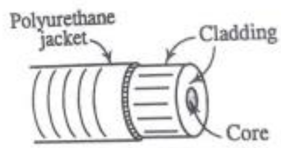
OPTICAL FIBERS

Optical fibers are essentially light guides used in optical communications as waveguides. They are transparent dielectrics and are able to guide visible and invisible infrared light over long distances.

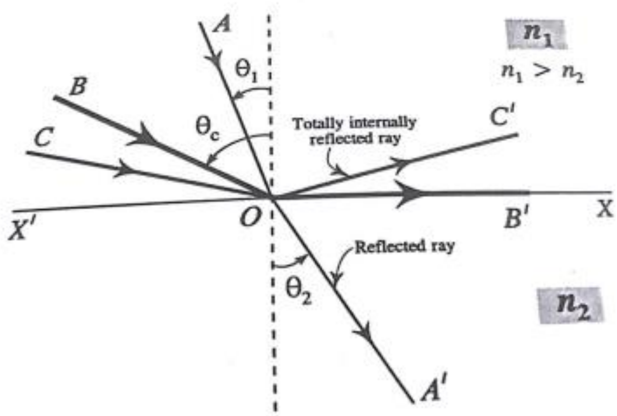
CONSTRUCTION OF OPTICAL FIBER :



OPTICAL FIBER

An optical fiber is cylindrical in shape and it has two parts. The inner part which is a cylindrical material is made up of glass or plastic and is called the **core**. The outer part which is a concentric cylinder surrounding the core is called **cladding**. The cladding is also made up of similar material but of lesser refractive index. The cladding is enclosed in a polyurethane jacket which safeguards the fiber against chemical reaction with the surroundings and against crushing. Many such fibers are grouped to form a cable. A cable consists of one to several hundred of such fibers.

THE PRINCIPLE OF PROPAGATION : (TOTAL INTERNAL REFLECTION)



TOTAL INTERNAL REFLECTION

The principle based on which the optical fiber works is total internal reflection. Consider a ray 'AO' travelling in a medium of refractive index n_1 . let XX' be the boundary of this medium separating it from another medium of lower refractive index n_2 .

Let the incident ray 'AO' make an angle θ_1 with the normal in the medium of refractive index n_1. As the ray is refracted into the medium of refractive index n_2 it bends away from the normal since $n_1 > n_1$.

If θ_2 is the angle made by the refracted ray with the normal, then $\theta_2 > \theta_1$. if θ_1 is increased then for certain value of $\theta_1 = \theta_c$, is called **critical angle** for which $\theta_2 = 90^o$. that is the refracted ray just grazes the boundary of separation along OB. For any angle of incidence which if θ_1 greater than θ_c , the incident ray like OC always reflected back into the medium undergoing total internal reflection.

For refraction from snell' s law we have

$$n_1 \ Sin\ \theta_1 = n_2 \ Sin\ \theta_2$$

But for total internal reflection

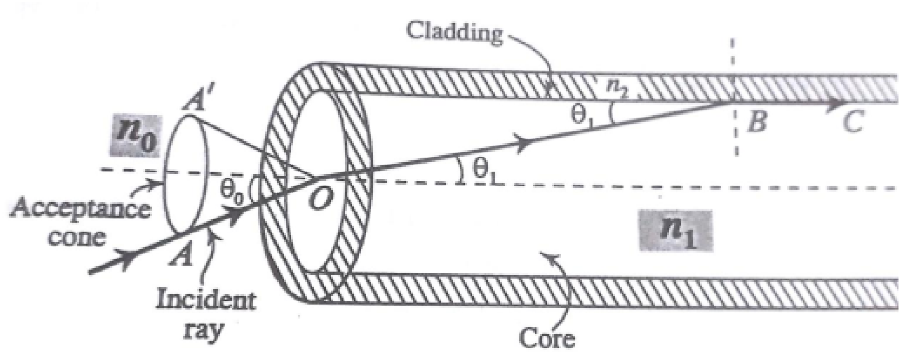
$$\theta_1 = \theta_c \quad \text{and} \quad \theta_2 = 90^o$$

$$n_1 \ Sin\ \theta_c = n_2 \ \sin 90^o \qquad (\text{since } Sin\ 90^o = 1)$$

$$\boldsymbol{\theta_c = \sin^{-1}\frac{n_2}{n_1}}$$

<u>EXPRESSION FOR THE ANGLE OF ACCEPTANCE AND NUMERICAL APERTURE AND CONDTION FOR PROPAGATION</u>

[QUESTION : Derive an expression for the angle of acceptance, numerical aperture and the condition for the propagation of light ray in an optical fiber]



Let n_0 , n_1 , n_2 be the refractive indices of the surrounding medium, core and the cladding material of the optical fiber respectively. Let AO be the ray entering into the core at an angle θ_o to the fiber axis , then it is refracted at OB at an angle θ_1 in the core and further proceeds to fall at critical angle of incidence equal to (90 - θ_1) at B on the interface between the core and cladding. Since it is the critical angle of incidence it is refracted at 90^o to the normal to the interface that is grazes the boundary along BC.

Any ray that enters into the core at an angle of incidence less than θ_o , will have the refractive angle less that θ_1 because of which its angle of incidence equals to (90 - θ_1) at the interface, will be greater that the critical angle of incidence and hence undergoes total internal reflection.

Similarly any ray that enters the core at an angle of incidence greater that θ_o at O, will have to be incident at the interface at an angle less that that critical angle because of which it gets refracted into the cladding region and travels across the cladding thickness and emerges into the surrounding and thus will be lost.

Therefore if a beam converges at a wide angle into the core at OA, then those rays which are funneled into the core with in this cone will be totally internally reflected and thus confined within for propagation and rest of the rays emerge from the sides of the fiber.

The angle $\boldsymbol{\theta_o}$ is called the **waveguide acceptance angle or the acceptance cone half – angle**. And **sin $\boldsymbol{\theta_o}$** is called as the **numerical aperture (NA)** of the fiber. The numerical aperture represents the light gathering capacity of the optical fiber.

CONDITION FOR PROPAGATION :

Now, for refraction at the point of entry of the ray 'AO' into the core, we have by applying Snell's law,

$$n_0 \sin \theta_o = n_1 \sin \theta_1$$

$$\sin \theta_o = \frac{n_1}{n_0} \sin \theta_1$$

[$\boldsymbol{\sin^2\theta_1 + \cos^2\theta_1 = 1}$ **OR** $\boldsymbol{\sin \theta_1 = \sqrt{(1 - \cos^2\theta_1)}}$ **]**

Therefore $$\sin \theta_o = \frac{n_1}{n_0} \sqrt{(1 - \cos^2\theta_1)} \quad \text{------------------------------} \; (1)$$

At the point 'B' on the interface

The angle of incidence = $90 - \theta_1$

Again applying snell's law at the point B, we have,

$$n_1 \sin(90 - \theta_1) = n_2 \sin 90$$

[because, $\sin(90 - \theta_1) = \cos\theta_1$ and $\sin 90 = 1$]

$$n_1 \cos\theta_1 = n_2$$

$$\cos\theta_1 = \frac{n_2}{n_1} \quad \text{----------------------- (2)}$$

Substituting equation (2) in equ (1)

$$\sin\theta_o = \frac{n_1}{n_0}\sqrt{1 - \frac{n_2^2}{n_1^2}}$$

$$\boldsymbol{\sin\theta_o = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}}$$

If the medium surrounding the fiber is air, then $n_0 = 1$

$$\sin\theta_o = \sqrt{n_1^2 - n_2^2} \quad \text{-------------------------- (3)}$$

OR $$\mathbf{N.A} = \sqrt{n_1^2 - n_2^2}$$

If θ_i is the angle of incidence of an incident ray, then, the ray will be able to propagate

$$\theta_i < \theta_o$$

$$\text{Sin } \theta_i < \sin\theta_o$$

OR $$\text{Sin } \theta_i < \sqrt{n_1^2 - n_2^2} \quad \text{[Using equation (3)]}$$

$$\mathbf{Sin}\ \boldsymbol{\theta_i} < \mathbf{N.A}$$

This the condition for propagation of ray in an optical fiber

FRACTIONAL INDEX CHANGE (Δ)

The fractional index change is the ratio of the refractive index difference between the core and cladding to the refractive index of the core of an optical fiber.

$$\Delta = \frac{(n_1 - n_2)}{n_1} \quad \text{--------------------- (1)}$$

Relation between N.A and Δ

From equ. (1) we have $(n_1 - n_2) = n_1\Delta$ -------- (2)

We know that, the Numerical Aperture is given by

$$N.A = \sqrt{n_1^2 - n_2^2}$$

$$N.A = \sqrt{(\boldsymbol{n_1} + \boldsymbol{n_2})(\boldsymbol{n_1} - \boldsymbol{n_2})}$$

$$N.A = \sqrt{(\boldsymbol{n_1} + \boldsymbol{n_2})\, n_1 \Delta} \qquad \text{[using equation (2)]}$$

If $\boldsymbol{n_1 \approx n_2}$, $\boldsymbol{(n_1 + n_2) = 2n_1}$

$$N.A = \sqrt{2n_1^2\,\Delta}$$

$$N.A = = \boldsymbol{n_1}\sqrt{2\,\Delta}$$

Though an increase in the value of Δ increases N.A., and thus enhances the light gathering the capacity of the fiber, we cannot increase Δ to a very large value, since it leads to what is called intermodal dispersion which causes signal distortion.

V – NUMBER

The number of modes supported for propagation in the fiber is determined by a parameter called V-number (denoted as V-number). If the surrounding medium is air, then V-number is given by

$$\mathbf{V} = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}$$

Where 'd' is the core diameter

n_1 is the refractive index of the core

n_2 is the refractive index of the cladding

λ is the wavelength of light propagating in the fiber

$$\mathbf{V} = \frac{\pi d}{\lambda}\,\mathbf{(NA)}$$

If the fiber is surrounded by a medium of refractive index $\boldsymbol{n_0}$ the expression is

$$\mathbf{V} = \frac{\pi d}{\lambda}\,\frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

For V > > 1, the number of modes supported by the fiber is given by

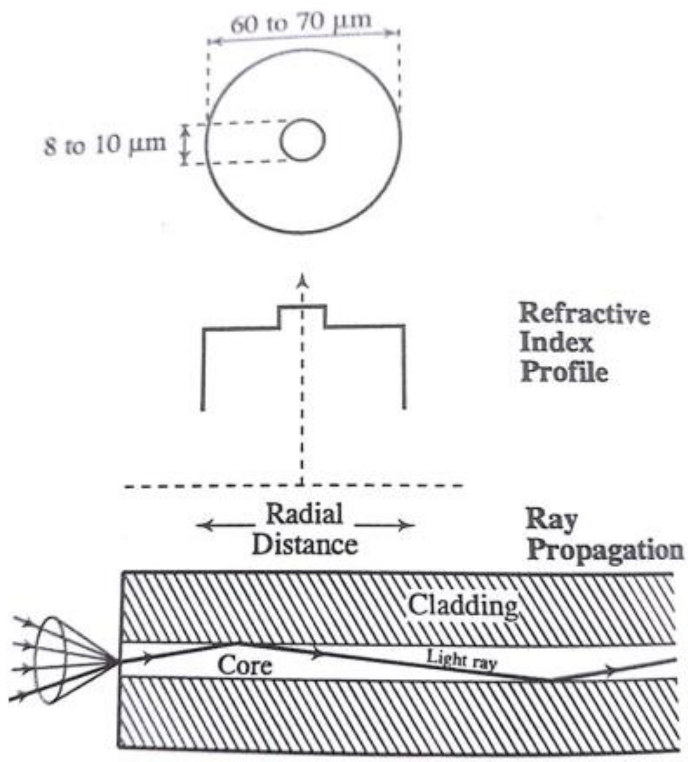
$$\textbf{Number of modes} = \frac{V^2}{2}$$

TYPES OF OPTICAL FIBERS

[QUESTION: Explain different types of optical fibers]

The optical fibers are classified under 3 categories, namely

a) **Single Mode optical fiber**

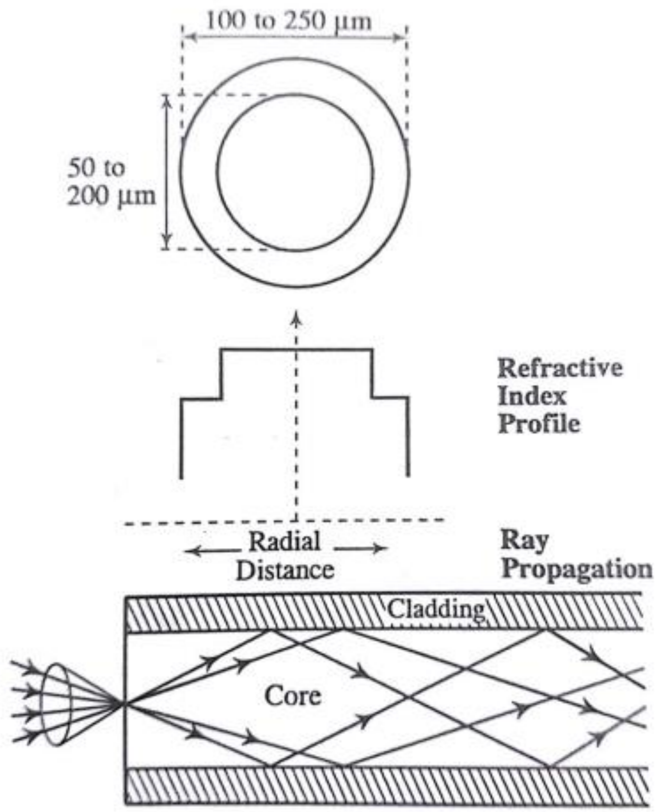


SINGLE MODE FIBER

A single mode fiber has a core material of uniform refractive index value. Similarly cladding also has a material of uniform index but of lesser value. This difference results in a sudden increase in the value of refractive index from cladding to core. Thus the refractive index takes the shape of a step.

The diameter value of the core is about 8 – 10 μm and external diameter of the cladding is 60 – 70 μm. Because of its narrow core, it can guide just a single mode. Hence it is called single mode fiber. They need lasers as the source of light. They find particular application in submarine cable system.

b) Step index multimode optical fiber

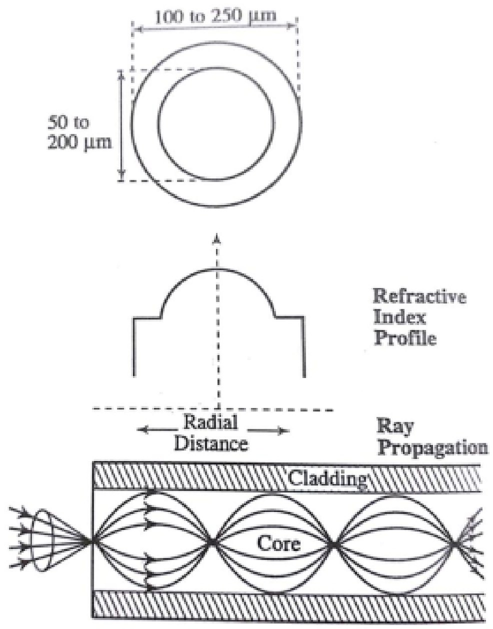


STEP - INDEX MULTIMODE FIBER

Its construction is similar to that of single mode fiber, but for the difference that its core has a much larger diameter by the virtue of which it will be able to support propagation of large number of modes as shown in the figure. Its refractive index profile is also similar to that of a single mode fiber but with larger plane region for the core. The diameter value of the core is about 50 – 200 μm and external diameter of the cladding is 100 – 250 μm.

The step index multimode fiber can accept either a laser or an LED as source of light. Its typical application is in the data links which has lower bandwidth.

c) **Graded index multimode optical fiber**



Graded index multimode fiber is also denoted as GRIN. The diameter value of the core is about 50 – 200 μm and external diameter of the cladding is 100 – 250 μm. Its core material has a special feature that its refractive index value decreases in the radially outward direction from the axis and becomes equal to that of cladding at the interface. But the refractive index of the cladding remains uniform. Either a laser or LED can be the source for GRIN multimode fiber. Its application is in the telephone trunk between central offices

ATTENUATION

[QUESTION: Define attenuation? Explain the various factors contributing to the fiber loss]

Attenuation is the loss of power suffered by the optical signal as it propagates through the fiber. It is also called as the **fiber loss**

Three mechanisms through which, attenuation takes place are

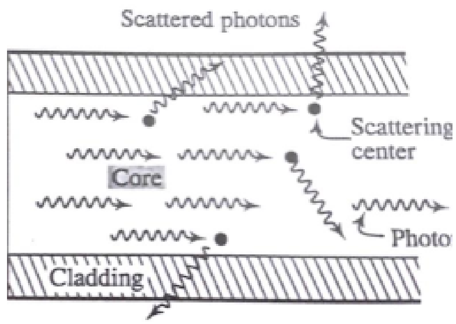
1] ABSORPTION LOSS

Here the loss of signal power occurs due to the absorption of photons associated with the signal.

a) **Absorption by impurities** : Iron, chromium, copper, cobalt etc are the transition metal ion impurities present in the fiber glass. During signal propagation when photons interact with these impurities, the electrons in the impurities absorb the photons and get exited to higher energy levels. Later these electrons give up these energies either as heat or light. But the reemission of light energy is of no use since it will usually of different wavelength and of different phase. Hence it is a loss

b) **Intrinsic absorption :** The fiber as a material has a tendency to absorb light energy. The absorption that takes place in the fiber assuming that there are no impurities in it, and that the material is free of all inhomogeneities is called as intrinsic absorption

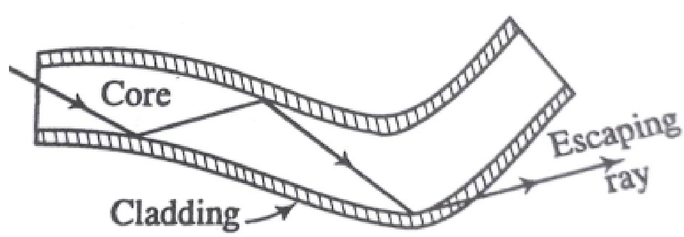
2] SCATTRING LOSS



While the signal travels in the fiber, the photons may be scattered because of sharp changes in refractive index values inside the glass over a distances that are small compared to the wavelength of light. This type of scattering is called as Rayleigh scattering. It occurs whenever a light travels through a medium having scattering objects whose dimensions are smaller than a wavelength thus it becomes a signal loss.

3] RADIATION LOSSESS:

a) Macroscopic bend losses: Macroscopic bends in a fiber has a much larger radii compared to fiber diameter. These bends occur while wrapping the fiber or turning it around a corner. If the radius of curvature of bending the fiber reaches the critical value, then the fiber loss becomes more.



RADIATION LEAKS

b) Microscopic bend losses : they occur due to the non-uniformities in the manufacturing of the fiber of by non-uniform lateral pressures created during the cabling of the fiber. The bends cause irregular reflection and some of them leak through the fiber causing fiber loss

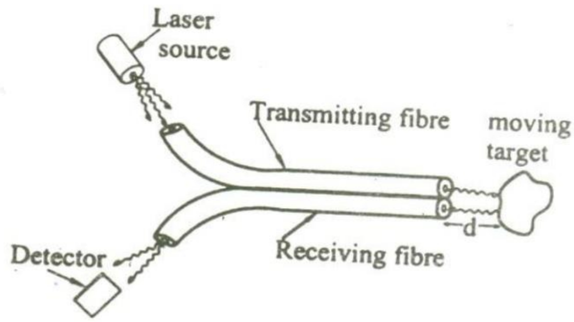
DISPLACEMENT SENSOR (EXTRINSIC SENSOR)

Principle:

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

Description:

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



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

Working:

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

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

1.6 Optical fibres as sensors

Generally, optic sensor consists of light source, optical fibres and detector. The sensors are Two types viz., active sensors and passive sensors.

The physical changes directly changes the electrical responses called active sensors; where as the physical changes are indirectly recorded to sensing is called passive sensors.

Displacement sensors

The light is sent through transmitting fibre and further it is allowed to fall on moving target. The light ray falls on the surface and gets reflected. The incident ray could mix with reflected wave and forms standing wave to which the phase angle shift can be measured. The fig indicates displacement sensors.

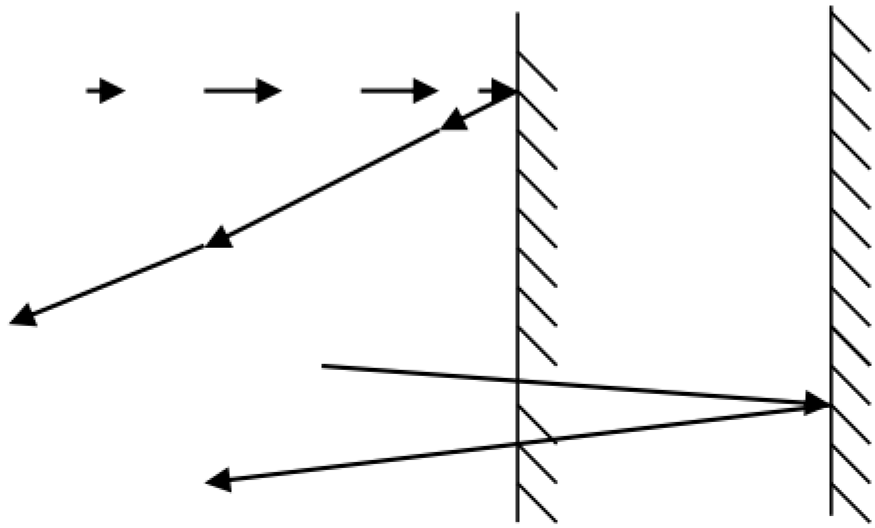


Fig.6 Displacement sensor

Temperature sensor

The light can be arranged to fall on reflecting surface and the associated phase angle is be measured. The reflecting surface can be varied using temperature variation, which causes additional phase angle to light wave as seen in the fig.5. When light thrown on the reflector by optical fibre, the initial and final response can be compared for measure of temperature by relative correlation.

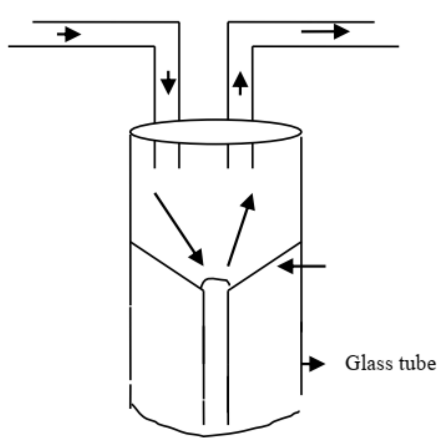


Fig.5 Temperature sensor