FIBER OPTICS

Introduction

Soon after the discovery of laser some experiments were carried out on propagation of information through light waves in open atmosphere. If light beam acting as a carrier wave is cable of carrying more information than radio waves and micro waves, because of its high frequency.

Due to atmospheric conditions like rain, fog etc... The efficient communication is disturbed. Hence to have an efficient communication system the light which carries the information requires a guiding media known as optical fiber. Optical fiber deals the transmission and receiving of light waves. The optical fibers working based on the principle of total internal reflection.

Fiber optics is a branch of optics which deals with the study of propagation of information in the form of light (rays or modes) through transparent dielectric optical fibers. The term optical fiber was first coined by N.S. Kapany.

Fiber optics is a technology related to transportation of optical energy (light energy) in guiding media specifically glass fibers.

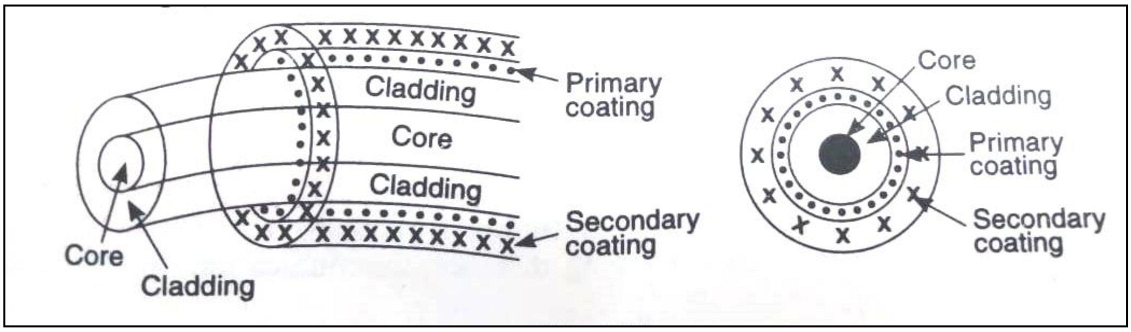
Optical fiber:

The word fiber comes from Latin *fibra* which means a thin thread like piece of material. Therefore; Optical fiber means a thin thread like piece of visible material. Optical fiber is a thin and transparent guiding dielectric medium or material which guides or transmits the information as light waves, using principle of total internal refection.

1. STRUCTURE OF OPTICAL FIBER

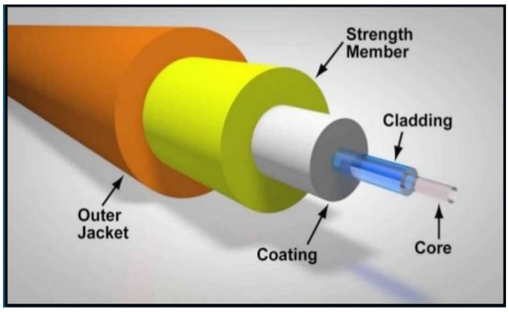
Optical fiber is a very thin, flexible and transparent dielectric medium having cylindrical shape. It guides the visible and infrared light over long distance using phenomenon of total internal reflection.

The structure of an optical fiber is shown in Fig. It consists of four parts, namely, core, cladding, primary coating and secondary coating.



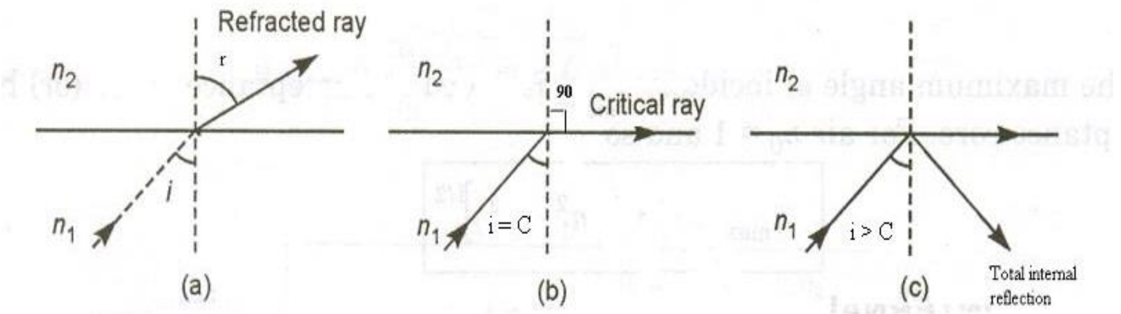
Structure of optical fiber

An optical fiber consists of an inner cylinder which is made of glass called the *Core*. The core carries light. The core is surrounded by another cylindrical shell of lower refractive index than core is called the *Cladding*. The cladding helps to keep the light within the core through the phenomenon of total internal reflection. The core diameter can vary from about 5 μm to about 100 μm. The cladding diameter is usually 125 μm. For greater strength and protection of the fiber, a soft plastic coating is done [Primary buffer coating]. This is often followed by another layer of coating known as Secondary buffer coating.



2. PRINCIPLE OF FIBER: TOTAL INTERNAL REFLECTION OF LIGHT

Principle: Optical fiber works based on the principle of total internal reflection of light.



Explanation: When light passes from denser medium to rarer medium, it bends away from the normal drawn at the point of incidence. For an increase in angle of incidence i, the angle of refraction also increases. For a particular value of incidence refracted ray grazes (touches) the surface separating both media. That is angle of refraction becomes 90^0, which is maximum. The angle of incidence for which angle of refraction becomes 90^0 is called critical angle. Further increase in angle of incidence, there is no possibility for refraction into the rarer medium, since the limits of variation for refraction are only from 0^0 to 90^0. So instead of refraction into the rarer medium once again light ray enter into the same denser medium. This phenomenon is called total internal reflection of light. Therefore an angle of incidence greater than the critical angle, the light is bounded to the denser medium.

At the critical angle of incidence, according to Snell's law of refraction, $n_1 \sin \theta_C = n_2 \sin 90^0$ or $\theta_C = \sin^{-1}(n_2/n_1)$ where n_1 is refractive index of the first medium, i.e. denser medium and n_2 is refractive index of the second medium i.e. rarer medium.

Conditions for Total Internal Reflection: If any light undergoes total internal reflection it must be satisfies the following conditions.

i. Light should travel from denser to rarer medium.

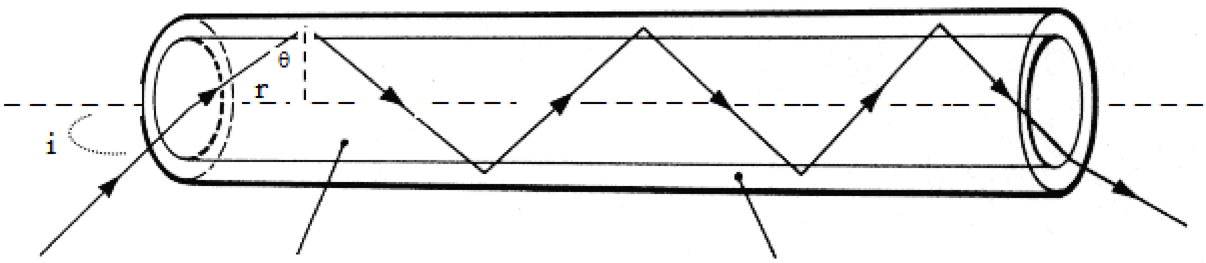
ii. Angle of incidence should be greater than critical angle of the medium.

Critical angle:

The angle of incidence in denser medium for which angle of refraction is 90^0 in rarer medium is called Critical angle.

Propagation of Light in Optical Fiber:

The principle of optical fiber communication is *total internal reflection*. When light is incident on one end of the fiber with small angle, it passes through the fiber as explained below.



Let **i** be the angle incidence of the light ray with the axis and **r** is the angle of refraction. If θ is the angle at which the ray is incident on the boundary, If $\theta \geq \theta_c$ (critical angle), then the ray is totally internally reflected. In this way, the ray undergoes repeated total internal reflections until it emerges out from the other end of the fiber, even if the fiber is bent. Thus the light ray is guided through the fiber from one end to other end without any loss of energy.

3. TYPES OF OPTICAL FIBER

Optical fibers are classified in to three categories based on

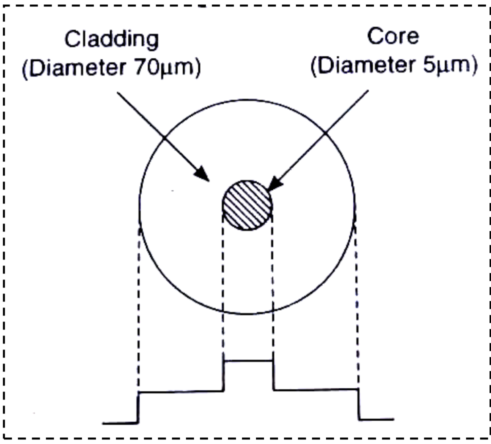
i. Material of the fiber **ii**. Number of modes and **iii**. Refractive index profile.

i. Based on fiber materials the fibers classified into two types.

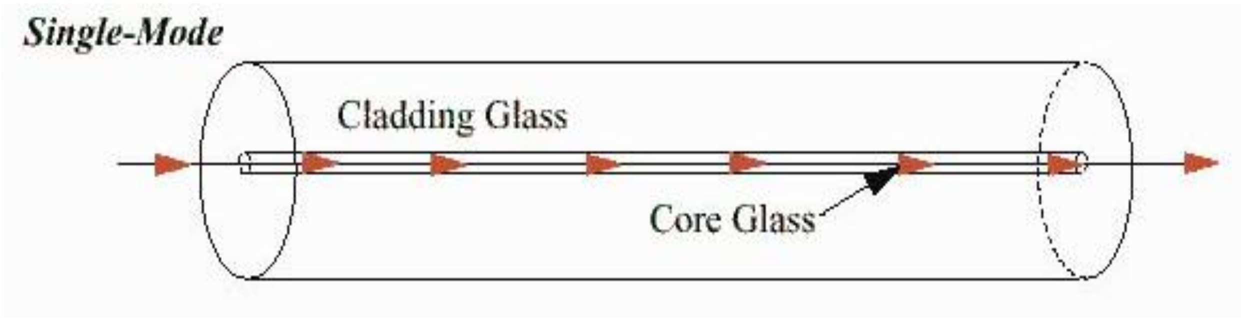
a. Glass fiber: - these fibers are made up of mixture of metal oxides and silica glasses.

b. Plastic fibers: - these fibers are made up plastics which can be handled without any care due to its toughness and durability it is called plastic fibers.

ii. Based on modes of propagation the fibers are classified in to two types.

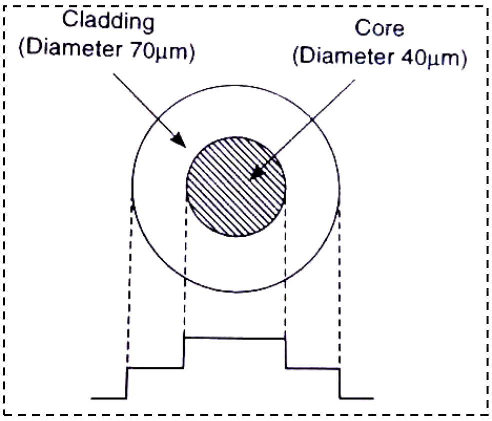


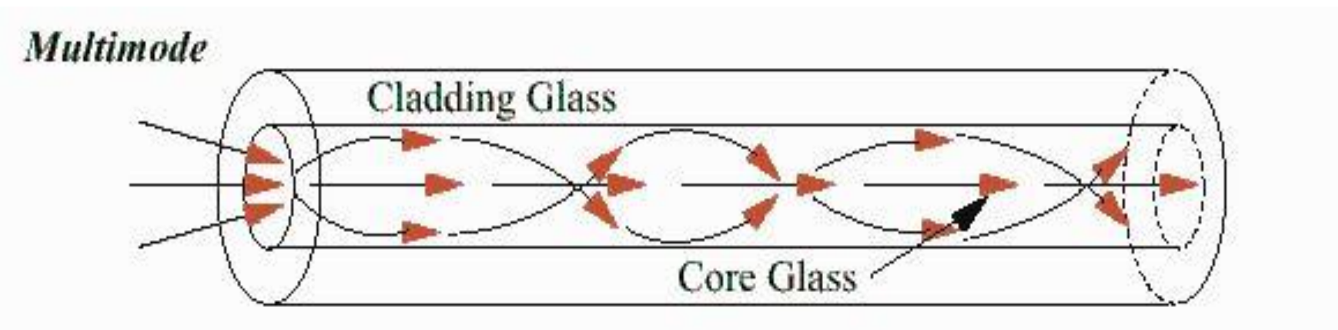
a) One mode [Single mode] fibers: - It has a very small core diameter so that it can allow only one mode of propagation and hence called single-mode fibers. It has smaller core diameter (5 μm) and high cladding diameter (70 μm). The difference between the refractive indices of the core and cladding is very small. In this, as only one mode can propagate there is no dispersion *i.e.,* no degradation of signal during travelling the fiber and hence supportable for long distance communication.



Many modes [Multi mode] fibers: -

Here the core diameter is very large compared to single mode fibers, so it can allow many modes to propagate through it and hence called Multi mode fibers. It has large core diameter than single mode fiber. The core diameter is (40 µm) and that of cladding is (70 µm). The relative refractive index difference is also larger than single mode fiber. As multimode fiber allows a large number of modes, there is a signal degradation (more dispersion) while travelling through it. Thus, these are not suitable for long distance communication.

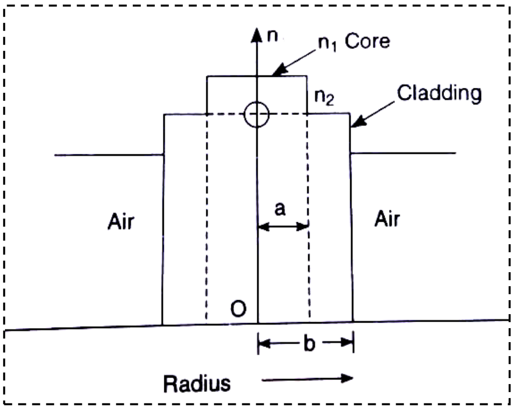


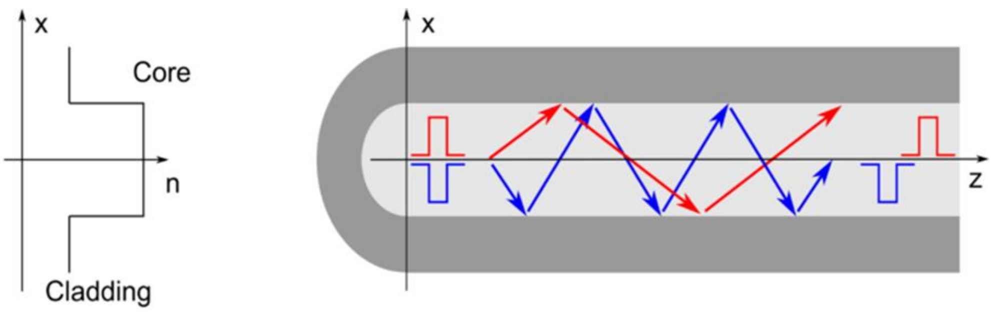


iii. Based on the variation in the refractive index of the core and the cladding the fibers are classified into two types.

a. <u>Step Index Fibers:</u>

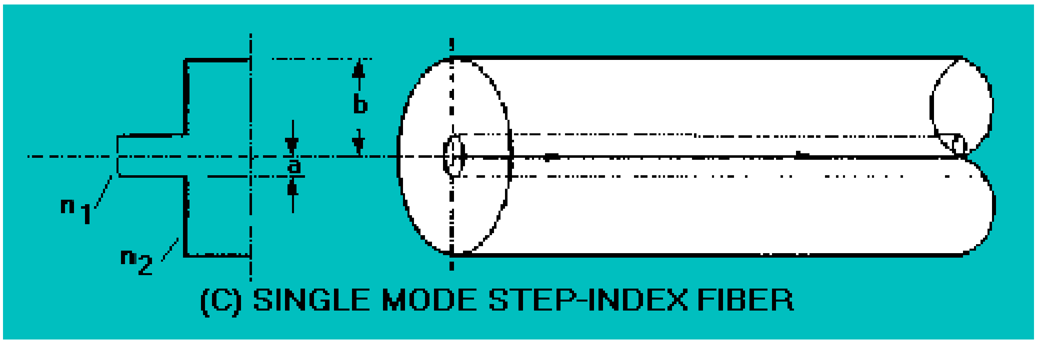
In step index fibers refractive index (say n_1) of the core is constant throughout the diameter of the core and the cladding has also a uniform refractive index (say n_2), of course $n_1 > n_2$. The refractive index profile is shown in figure. Let *a* and *b* the radii of core and cladding respectively. The refractive index profile and radius of core and cladding of a step-index fiber is shown in figure. At the core and cladding boundary, the refractive index suddenly changes which is shown in figure. These fibers have greatest range of core sizes (50-200 μm). As the diameter of the core is high, more number of modes of propagation of light is possible. So, the fiber is called as multi-mode step index fiber.





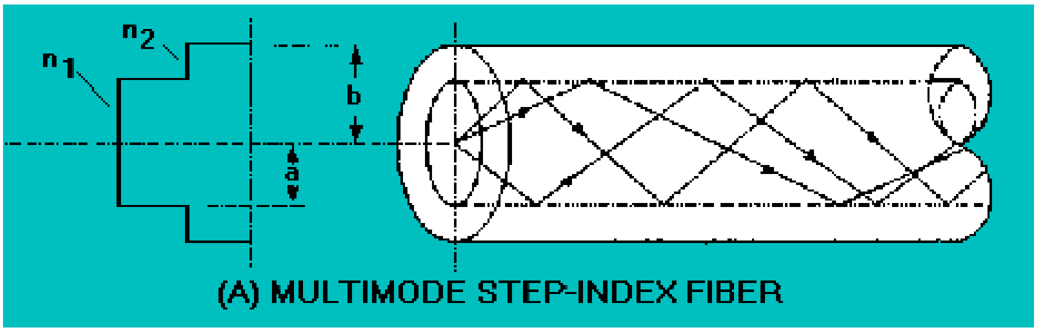
- ***<u>Single Mode Step Index Fiber</u> (SMF):***

The single mode step index fiber is shown in Fig. In single mode fiber the core diameter is of the order of 10 μm approximately and diameter of cladding is 110 μm. So it can support few wavelengths of light only. Light travels in SMF along a single path that is along the axis of the fiber. This is known as zero order propagation. Due to smaller core diameter, signal distortion is very less. That is there is only small waveguide dispersion only. The light rays propagate through it are in the form of meridional rays which cross the fiber axis during every reflection at the core-cladding boundary. The distortion does not take place in single mode step index fiber.



- ***Multi Mode Step Index Fiber (MMF):***

Multimode step index fiber is similar to that of single mode fiber except in core diameter. MMF has larger core diameter of the order of 100 μm. so it can support multi wavelengths. Light follows zigzag paths inside the fiber. Many zigzag paths are permitted in MMF by changing the frequency of the light. Signal distortion is more in multiple-mode step index fiber. This is due to the fact that the rays reflected at higher angles travel a greater distance than the rays reflected at low angles to reach the exit end of the fiber.



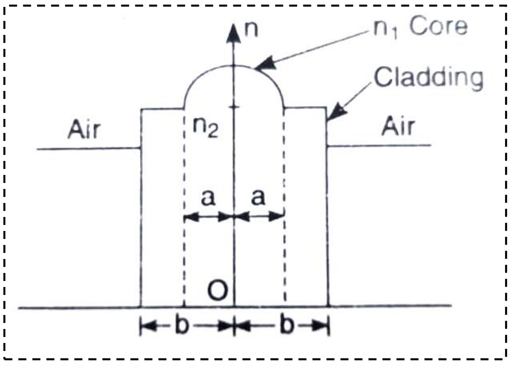
Advantages of Step-index multimode fiber:

- Relatively easy to manufacture
- Cheaper than other types
- Larger layer NA
- They have longer life times than laser diodes

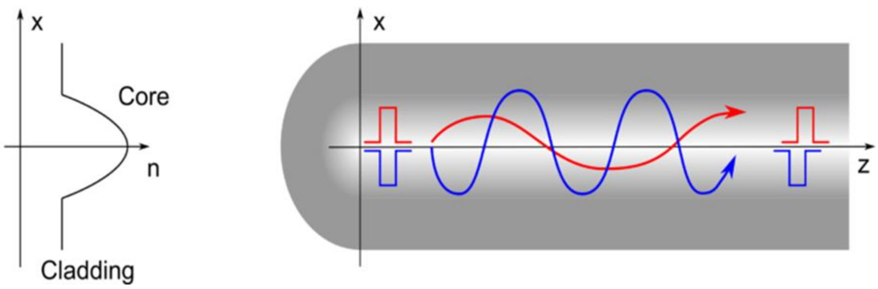
Disadvantages of Step-index multimode fiber:

- Lower bandwidth
- High dispersion and
- Smearing of signal pulse

b. Graded index optical fiber:



Here the refractive index of the core varies radically [non uniform] from the axis of the fiber as shown in refractive index profile figure. The refractive index of the core is maximum along the fiber axis and is gradually decrease towards the core-cladding interface. Thus it is called as graded index fiber. Here refractive index becomes minimum at the core cladding interference.



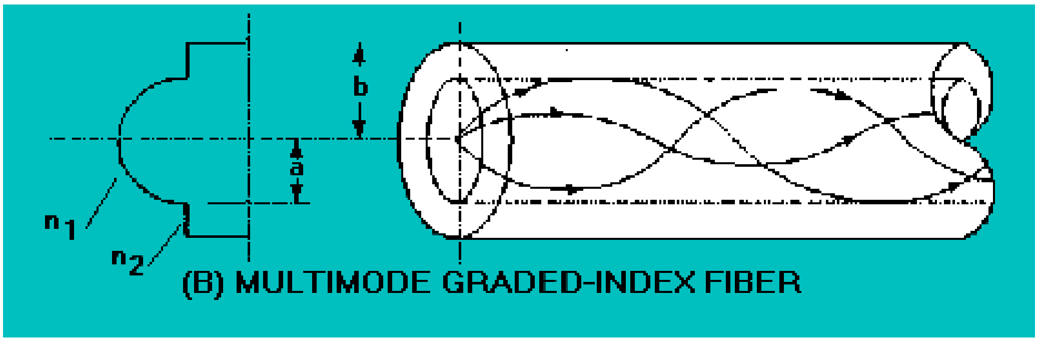
In this fiber, a ray is continuously bent and travels a periodic path along the axis. The rays entering at different angles follow different paths with the same period, both in space and time. Thus, there is a periodic focusing of the rays. Pulse dispersion is less.

- ***Single Mode Graded Index Fiber*** **:**

Graded index optical fiber has a property of gradual variation in refractive index (increasing from the outside of the fiber core to the centre of it). The propagation of light through single mode graded index fiber is similar to that for step index fiber. The light wave travels along the centre of the optical fiber.

- ***Multi Mode Graded Index Fiber*** **:**

The core and cladding diameters are about 50 μm and 70 μm respectively in case of multimode fiber. The light rays propagate through it in the form of skew rays or helical rays.



It is obvious from the figure that a ray is continuously bent and travels a periodic path along the axis. The rays entering at different angles follow different paths with the same period, both in space and time. Thus, there is a periodic self-focussing of the rays. Here, the signal distortion is very low because of self-focussing effect. In this case, the light rays travel at different speeds in different paths of the fiber because the refractive index varies throughout the fiber. As a result, light rays near the edge travel faster than the light rays near the centre of the core.

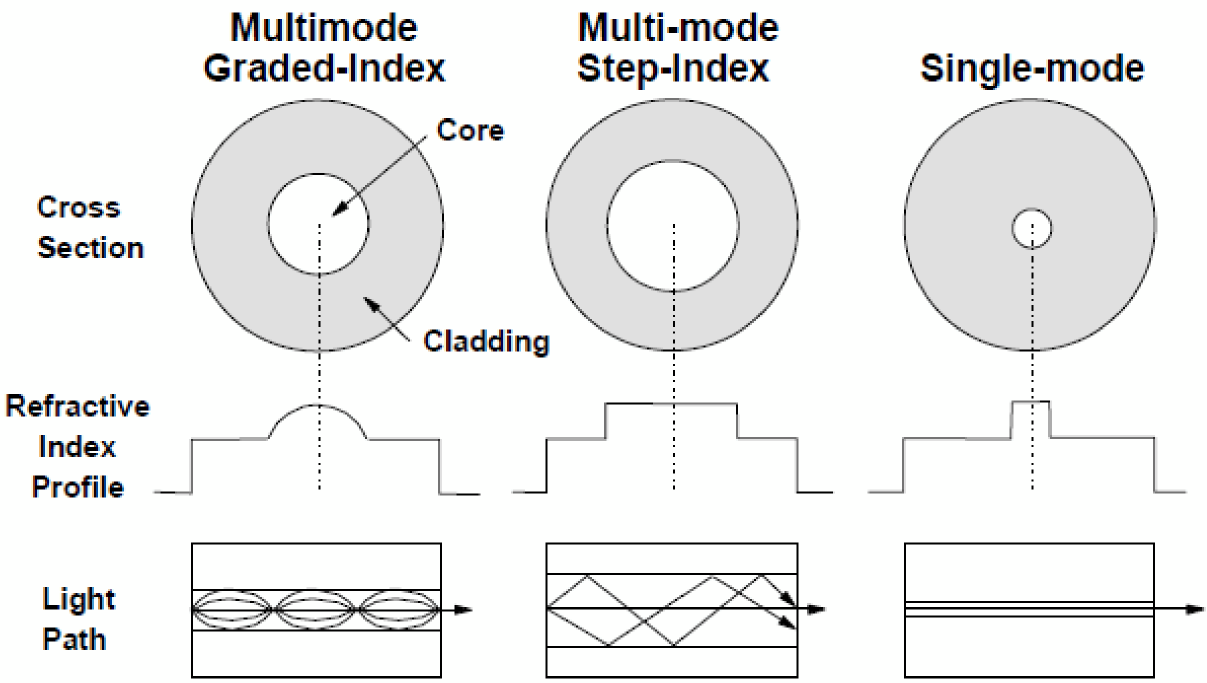
Advantages of Graded-index multimode fiber:

- Dispersion is low
- Bandwidth is greater than step-index multimode fiber, and
- Easy to couple with optical source

Disadvantages of Graded-index multimode fiber:

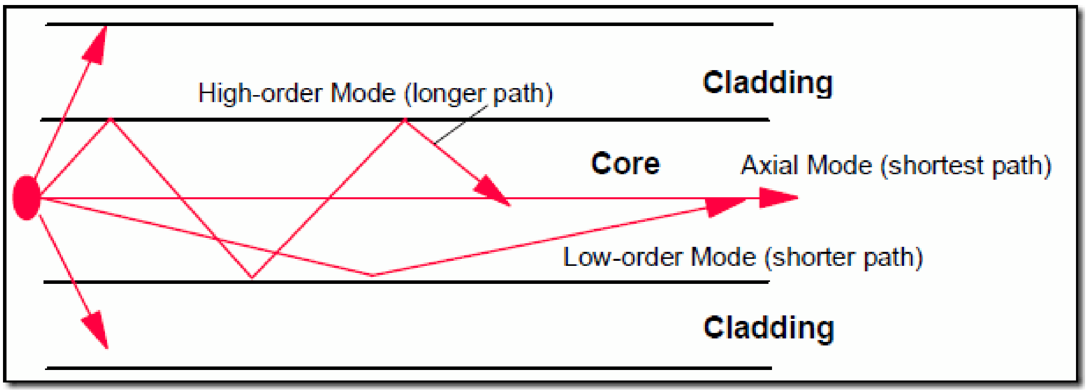
- Expensive
- Very difficult to manufacture

Comparison:



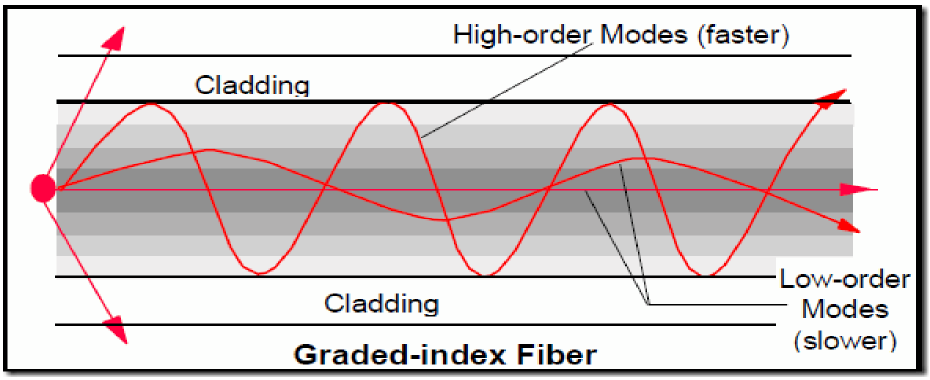
Meridional and Skew beams

All beams (modes) propagating within an optical fiber is divided into two categories: ***meridional*** *beams* and ***skew*** *beams*. Meridional beams are those that intersect the centerline of the fiber or fiber axis during every reflection at the core cladding boundary. The below figure show the paths of rays in step-index fiber.



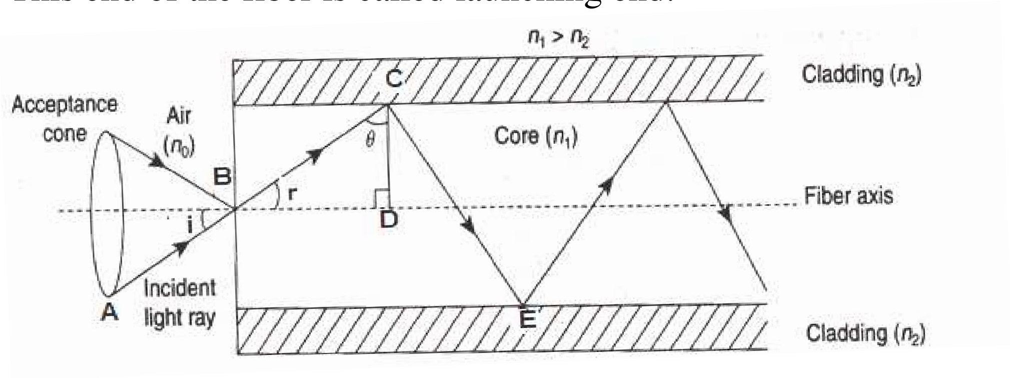
In this, three rays are entering at different angles of incidence with the axis. All these 3 rays travel in different path lengths and emerge out at different times. It is obvious from the figure that an input pulse gets widened as it travels along the fiber.

The light rays propagate through it in the form of skew rays or helical rays. They Skew beams propagate without intersecting the fiber's central axis. Skew rays are not confined to a single plane, so they cannot be tracked easily. The acceptance angle for skew rays is larger than the acceptance angle of meridional rays. Analyzing the meridional rays is sufficient for the purpose of result, rather than skew rays, because skew rays lead to greater power loss. Although skew rays constitute a major portion of the total number of guided rays, their analysis is not necessary to obtain a general picture of rays propagating in a fiber. Hence, it is sufficient to consider the meridional rays for all practical purposes.

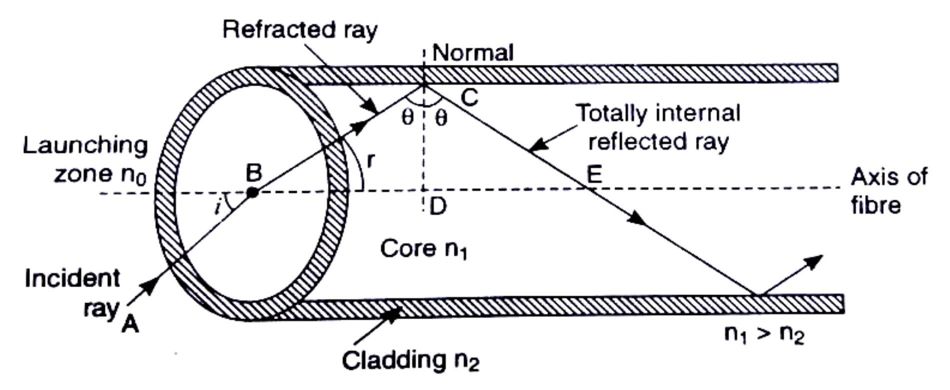


4. NUMERICAL APERTURE AND ACCEPTANCE ANGLE:

Consider a cylindrical fiber wire which consists of an inner core of refractive index n_1 and an outer cladding of refractive index n_2 where $n_1 > n_2$. Let n_0 be the refractive index of the medium from which the light ray enters the fiber. This end of the fiber is called launching end.



Let a ray of light enters the fiber at an angle of incidence 'i' with axis of fiber as shown in figure. The ray refracts with an angle 'r' and strikes the core-cladding interface at an angle θ. Let θ be greater than critical angle θ_c, then the light will stay within the fiber. Now calculate the angle of incidence 'i' for which the angle of $\theta \geq \theta_C$, so that the light reflected within the fiber.



Applying Snell's law at the point of entry of the ray AB into the core, then we have

$$n_0 \sin i = n_1 \sin r \quad \text{------------} \quad (1)$$

From Δ BCD ⇒ $r = (90 - \theta) \quad or \quad sir\ r = \sin(90 - \theta)$

$$\sin r = \cos\theta \quad \text{------------} \quad (2)$$

Substituting the value of sin r from eq. (2) in eq. (1), we get

$$n_0 \sin i = n_1 \cos\theta$$

$$\Rightarrow \quad \sin i = \frac{n_1}{n_0}\cos\theta \quad \text{-------------} \quad (3)$$

The largest value of i (I_{max}) occurs when $\theta = \theta_C$. Applying this condition in Eq. (3), we get

$$sin(i_{max}) = \left(\frac{n_1}{n_0}\right) cos\,\theta_C \quad \text{-------------} \quad (4)$$

But, $\sin\theta_C = \dfrac{n_2}{n_1}$

$$\Rightarrow \cos\theta_C = \sqrt{1-\sin^2\theta_C} = \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \quad \text{-------------} \quad (5)$$

From Eq. (4) and (5), we have

$$\sin(i_{max}) = \left(\frac{n_1}{n_0}\right) \times \frac{\sqrt{n_1^2 - n_2^2}}{n_1} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \quad \text{-------------} \quad (6)$$

Generally the incident ray is launched from air medium , i.e., n_0=1.Therefore,

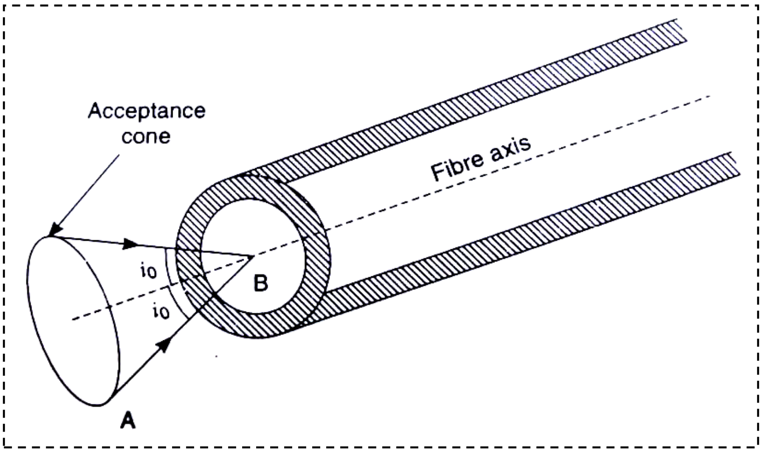
$$\sin(i_{max}) = \sqrt{\left(n_1^2 - n_2^2\right)}$$

Here i_{max} is called the acceptance angle of the fiber.

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

∴ ***<u>Acceptance angle</u> of fiber can be defined as "The maximum angle of incidence for which light confines to propagate in the core (denser medium) by total internal reflection".***

Acceptance Cone: If the ray AB is rotated around the fiber axis keeping i_0 same, then it describes a conical surface as shown in figure. Now only those rays which are funnelled into the fiber within this cone having a full angle $2i_0$ will only be totally internally reflected and thus confined within the fiber for propagation, *i.e.*, only the rays within the cone are accepted. Therefore, the cone is called **acceptance cone.** The light incident at an angle beyond i_0 will be refracted through the cladding and the corresponding optical energy is lost.



5. Numerical Aperture of Fiber:

The light collecting capacity of an optical fiber is called Numerical aperture. It is also defined as *sin* of the maximum acceptance angle is called numerical aperture (NA) of the fiber. Sometimes it is also refered as figure of merit for optical fiber. Therefore

$$NA = sin(i_{max}) = \sqrt{\left(n_1^2 - n_2^2\right)}$$

Condition for propagation of light:

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

$$i < i_0$$
$$\sin i < \sin i_0$$
$$\sin i < \sqrt{\left(n_1^2 - n_2^2\right)}$$
$$\sin i < NA$$

This is the condition for propagation of light within the fiber.

Numerical aperture characterizes the ability of the fiber to gather light from a source. It is more convenient to define a parameter called *relative index*, Δ, whose variation could get us fibers of different NA vales. It is given as,

$$\Delta = \left(\frac{n_1 - n_2}{n}\right)$$

where n is the average refractive index of the core and cladding.

$$\therefore \qquad \Delta = \frac{(n_1 - n_2)(n_1 + n_2)}{n(n_1 + n_2)}$$

$$\Delta = \frac{n_1^2 - n_2^2}{n(n_1 + n_2)} \qquad [\because n \approx n_1 \approx n_2]$$

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

$$n_1^2 - n_2^2 = n_1^2 \, 2\Delta$$

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

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