Optical Fibers

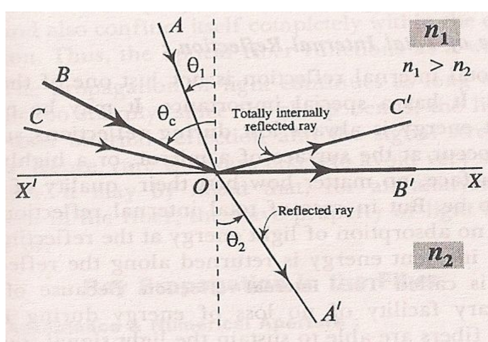
Total Internal Reflection:

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

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

For total internal reflection,

$\theta_1 = \theta_c$ and $\theta_2 = 90°$

$n_1 \sin\theta_c = n_2$ (because $\sin 90° = 1$)

$\theta_c = \sin^{-1}(n_2/n_1)$

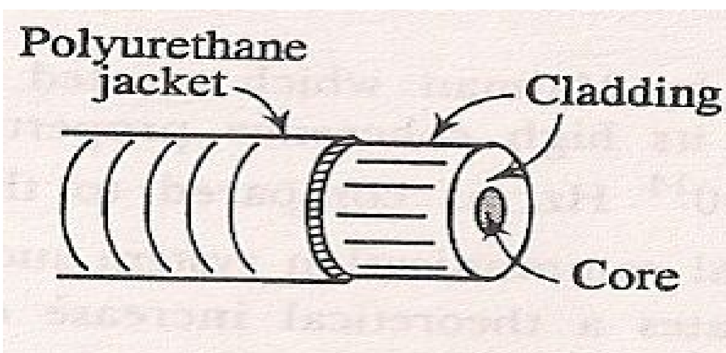
In total internal reflection there is no loss or absorption of light energy.

The entire energy is returned along the reflected light. Thus is called Total internal reflection.

Optical Fibers:

They are used in optical communication. It works on the principle of Total internal reflection(TIR).

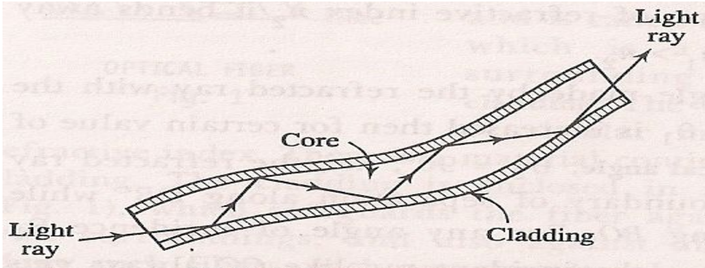
Optical fiber is made from transparent dielectrics. It is cylindrical in shape. The inner cylindrical part is called as core of refractive index n_1. The outer part is called as cladding of refractive index n_2, $n_1 > n_2$. There is continuity between core and cladding. Cladding is enclosed inside a polyurethane jacket. Number of such fibers is grouped to form a cable.



OPTICAL FIBER

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 fiber 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.



FIBER AS A WAVEGUIDE

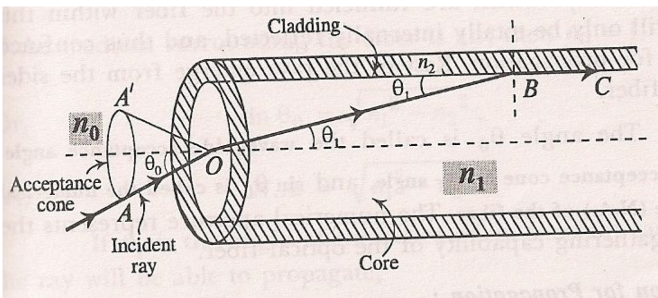
<u>Angle of Acceptance and Numerical Aperture:</u>

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.

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

From Snell's law,

$$n_o\sin\theta_0 = n_1\sin\theta_1 \rightarrow (1)$$



ACCEPTANCE CONE

From Snell's law,

At B the angle of incidence is (90 - θ_1)

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

$n_1\cos\theta_1 = n_2$

$\cos\theta_1 = n_2 / n_1 \rightarrow (2)$

From eqn (1)

$$Sin\theta_0 = \frac{n_1}{n_0}\sin\theta_1$$

$$= \frac{n_1}{n_o}\sqrt{1 - cos^2\theta}_1 \rightarrow (3)$$

Using eqn (2) in (3)

$$Sin\theta_0 = \frac{n_1}{n_0}\sqrt{1 - \frac{n_2^2}{n_1^2}}$$

$$= \frac{\sqrt{n_1^2 - n_2^2}}{n_o} \rightarrow (4)$$

The surrounding medium is air, $n_o = 1$

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

Where $\sin\theta_i$ is called numerical aperture.

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

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

$\theta_i < \theta_0$

$$\mathrm{Sin}\theta_i < Sin\theta_0$$

$$sin\theta_i < \sqrt{n_1^2 - n_2^2}$$

$sin\theta_i < N.A$ is the condition for propagation.

<u>Fractional Index Change:</u> **"**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 N.A and Δ:

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

$$n_1 - n_2 = \Delta n_1$$

We have

$$\text{N.A} = \sqrt{n_1^2 - n_2^2} = \sqrt{(n_1 + n_2)(n_1 - n_2)}$$

Considering, $n1 \approx n_2$

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

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

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

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 ≈ $V^2/2$.

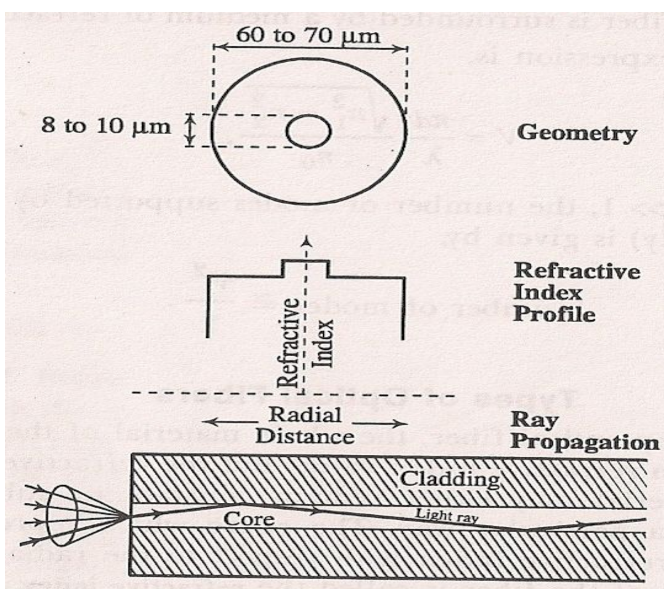
Types of optical fibers:

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, radially.

Following are the different types of fibers:

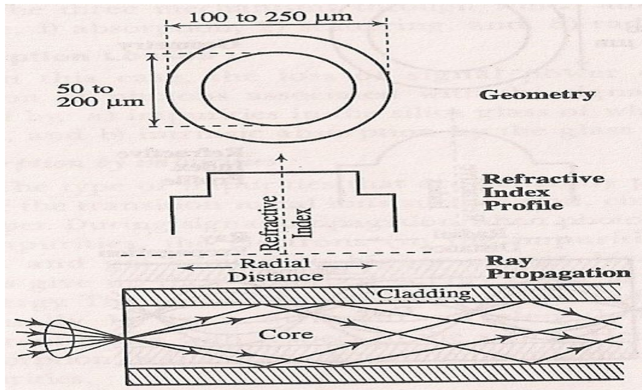
1. Single mode fiber
2. Step index multimode fiber
3. Graded index multimode fiber

***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.



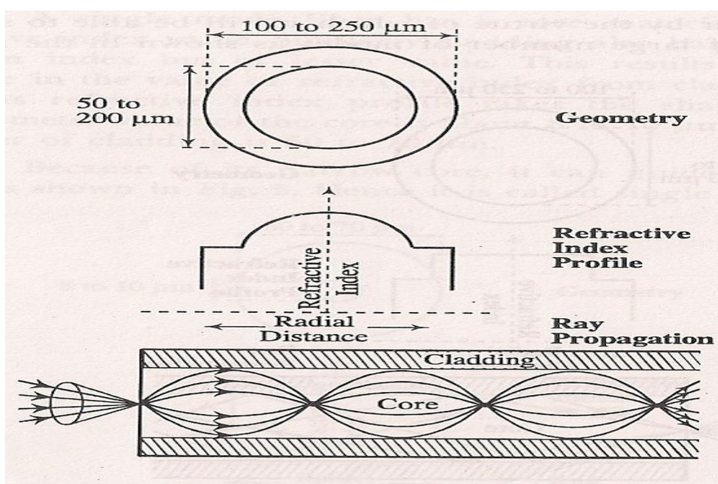
SINGLE MODE FIBER

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.



GRADED - INDEX MULTIMODE FIBER

Signal distortion in optical fibers:

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 fibers. In graded index fibers, 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 fibers.

<u>Signal attenuation in optical fibers:</u>

Attenuation is the loss of optical power as light travels through a fiber. It is expressed in decibel/kilometer [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

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

Attenuation can be caused by three mechanisms.

<u>Attenuation coefficient.</u>

When light travels in a material medium there will always loss in intensity with distance travelled .such a loss in intensity obeys a law is called Lamberts law. or
There is loss in its intensity with distance travelled. The intensity loss obeys Lambert's law i.e. from Lambert's law.

$- \frac{dP}{dL}\alpha P$ $\quad$ P → initial intensity

L → distance propagated in the medium

-ve sign confirms that it is decrease in power

$$-\frac{dP}{dL} = \alpha P \qquad \rightarrow (1)$$

Where α - *attenuation coefficient* or *fibre attenuation coefficient* or *attenuation* or *fibre loss.*

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

Integrating both sides,

$$\int \frac{dp}{p} = -\alpha \int dl$$

$$\int_{P_{in}}^{P_{out}} \frac{dP}{P} = -\alpha \int_{o}^{L} dL$$

Where $P_{out} \rightarrow$ intensity of light received at output

$P_{in} \rightarrow$ intensity of light launched at input

$$[ln\, P]_{P_{in}}^{P_{out}} = -\alpha [L]_{o}^{L}$$

$$ln\left[\frac{P_{out}}{P_{in}}\right] = -\alpha L$$

$$\alpha = -\frac{1}{L} ln\left[\frac{P_{out}}{P_{in}}\right]$$

As the dependence of loss of intensity is logarithmic in nature, α also takes the unit as Bel [as sound intensity variation is also logarithmic whose unit is also Bel]

$$\boldsymbol{\alpha} = -\frac{1}{L} \log_{10}\left[\frac{P_{out}}{P_{in}}\right] \text{Bel/Unit length}$$

As Bel is larger unit, α is expressed in decibel / kilometer (dB/km)

$$\boldsymbol{\alpha} = -\frac{1}{L} \log_{10}\left[\frac{P_{out}}{P_{in}}\right] 10\text{dB / km}$$

$$\boxed{\alpha = -\frac{10}{L} \log_{10}\left[\frac{P_{out}}{P_{in}}\right] \text{dB / km}}$$

Note : * P_{in} & P_{out} expressed in watt
* L in km

Attenuation can be caused by three mechanisms.

Type of Attenuation in an Optical fiber:

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.

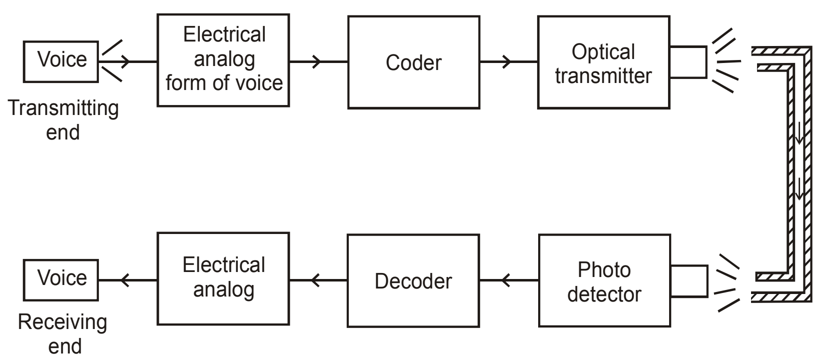
2. *Scattering*: When the wavelength of the photon is comparable to the size of the particle then the scattering takes place. Because of the non-uniformity in manufacturing, the refractive index changes with length leads to a scattering. This type of scattering is called as Rayleigh scattering. It is 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 fibers 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 fibers is due to non-uniformity of the optical fibers 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.

Application of optical fiber:(Point to point communication in OF)



Point of Point optical fibre communication system

A fiber optic communication system is very much similar to a traditional communication system and has three major components. A transmitter converts electrical signals to light signals, an optical fibre transmits the signals and a receiver captures the signals at the other end of the fiber and converts them to electrical signals.

The transmitter consists of a light source supported by necessary drive circuits. First voice is converted into electrical signals using a transducer. It is digitized (converted to binary electrical signals) using a coder. The digitized signal, which carries the voice information, is fed to an optical transmitter. The light source in optical transmitter (LED or laser diode) emits modulated light, which is transmitted through optical fiber. The light emitted by the source is in the IR range with a wavelength of 850nm, 1300nm or 1550nm.

On the other end the modulated light signal is detected by a photo detector is amplified and is decoded using a decoder. The output is fed to a suitable transducers to convert it into an audio or video form.

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.

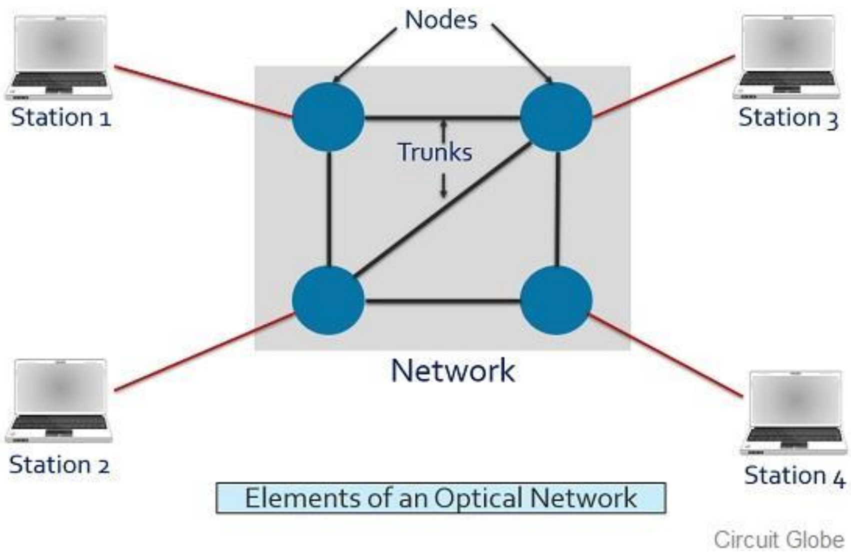
Optical Network

An Optical Network is basically a communication network used for the exchange of information through an optical fiber cable between one end to another. It is one of the quickest networks used for data communication.

As we already know that data signal through an optical fiber is transmitted in the form of light pulses. So, optical networks are used in order to have optical signal transmission.

Elements of optical network

An optical network is basically composed of the following elements:



Stations: Stations in an optical network serves as the source and destination of the information being transmitted and received. Stations are basically those devices that are used by the users of the network. For example, a computer or any other telecommunication device.

Trunk: A trunk is basically a transmission line i.e., optical fiber cable in order to transmit the optical signal. A network is composed of one or multiple trunks for signal transmission over large distance.

Node: Node is nothing but acts as a hub for multiple transmission lines inside the network. In case of a single transmission line, an optical network does not require nodes, as in this case stations at both the ends can be directly connected to the fiber cables.

Topology: When multiple fiber cables are employed in an optical network, then these are connected through nodes. But the way in which the multiple nodes are connected together denotes the topology of the network.

Router: A router is basically placed inside an optical network that provides a suitable path for signal transmission.

Categories of Optical Network

The categories of optical network are based on the area that connects the user of the network. These are classified as:

Local Area Network (LAN): Basically a LAN connection provides the interconnection of users that are present in localized areas like a building, a department or an office etc.

The example of networking topology of LAN is Ethernet. As in LAN, users are permitted to share the resources together like servers etc. These are personally owned by an organization. It is quite inexpensive.

Campus network: This network category is formed by the interconnection of multiple LAN's. This is basically extended to a large level but is still confined within a localized area. It is also governed by a single organization. The examples of campus network are university campus, a government organization, or a medical centre etc.

Metropolitan Area Network (MAN): It is also known as a metro network and covers a greater area than a campus network. It permits the interconnection of several buildings that are present in different cities. Due to its large operating area, MAN is controlled by several communication organizations.

Wide Area Network (WAN): Unlike MAN, a WAN provides interconnection of users from neighbouring cities as well as cross-country regions. It is employed to establish communication over a large geographical distance and is controlled and maintained by some private organizations or telecommunication service providers.