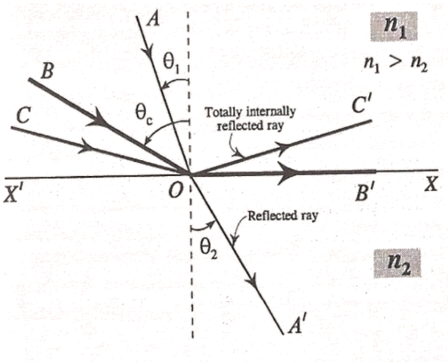
OPTICAL FIBRES

Total Internal Reflection:

When a ray of light travels from denser to rarer medium it bends away from the normal. As the angle of incidence increases in the denser medium, the angle of refraction also increases. For a particular angle of incidence called the "*critical angle*", the refracted ray grazes the surface separating the media or the angle of refraction is equal to 90°. If the angle of incidence is greater than the critical angle, the light ray is reflected back to the same medium. This is called *"Total Internal Reflection".* In total internal reflection, there is no loss of energy. The entire incident ray is reflected back.

XX^1 is the surface separating medium of refractive index n_1 and medium of refractive index n_2, $n_1 > n_2$. AO and OA^1 are incident and refracted rays. θ_1 and θ_2 are angle of incidence and angle of refraction, $\theta_2 > \theta_1$. For the ray BO, θ_c is the critical angle. OB^1 is the refracted ray which grazes the interface. The ray CO incident with an angle greater than θ_c is totally reflected back along OC^1.



TOTAL INTERNAL REFLECTION

From Snell's law,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

For total internal reflection,

$$\theta_1 = \theta_c \text{ and } \theta_2 = 90^0$$

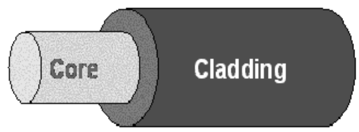
$$n_1 \sin\theta_c = n_2 \quad \text{(Because } \sin 90^0 = 1\text{)}$$

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

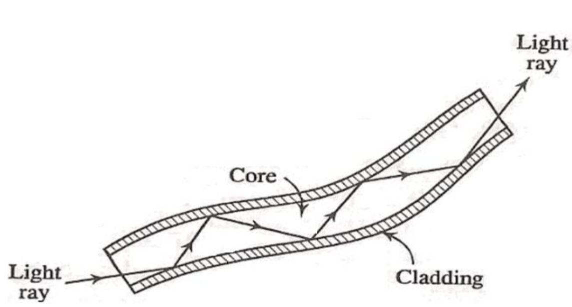
In total internal reflection there is no loss or absorption of light energy.
The entire energy is returned along the reflected light. Thus is called Total internal reflection.

Optical Fibres:

They are used in optical communication. It works on the principle of Total internal reflection (TIR). Optical fibre is made from transparent dielectrics. It is cylindrical in shape. The inner cylindrical part is called as core of refractive index n_1. The outer part is called as cladding of refractive index n_2, $n_1>n_2$. There is continuity between core and cladding. Cladding is enclosed inside a polyurethane jacket. Number of such fibres is grouped to form a cable.



Optical Fibre

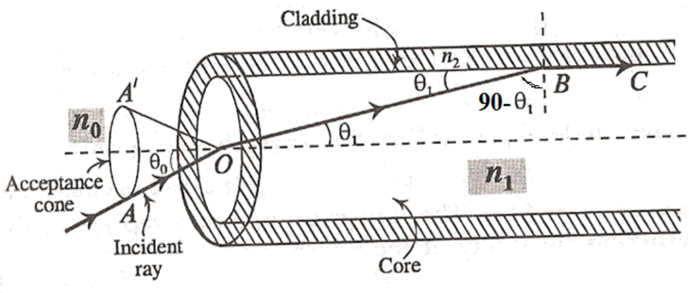


FIBER AS A WAVEGUIDE

The light entering through one end of core strikes the interface of the core and cladding with angle greater than the critical angle and undergoes total internal reflection. After series of such total internal reflection, it emerges out of the core. Thus the optical fibre works as a waveguide. Care must be taken to avoid very sharp bends in the fiber because at sharp bends, the light ray fails to undergo total internal reflection.

Angle of Acceptance and Numerical Aperture:

Consider a light ray AO incident at an angle θ_0 enters into the fiber. Let θ_1 be the angle of refraction for the ray OB. The refracted ray OB incident at a critical angle (90˚-θ_1) at B grazes the interface between core and cladding along BC. If the angle of incidence is greater than critical angle, it undergoes total internal reflection. Thus θ_0 is called the waveguide acceptance angle and $\sin\theta_0$ is called the numerical aperture.



ACCEPTANCE CONE

Let n_0, n_1 and n_2 be the refractive indices of the medium, core and cladding respectively.

From Snell's law at O,

$$n_0 \sin\theta_0 = n_1 \sin\theta_1 \quad \Rightarrow Sin\theta_0 = \frac{n_1}{n_0}\sin\theta_1 \qquad \text{................ 1}$$

At B the angle of incidence is ($90-\theta_1$)

From Snell's law,

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

$$n_1 \cos\theta_1 = n_2 \quad \Rightarrow \cos\theta_1 = \frac{n_2}{n_1} \qquad \text{............ 2}$$

From equation (1)

$$\sin\theta_0 = \frac{n_1}{n_0}\sqrt{1-\cos^2\theta_1} \qquad \text{................. 3}$$

Using equation (2) in (3)

$$\sin\theta_0 = \frac{n_1}{n_0}\sqrt{1-\frac{n_2^2}{n_1^2}} \quad \Rightarrow \sin\theta_0 = \frac{n_1}{n_0}\sqrt{\frac{n_1^2-n_2^2}{n_1^2}}$$

$$NA = \sin\theta_0 = \frac{\sqrt{n_1^2-n_2^2}}{n_0}$$

Where $\sin\theta_0$ is called numerical aperture

The surrounding medium is air, then n_1 = 1

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

Therefore for any angle of incidence equal to θ_1 equal to or less than θ_0, the incident ray is able to propagate.

$\theta_1 < \theta_0$ i.e., $\sin\theta_i < \sin\theta_0$

i.e., $\sin\theta_i < \sqrt{n_1^2-n_2^2}$ i.e., $\sin\theta_i < NA$ is the condition for propagation

Fractional Index Change (Δ):

"It is the ratio of the refractive index difference between the core and cladding to the refractive index of the core of an optical fiber".

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

Relation between NA and Δ:

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

$$n_1 - n_2 = \Delta n_1$$

We have $NA = \sqrt{n_1^2 - n_2^2} = \sqrt{\left(n_1 + n_2\right)\left(n_1 - n_2\right)}$

Considering $n_1 \approx n_2$ and $n_1 - n_2 = \Delta n_1$

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

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

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

Increase in the value of Δ increases N.A

It enhances the light gathering capacity of the fiber. Δ value cannot be increased very much because it leads to intermodal dispersion intern signal distortion.

V-number:

The number of modes supported for propagation in the fiber is determined by a parameter called V-number.

If the surrounding medium is air, then

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

Where '*d*' is the core diameter, n_1 and n_2 are refractive indices of core and cladding respectively, 'λ' is the wavelength of light propagating in the fiber.

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

If the fiber is surrounded by a medium of refractive index n_0, then,

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

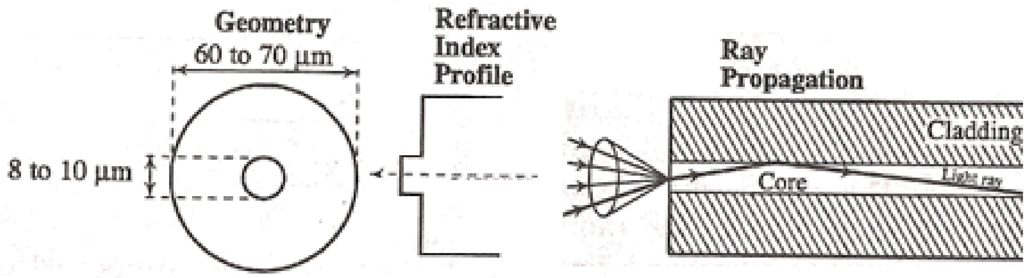
For V >1, the number of modes supported by the fiber is given by, number of modes ≈ $V^2/2$.

Types of optical fiber:

In an optical fiber the refractive index of cladding is uniform and the refractive index of core may be uniform or may vary in a particular way such that the refractive index decreases from the axis, radically. Following are the different types of fibers:

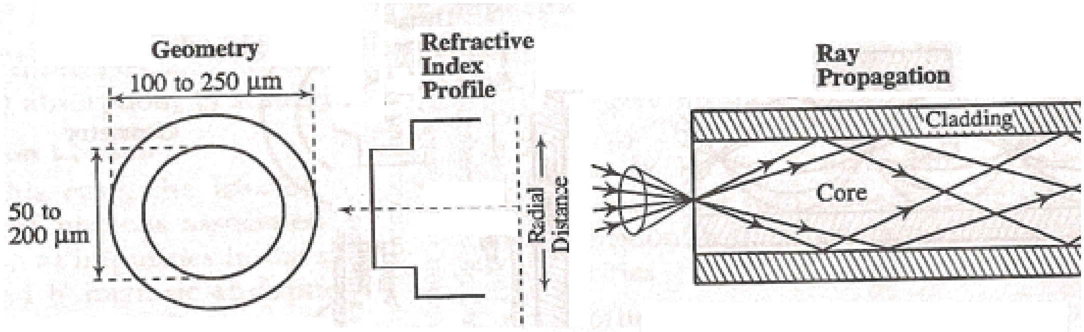
1. Step index Single mode fiber
2. Step index multimode fiber
3. Graded index multimode fiber

1. Step index Single mode fiber: Refractive index of core and cladding has uniform value; there is an increase in refractive index from cladding to core. They are used in submarine.



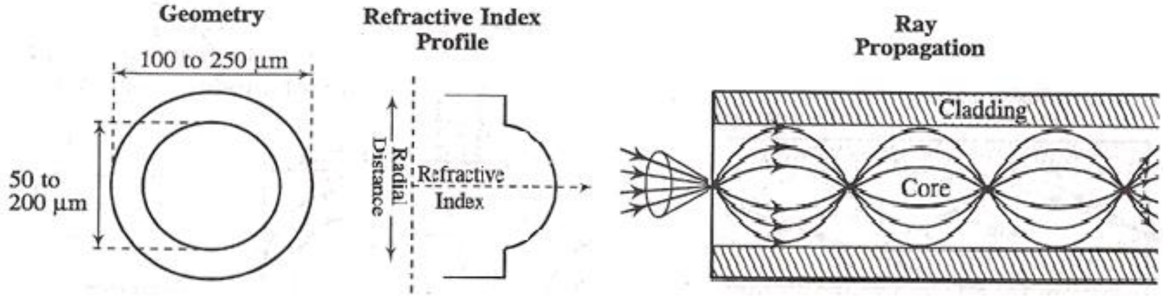
SINGLE MODE FIBER

2. **Step index multimode fiber:** It is similar to single mode fiber but core has large diameter. It can propagate large number of modes as shown in figure. Laser or LED is used as a source of light. It has an application in data links.



STEP - INDEX MULTIMODE FIBER

3. **Graded index multimode fiber:** It is also called GRIN. The refractive index of core decreases from the axis towards the core cladding interface. The refractive index profile is shown in figure. The incident rays bends and takes a periodic path along the axis. The rays have different paths with same period. Laser or LED is used as a source of light. It is the expensive of all. It is used in telephone trunk between central offices.



Signal distortion in optical fiber:

The propagation of a signal through the optical fiber involves total internal reflection of light rays many times. Further, the rays are reflected at various angles. The rays reflected at higher angles travel greater distances than the rays reflected at lower angles. As a result, all the rays do not arrive at the end of the fiber simultaneously and the light pulse broadens as it travels through the fiber. Since the output pulse does not match with the input pulse, the signal is said to be distorted.

If white light is used instead of monochromatic light, another kind of distortion occurs. Since radiation of different wavelengths has different velocities, they do not arrive at the output simultaneously. This distortion is called chromatic dispersion.

The signal distortion is quite considerable in multimode step index fiber. In graded index fiber, the light travels with different velocities in different parts of the core as the refractive index varies radially along the core. The rays travel faster near the interface. Hence all the rays arrive at the output almost at the same time and the signal distortion is reduced. In a single mode step index fiber the distortion is less than that in multimode step index fiber.

Signal attenuation in optical fiber:

Attenuation is the loss of optical power as light travels through a fiber.

As per Lambert's law, the rate of decrease of intensity of light with distance travelled in a homogeneous medium is proportional to the initial intensity

i.e., $-\frac{dP}{dL} \propto P$ (negative sign indicates the decrement in intensity with distance)

$$\frac{dP}{dL} = -\alpha P$$

Where α is called attenuation coefficient,

By rearranging the equation

$$\frac{dP}{P} = -\alpha \; dL$$

Integrating both the sides

$$\int \frac{dP}{P} = -\alpha \int dL$$

It is expressed in decibel/kilometre [dB/km]. A fiber with lower attenuation will allow more power to reach its receiver than a fiber with higher attenuation. If P_{in} is the input power and P_{out} is the output power after passing through a fiber of length 'L', the mean attenuation constant or coefficient 'α' of the fiber, in units of db/km is given by

$$\alpha = -\frac{10}{L} \log_{10}\left(\frac{p_{out}}{p_{in}}\right) \qquad \textbf{dB/km}$$

Attenuation or Fiber loss can be caused by three mechanisms.

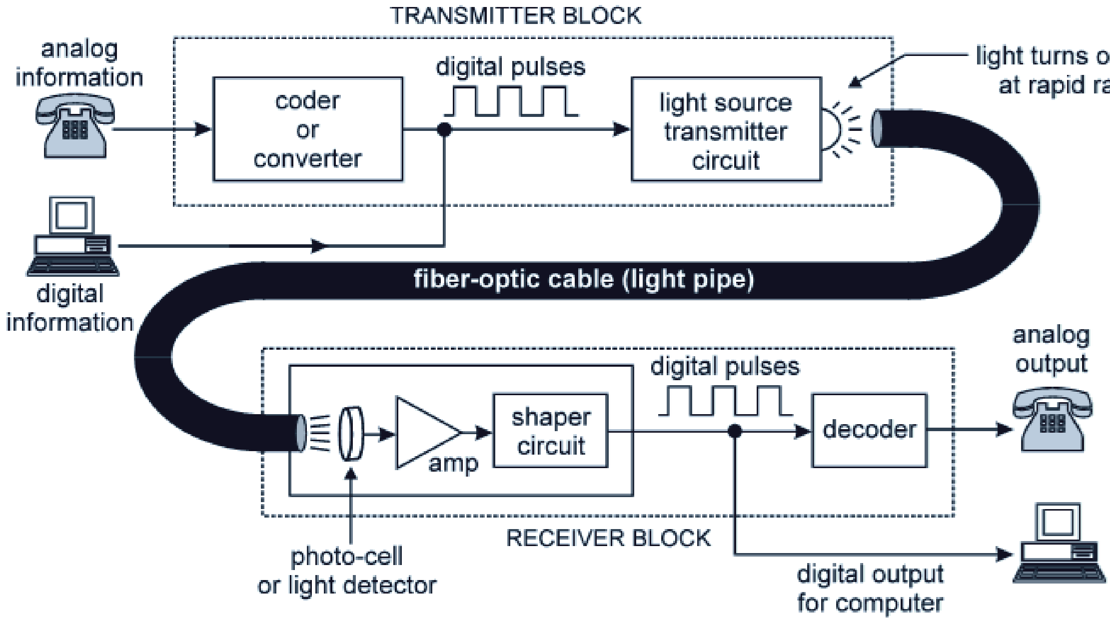
1. Absorption: Absorption of photons by impurities like metal ions such as iron, chromium, cobalt and copper in the silica glass of which the fiber is made of. During signal processing photons interact with electrons of impurity atoms. The atoms are excited and de-excite by emitting photons of different characteristics. Hence it is a loss of energy. The other impurity such as hydroxyl ions (OH) causes significant absorption loss. The absorption of photons by fiber material itself is called intrinsic absorption.

2. Scattering: When the wavelength of the photon is comparable to the size of the particle then the scattering takes place. Because of the non-uniformity in manufacturing, the refractive index changes with length leads to a scattering. This type of scattering is called as Rayleigh scattering. It is inversely proportional to the fourth power of wavelength. Scattering of photons also takes place due to trapped gas bubbles which are not dissolved at the time of manufacturing.

3. Radiation losses: Radiation losses occur due to macroscopic bends and microscopic bends. Macroscopic bending: All optical fiber are having critical radius of curvature provided by the manufacturer. If the fiber is bent below that specification of radius of curvature, the light ray incident on the core cladding interface will not satisfy the condition of TIR. This causes loss of optical power.

Microscopic bending: Optical power loss in optical fiber is due to non-uniformity of the optical fiber when they are laid. Non uniformity is due to manufacturing defects and also lateral pressure built up on the fiber. The defect due to non-uniformity (microbendings) can be overcome by introducing optical fiber inside a good strengthen polyurethane jacket.

Fiber Optics Communication System:



Optical fiber communication system consists of transmitter, information channel and receiver. Transmitter converts an electrical signal into optical signal. Information channel carries the signal from transmitter to receiver. The receiver converts optical signal to electrical form. The block diagram of optical fiber communication system is shown in fig.

Message origin: It converts a non-electrical message into an electrical signal.

Coder: It converts the electrical message into proper format and it helps to improve the signal onto the wave which is generated by the carrier source.

There are two types of format. They are analog and digital. Analog signal is continuous and it doesn't make any change in the original format. But digital signal will be either in ON or OFF state.

Carrier source: It generates the waves on which the data is transmitted. These carrier waves are produced by the electrical oscillator. Light emitting diodes (LED) and laser diodes (LD) are the different sources.

Information channel: It is path between transmitter and receiver. Here optical fibre is the Information channel

Detector: The detector separates the information from the carrier wave. Here a photo-detector converts optical signal to electronic signal.

Signal processor: Signal processor amplifies the signals and filters the undesired frequencies.

Message output: The output message will be in two forms. Either person can see the information or hear the information. The electrical signal can be converted into sound wave or visual image by using CRO.

Advantages of optical communication system:

1) It carries very large amount of information in either digital or analog form due to its large bandwidth.
2) The materials used for making optical fiber are dielectric nature. So, it doesn't produces or receives any electromagnetic and R-F interferences.
3) Fibers are much easier to transport because of their compactness and lightweight.
4) It is easily compatible with electronic system.
5) It can be operated in high temperature range.
6) It does not pick up any conducted noise.
7) Not affected by corrosion and moisture.
8) It does not get affected by nuclear radiations.
9) No sparks are generated because the signal is optical signal.

Note:

- Optical fibers are used in sensors like pressure sensor, voltage sensor and current sensors.
- Optical fibers are used in local networks like data link purpose.