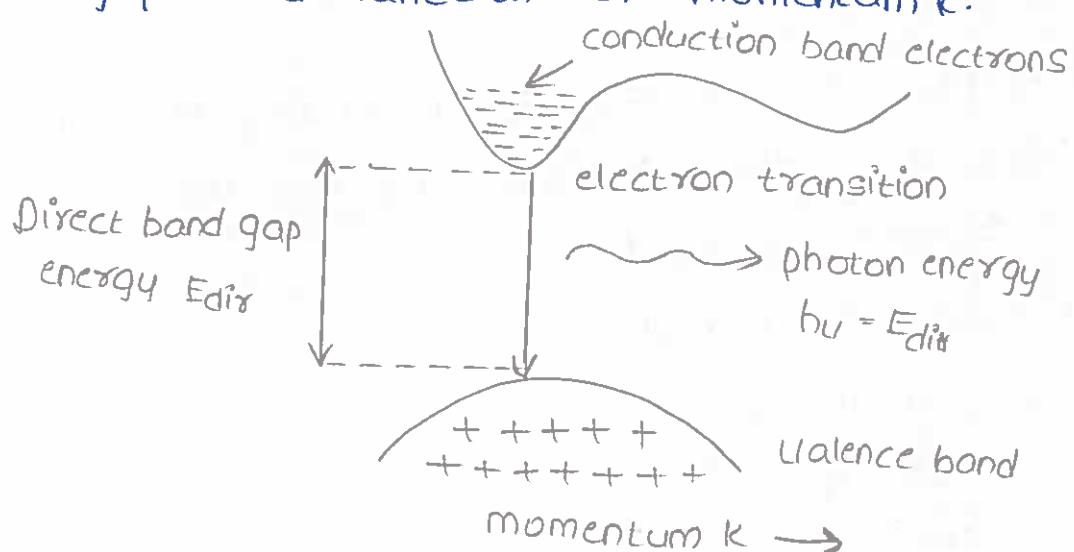


fig :- Electronic recombination of direct band gap

The simplest and best possible recombination process will be that where the electron and hole have the same momentum value.

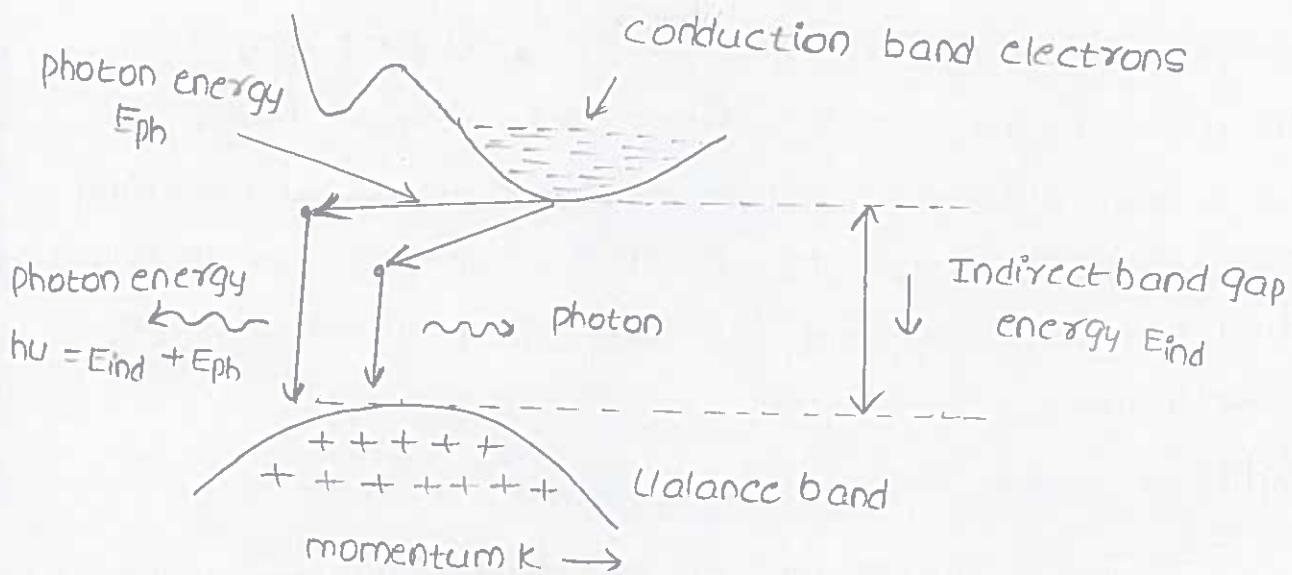


Fig :- Electronic recombination of indirect band gap.

Optical Sources :-

→ The basics of optical sources, principles of light propagation and various types of optical sources normally used in fiber optic communication systems.

→ In the electromagnetic spectrum, the human eye can detect only a very narrow segment of light frequencies.

→ Wavelengths of light sources must be chosen in such a way that they are efficient for the propagation through optical fiber

* Optical power is given as,

$$\text{Power} = \frac{d(\text{energy})}{d(\text{time})}$$

(or)

$$P = \frac{dQ}{dt} \text{ (watts)}$$

where,

P → Optical power (watts)

dQ → Instantaneous charge (joules)

$dt \rightarrow$ Instantaneous change in time (seconds)

* Optical power is also called as radiant flux [ϕ] = joules/sec. and is the same power measured electrically (or) thermally in watts

Properties of optical fibers sources

S.No	Parameter	Requirement	Target
1,	Wavelength	Operating wavelength must be chosen such that it gives low loss and low dispersion in fibers	0.85, 1.3, 1.6 micron bands.
2,	modulation	Direct modulation must be possible (or) it must be easy to couple for an external modulation	-
3,	Output power and power efficiency	System demand must be met. It must depends operate with an electric Power Supply requiring Only a low power and loss voltage and the amount of waste heat generated must be small.	> one milliwatt $> 10\%$.
4,	Reliability	long life, good stability of operation and good reproducibility of output are necessary	life of 10 hrs must be minimum
5,	Focusing effect	It should be possible to focus the output onto the fiber and to obtain higher coupling efficiency	

6,	Size and weight	It must be small in size and light in weight	
7,	Cost	mass production in size and low cost are desirable.	

LED's (light emitting diodes)

A light emitting diode is a p-n junction diode, usually made from a Semiconductor material such as aluminium - gallium arsenide (AlGaAs) (or) gallium arsenide phosphide (GaAsP). LED's emit light by spontaneous emission, light is emitted as a result of the recombination of electrons and holes. When forward biased, minority carriers are injected across the p-n junction.

material	wavelength
AlGaInP	630 - 680
GaInP	670
AlGaAs	620 - 895
GaAs	904
InGaAs	980
InGaAsP	1100 - 1650
InGaAsb	1700 - 4400

Advantages :-

i, Simpler fabrication :-

There are no mirror facets and in some structure no striped geometry.

ii, Cost :- The simpler construction of LED leads to much reduced cost which is always likely to be maintained.

iii, Reliability :- The LED does not exhibit catastrophic degradation and has proved to be less sensitive to gradual degradation than the injection laser.

iv, Simpler drive circuitry :-

This is due to lower drive currents and reduced temperature dependence which makes temperature compensation circuits unnecessary.

v, Linearity :- Ideally, the LED has a linear light output against current characteristics unlike the injection laser.

Disadvantages :-

* An LED radiates rather dispersed light, which makes coupling this light into an optical fiber a problem.

→ Structures :-

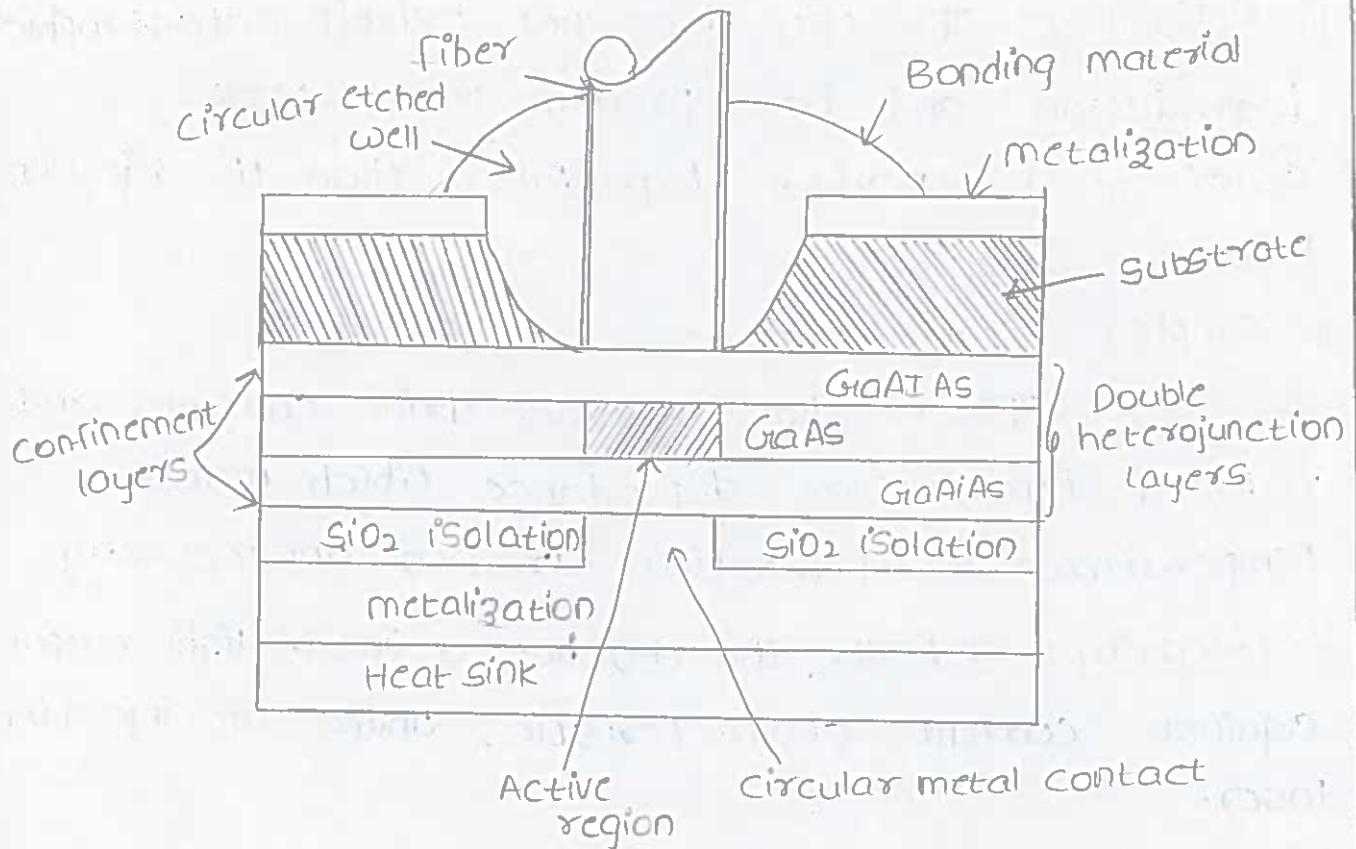
The requirements for an LED to be used for fiber transmission are,

1, High radiance output

2, High quantum efficiency and

3, Fast emission response time

→ LED's radiance (or) brightness is a measure in watts of the optical power radiation into a unit solid angle per unit area of the emitting surface. Higher brightness is required to couple sufficiently large output power levels into the fiber. The quantum efficiency is related to the fraction of the injected electron hole pairs that recombine radiatively.



Injection laser diodes:-

- Laser action means the production of high intense, monochromatic and coherent light through stimulated emission.
- Laser functioning is based on the principle of emission of light by the stimulated emission such that the energy of the stimulating photon should be equal to the energy difference between the transmission levels.
- There are certain conditions to be fulfilled to achieve laser action, They are,
 1. The state of the atomic system at which the number of atoms in the higher state is more than the number of atoms in the lower (or) ground state.
 2. There should be photons with proper energy to start the stimulated emission.

3, There should be an arrangement for multiple reflections to increase the intensity of laser beam.

* When there is an EM radiation through a laser material, following physical process takes place depending upon the nature of EM radiation and the level of material that is interacting with it.

1, Absorption

2, Spontaneous emission

3, Stimulated emission.

Difference between Spontaneous emission and Stimulated emission.

* Spontaneous Emission

i, During the transition of atoms from higher energy level to lower energy level, emission of photons takes place immediately without any inducement.

ii, This is a polychromatic radiation

iii, less intensive

iv, Has more angular spread during propagation meaning less directly.

v, Incoherent radiation.

* Stimulated Emission :-

i, Emission of light photon takes place through an inducement given by a photon having energy level equal to the emitted photon's energy level.

ii, Monochromatic radiator

iii, High intensive.

iv, High directionality and less angular spread during propagation

v, Coherent radiation.

Types of laser diode :-

There are two types in P-N junction laser diodes,

i, Homojunction laser diode

ii, Heterojunction laser diode

* Homojunction laser diode :-

If a P-N junction is formed by a single material, it is said to be homojunction laser diode.

* Heterojunction laser diode :-

If a P-N junction is formed by two different types of materials then it is said to be heterojunction laser diode

* WDM, necessity and principles

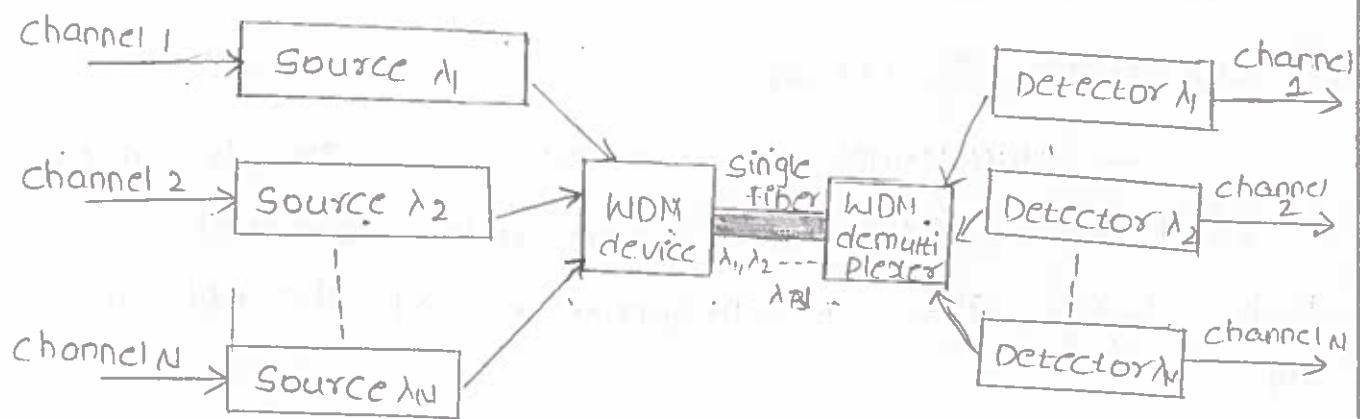
Wavelength division multiplexing (WDM).

FDM stands for frequency Division multiplexing. In this scheme the number of different frequencies are combined together and pass through low pass filter. in order to remove unwanted interferences and an adder, which combines frequencies at the output.

At the demultiplexer the individual frequency signals can be obtained by means of a decoder. FDM provides high frequency range in order to associate 'n' number

OF USERS.

→ An interesting and powerful aspect of an optical communication link is that many different wavelength can be sent along a fiber simultaneously in 1300 to 1600 nm spectrum.



→ Each of the streams could be a different data rate. Each information stream maintains its individual data rate after being multiplexed with other streams and operates at its unique wavelength.

Features of WDM :-

1. Capacity upgrade :-

The classical application of WDM is to upgrade the capacity of existing point to point fiber optic transmission links. If each wavelength supports an independent network signal of a few gigabits per second, then WDM can increase the capacity of a fiber network dramatically.

2. Transparency :-

An important aspect of WDM is that each optical channel can carry any transmission format.

3. Wavelength Routing :-

In addition to the usage of multiple

Wavelength to increase link capacity and flexibility the use of wavelength sensitive optical routing devices, in designing communication networks and switches has an very important role.

* Wavelength routed networks use the actual wavelength as final address

4, wavelength switching :-

→ Wavelength routed networks are based on a rigid fiber structure, wavelength switched architectures allow reconfigurations of the optical layer.

Operation principle of WDM :-

→ The key feature of WDM is that the discrete wavelengths form an orthogonal set of carriers that can be separated, routed and switched without interfering with each other.

* The optical bandwidth can be expressed in terms of wavelength deviations " $\Delta\lambda$ "

$$(\Delta v) = \left(\frac{c}{\lambda^2} \right) (\Delta\lambda)$$

Types of WDM :-

Unidirectional WDM :-

→ In unidirectional WDM technique, optical signals from different light sources each comprising of a channel are simultaneously transmitted through the same optical fiber.

* Each light source is operating at different carrier frequency (or) light wavelengths using LED (or) laser

- * The light from each source is combined using a device called optical multiplexer. As the signal transmits through the fiber and reaches the far end, a device called optical demultiplexer sends signal of each channel to its own receiver.
- * At the receiver, photodetectors convert light signals into corresponding electrical signals.

→ When N channels at bit rates B_1, B_2, \dots, B_N are transmitted simultaneously over a fiber of length L , the total bit rate-distance product, BL is given by,

$$BL = (B_1 + B_2 + \dots + B_N)L$$

If $B_1 = B_2 = B_3 = \dots = B_N = B$, we get

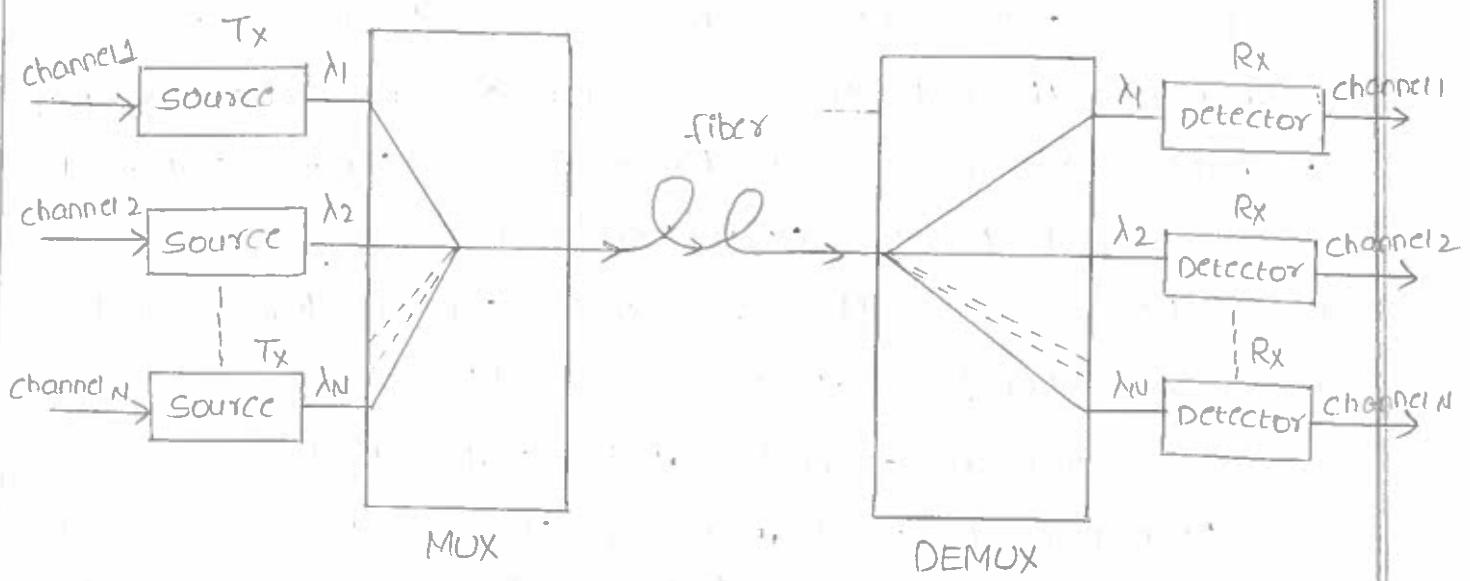
$$BL = NBL$$

Therefore, the system capacity is enhanced by a factor N .

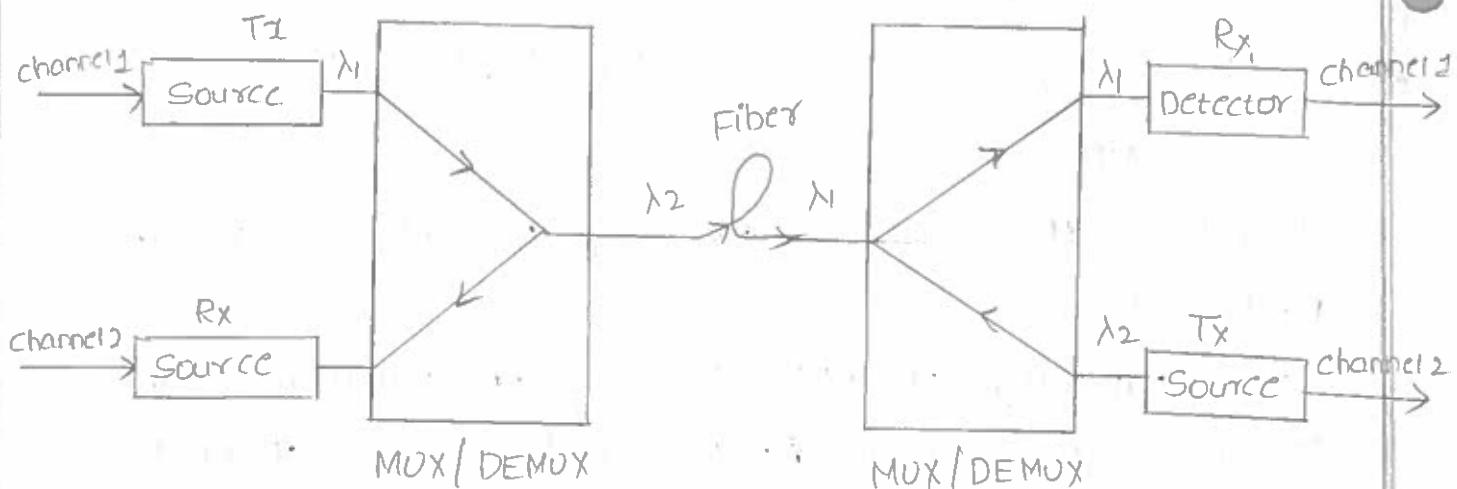
* The capacity of WDM depends on minimum channel spacing $\Delta\lambda_{ch}$ which is limited by inter-channel cross talk. Minimum channel spacing is $\Delta\lambda_{ch} \geq 2B$ where B is bit rate. The spectral efficiency n_s of WDM is given by

$$n_s = \frac{B}{\Delta\lambda_{ch}}$$

* Common used channel spacing for most commercial WDM systems is 100GHz with only 10% efficiency at 10 bit rate of 10 Gb/s. However, to improve the efficiency up to 80%, lower channel spacing of 50GHz and bit rate of 40 Gb/s is used.

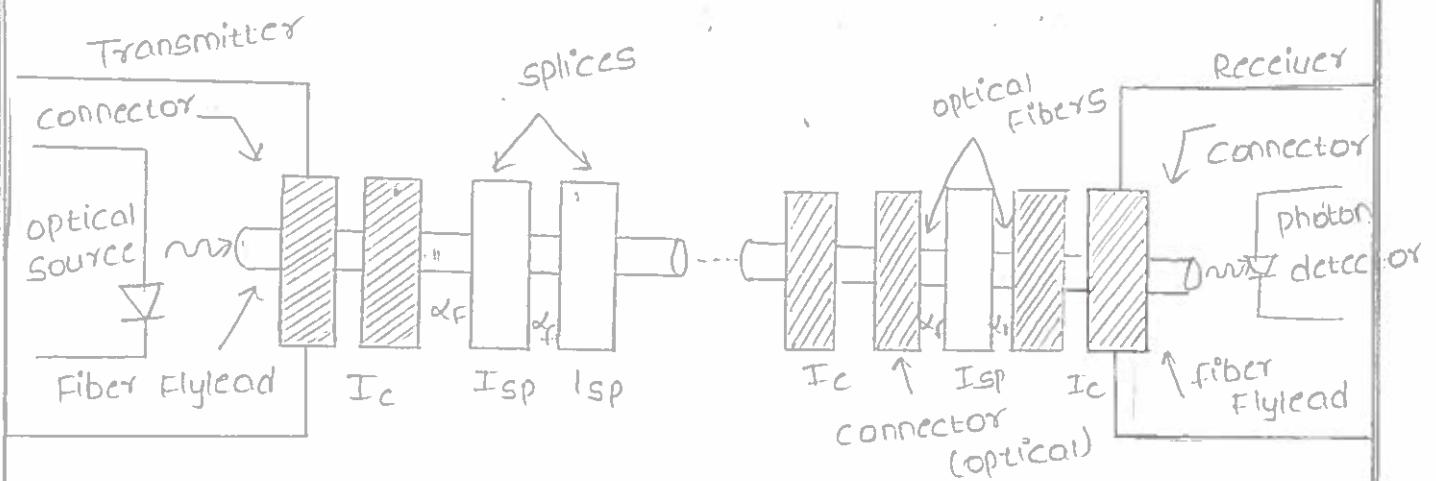


Bidirectional WDM :-



In bi-directional WDM system, the multiplexing device operates in two directions i.e., they work as MUX/DEMUX at the same time. The device acts as multiplexer for the light source of channel 1 and as a demultiplexer for the received light signal of channel 2. The device present at the far end acts in reverse fashion i.e., it acts as demultiplexer for signal of channel 1 and multiplexer for the signal of channel 2 from the light source. Thus, light signal travels simultaneously along the fiber in opposite direction in two channels. The important use of WDM Systems are in loop and trunk system applications.

* optical fiber system link budget :-



→ The power budget determines whether the fiber optic link meets the attenuation requirements (or) amplifier are needed to boost the power level. It also determines the power margin between the optical transmitter and the minimum receiver sensitivity needed to establish a specific bit error rate (BER).

→ In addition to losses, a link power margin is provided in the analysis to allow for component aging, temperature fluctuation and losses arising from components that might be added in future.

→ The link loss budget considers the total optical power loss P_T that allowed between the light source and photodetector. This loss is allocated to cable attenuation, connector loss, splicing loss and system margin.

The total power loss in the link is given by,

$$P_T = P_S - P_R \\ = 2I_c + \alpha_F L + \text{System margin}$$

where,

P_S → Optical power emerging from the end of a fiberfly lead

P_R → Receiver sensitivity

I_c → Connector loss

$\alpha_f \rightarrow$ Fiber attenuation in dB/km

$L \rightarrow$ Transmission distance.

A margin of 6 to 8 dB is generally used for systems which do not have additional components incorporated into the link in future.