Assignment on Optical Fibre

Q.1.What is optical fibre? Which principle is involved in its working?Explain.

Q.2.Deduce an expression for acceptance angle of an optical fibre

Q.3. Derive the mathematical expressions for numerical aperture and acceptance angle for step index fibre.

Q.4. Deduce expression for the acceptance angle for an optical fibre. Show how it is related to numerical aperture.

Q.5 State applications of optical fibre.

Q.6 What is the difference between step index fibre and graded index fibre.

Q.7 What is meant by attenuation in optical fibre? State the factors responsible for losses in optical fibre.Or Explain Mechanisms of Attenuation.or State the different mechanisms that contibute to Attenuation.

Q.8 Write in brief about the classification of the optical fibers based on materials.
Q.9 Expliun How optical fibres are classified ?

OR

Explain types of optical fibre on the basis of refractive index. (Winter 2016)

Q.10 Explain the phenomenon of total internal reflection of light. How it is used in fibre optics communications?

Q.11 What do you understand by the term acceptance angle and acceptance cone?Derive an expression for acceptance angle in terms of refractive indices of the cone and cladding.

OR

Derive an expression for numerical aperture of a step index fibre in terms of Δ. (summer 2016)

Q12.What is attenuation in dB/km if 15 % of the power fed at the launching end of a 0.5 km fibre is lost during propagation ?

Q.13What is the difference between Multimode step index fibre and graded index fibre.
Q.14 What is meant by Dispersion in optical fibre? State the factors or the different mechanisms that contibute to Attenuation in optical fibre.
Q.15 (a) Explain (i) Total internal reflection (ii) One application of optical fiber as a temperature sensor (iii)Advantages of optical Fiber over conventional cable.
Q.16 Draw structure of optical fibre and write function of each part. (summer 2016)
Q.17 Define the terms i) attenuation & dispersion ii) modes of propagation in optical fibre. (summer 2016)
Q18. What is index profile of optical fibre? Classify the optical fibres on the basis of index profile (winter 2017).

Fiber optics:

Fibre optics is a technology in which signals are converted from electrical into optical signals, transmitted through a thin glass fibre and reconverted into electrical signals.

Introduction:

Que.- What is Optical fibre? What is the principle involved in its working? [4m]

Q.) What is an Optical fibre? Explain the principle involved in its working. (S-13/4m)

Q.) Write short notes on the following:

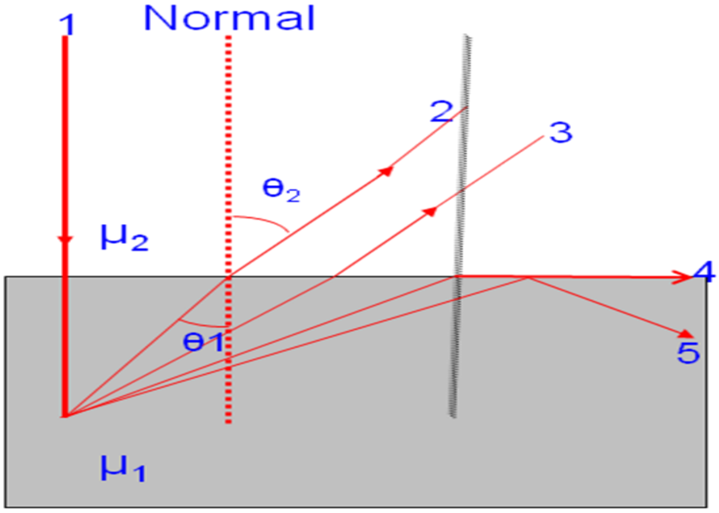
(i)Total internal reflection

(ii)Attenuation in optical fibre (S-14/4m)

An optical fibre is a thin transparent cylindrical conduit/ wave-guide. It is as thin as human hair, made up of glass or clear plastic. It is designated to guide light waves along its length. An optical fibre works on the principle of total internal reflection.

An optical fibre works on the principle of total internal reflection:

A medium having lower refractive index is said to be optically rarer medium and a medium having higher refractive index is called an optically denser medium. When a light ray passes from rarer medium to denser medium, it bends towards the normal in the denser medium. Incident ray &refracted ray are reversible. Hence when a ray passes from a denser medium to a rarer medium, it is bent away from the normal.



Let if φ_i is angle of incidence φ_r is the angle of refraction, then by Snell's law,

$$\frac{\sin \Phi i}{\sin \Phi r} = \frac{\mu_2}{\mu_1}$$

$$\therefore \sin \Phi r = \frac{\mu_2}{\mu_1} \sin \Phi i$$

Transmission or refraction angle φ_r increases faster than the angle of incidence φ_i and refracted rays bent more and more away from the normal. At some particular angle of incidence φ_c the refracted ray glides along boundary surface so that $\varphi_r = 90^o$. At angles greater than the φ_c no refracted rays at all points but the set of rays are reflected back into the denser medium .Such **a phenomenon in which light is totally reflected from a denser to rarer medium boundary is known as total internal**

reflection .Rays experiencing total internal reflection obey the law of reflection.(i.e. angle of incidence = angle of reflection)

Critical angle can be found from Snell's law,

(When $\varphi_i=\varphi_c$ and $\varphi_r=90^o$)

$$\frac{\sin \Phi c}{\sin 90} = \frac{n_2}{n_1} = \frac{\mu_2}{\mu_1}$$

$$\therefore \sin \Phi c = \left(\frac{n_2}{n_1}\right)\sin 90$$

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

For rarer medium of air $n_2=1$

$$\therefore \sin \Phi c = \frac{1}{n_1}$$

Total internal reflection does not takes place when light propagates from a rarer medium to denser medium.

Definition of critical angle: It is that angle of incidence made by the incident ray with the normal at the denser to rarer boundary so that refracted ray makes an angle of 90^0 with the normal & glides along the boundary surface. The ray whose angle of incidence is above critical angle Φc undergoes total internal reflection.

Structure of Optical fibre:

Q.) Draw structure of optical fibre and write function of each part. (S-16/1+2m)

When light enters at one end of the fibre it undergoes successive total internal reflections and travels down the length of the fibre along a zigzag path. (fig.(1)). A small fraction of light may escape through sidewalls but a major fraction emerges out from the other end of the fibre.

A practical optical fibre has in general three co-axial regions.

1. The innermost region is the light guiding region called **as Core**.
2. It is (core) surrounded by a Co-axial middle region called as the **Cladding.**

The refractive index of cladding is lower than that of the core ($\mu_{clad} < \mu_{core}$) The purpose of cladding is to make the light to be confined to the core.

Light launched into the core and striking the core to cladding interface at angle > critical angle, will be reflected back into the core. Since the angles of incidence and reflection are equal, the light will continue to rebound and propagate through the fibre

3. The outermost region is called the **Sheath.**

Sheath protects the cladding and the core from abrasions, contamination and the harmful influence of moisture. It also increases the mechanical strength of the fibre.

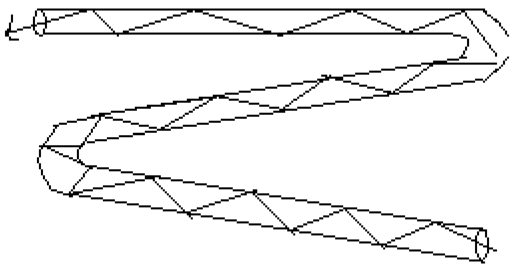


Fig.1

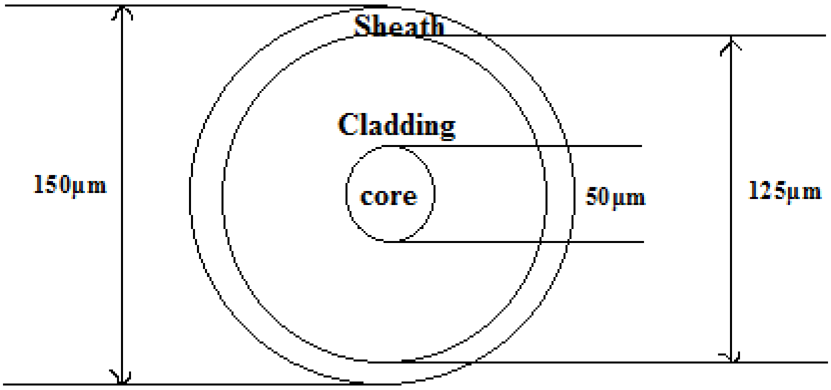


Fig.2

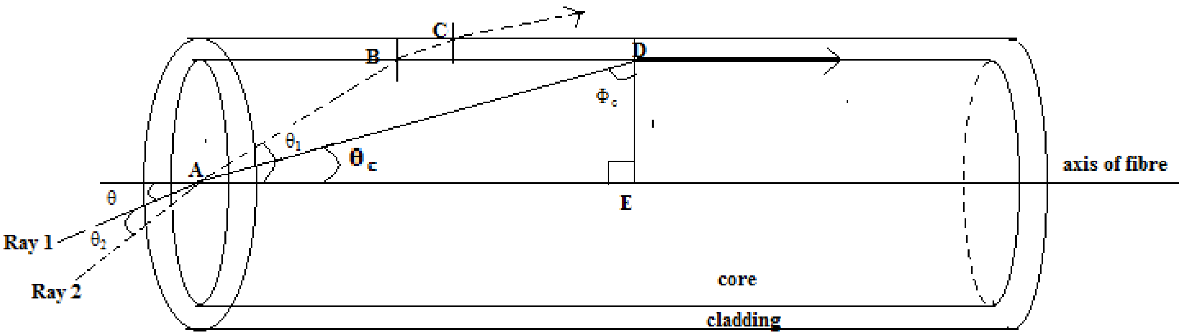
Q. → Explain terms (1) Critical angle (2) Acceptance cone (3) N.A.

Critical Angle of propagation θ_c and critical angle of incidence Φ_c:-

Consider a step-index optical fibre into which light is launched at one end. The end at which light enters the fibre is called **Launching end**.

Fig (3) shows the conditions at the launching end. In a step-index fibre, refractive index changes abruptly from the core to cladding.

Consider two rays entering the fibre at two different angles of incidence.



1. The ray 2 shown by broken line is incident at an angle θ_2 with respect to the axis of the fibre. This ray undergoes refraction at point A on the interface between air and the core. The ray refracts into the fibre at an angle θ_1 ($\theta_1 < \theta_2$). The ray reaches the core- cladding interface at point B. At point B, refraction takes place again and the ray travels in the cladding. Finally at point C, the ray refracts once again and emerges out of the fibre into the air. That means, the ray does not propagate through the fibre.
2. Consider the next ray (1) shown by the solid line. The ray incident at an angle θ undergoes refraction at point A on the interface and propagates at an angle θ_c in the fibre. At point D on the core-cladding interface,when the angle of incidence is Φ_c the refracted ray emerges tangent to the boundary surface .When angle of incidence $\Phi > \Phi_c$ the ray undergoes total internal reflection at the interface, since $\mu_1 > \mu_2$. In the above fig .3 angle of incidence at the core-cladding interface represent the Critical angle Φ_c .

From, ΔADE,

$$\sin\Phi_c = AE/AD$$

$$=> \quad \Phi_c = \sin^{-1}(AE/AD) \text{ --------(1)}$$

Φ_c is given by, $\Phi_c = \sin^{-1}(\mu_2/\mu_1)$ -----------(2)

A ray incident with an angle larger than Φ_c will be confined to the fibre and propagate in the fibre. A ray incident at the critical angle is called **a Critical – ray**. The critical ray makes an angle θ_c with the axis of the fibre. The rays with propagation angles larger than θ_c will not propagate in the fibre then they will undergo refraction .Therefore angle θ_c is called **the Critical propagation angle**. (As θ_i increases, as θ_c increases, Φ_c decreases, i.e. $\Phi < \Phi_c$).

Definition of Critical angle : When light ray travels from denser to a rarer medium ,the angle of incidence for which the refracted ray emerges tangent to the boundary surface is called **the critical angle**.

From Δ ADE,

$$\cos\theta c = \frac{AE}{AD} \quad \ldots\ldots\ldots\ldots\ldots(3)$$

From eq (1) &(2)

$$\frac{AE}{AD} = \sin\Phi c$$

$$\therefore \sin\Phi c = \frac{n_2}{n_1} \, or \, \frac{\mu_2}{\mu_1}$$

$$\cos\theta c = \frac{\mu_2}{\mu_1} = \sin\Phi c$$

$$\theta c = \cos^{-1}\left(\frac{\mu_2}{\mu_1}\right)$$

Modes of propagation:-

When light is launched into an optical fibre waves having ray directions more than the critical angle ($\Phi > \Phi_c$) will be trapped within the fibre due to the total internal reflection.But all such waves do not propagate along the fibre.

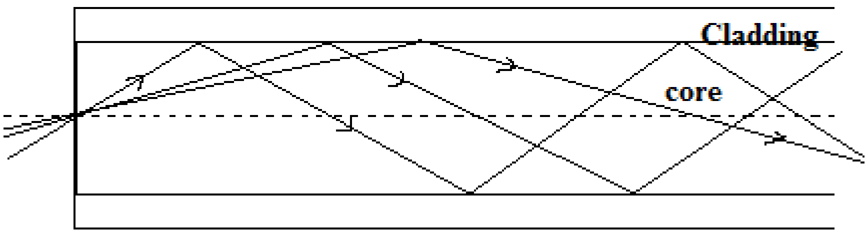
In reality **only certain ray directions are allowed to propagate. These allowed ray directions correspond to the modes of the fibre.**

Modes can be visualized as the possible no. of paths of light in an optical fibre. The paths are all zigzag excepting the axial direction. As a zigzag ray gets repeatedly reflected at the walls of the fibre, phase shift occurs.

Consequently waves travelling along certain zigzag paths will be in phase and intensified while the waves travelling along certain other paths will be out of phase and diminish due to destructive interference.

The light ray paths along which the waves are in phase and intensified inside the fibre are known as modes.

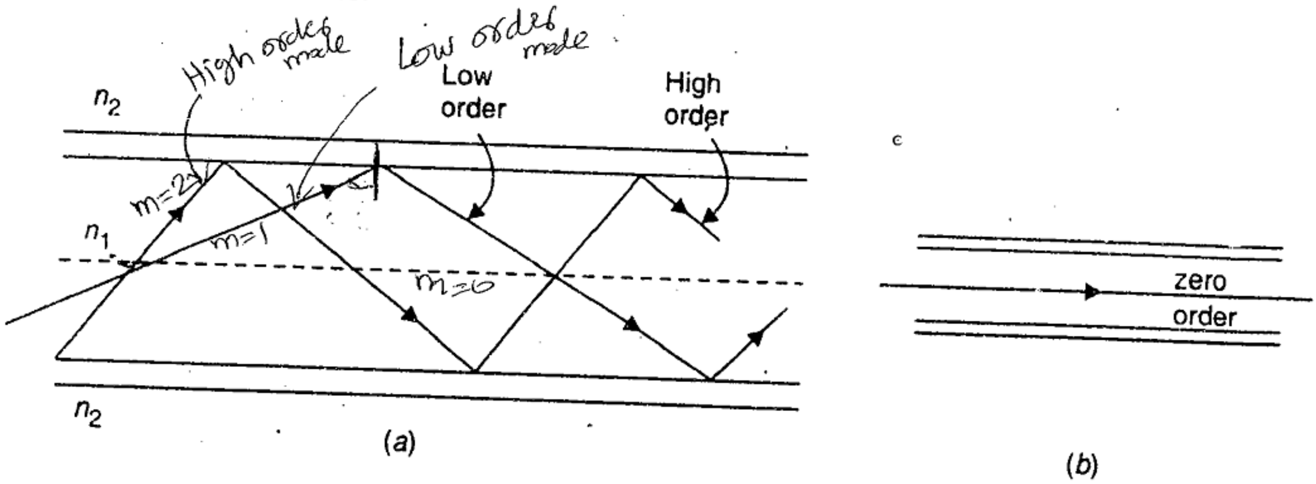
The no. of modes that a fibre will support depend on the ratio d/λ, where d is the diameter of the core and λ is the wavelength of the wave being transmitted.



Modes are designated by an order number ‘m’ or ‘n’. In a fibre of fixed thickness higher order modes propagate at angles close to the critical angle Φ_c and lower order modes propagate with angle much higher than the critical angle Φ_c.

Zero order (mode) ray travel along the axis and is known as **axial ray.** (The lower order modes tend to send light energy into the cladding. This energy is lost ultimately)

This energy is lost ultimately. The higher order modes have to traverse longer paths and hence take larger time than the lower order modes to cover a given length of the fibre. Thus, the higher order modes arrive at the output end of the fiber later than the lower order modes.



Q. Deduce an expression for acceptance angle of an optical fiber?

Q.) What is an optical fiber? Deduce the expression for acceptance angle of an optical fibre. (W-13/1+4m)

Q.) Derive an expression for angle of acceptance and numerical aperture of optical fibre. (W-14/4m)

Q.) What is acceptance angle? Derive an expression for acceptance angle and numerical aperture in optical fibre. (S-15/4m)

Q.) Deduce an expression for acceptance angle of an optical fibre. (W-15/3m)

Q.) Derive an expression for numerical aperture of a step index fibre in terms of Δ. (S-16/4m)

Q.) Derive an expression for acceptance angle in terms of refractive index of the core and cladding.(W-16/3m)

Acceptance angle and acceptance cone :-

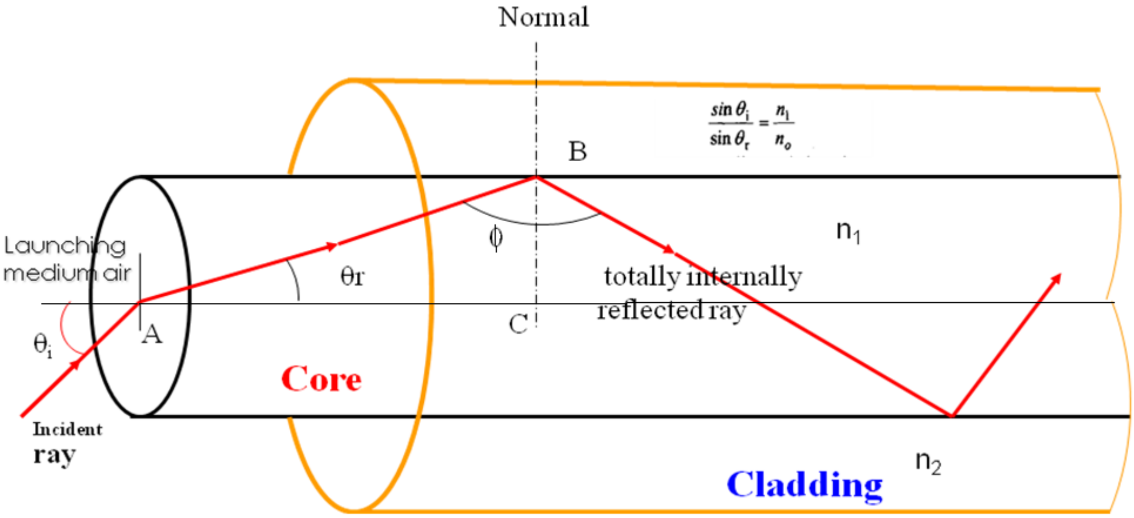


Fig. 5 illustration of the path of a light ray incident on the end of an optical fibre at angle θ_i to the fibre axis.

Consider a step index optical fibre into which light is launched at one end as in fig.(5) Let refractive index of core = $n_1$or μ_1, refractive index of cladding = n_2 or μ_2

Where $n_2 < n_1$ ($\mu_2 < \mu_1$), n_0 = refractive index of the medium from which light is launched into the fibre.

Let a light ray enters the fiber at an angle θ_i to the axis of the fibre. The ray refracts at an angle θ_r and strikes the core – cladding interface at angle of Φ. If $\Phi > \Phi_c$ the ray undergoes total internal reflection at the interface because $n_1 > n_2$.

As long as $\Phi > \Phi_c$, the light will stay within the fibre.

By Snell's law, apply it to the launching face of the fibre

$$\frac{\sin\theta i}{\sin\theta r} = \frac{n_1}{n_0} = \frac{\mu_1}{\mu_0} \text{..................(1)}$$

If θi increases θr will also increases hence Φ decreases ,when Φ will drop below the critical angle Φ_c then the ray will escape from the side wall of the fibre.

The largest value of θ_i occur when $\Phi = \Phi_c$

FromΔABC,

$$\left\{ \begin{array}{l} \because \angle\theta_r + \angle\phi + 90^\circ = 180^\circ \\ \therefore \angle\theta_r = 90 - \angle\phi \\ \therefore \sin\theta_r = \sin(90-\phi) = \cos\phi) \end{array} \right\}$$

From eq 1 & eq2,

$$1 \Rightarrow \frac{\sin\theta i}{\sin\theta r} = \frac{\sin\theta i}{\cos\phi} = \frac{n_1}{n_0} = \frac{\mu_1}{\mu_0}$$

$$\therefore \sin\theta i = \frac{n_1}{n_0}\cos\phi = \frac{\mu_1}{\mu_0}\cos\phi$$

$$\therefore when \phi = \phi_c, \theta i = \theta_{i\max}$$

$$\therefore \sin(\theta_{i\max}) = \frac{n_1}{n_0}\cos\phi_c = \frac{\mu_1}{\mu_0}\cos\phi_c$$

$$but \sin\phi_c = \frac{n_2}{n_1} \because bySnell's law \frac{\sin\phi_c}{\sin 90} = \frac{n_2}{n_1}$$

$$\therefore \cos\phi_c = \sqrt{(1-\sin^2\Phi c)} = \sqrt{1-\frac{n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2-n_2^2}}{n_1}$$

$$\therefore \cos\phi_c = \frac{\sqrt{n_1^2-n_2^2}}{n_1} \therefore \sin\phi_{i\max} = \frac{n_1}{n_0}\times\left(\frac{\sqrt{n_1^2-n_2^2}}{n_1}\right)$$

$$\sin(\theta_{i(\max)}) = \frac{\sqrt{n_1^2-n_2^2}}{n_0}$$

(n_0=1 since air medium.)

Quite often the incident ray is launched from air medium, for which $n_0=1=\mu_{air}$

let

$$\theta_{i\max} = \theta_0$$

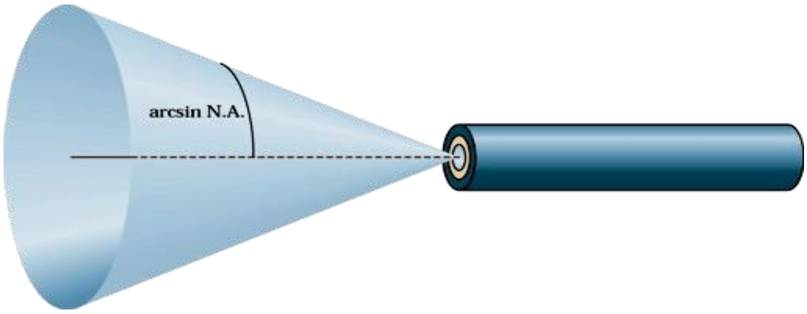
$$\therefore \sin\theta_0 = \sqrt{n_1^2-n_2^2}$$

$$\theta_0 = \sin^{-1}\left(\sqrt{n_1^2-n_2^2}\right)$$

θ_0 is called the acceptance angle of the fibre. Acceptance angle is the maximum angle that a light ray can have relative to the axis of the fibre and propagate down the fibre.

In 3-dimension the light rays contained within the cone having full angle 2 θ_0 are accepted and transmitted along the fibre. Therefore, the cone is called the **acceptance cone.**

Light incident at an angle beyond i.e. $\theta_i > \theta_0$, θ_0 refract through the cladding $\because \Phi < \Phi c$ as θr increases Φ decreases since θi increases and the corresponding optical energy is lost. Larger the diameter of the core larger the acceptance angle.



Fig(6). An optical fibre accept only those rays which are incident with in a cone having a semi-angle θ_0.

Fractional Refractive index change:-

The fractional difference Δ between the refractive indices of the core and the cladding is known as fractional refractive index change. It is expressed as

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

Δ is always positive because n_1 must be larger than n_2 for the total internal reflection condition. To guide the light rays effectively through a fibre Δ<<1, i.e. of the order of 0.01.

Q: - Explain term

Q: Derive an expression for numerical aperture of a step index fibre in terms of Δ. (5M, summer 2007)

Numerical Aperture (NA):-

The main function of an optical fiber is to accept & transmit as much light from the source as possible. The light gathering ability of a fiber depends on two factors, namely core size & the numerical aperture. The acceptance angle & fractional R.I. change determine the numerical aperture of fiber**.**

It is defined as **the sine of the acceptance angle.**

$$N.A = \sin\theta_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

$$N.A = \sqrt{n_1^2 - n_2^2} \;----(1)(\because n_0 = 1)$$

$$n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2)$$

$$= (\frac{n_1 + n_2}{2})(\frac{n_1 - n_2}{n_1}) \times 2n_1$$

$$Approximately\ \frac{n_1 + n_2}{2} \approx n_1 (\because n_1 > n_2)$$ (multiply & divide by $2n_1$)

$$\therefore n_1^2 - n_2^2 = (n_1)\left(\frac{n_1 - n_2}{n_1}\right)(2n_1)$$

$$= (2n_1^2)\Delta$$

$$\therefore \sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta}$$

$$N.A. = n_1\sqrt{2\Delta}........................(2)$$

Numerical aperture determines the light gathering ability of the fibre. It is a measure of the amount of light that can be accepted by a fibre. From equation (1)it is seen that N.A.=$\sqrt{n_1^2 - n_2^2}$ N.A. is dependent only on refractive indices of the core and cladding materials. Its value ranges from 0.13 to 0.5. Larger N.A. means a fibre will accept large amount of light from the source. Large N.A.

allows more modes of propagation of light which will result in greater model dispersion and lowers the band width. A Smaller N.A. limits the no. of modes. Hence, reduces dispersion and increases the bandwidth.

V-number/Normalized frequency:-

An optical fibre is characterised by one more important parameter called as **V-number which is called as Normalized frequency of the fibre**. It is given by ,

$$V = \frac{2\pi a}{\lambda}\sqrt{(n^2{}_1 - n_2{}^2)} \quad \text{--------(1)}$$

Normalized frequency (V) is a relation among the fibre size, the refractive indices (n_1,n_2) & the wavelength(λ).

In equation (1), 'a' is the radius of the core, λ is the free space wavelength, n_1 & n_2 is R.I. of the core & cladding.

$$V = \frac{2\pi a}{\lambda}(\text{NA})$$

$$= \frac{2\pi a}{\lambda}(n_1\sqrt{2\Delta}) \quad \text{---------------(2)}$$

$$= \frac{\pi d}{\lambda}(n_1\sqrt{2\Delta}) \qquad (\because N.A = \sqrt{n^2{}_1 - n^2{}_2})$$

V- number determines the number of modes N_m that can propagate through a fiber.

According to equation (2), the number of modes that propagate through a fibre increases with increase in numerical aperture.

The maximum number of modes N_m supported by SI fibre is determined by

$$N_m = \frac{1}{2}V^2 \quad \text{----------(3)}$$

While the number of modes in the GRIN fibre is about half that in a similar step-index fibre.

$$N_m = \frac{1}{4}V^2 \quad \text{------------(4)}$$

From equation (3), for V=10, Nm=50.

For V< 2.405, the fibre can support only one mode and is classified as a SMF. MMFs have values of V>2.405 & can support many modes simultaneously.

Wavelength corresponding to value V=2.405 is known as Cut off wavelength of the fibre.

$$\lambda_c = \frac{\lambda}{2.405}V \quad \text{-----(5)}$$

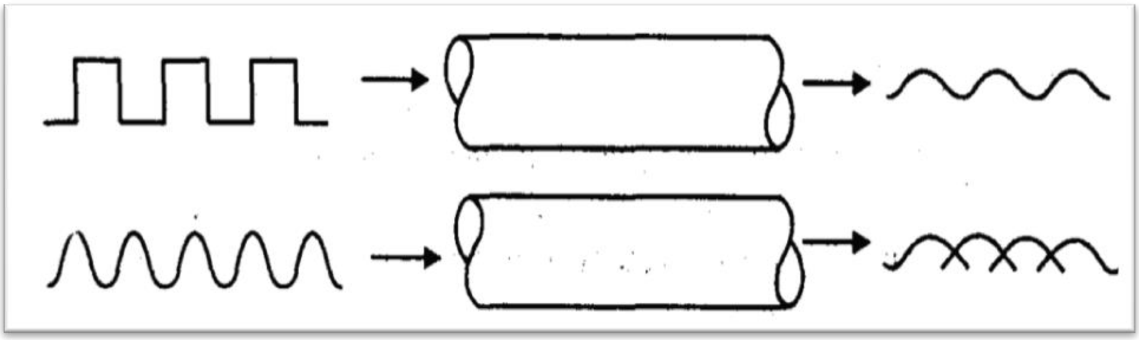
From equation (2), By decreasing core diameter or decreasing Δ, such that V< 2.405, single mode properties can be realized.

Dispersion:-

Pulse Dispersion: - Term dispersion is used to describe pulse- broadening effect by fibres.

When light pulse is launched into a fibre it decreases in its amplitude, as it travels along the fibre It also spreads during its travel. So the pulse received at the output is wider than the input pulse.

when a light pulse is launched into a fibre it decreases in its amplitude, so the light pulse broaden and spread into a wider time interval because of the different times taken different rays propogating through the fibre. This phenomenon is called pulse dispersion. The pulse received at the output is wider than the input pulse.



That means the pulse becomes distorted as it propagates through the fibre. So the distortion of the pulse arises due to dispersion effect. Dispersion is measured in **nanosecond per kilometer (ns/km)**

In practical terms if we have an input pulse of width tp1 and output pulse tp2 per unit length, then dispersion Δt is defined as,

$$\Delta t = \sqrt{t^2 p_2} - t^2 p_1$$

Total dispersion of a fibre depends on its length (L). Longer fibre causes more pulse broadening i.e. it have a larger dispersion. Total dispersion for a given length of a fibre can be calculated as

$$\Delta t = L \times (\text{Dispersion/km})$$

There are three mechanisms which contribute to the distortion of light pulse in a fibre.

1. Material dispersion or intramodal dispersion.
2. Waveguide dispersion.
3. Intermodal dispersion.

1. Material Dispersion or Intramodal dispersion:-

It is a direct result of the fact that the light in the fibre consists of a group of wavelengths travel at different speeds in a medium. The short wavelength waves travel slower than long wavelength waves causing **pulse- broadening (**Narrow pulse of light tends to broaden as they travel down the optical fibre). This is known as **Material Dispersion or Intramodal dispersion**.

The material dispersion is given by the equation,

$$\text{Dm}=\frac{\lambda(\Delta\lambda)}{C} L \frac{d^2 n}{d\lambda^2} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

λ - peak wavelength, Δ λ - spectral width.

L- Length of the core, n- Refractive index of the core.

2) **Waveguide Dispersion:**

It arises from the guiding properties of the fibre. The effective refractive index for any mode varies with wavelength, which causes pulse spreading just like the variation in refractive index does. This is known as **waveguide dispersion**.

The amount of waveguide dispersion is governed by an equation similar to a equation (1). with the material refractive index being replaced by the effective refractive index.

[As we know light wave is in the form of wavepacket. Each wavepacket consists of waves of slightly different wavelengths

$\therefore \nu = \frac{c}{\lambda}$ & R.I. n or $\mu = \frac{c}{v}$

$$\therefore \boxed{\mu = \frac{\nu \lambda}{v}}$$

Since each wave is of different wavelength λ, R.I. μ or n changes with λ, which causes pulse spreading.]

Fig.(2)Illustration of signal spreading due to various dispersion processes.

(a) Material dispersion:-Pulses at different wavelengths travel with different velocities.

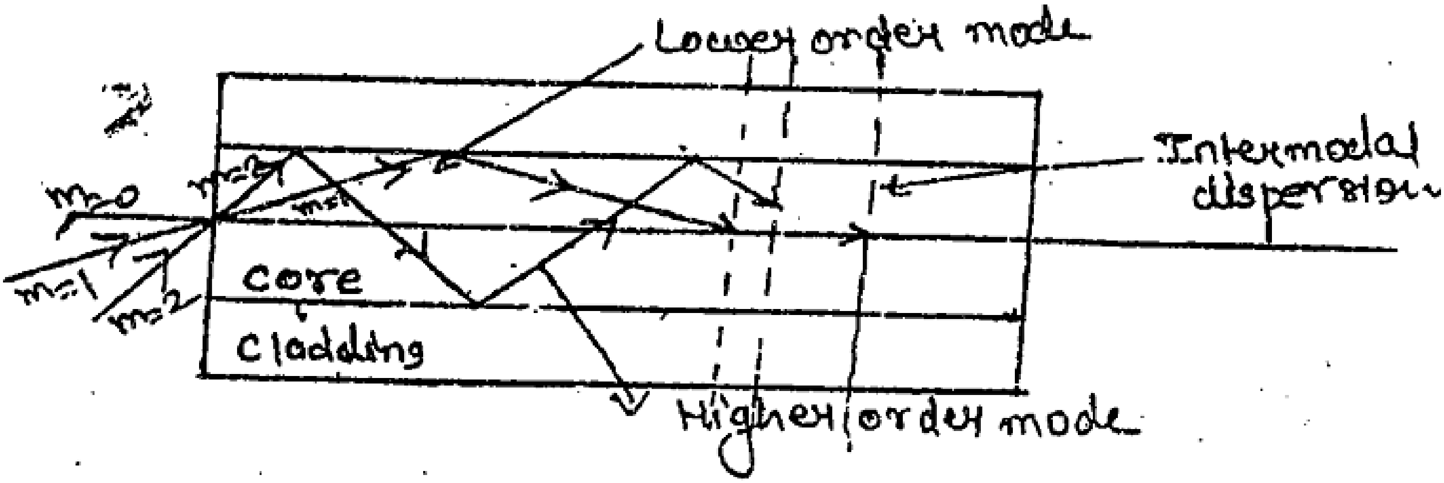
(b) Waveguide dispersion:-Pulses at different wavelength, though propagating in the same mode travel at slightly different angles.

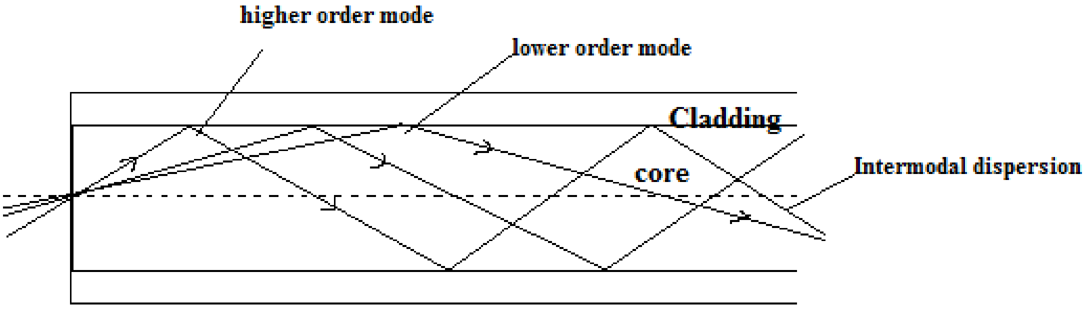
(c) Inter modal dispersion:-A pulse at a single wavelength divides itself into modes which travels at different axial velocities.

(3)Inter-modal Dispersion:-

It results from the fact that the wave propagates in modes. It is dispersion between the modes caused by the difference in propagation time for the different modes.

When light travels in an optical fibre, each light ray is reflected hundreds or thousands of times. (The rays reflected at larger angles) Lower order modes.) travel a (greater distance) faster than (the lower angle rays) higher order modes. Because of this difference, the higher order modes reach the end of the fibre later than the lower order modes. It means some parts of light waves arrive at the output before other parts. As a result, light pulses broaden as they travel down the fibre, causing signal distortion. The output pulses no longer resemble the input pulses. This type of distortion is called as **intermodal** or modal dispersion.





Types of optical fibre:-

What is index profile of optical fibre? Classify the optical fibres on the basis of index profile (winter 2017).

Optical fibres are classified as follows.

1. On the basis of refractive index profile they are classified as:
   (a) Step index and (b) graded index (GRIN)

   The curve /graph which represents the variation of R.I. with respect to radial distance is called R.I. profile. Index profile is a plot of R.I. drawn on horizontal axis verses the distance from core axis drawn on the vertical axis.
2. On the basis of modes of light propagation as
   (a) A single mode: A single mode has a smaller fiber (SMF) core diameter & can support only one mode of propagation.
   (b) multimode fibres: A multimode fiber(MMF) has a larger core diameter & supports a no. of modes.
3. On the basis of material used for core and cladding
   (a) glass/ glass (b) glass/ plastic (c) plastic/ plastic fibres

Q.) Differentiate between step index and graded index fibre on the basis of index profile. (W-13/3m)

Q. Explain what is step index, graded index, monomode and multimode fibre. Draw relevant sketches (4M summer 2007)

Q.) **Differentiate between Step Index Fibre and Graded Index Fibre. (S-15/3m)**

Q.) Explain the classification of optical fibres with well labeled diagrams.(S-14/3m)

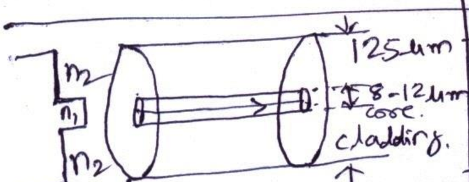
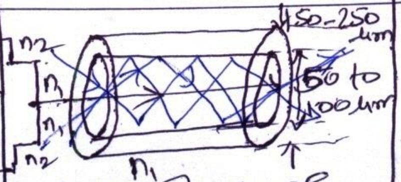
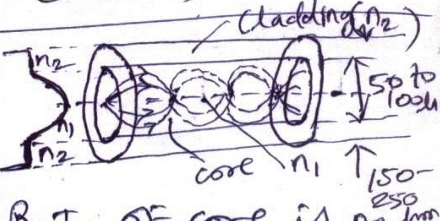
Classification of optical fibres

Optical fibres are classified into different types based on different parameter

Classification of optical fibres

- Based on R.I. profile
  - ① Step Index fibre (SIF)
    - Single mode step index optical fibre
    - multimode step index optical fibre
  - ② Graded index fibre (GRIN)
- Based on No. of modes
  - ① Single mode step index (SMF)
  - ② Multimode step index fibre (MMF)
    - ① multimode step index
    - ② multimode graded index
  - ③ ~~Multimode~~ Graded index (Multimode fibre) (GRIN)
- Based on materials
  - ① glass-glass (core)(cladding)
  - ② glass plastic
  - ③ plastic - plastic

Difference or Comparision between types of optical fibre.

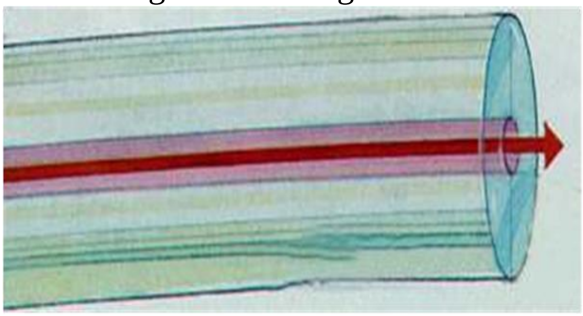
① Single mode step index fibre (SMF)	② Multimode step index fibre (MMF)	③ Graded index multimode fibre (GRIN).
		
① R.I. changes in steps R.I. n_1 of core remains constant along the radial direction and ~~abruptly~~ falls abruptly to a lower value n_2 at the core-cladding boundary. n_2 remains constant in cladding	R.I. n_1 of core remains const. along the radial dirn. and abruptly falls to a lower value n_2 at core-cladding boundary. n_2 remains const. in cladding.	R.I. of core is not const. but varies gradually over the diameter of core. At ~~its~~ maximum at the centre along the axis and decreases gradually towards core-cladding boundary. At the boundary n_1 becomes equal to n_2. n_2 remains constant in cladding.

Comparision between Types of optical fibres:

Single Mode Step Index Fibre (SMF)	Multimode Step Index Fibre (MMF)	Graded Index Multimode Fibre (GRIN)
(1) R.I. changes in steps. R.I. n_1, of core remains constant along the radial direction & falls abruptly to a lower value n_2 at the core-cladding boundary. n_2, remains constant in cladding	R.I. of core remain constant along the radial direction & abruptly falls to a lower value n_2 at core-cladding boundary. n_2 - remains constant in cladding	R.I. of core is not constant but varies gradually over the diameter of core. It is maximum (at the centre) along the axis & decreases gradually towards core cladding boundary. At boundary n_1 becomes equal to n_2. n_2 remains constant in cladding.
(2) It has small core diameter of about 10 um	It has large core diameter of order of 50 um	Core diameter is in the range of 50-100 um
(3) Its N.A. is very small	N.A. is large.	N.A. is smaller than that of Step Index multimode fibre.
(4) It allows (support) only one mode ie along the axis of the fibre (called Axial ray) m=0 order	It allows many no. of modes to propogate	It allows many modes but no. of mode is half that in a similar multimode step in fibre.
(5) There is no inter-modal dispersion due to single mode propogation	Multimodes cause large dispersion ie intermodal dispersion	Inter modal dispersion is zero, but material dispersion exists.

6	The attenuation is least	Attenuation is high.	Attenuation is medium.
7	• It has higher bandwidth (suitable for high data rates)	Smaller bandwidth	Medium bandwidth (Better bandwidth than multimode step index fibre)
8	• Requires monochromatic & coherent light source like Laser diode.	Non-coherent sources like LEDs can be used as light sources	Either a LED or a LASER can be used as light source.
9	• Launching of light into fibre is difficult.	Launching of Light into fibre is easier	Launching of light into the fibre is easier.
10	• Manufacturing & handling is difficult. Coupling is difficult. Hence fibre is costly.	Manufacturing is easy. coupling is easier hence less expensive	Manufacturing is more complex. Coupling to light source is difficult hence most expensive.
11	• No self focussing of light rays	There is no self focussing	Light rays are self focussed periodically while propagating through the fibre.

1. **Single (mono) mode step index fibre (SMF)**:-
   - It has smaller core diameter of 4µm which is of the order of few wavelengths of light. Fibre is surrounded by an opaque protective sheath.
   - R.I. of the fibre changes abruptly at the core- cladding boundary hence called as Step index fibre.
   - Light travels along a single path i.e. along the axis called **zero order mode.**
   - It is designed to have a V number between 0 and 2.4 i.e. small value obtained by reducing fibre radius and by making Δ to be small.
   - Δ and N.A. are very small. Low N.A. means low acceptance angle. Therefore light coupling into the fibre becomes difficult.
   - **Inter modal** dispersion does not exist due to one mode only. Total dispersion can be made small which makes the fibre suitable for use with high data transfer rate.
   - Part of the light propagates in the cladding. Hence, it is relatively thick.
   - Manufacturing and handling is difficult and hence, fibre is costly.



2. **Multimode step index fibre (MMF):-**
   - It is similar to the single mode step index fibre. But its core diameter is large i.e. of the order of 100 µm which is very large compared to the wavelength of light.
   - A light follows zigzag paths inside the fibres. Many such zigzag paths of propagation are permitted in a MMF.
   - N.A. is large of the order of 0.3.
   - Larger N.A. leads to more modes which means higher dispersion. Hence, lower data transfer rate and hence less efficient transmission.
   - Dispersion is **inter modal** .
   - Easy to manufacture and is less costly.
   - MMF have value of V No. is greater then 2.4 and can support many modes simultaneously.

3. **Graded index (GRIN) fibre:-**
   - It is a multimode fibre with a core consisting of concentric layers of different R.I. Hence, R.I. of the core varies with distance from the fibre axis. R.I. is high at the center and falls off with increasing radial distance from the axis. Such a index profile causes a periodic focussing of light propagating through the fibre.
   - Acceptance angle(θ_0) and N.A. decrease with radial distance from the axis.

- No. of modes is about half that in a similar multimode step index fibre.i.e. Nm = $V^2/4$ for GRIN fibre.
- The lower no. of modes results in lower dispersion than is found in MM SIF.
- The size is same as the step index fibre.
- Manufacturing of GRIN fibre is more complex.
- Effective acceptance angle of GRIN fibre is less than that of an equivalent SI fibre. It makes coupling fibre to the light source more difficult.

Write in brief about the classification of the optical fibres based on materials (W-2009)(4M)

(i) A glass core cladded with a glass having a slightly lower refractive.
(ii) A silica glass core cladded with plastic.
(iii)A plastic core cladded with another plastic.

1. All glass fibres

The basic material for fabrication of optical fibres is silica(SiO_2). It has a refractive index of 1.458. If the basic silica material is doped with Germania (GeO_2) or phosphorous pentoxide (P_2O_5), the refractive index of the material increases. Such materials are used as core materials and pure silica is used as cladding material. When pure silica is doped with boria (B2O3) or fluorine, its refractive index decreases. These materials are used for cladding when pure silica is used as core material.

SiO_2 core – $B_2O_3.SiO_2$ cladding
$GeO_2.SiO_2$ core – SiO_2 cadding

2. All Plastic fibres

In these fibres, perspex (PMMA) and polysterene are used for core. Their refractive indices are 1.49 and 1.59 respectively. A fluorocarbon polymer or a silicone resin is used as a cladding material. Plastic fibres have large NA of the order of 0.6 and large acceptance angles up to 70°. The main advantages of the plastic fibres are low cost and higher mechanical flexibility. The mechanical flexibility allows the plastic fibres to have large cores, of diameters ranging from 110 to 1400μm.

Polysterene core $n_1 = 1.59$ NA = 0.60
-Methyl methacrylate cladding $n_2 = 1.49$
Polymethyl methacrylate core $n_1 = 1.49$ NA = 0.50
-cladding made of its copolymer $n_2 = 1.40$

3. PCS fibres

The plastic clad silica (PCS) fibres are composed of **silica cores** surrounded by a low refractive index **transparent polymer** as cladding. The **core** is made from **high purity quartz**. The **cladding** is made of a **silicone resin** having a refractive index of 1.405 or of **perfluoronated ethylene propylene (Teflon)** having a refractive index of 1.338. Plastic claddings are used for step-index fibres only. The

PCS fibres are less expensive but have high losses. Therefore, they are mainly used in short distance applications.

Attenuation:-

Q.) What is attenuation in optical fibre? State the different mechanism that contribute to attenuation. (W-15/4m)
Q.) What is attenuation in optical fibre? State the different mechanism that contribute to attenuation. (W-15/4m)
Q.) Define the terms: (S-16/1+1m)
i) Attenuation and Dispersion ii) Modes of propagation in optical fibre.

Attenuation:-

An optical signal propagating through a fibre gets progressively attenuated. The signal attenuation is defined as the ratio of the optical power output from a fibre of length L to the input optical power. It is expressed in decibel/Km (dB/ Km).

$$\alpha = \frac{10}{L}\log\left(\frac{Pi}{Po}\right)$$

$P_i \rightarrow$ power of optical signal launched at one end of the fibre (input).
$P_o \rightarrow$ power of optical signal emerging out from the other end of the fibre.

In ideal fibre $P_i=P_o$, so attenuation = 0, but in practice attenuation = 3dB/Km it depends on wavelength.

Q. Describe various mechanisms of attenuation in optical fibre. (4M,summer2007)
Different mechanisms of attenuation:-

Ans :- There are several loss mechanisms responsible for the signal attenuation in optical Fibres. They are broadly divided into two categories. i) intrinsic losses, ii) extrinsic losses.

Attenuation Mechanisms

(I) Intrinsic losses — II Extrinsic losses

Attenuation mechanisms

- (1) Intrinsic losses
  - (i) Absorption by material
  - (ii) Rayleigh scattering.
- (2) Extrinsic losses
  - (i) Microbend losses
  - (ii) Macrobend losses.
  - (iii) waveguide losses
  - (iv) Mode-coupling losses.

[There are 3- fundamental mechanisms responsible for attenuation:-
1) Absorption by material 2) Rayleigh scattering 3) Waveguide and micro bend losses OR Geometric effects.]

(I) Intrinsic losses are influenced by the material composition & purification level. Impurities & Inhomogeneities in material cause a) signal absorption & b) scattering.

1. **Absorption by material(**3-5% loss):- This includes absorption (a) due to light interacting with the molecular structure of the material, (b) As well as loss because of material impurities.

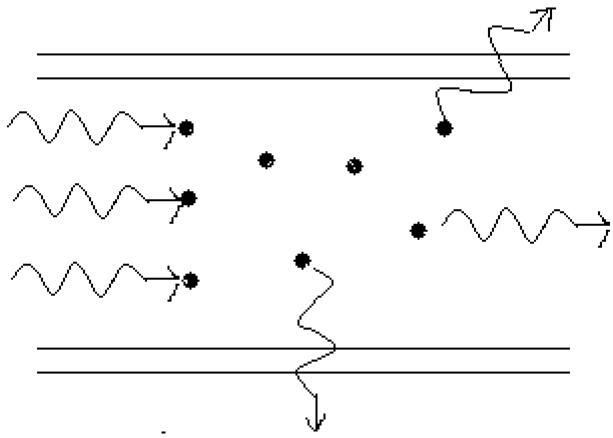
   Due to absorption, 3-5 % fibre attenuation. In this case, a light signal is to be absorbed by natural impurities in the glass & converted to vibrational energy or some other form of energy.

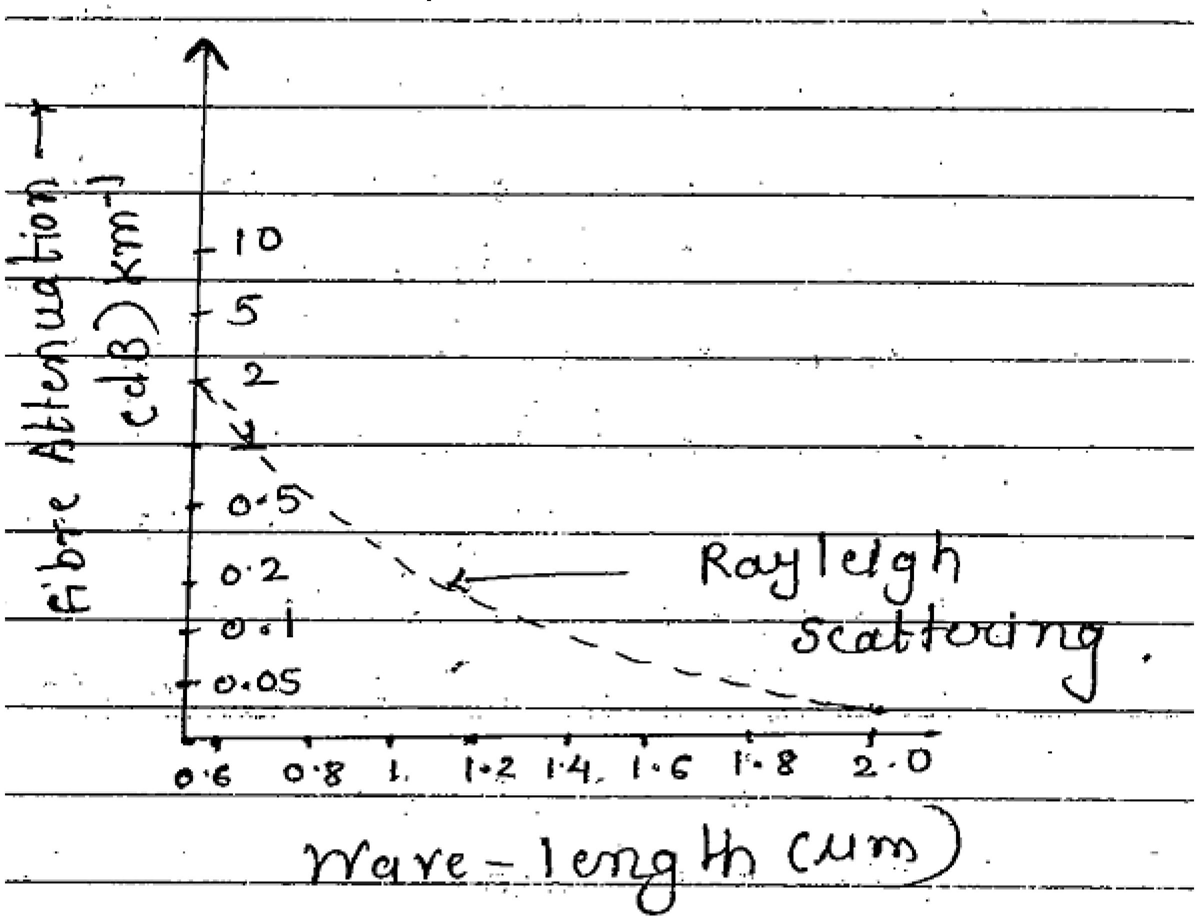
(a) Even a highly pure glass also absorbs light in specific wavelength regions. Strong electronic absorption occurs at UV wavelengths and vibrational absorption occurs at IR wavelength. These absorption losses are inherent properties of the glass and are known as intrinsic absorption.

(b) Major source of losses in fibres are impurities- Hydroxyl radical ions (OH) and transition metals such as copper, nickel, chromium have electronic absorption in and near visible part of the spectrum. Their presence causes heavy losses. The losses due to impurities can be reduced by better manufacturing processes. Largest loss is caused by OH ions which can not be sufficiently reduced.

The absorption of light either through intrinsic or impurity process constitutes a transmission loss because that much energy is subtracted from the light through the fibre. Absorption losses are found to be minimum at around 1.3 μm .

2.Rayleigh scattering(96% loss):- It accounts for majority of 96% of attenuation.When light is scattered by an obstruction there is power loss. Glass is disordered structure having local microscopic density variations which causes local variations in R.I. These variations are inherent in manufacturing processes and cannot be eliminated. They act as obstructions and scatter light in all directions. Light propagating through such a disordered structure of Glass suffers scattering losses. This is known as **Rayleigh scattering**. Rayleigh scattering loss is proportional to $1/\lambda^4$ and hence, it is important at lower wavelength. Rayleigh scattering sets a lower limit on the wavelengths that can be transmitted by glass fibre at 0.8 μm below which scattering loss is very high.(fig. 1)





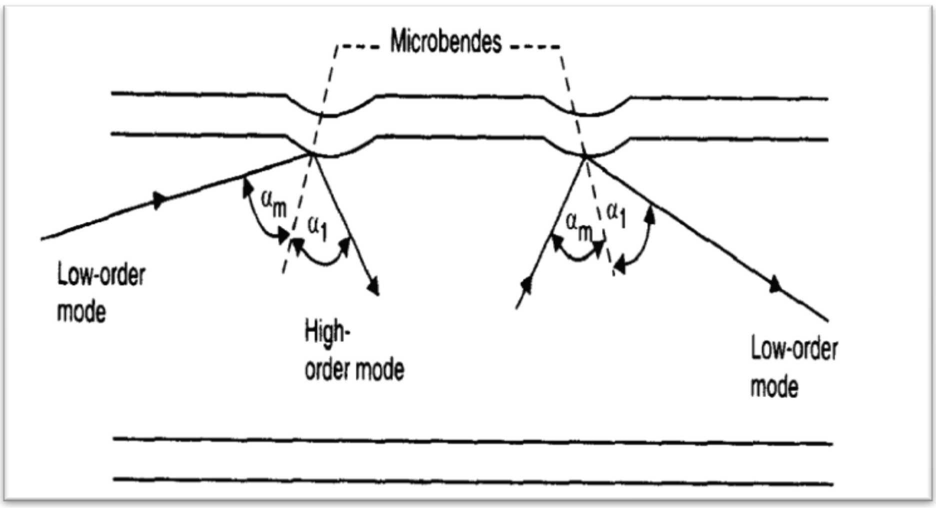
Extrinsic losses :

These are caused by geometric effects. Irregularities of geometric nature cause light energy losses because the condition of total internal reflection is no longer satisfied. Any bends in optical fibre produce radiative losses.

(i) Microbend losses :

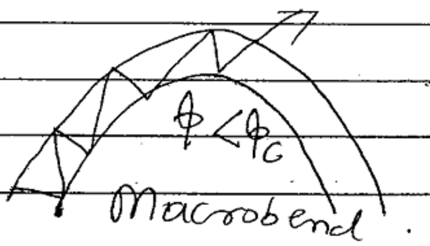
Microbend is a small scale distortion.

fiber. The bend may not be clearly visible. Microbends may be introduced during manufacturing or installation processes structural variations in the fibre or fibre deformation cause radiation of light away from the fibre. For example microbending may occur due to winding of optical fibre over spools. light rays get scattered at the small bends and escape into the cladding. Such losses are known as microbend losses.



(ii) Macrobend losses :-

It is a large-scale bend that is visible. When a fibre is bent through a large angle, strain is placed on the fiber along the region that is bent. The bending strain will affect the refractive index and the critical angle of the light ray in that specific area. As a result, light traveling in the core can refract out and loss occurs.



To prevent macrobends, optical fibre has a minimum bend radius specification that should not be exceeded.

(iii) Wave-guide losses

Due to irregularities in the optical fibre geometry, the incident ($\phi < \phi_c$) angle (at the core-cladding boundary) becomes less than the critical angle $\phi < \phi_c$ for higher order modes. As a result part of the light ray will be refracted into the cladding. They are known as leaky modes. The leaky modes are regarded as wave-guide losses.

(iv)] Mode coupling losses The power launched into a propagating mode may get coupled into a leaky mode at some pts. of the fibre. The coupling occurs due to the small imperfections present in the core & imperfectly aligned connectors. (condⁿ $\phi > \phi_c$ may not be satisfied)

<u>Application of Fibre optics as Sensor:-</u>

Q.) Discuss any one application of an optical fibre as sensor. (W-14/3m)

Q.) Discuss the working of optical fibre as a temperature sensor. (S-13/3m)

Q.) Explain (i) Optical fibre as a sensor (ii) Types of optical fibre on the basis of R. I. (W-16/4m)

Fibre optic sensors:-

Fibre optic sensors are transducers which consist of light source coupled with an optical fibre and a light detector held at the receiver end.

Fibres used could be single mode or multimode type.

Sensors can be used to measure :- (1) Pressure (2) Temperature (3) Strain (4) The acoustic field (5) Magnetic field etc. physical parameters.

The adavantages of these sensors are that they are (i) lighter (ii) occupy lesser volume (iii) cheaper.

In some of the sensors the optical fibre carries the light beam and in others fibre it self acts as the sensors.

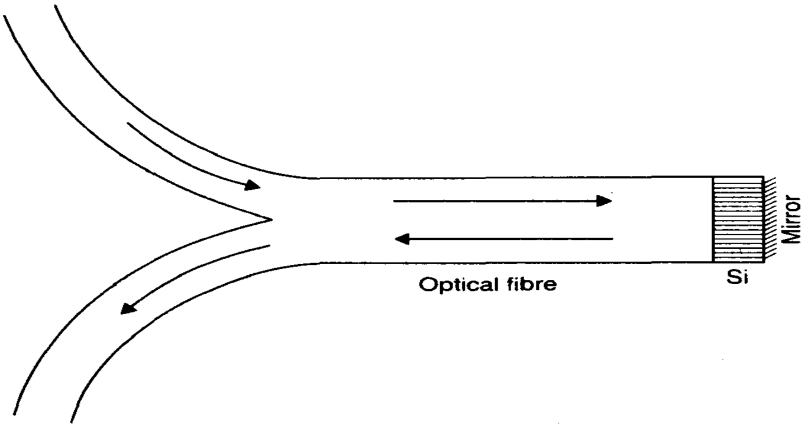
Examples of sensors:-

1. **Temperature sensor:-**

   (a) Operation of this sensor is based on the 1 μm wavelength light- absorption characteristics of silicon as a function of temperature.

   Fig shows the multimode fibre temp. sensor.

Light source



Light Detector

Fibre is coated at end with a thin silicon layer. The silicon layer is coated with a reflective coating at the back. Light launched into the fibre from one of its ends passes first through the fiber and then after traveling through the silicon layer twice returns to a detector.

The absorption of light by the silicon layer varies with the temp. this variation changes the intensity of light received at the detector. Temp. measurement can be made with a sensitivity of 0.001°C.

(b) The variation of R.I. of the optical fibre under the influence of temp. can be utilized in fabrication of optic temp. sensor.

If an optical fibre is heated the temp. causes change in R.I. of the fiber. As temp. increases the difference between R.I. of the core and cladding materials reduces and light tends to leak away from the cladding.

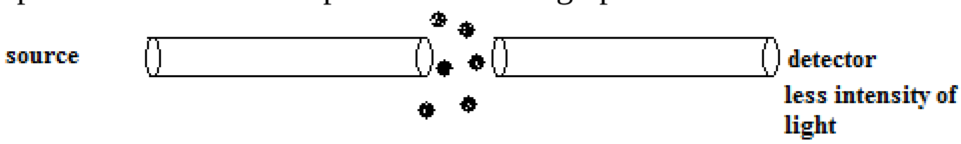
A simple thermometer can be built using LED as a light source, a coil of optical fiber as heat sensing element and a photo detector to measure the intensity of light. Temp. from 80 °C to 700 °C can be measure using this technique.

3. Temperature Sensor

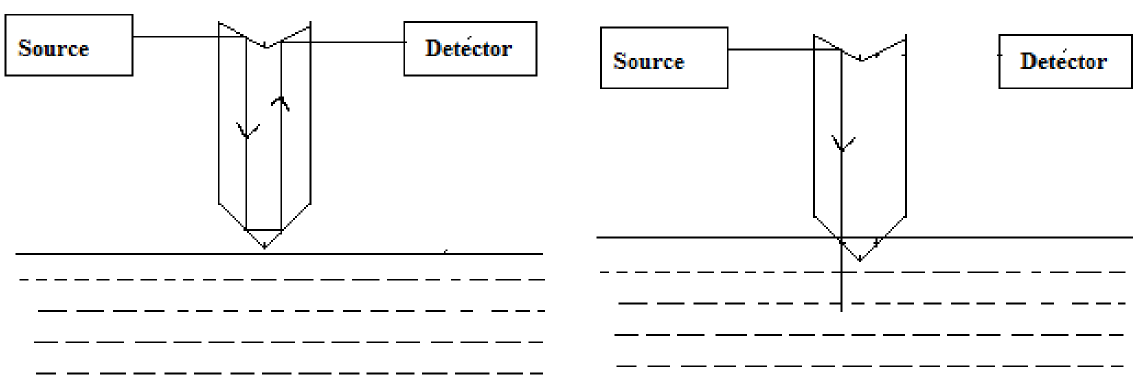
- A thermometer can be built by using :
  - (i) Light source - LED
  - (ii) Heat sensing element - an optical fibre coil
  - (iii) Photodetector - to measure intensity of light.
- When temperature increases, fibre gets heated due to which difference between R.I. of core and that of cladding reduces.
- The reduction in difference of R.I. of core and cladding will reduce the percentage of light propagating by total internal reflection through optical fibre.
- Thus more light will leak into the cladding and finally escapes out of fibre.
- The temperature in the range of $80^0C - 700^0C$ can be measured with the help of optical fibre thermometers.

2. POLLUTION DETECTOR:-

Smoke and pollution detector can be built using optical fibres. A beam of light radiating from one end of a fibre can be collected by another optical fibre. It foreign particles are present in the region between in two fibres, they scatters light. The variation of intensity of light collected by the second optical fibre shows the presence of foreign particles.



3.LIQUID LEVEL DETECTOR:-



($\mu_{air} < \mu_f < \mu_L$)

(a) A simple liquid level detector is as shown in fig.(1).An optical fibre with one of lt's ends chamfered (at an edge on a piece of wood.) is arranged at the desired height in a vessel. Refractive index of the fibre is chosen < refractive index of the liquid whose level is to be detected. A light beam entering into the fibre is internally reflected at the chamfered end i.e. at the fibre to air boundary & travels back & is detected at the detector. When the liquid rises and touches the fibre end, total internal reflection ceases & the light is transmitted into the liquid. Liquid level is indicated at the detector.

(b) A loop of optical fibre can be used to determine the level of the level in a container. Apart of the cladding is scraped &the fibre loop is suspended above the liquid level. Light is directed to pass through one end of the fibre & it's intensity is measured at the other end.

A bare core looses more light when it is immersed in liquid than when it is in air. Therefore a sudden change of out coming light intensity indicates liquid level. An LED, a MMF &a photo-detector are used in fabricating such a liquid level sensor. Such sensors are used to monitor the filling of Petroleum Tanks.

Whenever higher sensitivity is necessary, single mode fibre sensors are used & multimode fibre sensors can be used when the sensitivity is less.

Above fig. shows a phase change sensor. To detect variation in temperature the fibre is placed in

1. Liquid Level Sensor :

- A loop of an optical fibre is suspended at a level in the liquid container up to which liquid is to be filled.

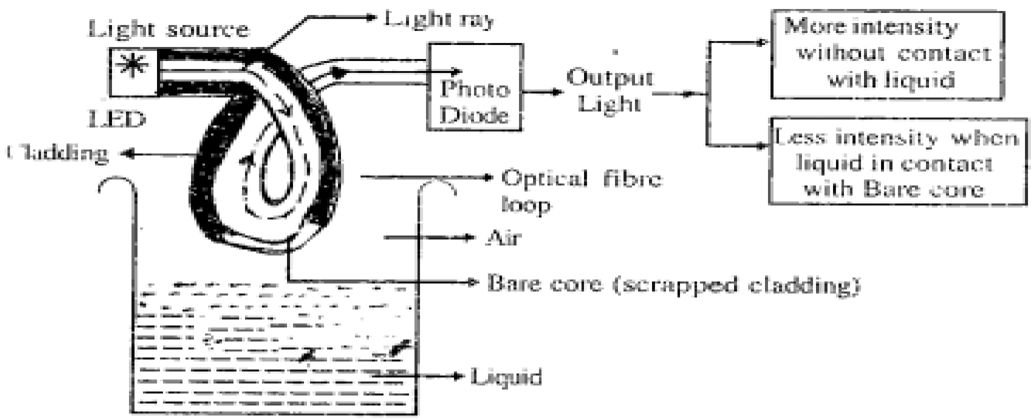


Fig. 5.25 : Experimental set-up for liquid level sensor

- In this application, small part of cladding is scrapped.
- Light is passed through one end of suspended optical fibre and comes out through another end.
- Usually, LED i.e. light emitting diode is used as a light source and a photodetector is used to detect the light at the other end of fibre.
- The intensity of light is measured at output end.

- The **intensity of light is more when bare core is in contact with air**.
- When level of liquid rises and it touches the optical fibre, the **bare core is in contact with the liquid, the intensity of light at output end reduces drastically**.
- Sudden decrease in intensity of light at the output end indicates the filling of liquid up to the desired level in a container.
- Such type of sensors are very useful for monitoring the filling of oil tankers, petroleum tanks or huge liquid reservoirs.

2. Smoke Detector or Pollution Detector

It consists of two co-axial optical fibres having a small gap between them as shown in the figure (4.12).

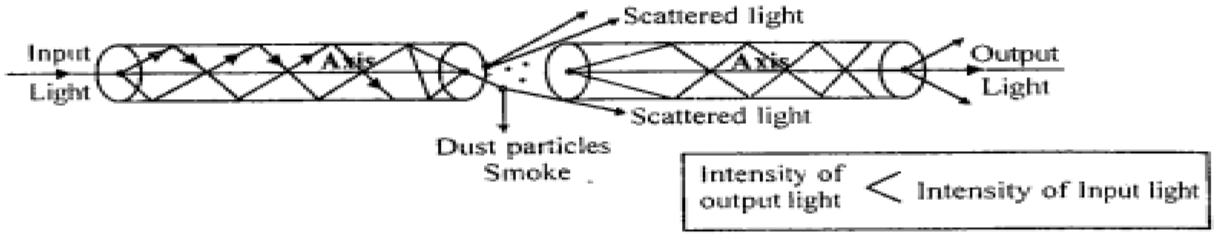


Fig. 4.12 : Smoke detector sensor

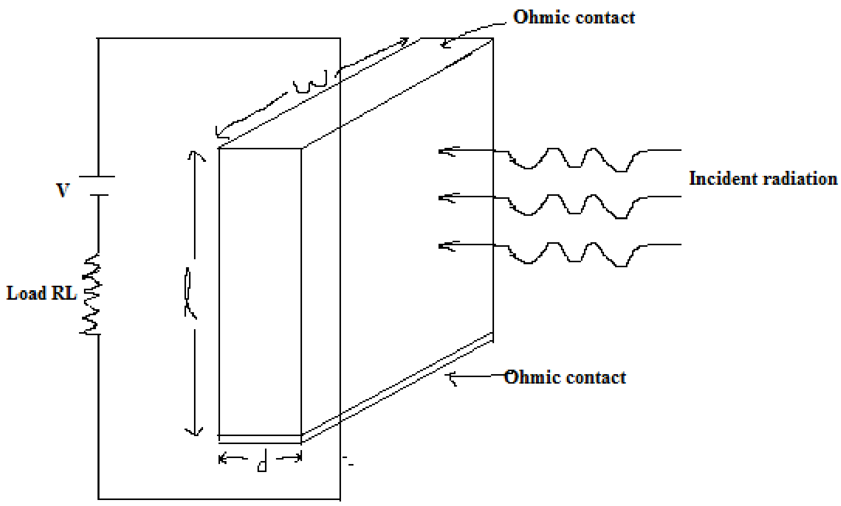
- Light entered in the first fibre comes out of end of second optical fibre.
- In the gap between two optical fibres, air molecules are present. Therefore, a small amount of light may scatter from the air molecules.
- The light rays which doesn't get scattered, enter in the second optical fibre and get propagated by total internal reflection.
- Due to scattering process, intensity of light at the output end is less than that at the input end.
- But, in the gap region, if smoke or dust particles are in abundance, the percentage of scattering increases considerably.

Photo detectors :-

Photo-detectors are a device that absorb optical energy and convert it to electrical energy. The operation of photo-detector is based on the photoelectric effect where the absorption of photons by some materials leads to the generation of mobile carriers. These mobile charge carriers move and produce electric current under the influence of an electric field. The photoelectric effect takes two forms: external photoelectric effect and internal photoelectric effect. External photoelectric effect is known as photoelectric emission in which electrons escape from the metal surface under the action of light. The internal photoelectric effect is known as photoconductivity and occurs in semiconductors. In this effect, the mobile charge carriers generated by light remain within the semiconductor material. Photo detector based on external photoelectric effect are vacuum tube called photocells and photomultiplier tubes. These devices are too bulky and require high voltage for operation. These are four main types of photo detectors, namely photoconductors, photodiodes, pin diodes and avalanche photodiodes, which are widely used in optical communication systems.

(a) Photoconductor:-

The photoconductor is the simplest photodetector. Its operation is based on the increase in conductivity of the semiconductor material. When light is incident on the device, the photons generate electron & hole pairs. They are collected by opposite contacts & result in a photocurrent.



The schematic of a simple photoconductor is shown in fig. A photon incident on the surface of the photoconductor which has energy greater than or equal to the band gap energy Eg of the semiconductor material will excite an electron from the valence band into the conduction band. This process generates a hole in valence band. Thus an electron hole pair is generated by an optical photon. These are known as photocarriers. A suitable bias is applied across the contact to collect the carriers. Thus photogenerated carriers increase the conductivity of the material, which leads to current in the external circuit.

(b) The p-in photodiode

The pin photodiode is a device that consists of p & n region separated by a very lightly doped intrinsic region (i). It is shown schematically in fig. A sufficiently large reverse bias is applied across the device. Because of very low density of free carriers in the intrinsic region & its high resistivity, the applied bias appear almost entirely across the i-layer. The intrinsic layer in effect widens the depletion region & therefore increases area available for capturing light.

When an incident photon has energy greater than or equal to the band gap energy of semiconductor materials, the photon can give up its energy & excite an electron from the valence band to the conduction band. This process generates free electron hole pairs. These carriers are mainly generated in depletion region where most of the incident light is absorbed. The high electric field present in depletion region causes the carriers to separate & be collected across the reverse bias junction. This gives rise to a current flow in the external circuit.

2. Avalanche Photodetector (APD) :

- It is a reverse biased P-N junction which uses phenomenon of **avalanche breakdown** for the amplication of photocurrent within detector.
- Free electrons and holes are generated in the depletion region due to absorption of light.
- These charge carriers gain K.E. due to applied reverse biased voltage.
- The fast moving charge carriers when collide with neutral atoms, an electron can be removed from the valence shell.
- Thus, neutral atom gets ionized and generates a free electron and a free hole. Free electrons and holes generated by this **Impact Ionization** process are called as **Secondary charge carriers**.
- The secondary charge carriers also gain addition K.E. and can create a pair of free hole and electron due to collision with neutral atoms. This process continues and a large number of free electrons holes are generated within detector itself.
- Thus, carrier multiplication process occurs internally.
- This process is responsible for the **higher responsivity** of the detector.

Drawback of Avalanche Photodetector :

1. High voltage power supply is required for its operation which adds complexity to the circuit.
2. APDs are temperature sensitive.
3. Less reliable than PIN detector.

1. PIN Detector :

- It consists of three regions : **P-type SC, Intrinsic (pure)** SC and **N-type SC**.
- Intrinsic SC (I) region is wide and very lightly doped region.
- Intrinsic (I) region is present between P-type and N-type region and hence the name PIN.
- PIN photodiode is reverse biased. Intrinsic (I) region has no free charge carriers and hence offers a high resistance to the current flow. So, most of the reverse applied voltage acts in the (I) region.
- Due to high electric field in the (I) region, electron-hole pairs generated in this region are immediately drifted away by the field. It gives rise to current flow in the circuit.
- On the contrary, electron-hole pairs generated in p or n region have to first diffuse into depletion region before they are drifted by field.

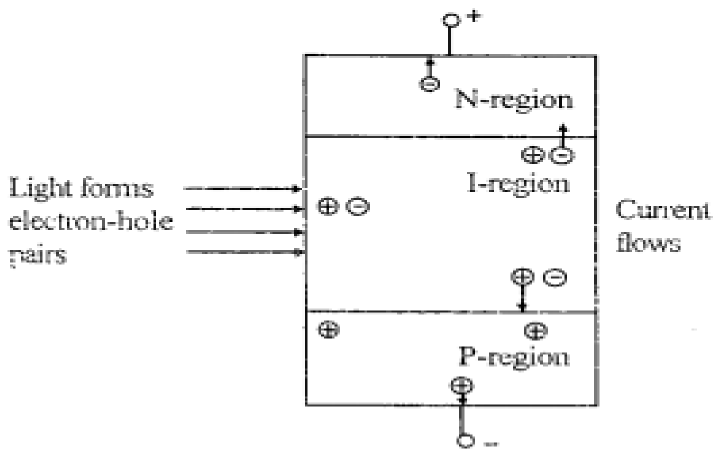


Fig. 4.13 : P-I-N Photodetector

Q. Dicuss the advantages and disadvantages of optical fibre.

MERITS OF OPTICAL FIBRES:-

Optical fibres have many advantages over the conducting wires.

(1) **Cheaper:** Optical fibres are made from silica(SiO_2) which is one of the most abundant material on the earth. The overall cost of a fibre optic communication is lower than that of an equivalent cable communication system.

(2) **Smaller in size, lighter in weight, flexible yet strong:** The cross section of an optical fibre is about a few microns. Hence, the fibres are **less bulky.** Optical fibres quite flexible & strong.

(3) Not Hazardous : A wire communication link could accidentally short circuit high voltage lines and the sparking occurring thereby could ignite combustible gases in the area leading to a great damage . Such accidents cannot occur with fibre links sinces fibres are made of insulating material.

(4) Immune to electromagnetic interference(EMI)& radiofrequency interference (RFI). In optical fibres information is carried by photons. Photons are electrically neutral and can not be disturbed by high voltage fields , lightening, etc.Therefore , fibres are immune to externally caused background noise generated through EMI & RFI.

(5) **No cross talk** : The light waves propagating along the optical fibre are completely trapped within the fibre and can not leak out further , light can not couple into the fibre from sides . Therefore, the possibility of cross talk is minimized when optical fibre is used. Thus transmission is more secure and private.

(6) Wider band-width: Optical fibres have ability to carry large amounts of information . A 1 mm optical fibre can transmit 50,000 calls .

(7) **Low loss per unit length**: The transmission loss per unit length of an optical fibre is about 4 dB/km. Therefore, longer cable-runs between repeaters and feasible.

DISADVANTAGES OF OPTICAL FIBRE:

Installation and maintenance of optical fibers require a new set of skills. They required specialized and costly equipment like optical time domain reflectometers etc.

5.14. APPLICATIONS OF OPTICAL FIBRE

Optical fibre has wide variety of applications. If classified broadly, optical fibre has three different applications, apart from other miscellaneous applications.

a] **Optical fibres**are used for **illumination** and short distance **transmission of image.**
b] **Optical fibres** are used as wave guides in **telecommunication**.
c] **Optical fibres** are used in fabricating a new family of **sensors**.

5.14.1. ILLUMINATION AND IMAGE TRANSMISSION

The optical fibres are capable to conduct light from one region to another. This property of optical fibre is used for illumination purpose. As optical fibres are flexible light carriers and inexpensive due to their easy manufacturing, they are the best illuminators.

When bundles of fibres are carefully arranged so that their terminations occupy the same relative position in both the bound ends of the bundle, the bundle is said to be ***coherent***. Such a bundle is capable of transmitting images. When one end of such bundle is placed face down flat on an illuminated surface appears at the other end. ***Endoscope*** is such coherent bundles used in medical field.

5.14.2. FIBRE OPTIC COMMUNICATION SYSTEM

Traditionally, electronic communication was carried out by sending electrical signals through copper cables, co-axial cables or waveguides. In recent years optical fibres are being used, where light signals replace electrical signals.

Optical Fiber Communication is the method of communication in which signal is transmitted in the form of light and optical fiber is used as a medium of transmitting those light signal from one place to another. The signal transmitted in optical fiber is converted from the electrical signal into light and at the receiving end, it is converted back into the electrical signal from the light. The data sent can be in the form of audio, video or telemetry data that is to be sent over long distances or over Local Area Networks. Optical fiber communication having good results in long-distance data transfer at high speed, it has been used as an application for various communication purposes. The block diagram of optical fiber communication system is as shown in fig. 5.16.

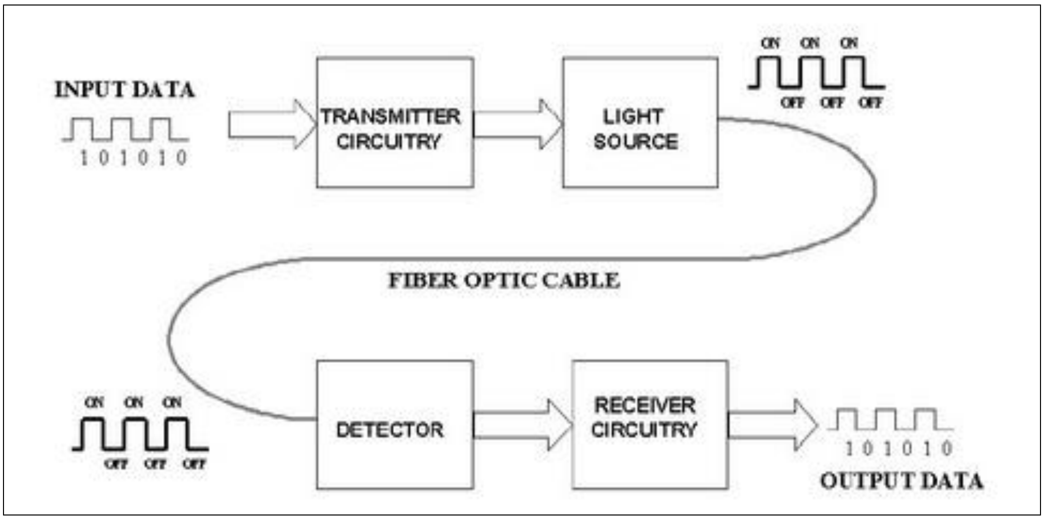


Fig.5.16: Block Diagram of optical fiber communication System

There are three main basic elements of fiber optic communication system. They are:

- Transmitter with light source
- Fibre optic cable
- Receiver with Detector

Transmitter:

When the input data, in the form of electrical signals, is given to the transmitter circuitry, it converts them into light signal with the help of a light source. This source is of LED or Laser whose amplitude, frequency and phases must remain stable and free from fluctuation in order to have efficient transmission.

This type of communication uses the wavelengths near to the infrared band that are just above the visible range. Both LED and Laser can be used as light sources based on the application.

Fibre optic cable:

Optical fibre acts as a path way to the signal to be passed. The light beam from the source is carried by a fiber optic cable to the destination circuitry. The light passing down the fiber optic cable undergoes total internal reflection and reaches the receiver end.

Receivers:

Light travelling along a fibre optic cable needs to be converted into an electrical signal so that it can be processed and the data that is carried can be extracted. The component that is at the heart of the receiver is a photo-detector. Once the optical signal from the fibre optic cable has been applied to the photo-detector and converted into an electrical format it can be processed to recover the data which can then be passed to its final destination.

WORKED-OUT PROBLEMS

Example 8.1: *In an optical fibre, the core material has refractive index 1.43 and refractive index of clad material is 1.4. Find the propagation angle.*

Solution: $$\cos\theta_C = \frac{n_2}{n_1} = \frac{1.40}{1.43} = 0.979$$

Therefore, propagation angle $\theta_C = \cos^{-1}(0.979) = \mathbf{11.8^o}$

Example 8.2: *In an optical fibre, the core material has refractive index 1.6 and refractive index of clad material is 1.3. What is the value of critical angle? Also calculate the value of angle of acceptance cone.*

Solution: Critical angle is given by $sin\ \phi_c = \frac{n_2}{n_1} = \frac{1.3}{1.6} = 0.8125$

$\therefore$ $\phi_c = \mathbf{54.3^o}$

Acceptance angle $\theta_0 = sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right] = \sin^{-1}\left[\sqrt{1.6^2 - 1.3^2}\right]$

$= \sin^{-1}(0.87)$

$= \mathbf{60.5^o}$

Angle of acceptance cone $= 2\theta_o = \mathbf{121^o}$

Example 8.3: *Calculate the numerical aperture and acceptance angle of an optical fibre from the following data:*

$$\mu_1(core) = 1.55 \ \ and \ \ \mu_2(cladding) = 1.50$$

Solution: $$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.55^2 - 1.50^2} = \sqrt{0.153} = \mathbf{0.391.}$$

Acceptance angle $\theta_0 = sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right] = \sin^{-1}\left[\sqrt{1.55^2 - 1.50^2}\right] = \mathbf{23.02^o}$

Example 8.4: *What is the numerical aperture of an optical fibre cable with a clad index of 1.378 and a core index of 1.546?*

Solution: $NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.546^2 - 1.378^2} = \sqrt{0.491} = 0.70$

Example 8.5: *A fibre cable has an acceptance angle of 30° and a core index of refraction of 1.4. Calculate the refractive index of the cladding.*

Solution: $\sin\theta_o = \sqrt{n_1^2 - n_2^2}$

$\therefore$ $\sin^2\theta_o = n_1^2 - n_2^2$

$n_2^2 = n_1^2 - sin^2\theta_o = (1.4)^2 - sin^2 30^o = 1.96 - 0.25 = 1.71$

$\therefore$ $n_2 = \mathbf{1.308}$

Example 8.6: *Calculate the angle of acceptance of a given optical fibre, if the refractive indices of the core and the cladding are 1.563 and 1.498 respectively.*

Solution:
$$\sin\theta_0 = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.563)^2 - (1.498)^2} = 0.4461$$
$$\theta_o = \sin^{-1}(0.4461) = \mathbf{26.49^\circ}$$

Example 8.7: *Calculate the fractional index change for a given optical fibre if the refractive indices of the core and the cladding are 1.563 and 1.498 respectively.*

Solution: Fractional index change $\Delta = \dfrac{n_1 - n_2}{n_1} = \dfrac{1.563 - 1.498}{1.563} = \dfrac{0.065}{1.563} = \mathbf{0.0415}$

Example 8.8: *Calculate the refractive indices of the core and the cladding material of a fiber from the following data:*

Numerical aperture (NA) = 0.22 and $\Delta = 0.012$ *where* Δ *is the fractional refractive index change.*

Solution:
$$NA = n_1\sqrt{2\Delta}$$
$$0.22 = n_1\sqrt{2\times 0.012} = 0.155\ n_1$$
$$\therefore \quad n_1 = \frac{0.22}{0.155} = \mathbf{1.42}$$
$$\Delta = \frac{n_1 - n_2}{n_1} \quad \therefore \quad \frac{1.42 - n_2}{1.42} = 0.012$$
$$n_2 = 1.42 - 1.42\times 0.012 = \mathbf{1.403}$$

Example 8.9: *Find the fractional refractive index and numerical aperture for an optical fibre with refractive indices of core and cladding as 1.5 and 1.49 respectively.*

Solution:
$$\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.5 - 1.49}{1.5} = \mathbf{0.0067}$$
$$NA = n_1\sqrt{2\Delta} = 1.5\sqrt{2\times 0.0067} = \mathbf{0.174}$$

Example 8.10: *A step-index fibre is made with a core of refractive index 1.52, a diameter of 29 μm and a fractional difference index of 0.0007. It is operated at a wavelength of 1.3 μm. Find the V-number and the number of modes that the fibre will support.*

Solution: $V = \dfrac{\pi d}{\lambda_o} n_1\sqrt{2\Delta} = \dfrac{3.143\times 29\times 10^{-6}\,m}{1.3\times 10^{-6}\,m}\times 1.52\sqrt{2\times 0.0007} = \mathbf{4.049}$

Number of modes, $N = \frac{1}{2}V^2 = \frac{1}{2}(4.049)^2 = \mathbf{8\ modes}$

Example 8.12: *Optical power of 1 mW is launched into an optical fibre of length 100 m. If the power emerging from the other end is 0.3 mW, calculate the fibre attenuation.*

Solution: Attenuation, $\alpha = \dfrac{10}{L}\log\dfrac{P_i}{P_o} = \dfrac{10}{0.1km}\log\dfrac{1mW}{0.3mW} = \mathbf{52.3\ dB/km}$

Example 8.13: *What is the attenuation in dB/km, if 15% of the power fed at the launching end of a* $\frac{1}{2}$ *km fibre is lost during propagation?*

66 500m

1.412

Solution: Attenuation, $\alpha = \dfrac{10}{L}\log\dfrac{P_i}{P_o} = \dfrac{10}{0.5km}\log\dfrac{1}{0.85} = \cancel{16.48}$ dB/km

14.01 *What is meant by total internal reflection ?*

Ans : When light travelling from an optically denser medium is incident on the interface with an optically rarer medium, refraction of light does not occur for angles of incidence greater than critical angle. The light gets reflected back into the denser medium. This phenomenon is called **total internal reflection.**

If light passes from a medium of refractive index n_1 to a medium of refractive index n_2, the critical angle θ_c is given by

$$\sin\theta_c = \frac{n_2}{n_1} \qquad (n_2 < n_1) \qquad \text{........(14.01)}$$

14.04 *Determine the critical angle for a ray travelling from water (n = 1.333) to air.*

Solution : $\sin\theta_c = \frac{n_2}{n_1} = \frac{1}{n_1} = \frac{1}{1.333} = 0.75$

$\therefore\ \theta_c = \mathbf{48.61^0}$

14.05 *Find the critical angle for a ray travelling from a glass with refractive index 1.7 to water (n = 1.333).*

Solution : $\sin\theta_c = \frac{n_2}{n_1} = \frac{1.333}{1.70} = 0.784$

$\therefore\ \theta_c = \mathbf{51.64^0}$

14.11 *The numerical aperture of an optical fibre is 0.5 and the core refractive index is 1.54. Find the refractive index of the cladding.* ***(Bombay Univ., 1995)***

Given : Core refractive index, $n_1 = 1.54$

Numerical Aperture, $NA = 0.5$

$n_o = 1$

Formula : $NA = \dfrac{\sqrt{n_1^2 - n_2^2}}{n_o} = \sqrt{n_1^2 - n_2^2}$

or Cladding refractive index, $n_2 = \sqrt{n_1^2 - (NA)^2}$

Solution : $n_2 = \sqrt{n_1^2 - (NA)^2}$

$= \sqrt{(1.54)^2 - (0.5)^2}$

$= \sqrt{2.1216}$

$= \mathbf{1.46}$

14.12 *What is the numerical aperture of a cable whose critical angle is* 26.1^o *?*

Solution : Critical angle $\theta_o = 26.1^0$

$NA = \sin\theta_o = \sin 26.1^0$

= 0.44

14.13 *What is the numerical aperture of a cable with a clad index of 1.378 and a core index of 1.546 ?*

Solution : $NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.546^2 - 1.378^2}$

$$= \sqrt{2.390 - 1.899} = \sqrt{0.491}$$

$$\therefore \; NA = \mathbf{0.70}$$

14.14 *The core has $n = 1.6$ and the clad has $n = 1.3$. What is the value of critical angle ? What is the angle of the cone of acceptance ?*

Solution : Critical angle is given by

$$\sin \varphi_c = \frac{n_2}{n_1} = \frac{1.3}{1.6} = 0.8125$$

$$\therefore \; \varphi_c = \mathbf{54.3^0}$$

Acceptance angle $\theta_o = \sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right]$

$$= \sin^{-1}\left[\sqrt{1.6^2 - 1.3^2}\right] = \sin^{-1}\left[\sqrt{2.56 - 1.69}\right]$$

$$= \sin^{-1}\,(0.87) \quad 7.93$$

$$= \mathbf{60.5^0} \quad 68.86^0$$

Angle of the cone $= 2\,\theta_o =$ $\mathbf{121^0}$ 137.93°

14.15 *A fibre cable has an acceptance angle of 30^o and a core index of refraction of 1.4. Calculate the cladding index of refraction.*

Solution :

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

$$\therefore \; \sin^2 \theta_o = n_1^2 - n_2^2$$

$$\text{or } n_2^2 = n_1^2 - \sin^2 \theta_o$$

$$= (1.4)^2 - \sin^2 30^0$$

$$= 1.96 - 0.25$$

$$= 1.71$$

$\therefore$ The index of refraction of cladding $n_2 =$ **1.308**

14.17 *For a SI fibre refractive indices of core and cladding are 1.44 and 1.42 respectively. Calculate the acceptance angle in air for skew rays that change direction by 120^o at each reflection.*

(N.U., IV B. E., W-96)

Solution : The critical angle $\varphi = \dfrac{120^0}{2} = 60^0$

The acceptance angle θ_i in air is given by

$$\sin \theta_i = \frac{n_1}{n_o} \cos \varphi$$

$$= \frac{1.44}{1} \cos 60^0$$

$$= 0.72$$

$$\therefore \ \theta_i = \sin^{-1} (0.72)$$

or $\theta_i =$ **46^0**

14.19 do *A glass clad fibre is made with core glass of refractive index 1.5 and the cladding is doped to give a fractional index difference of 0.0005. Find (a) the cladding index (b) the critical internal reflection angle (c) the external critical acceptance angle and (d) the numerical aperture.*

Solution : a) $\Delta = \dfrac{n_1 - n_2}{n_1}$

$$\therefore \ 0.0005 = \frac{1.5 - n_2}{1.5}$$

$$\therefore \quad n_2 = \mathbf{1.49925}$$

b) $\varphi_c = \sin^{-1}\left[\dfrac{n_2}{n_1}\right] = \sin^{-1}\left[\dfrac{1.49925}{1.5}\right] = \mathbf{88.2^0}$

c) $\theta_o = \sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right] = \sin^{-1}\left[\sqrt{1.5^2 - 1.49925^2}\right]$

$$= \sin^{-1} (0.0474) = \mathbf{2.72^0}$$

d) $NA = n_1 \sqrt{2\,\Delta} = 1.5 \sqrt{2\,(0.0005)}$

$\therefore \ NA =$ **0.0474**

14.20 *An optical fibre has a NA of 0.20 and a cladding refractive index of 1.59. Determine the acceptance angle for the fibre in water which has a refractive index of 1.33.* **(N.U., IV B.E.; W-92)**

Solution : $NA = \dfrac{\sqrt{n_1^2 - n_2^2}}{n_{air}} = \sqrt{n_1^2 - n_2^2} = 0.20$

$$\therefore\ n_1 = \sqrt{(NA)^2 + n_2^2} = \sqrt{(0.20)^2 + (1.59)^2}$$

$$= \mathbf{1.6025}$$

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_{water}} = \frac{\sqrt{1.6025^2 - 1.59^2}}{1.33} = \mathbf{0.15}$$

$$\therefore\ \theta_o = \sin^{-1}(NA) = \sin^{-1}(0.15) = \mathbf{8.6^0}$$

14.21 *Core glass of index 1.6200 is to be used to make a step - index fibre with an acceptance cone half - angle of 5°. (a) What will the internal critical reflection angle be ? (b) What should be the cladding index be ?*

Solution : a) $\sin\theta_o = \dfrac{n_1}{n_2}\cos\varphi_c$

$$\therefore\ \sin 5^0 = 1.6200\ \cos\varphi_c$$

$$\text{or}\ \cos\varphi_c = \frac{0.087}{1.620} = 0.054$$

$$\therefore\ \varphi_c = \mathbf{86.9^0}$$

b) $\cos\varphi_c = \dfrac{\sqrt{n_1^2 - n_2^2}}{n_1} = \dfrac{\sqrt{1.62^2 - n_2^2}}{1.62}$

$$\text{or}\ \cos^2\varphi_c = \frac{1.62^2 - n_2^2}{1.62^2}$$

$$\therefore\ (0.054)^2(1.62)^2 = 1.62^2 - n_2^2$$

$$\therefore\ n_2^2 = (1.62)^2\ (1 - 0.054^2) = 2.617$$

$$\therefore\ n_2 = \mathbf{1.618}$$

14.26 *A step index fibre in air has a NA of 0.16, a core refractive index of 1.45 and a core diameter of 60 μm. Determine the normalized frequency for the fibre when light at a wavelength of 0.9 μm is transmitted.* ***(N.U., IV B. E.; W-92)***

Solution : $V = \dfrac{\pi d}{\lambda}(NA) = \dfrac{3.143 \times 60 \times 10^{-6} m \times 0.16}{0.9 \times 10^{-6} m}$

$= \mathbf{33.5}$

14.28 *A SI fibre made with a core index 1.52 and a fractional difference index of 0.0007 has a diameter of 29 μm. It is operated at a wavelength of 1.3 μm. Find (a) the fibre V-number and (b) the number of modes the fibre will support.*

Solution : $n_1 = 1.52, \quad \Delta = 0.0007.$

$$\Delta = \frac{n_1 - n_2}{n_1} \quad \therefore\ 0.0007 = \frac{1.52 - n_2}{1.52}$$

$\therefore\ n_2 = 1.5189.$

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.52^2 - 1.5189^2} = \sqrt{0.0033}$$

$= \mathbf{0.06}$

(a) $V = \dfrac{\pi d}{\lambda}(NA) = \dfrac{3.143 \times 29 \times 10^{-6} m \times 0.06}{1.3 \times 10^{-6} m}$

$= \mathbf{4.2}$

(b) $N_m = \dfrac{1}{2} V^2 = \dfrac{1}{2}(4.2)^2 = 8.8 \approx$ **9 *modes***

14.32 *Calculate the numerical aperture of a step index fibre having $n_1 = 1.48$ and $n_2 = 1.46$. What is the maximum entrance angle for this fibre if the outer medium is air with n = 1 ?*

(N.U., IV B.E.; W-94)

Solution : $n_1 = 1.48, \quad n_2 = 1.46.$

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.48^2 - 1.46^2} = \sqrt{0.0588}$$

$$= \mathbf{0.242}$$

$$\sin\theta_o = NA$$

$$\therefore \theta_o = \sin^{-1}(NA) = \sin^{-1}(0.242)$$

$$= \mathbf{14^o}$$