V P & R P T P SCIENCE COLLEGE - Vallabh Vidyanagar-388120
B.Sc. (semester -3)
Subject; Physics
Course; US03CPHY21
Optics
(Four credit Course-4 hours per week)
(Effective from –June 2019)

Unit: IV: Fiber optics [Chapter-24]

Introduction: In 1870 John Tyndall state that light can be guided along the curve of a stream of water and the total internal reflected light gets confined to the water stream and the stream appears luminous. A luminous water stream is considered as an optical Fiber.

In 1950, the transmission of images through optical Fibers was realized in practice. Hopkins and Kapany developed the flexible Fiberscope, which was used by the medical word and viewing the interior of human body. The Kapany has assigned the term Fiber optics. In 1960, it was established that light could be guided by a glass Fiber. In 1966 Charles Kao and George Hockham proposed the transmission of information over glass Fiber. In 1970 corning glass works produced low-loss glass Fibers. The invention of solid state lasers in 1970 made optical communications practicable.

Commercial communication systems based on optical Fibers are widely used in other areas. Fiber-scopes made of optical Fibers are widely used in a variety of forms in medical diagnostics. Sensors for detecting electrical, mechanical, thermal energies are made using optical Fibers.

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

Optical Fiber:

Definition: An optical Fiber is a cylindrical wave guide made of transparent dielectric, (glass or clear plastic), which guides light waves along its length by total internal reflection. It is very thin like human hair, approximately 70um or 0.003 inch diameter. The thin strand of a metal is called a wire and a thin strand of dielectric materials is called a Fiber.

Principle: Light propagate in optical Fiber from one of its ends to the other end is based on the principle of total internal reflection. When light enters at one end of the Fiber, it undergoes successive total internal reflection from side

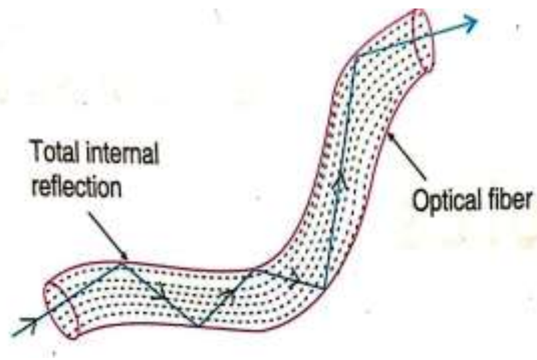


Figure: 1 Optical Fiber

walls and travels along the length of the Fiber in a zigzag path as shown in figure 1. A small fraction of light may escape through sidewalls but a major fraction emerges out from the exit end of the Fiber. Light can travel through Fiber even if it is bent.

Structure: A practical optical Fiber is cylindrical in shape (refer figure 2a) It has in general three coaxial regions as shown in figure 2b.

Figure: 2. practical optical Fiber

Core:

- The innermost cylindrical region is the light guiding region known as the core.
- In general the diameter of the core is of the order of 8.5 um to 62.5 um

Cladding:

- The core is surrounded by a coaxial middle region known as the cladding.
- The diameter of the cladding is of the order of 125 um.
- The refractive index of cladding (n_2) is always lower than that of core (n_1).

- ❖ Light launched into the core and striking the core -to-cladding interface at angle greater than critical angle will be reflected back into the core.
- ❖ When the angles of incidence and reflection are equal, the light will continue to rebound and propagate through the Fiber.

Buffer:

- ❖ The outermost region is called the sheath or a protective buffer coating.
- ❖ It is a plastic coating given to the cladding for extra protection.
- ❖ This coating is applied during the manufacturing process to provide physical and environmental protection for the Fiber.
- ❖ The buffer is 'elastic in nature and prevents abrasions.
- ❖ The coating varies in size from 250 um or 900 um.

In short,

- ❖ Core is the inner light-carrying member.
- ❖ Cladding is the middle layer-which serves to confine the light to the Core.
- ❖ Buffer coating surround the cladding, which protects the Fiber from physical damage and environmental effects.

Necessity for Cladding:

The actual Fiber is very thin and light entering a bare Fiber will travel along the Fiber through repeated total internal reflections at the glass-air boundary. However, bare Fibers are used only in certain applications. For use in communications and some other applications, the optical Fiber is provided with a cladding. The cladding maintains uniform size of the Fiber, protects the walls of the Fiber from chipping, and

reduces the size of the cone of light that will be trapped in the Fiber.

- ❖ It is necessary that the diameter of an optical Fiber remains constant throughout its length and is surrounded by the same medium. Any change in the thickness of the Fiber or the medium outside the Fiber (when the Fiber gets wet due to moisture etc) will cause loss of light energy through the walls of the Fiber.
- ❖ A very large number of reflections occur through the Fiber and it is necessary that the condition for total internal reflection must be accurately met over the entire length of the Fiber. If the surface of the glass Fiber becomes scratched or chipped, the normal to the edge will no longer be uniform. As a result, the light traveling through the Fiber will get scattered and escapes from the Fiber. This also causes loss of light energy.

- Part of light energy penetrates the Fiber surface. The intensity of the light decreases exponentially as we move away from the surface, as the light is able to penetrate only a very small distance outside the Fiber. However, anytime the Fiber touches something else, the light can leak into the new medium or be scattered away from the Fiber. This effect causes a significant leakage of the light energy out of the Fiber. Even a small amount of dust on the surface would cause a fair amount of leakage.
- If bare optic Fibers are packed closely together in a bundle, light energy traveling through the individual Fibers tends to get coupled through the phenomenon of frustrated total internal reflection. Cladding of sufficient thickness prevents the leakage of light energy from one Fiber to the other.
- The Fiber is provided with a cladding in order to prevent loss of light energy due to the above reasons.
- The cladding causes a reduction in the size of the cone of light that can be trapped in the Fiber. Light entering the Fiber at larger angles will strike the Fiber walls at smaller angles (higher modes) and ultimately travel a longer distance. Such higher modes of a light signal will take longer time to reach the end of the Fiber than the lower modes. Therefore, a pulse sent through optical Fiber spreads out. The spreading would be larger, the larger the cone of acceptance. Such pulse spreading limits the rate of data transmission through the Fiber. A Fiber with a cladding have smaller cone of acceptance, they carry information at a much higher bit rate than those without a cladding.

Therefore, the cladding performs the following important functions:

- Keeps the size of the Fiber constant and reduces loss of light from the core into the surrounding air.
- Protects the Fiber from physical damage and absorbing surface contaminants
- Prevents leakage of light energy from the Fiber through evanescent waves.
- Prevents leakage of light energy from the core through frustrated total internal reflection.
- Reduces the core of acceptance and increases the rate of transmission of data.
- A solid cladding, instead of air, also makes it easier to add other protective layers over the Fiber.

Optical Fiber System:

An optical Fiber is used to transmit light signals over long distances. The role of a light transmitting medium is similar to a coaxial cable or wave guide used in microwave communications. Optical Fiber requires a light source for launching light into the Fiber at its input end and a 'photo detector' to receive light at its output end.

As the diameter of the Fiber is very small, the light source has to be dimensionally compatible with the Fiber core. Light emitting diodes and laser diodes, which are very small in size, are used as the light sources.

The electrical input signal is in general of digital form. It is converted in to optical signal by varying the current flowing through the light source. Hence, the intensity of the light emitted by the source of modulated with the input signal and the output will be in the form of light pulses. The light pulses constitute the signal that travels through the optical Fiber. At the receiver end, semiconductor photo diodes, which are very small in size, are used for detection of these light pulses. The photo detector converts the optical signal into electrical form. Thus a basic optical Fiber system consists of LED /laser diode, optical Fiber cable and a semiconductor photodiode.

Optical Fiber Cable:

Optical Fiber cables are designed in different ways to serve different applications. More protection is provided to the optical Fiber by the 'cable' which has
the Fibers and strength members inside an outer covering called a 'jacket'. We study here two typical designs, a single Fiber cable or a multi Fiber cable.

Single Fiber Cable:

Around the Fiber a tight buffer jacket of Hytrel is used as illustrated in the figure3.

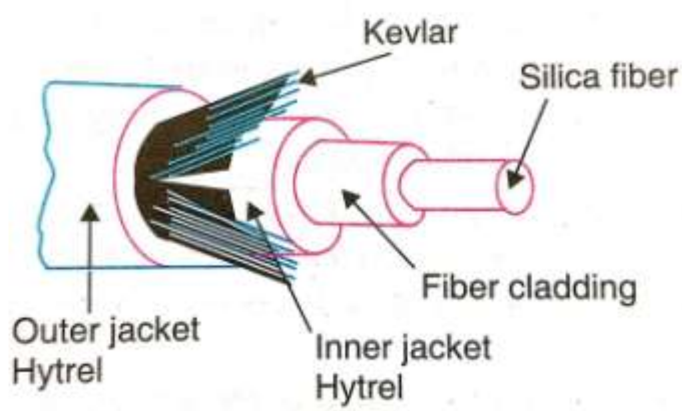


Figure: 3. Single Fiber Cable

The buffer jacket protects the Fiber from moisture and abrasion. A strength member is arranged around the buffer jacket in order to provide the necessary toughness and tensile strength. The strength may be provided by a steel wire, polymer film, nylon yarn or Kevlar yarn. Then the Fiber cable is covered by a Hytrel outer jacket. Because of this arrangement Fiber cable will not get damaged during bending, rolling, stretching, pulling, transportation and installation processes. The single Fiber cable is used for indoor applications.

Multi Fiber Cable:

A multiple cable consists of number of Fibers in a single jacket. Each Fiber carries light independently. The cross-sectional view of a typical telecommunication cable is shown in figure 4.

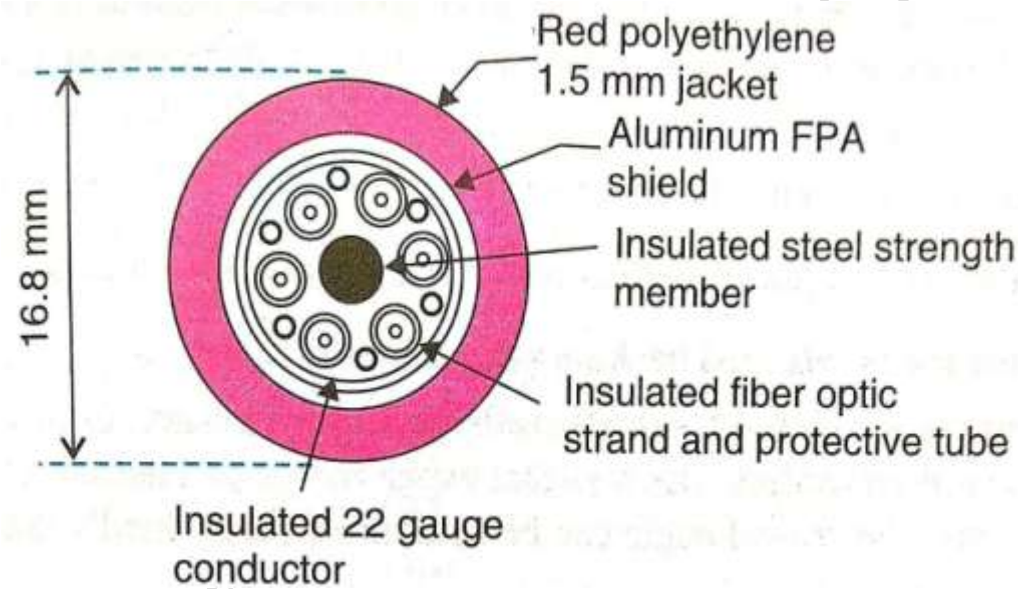


Figure: 4. Cross sectional view of a typical multi Fiber cable.

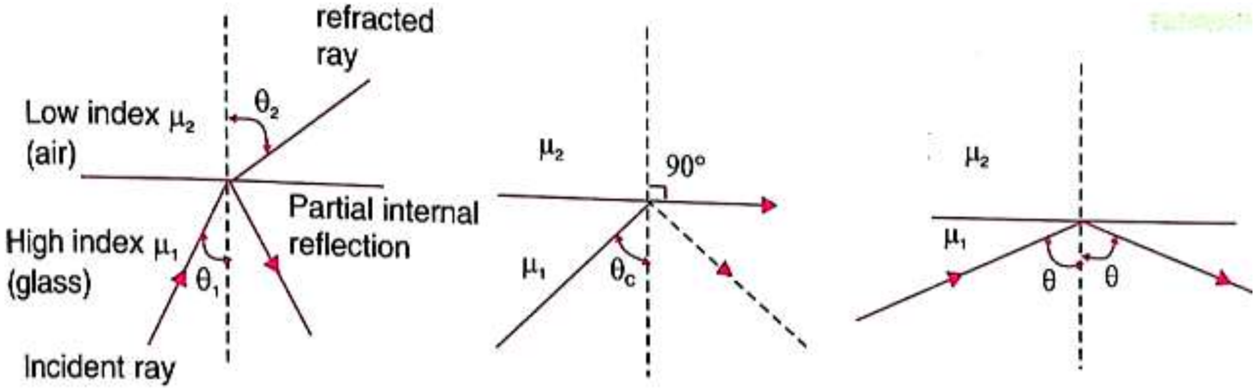
It contains six optical Fiber strands and has an insulated steel cable at the centre for providing tensile strength. Each optical Fiber strand consists of a core surrounded by a cladding, which in turn is coated with insulating jacket. The Fibers are thus individually buffered and strengthened. Six insulated copper wires are distributed in the space between the Fibers. They are used for electrical transmission. The assembly is then fitted within aluminum sheath, which acts as a shield. A polyethylene jacket is applied over the top.

Total Internal Reflection:

A medium having a lower refractive index is said to be an optically rare medium while a medium having higher refractive index is known as an optically denser medium.

When a ray of light passes from denser medium to rare medium, it is bent in the rare medium, as shown in figure 5a.
Snell's law for this case may be written as

$$sin\theta_2 = \left(\frac{\mu_1}{\mu_2}\right) sin\theta_1 \quad \text{.............1}$$



[a] [b] [c]

Figure: 5.Phinomenon of total internal reflection

Where, θ_1 is the angle of incidence of light ray in the denser medium and $\theta_2$is the angle of refraction in the rare medium. Also, $\mu_1 > \mu_2$. When, the angle of incidence θ_1 in the denser medium is increased then the transmission angle θ_2 increases and the refracted rays bend more and more away from the normal. At some particular angle θ_c the refracted ray glides along the boundary surface so that $\theta_2 = 90^0$ as seen figure 5b.

At an angle greater than 6c there are no refracted rays at all. The rays are reflected back into denser medium as shown in figure 5c. Thus,

1. If $\theta_1 < \theta_c$, the ray refracts into the rare medium.
2. If $\theta_1 = \theta_c$, the ray just grazes the interface of rarer-to-denser media.
3. If $\theta_1 > \theta_c$, the ray is refracted back into the denser medium.

The phenomenon in which light is totally reflected from a denser -to-rare medium boundary is known as total internal reflection. The rays that experience total internal reflection obey the laws of reflection.

Therefore, the critical angle can be determined from Snell's law.

When, $\theta_1 = \theta_c$ then θ_2 = 90^0

Therefore, from equation (1), we get

$\mu_1 \text{Sin}\theta_c = \mu_2 \sin 90^0 = \mu_2$

$$sin\theta_c = \frac{\mu_2}{\mu_1} \quad \text{..............2}$$

when the rare medium is air, then μ_2 =1 and writing μ_2 = μ, we get

$sin\theta_c = \frac{1}{\mu}$ 3

Propagation of light through an optical Fiber:

The diameter of an optical Fiber is very small hence cannot use bigger light sources for launching light beam into it. Light emitting diode (LED) and LASER diodes are the optical sources used in Fiber optics. The focusing lens is used to concentrate the beam on to the Fiber core. The Light propagates as an electromagnetic wave through an optical Fiber. According to the ray model, light rays entering the Fiber strike the core clad interface at different angles.

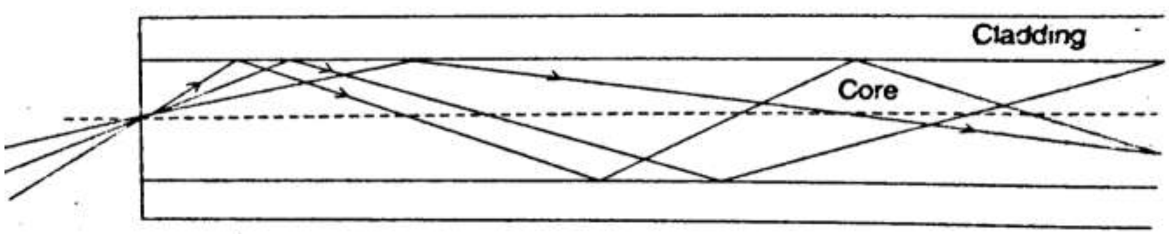


Figure: 6. Propagation of light through an optical Fiber due to total internal reflection

As the refractive index of the cladding is less than that of the core, majority of the rays undergo total internal reflection and the angle of reflection is equal to the angle of incidence in each case. The refracted rays will suffer total internal reflections inside the core. Thus, the rays travel through the Fiber via a series of total internal reflections and emerge out from the exit end of the Fiber shown in figure 6.

Since each reflection is a total internet reflection, there is no loss of light energy and light confines itself within the core during the propagation. Because of the negligible loss during the total internal reflections, optical Fiber can carry the light waves over very long distances. Thus, the optical Fiber acts as wave guide and is called a light guide or light pipe. At the exit end of the Fiber, the light is received by a photo-detector.

The following two conditions must be satisfied for total internal reflection.

1. The refractive index of the core material n_1 must be slightly greater than that of the cladding n_2.
2. At the core -cladding interface in figure-7, the angle of incidence ϕ must be greater than the critical angle ϕ_c is defined as, $sin\Phi_c = \frac{n_2}{n_1}$ 4

   Hence, the rays, which are incident at an angle greater than the critical angle, will propagate through the Fiber. The rays that are incident at smaller angles are refracted into the cladding and are lost.

Critical Angles of Propagation:

Consider a step index optical Fiber into which light is launched at one end. The end at which light enters the Fiber is called launching end.

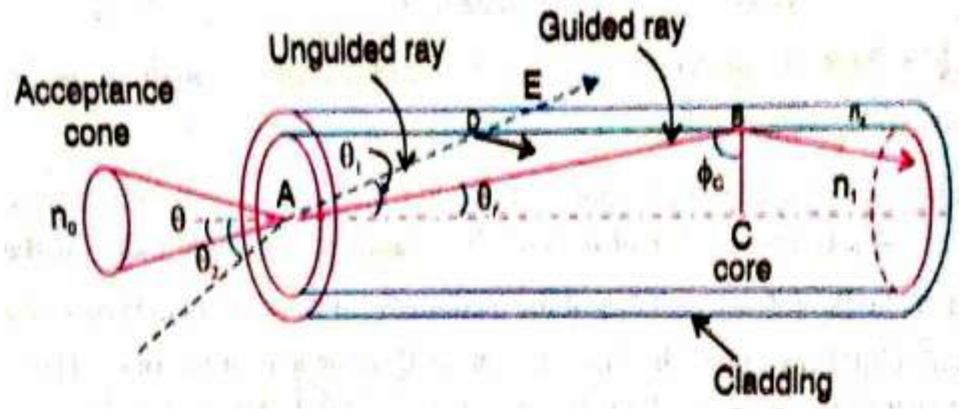


Figure: 7. Light rays incident at an angle smaller than critical propagation angle will propagate through the Fiber

In a step-index Fiber, the refractive index changes from the core to the cladding. Now, we consider two rays entering the Fiber at two different angles of incidence. The ray shown by the broken line is incident at an angle θ_2 with respect to the axis of the Fiber as shown in figure7. This ray undergoes refraction at point A, The ray refracts into the Fiber at an angle ($\theta_1 < \theta_2$). The ray reaches the core–cladding interface point at D. At point D, refraction takes place again and the ray travels in the cladding. Finally, at point E, the ray refracts once again and emerges out of Fiber into the air. It means that the ray does not propagate through the Fiber.

Now consider the ray shown by the solid line in the same figure 7. The ray incident at an angle θ undergoes refraction at point A and propagates at an angle θ_c in the Fiber. At point B on the core-cladding, interface, the ray undergoes total internal reflection. Let us assume that the angle of incidence at the core-cladding interface is the critical angle ϕ_c, where ϕ_c is given by

$$\Phi_c = sin^{-1}\left(\frac{n_2}{n_1}\right) \quad \text{…………….1}$$

A ray incident with an angle larger than dc will be confined to the Fiber and propagate in the Fiber. A ray incident at the core-cladding boundary, at the critical

angle is called critical ray.

The critical ray makes an angle θ_c with axis of the Fiber. If the rays propagation an angles larger than θ_c will not propagate in the Fiber. Therefore, the angle θ_c is called the critical propagation angle.

From the Δl^{es} ABC,

$$\frac{AC}{AB} = sin\Phi_c$$

Also,

$$\frac{AC}{AB} = cos\Phi_c$$

From relation equation-1,

$$sin\Phi_c = \frac{n_2}{n_1}$$ and

$$cos\Phi_c = \frac{n_2}{n_1}$$

$$\therefore \theta_c = cos^{-1}\left(\frac{n_2}{n_1}\right) \qquad \text{............2}$$

Thus, only those rays which are refracted into the cable at angles $\theta_r < \theta_c$ will propagate in the optical Fiber.

Acceptance Angle:

Considering a step index optical Fiber into which light is launched at one end, as shown in the figure 8. Let the refractive index of the core be n_1 and the refractive index of the cladding be n_2 ($n_2 < n_1$). Let n_0 be the refractive index of the medium from which light is launched into the Fiber.

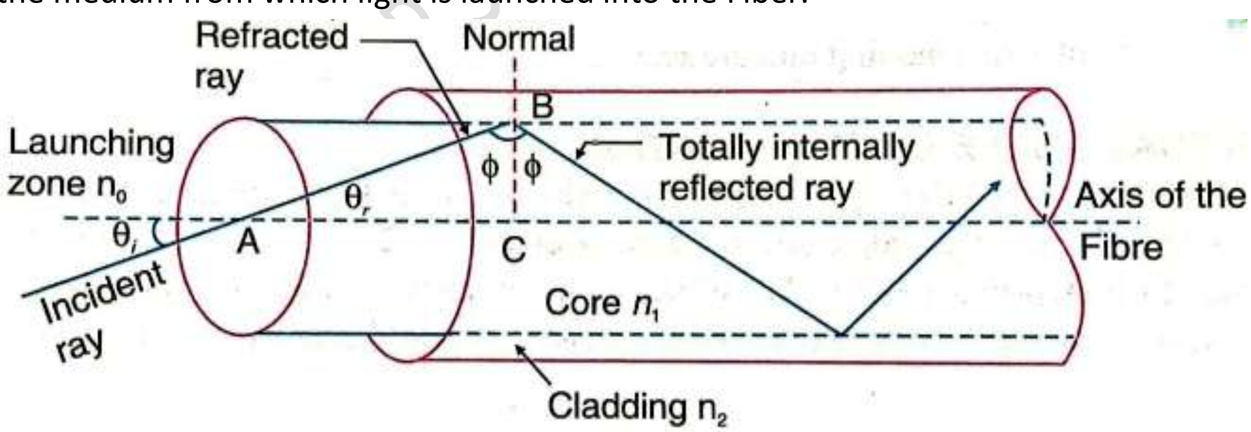


Figure: 8. Geometry for calculation of acceptance angle of the Fiber.

Assume that a light ray enters the Fiber an angle θ_i, to the axis of the Fiber. The ray refracts at an angle θ_r, and strikes the core-cladding interface at an angle ϕ. If ϕ is greater than critical angle ϕ_c, the ray undergoes total internal reflection, since $n_1 > n_2$. When the angle ϕ is greater than ϕ_c, the light will stay within the Fiber.

Applying Snell's law to the launching face of the Fiber, we get

$\frac{sin\theta_i}{sin\theta_r} = \frac{n_1}{n_0}$ ………….1

If θ, is increased beyond a limit, ϕ will drop below the critical value ϕ_c and the ray escapes from the sidewalls of the Fiber. The largest value of θ_i, occurs when $\phi = \phi_c$.

In Δ^{les} ABC

$sin\theta_r = \sin(90 - \phi) = \cos\phi$ ………..2

Using equation - 2 in equation – 1, we get

$sin\theta_i = \frac{n_1}{n_0} cos\Phi$ …………..3

When $\phi = \phi_c$,

$sin\Phi_c = \frac{n_2}{n_1}$ ………….4

But

$sin\Phi_c = \frac{n_1}{n_0}$

$\therefore cos\Phi_c = \sqrt{\frac{{n_1}^2 - {n_2}^2}{n_1}}$ ………….5

Substituting the equation - 5 into - 4, we get

$sin\left[\theta_i\,(\max) = \sqrt{\frac{{n_1}^2 - {n_2}^2}{n_0}}\right]$ ………….6

generally the incident ray is launched from air medium, for which n_o=1.

Now considering $\theta_{i\,max} = \theta_0$, the equation (6) may be simplified to

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

$\theta_0 = sin^{-1}\sqrt{{n_1}^2 - {n_2}^2}$ …………..7

The angle θ_0 is called the acceptance angle of the Fiber. Acceptance angle is the maximum angle that a light ray can have relative to the axis of the Fiber and propagate down the Fiber. Thus, only those rays that are incident on the face of the Fiber making angles less that p will undergo repeated total internal reflection and reach the other end of the Fiber. Hence, larger acceptance angles make it easier to launch light into Fiber.

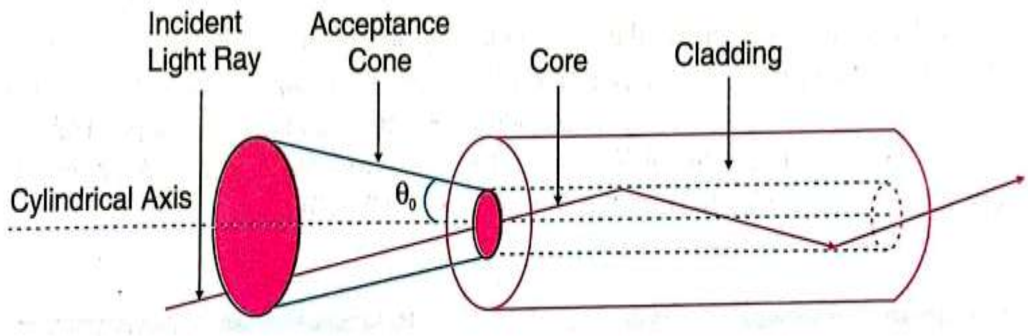


Figure: 9. Acceptance cone

In three dimensions, the light rays contained within the cone having a full angle $2\theta_0$ are accepted and transmitted along the Fiber as shown in figure 9. Therefore, the cone is called the acceptance cone. Light incident at an angle beyond θ_0 refracts through the cladding and corresponding optical energy is lost.

Fractional Refractive Index Change:

The fractional difference A between the refractive indices of the core and the cladding is known as the fraction al refractive index change. It is given by

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

The value of Δ is always positive because n_1 must be greater than n_2 for the total internal reflection condition. In order to guide light rays effectively through a Fiber, Δ<<1 and Δ is of the order of 0.01.

Numerical Aperture:

The main function of an optical Fiber is to accept and transmit as much light from the source as possible. The light gathering ability of a Fiber depends on the numerical aperture. The acceptance angle and the fractional refractive index change determine the numerical aperture of Fiber.

The numerical aperture NA is defined as the sine of the acceptance angle.

Thus, NA = $\sin\theta_o$, where θ_o is the acceptance angle.

But

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

$$NA = \sqrt{{n_1}^2 - {n_2}^2} \qquad \text{............1}$$

$${n_1}^2 - {n_2}^2$$

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

Multiplying and divide by $2n_1$ we get,

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

Now, approximating

$\left(\frac{n_1+n_2}{2}\right) \approx n_1$, and $\Delta = \frac{n_1-n_2}{n_1}$,

We can express the above relation as

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

This gives,

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

$$NA = n_1\sqrt{2\Delta} \qquad \text{.................2}$$

Numerical aperture determines the light gathering ability of the Fiber. It is a measure amount of light that can be accepted by a Fiber. From equation - 1 we can says that NA is dependent only on the refractive indices of the core and cladding materials and does not depend on the physical dimensions of the Fiber. The value of NA ranges from 0.13 to 0.5. A large NA implies that a Fiber will accept large amount of light from the source as shown in the figure 10.

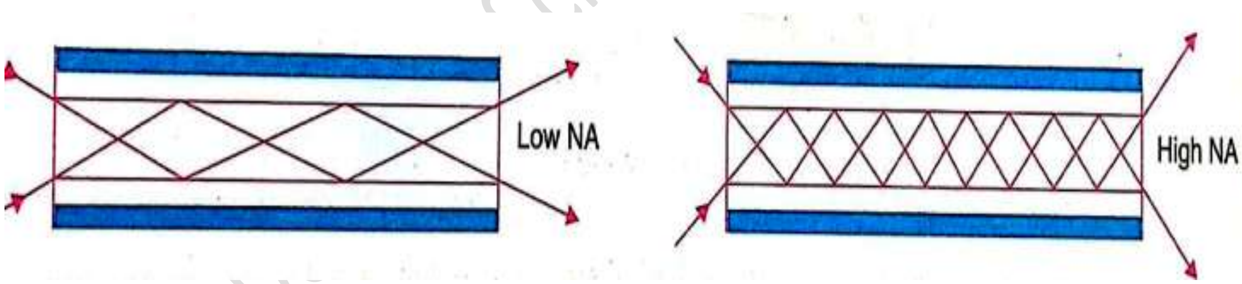


Figure: 10. Illustration of the propagation of light through low and high numerical aperture Fiber

Modes of Propagation:

We known that the light propagates as an electromagnetic wave through an optical Fiber and its propagation is governed by Maxwell's equations. To understand the propagation of light waves through optical Fiber in details requires a complete understanding of solution of these equations in the context of optical Fibers.

When a plane electromagnetic wave propagates in free space, it travels as transverse electromagnetic waves. The electric field and magnetic field components associated with the wave are perpendicular to each other and also perpendicular to the direction of propagation. It is known as a TEM wave. When the light ray is guided through an optical Fiber, it propagates in different types of modes. Each of these guided modes consists of a variety of electromagnetic field configurations, such as transverse electric TE, transverse magnetic TM and hybrid modes. Hybrid modes are combinations of transverse electric and magnetic modes. In simple terms, these visualized as the possible number of allowed paths of light in an optical Fiber as shown in following figure 11.1.

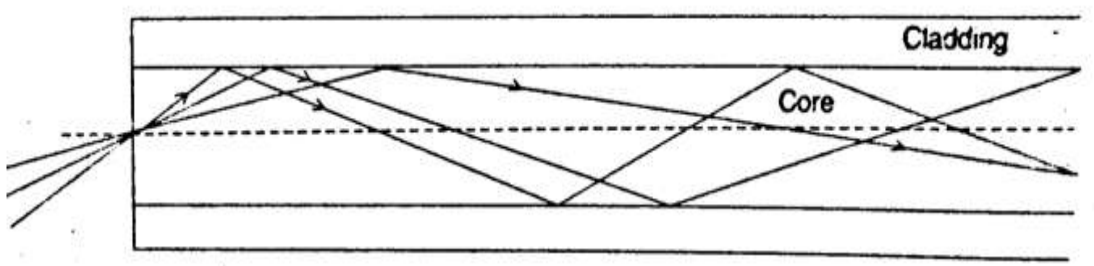


Figure: 11.1 Propagation of light through an optical Fiber due to total internal reflection

We can see that all the paths are zigzag paths excepting the axial direction. The rays having propagation angle between $\theta = 0^0$ and $\theta = \theta_c$ will be in a position to undergo total internal reflection reflections, all of them will not however propagate along the optical Fiber. Only a certain ray directions are allowed. As zigzag ray gets repeatedly reflect at the walls of the Fiber, phase shift occurs. Consequently, the waves traveling along certain zigzag paths will be in phase and undergo constructive interference, while the waves 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 inside the Fiber are known as modes.

Each mode is a pattern of electric and magnetic field distributions that is repeated along the Fiber at equal intervals. The number of modes propagating in a Fiber increases as θ_c or Δ increases. Increasing the core refractive index increases the number of propagating modes. On the other hand, increasing the clad refractive index decreases the number of propagating modes. The number of modes that a Fiber will support depends on the ratio d/λ, where d is the diameter of the core and λ is the wave length of the wave being transmitted. The zero order ray travels along the axis in known as the axial ray. Note that each mode carries a portion of the fight from the input signal.

Types of modes:

In a Fiber of fixed thickness, the modes that propagate at angles close to critical angle ϕ_c (i.e. critical propagation angle θ_c) are higher order modes, and modes that propagate with angles larger than the critical angle (i.e. lower than the critical propagation angle) are lower order modes as shown in figure 11.

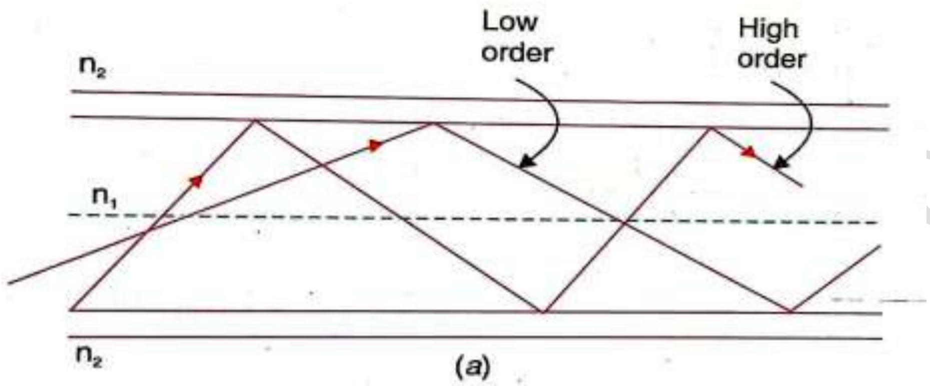
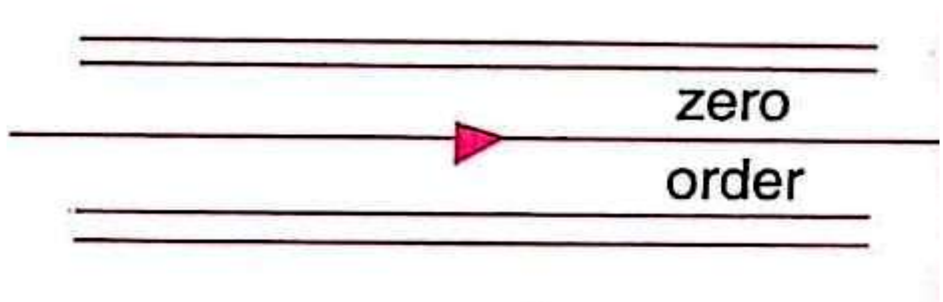


Figure: 11. (a) Low and high order ray path in multimode Fiber



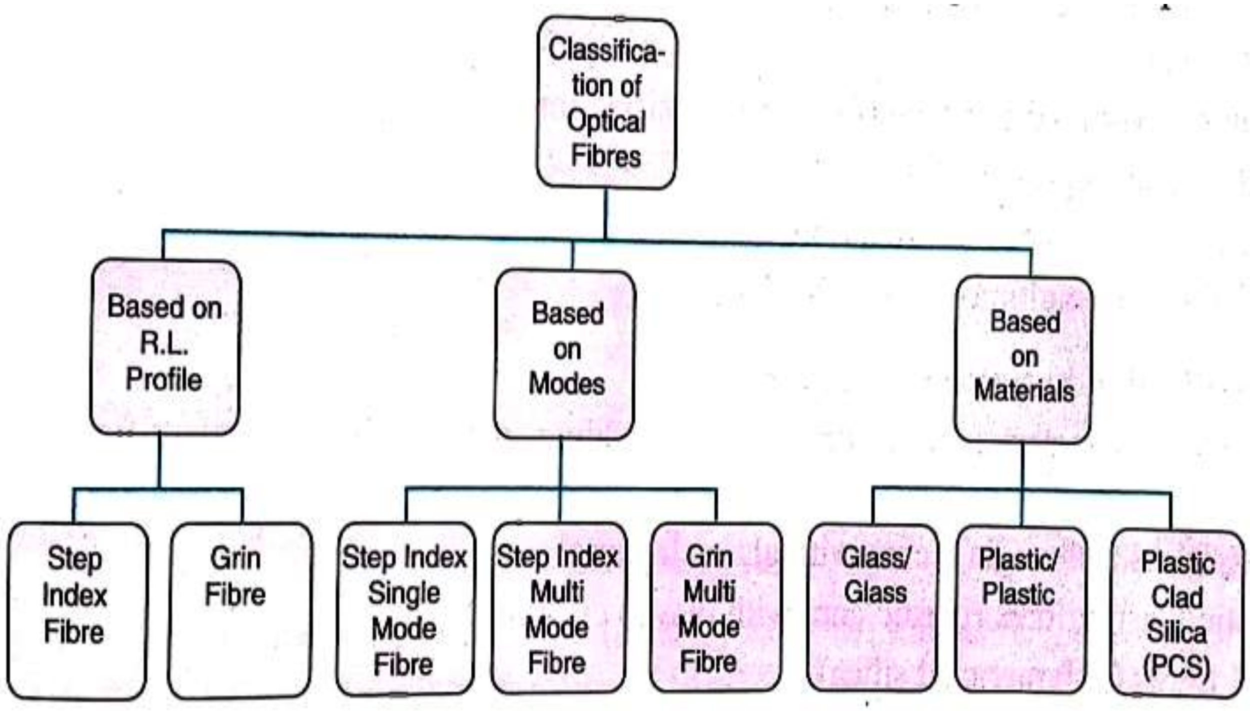
(b)

Figure: 11. (b) Axial ray in single mode Fiber

In case of lower order modes, the fields are concentrated near the centre of the Fiber. In case of higher order modes, the fields are distributed more towards the edge of the wave-guide and tend to send light energy into the cladding. 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 Fiber. Thus, the higher order modes arrive at the output end of the Fiber later than the lower order modes.

Classification of Optical Fibers:

Optical Fibers are differently classified into various types basing on different parameters, like refractive index profile, modes of light propagation, on material Wise, etc.



Optical Fibers are differently classified into various types basing on different parameters such as,

i. Based on refractive index profile
ii. Based on the modes of light propagation
iii. Based on materials

i. Classification basing on refractive index profile:

The refractive index profile of an optical Fiber is a plot of refractive index drawn on one of the axes and the distance from the core axis drawn' on the other axis as shown in figure 12.

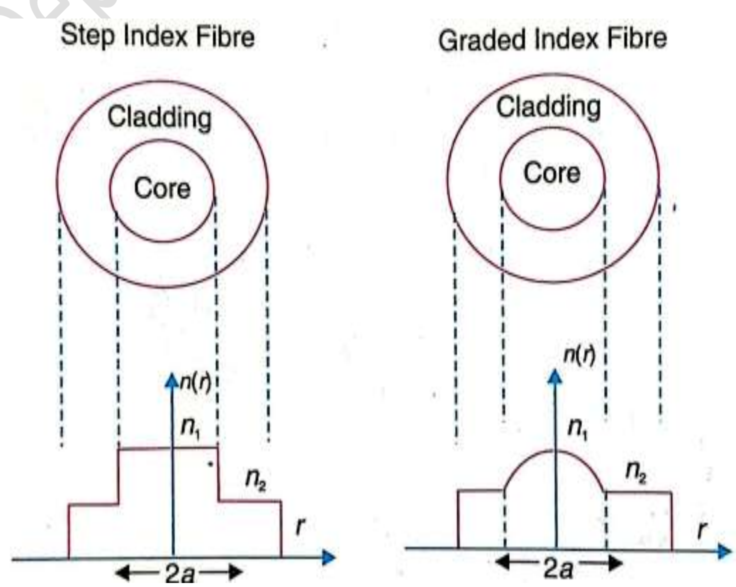


Figure: 12. Classification of optical Fibers based on the refractive index profile (a) Step Index Fiber (b) GRIN Fiber

Optical Fibers are classified in to two categories on the bases of refractive index, (a) Step Index Fiber (b) Graded Index Fiber.

(a) Step index Fiber:

This refers to the fact that the refractive index of the core is constant along the radial direction and abruptly falls to a lower value at the cladding and core boundary as shown in figure 12a.

(b)Graded index (GRIN) Fiber:

In the GRIN Fiber the refractive index of the core is not constant but varies smoothly over the diameter of the core as shown in figure 12b. It has a maximum value at the centre and decreases gradually towards the outer edge of the core. At the core-cladding interface the refractive index of the core matches with the refractive index of the cladding. The refractive index of the cladding is constant.

(ii) Classification basing on the modes of light propagation:

According to the modes of light propagation, the optical Fibers are classified into two categories viz., (a) Single mode Fiber (SMF) and (b) Multimode Fiber (MMF).

(a) Single mode Fiber (SMF): Single mode Fiber (SMF) has a smaller core diameter and can support only one mode of propagation.

(b) Multimode Fiber (MMF): A multimode Fiber has a larger core diameter and supports a number of modes.

There is one more mode which is also multimode is **Graded index (GRIN) Fiber**.

(iii) Classification basing on materials:

This classification deals with the materials used for core and cladding. The optical Fibers, under this consideration are classified in to three categories.

(a) Glass/glass Fibers (glass core glass cladding)
(b) Plastic/plastic Fibers (plastic core with plastic cladding)
(c) PCS Fibers (polymer clad silica)

The Three Types of Fiber: Let us study in detail the structure and characteristics of the three LEG types of optical Fibers. They are

(i) Single Mode step index Fiber.
(ii) Multimode step index Fiber.
(iii) Graded index (GRIN) Fiber.

(i) Single Mode step index Fiber:

Structure: A single mode step index Fiber has a very fine thin core of diameter of 8um to 12µm as shown in the figure 13. It is usually made of germanium doped silicon. The core is surrounded by a thick cladding of lower refractive index. The cladding is composed of silica lightly doped with phosphorous oxide. The external diameter of the cladding is of the order of 125um. The Fiber is surrounded by an

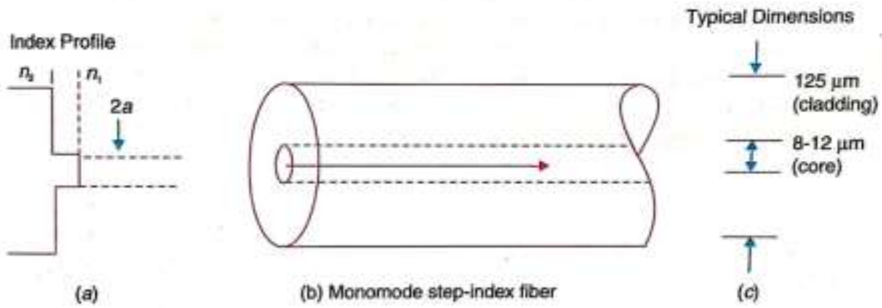


Figure: 13. Single Mode step index Fiber
(a) R.I. Profile (b) ray paths (c) typical dimensions

opaque protective sheath. The Fiber is surrounded by an opaque protective sheath. The refractive index of the Fiber changes abruptly at the core-cladding boundary, as shown in the figure 13a.

The variation of the refractive index of a step index Fiber as a function of radial distance be mathematically represented as

$n(r) = n_1[r < a \text{ inside core}]$

$n(r) = n_2[r > a \text{ incladding}]$ …………1

Propagation of light in SMF:

Light travels in SMF along a single path that is along the axis as shown in figure 13b. Obviously, it is the zero order mode that is supported by a SME, Both Δ and N.A. are very small for single mode Fibers. This small value is obtained by reducing the Fiber radius and by making Δ, the relative refractive index change, to be small. The low N.A. means low acceptance angle. Therefore, light coupling into the fiber becomes difficult. Costly laser diodes are needed to launch light into SMDF.

Multimode step index Fiber:

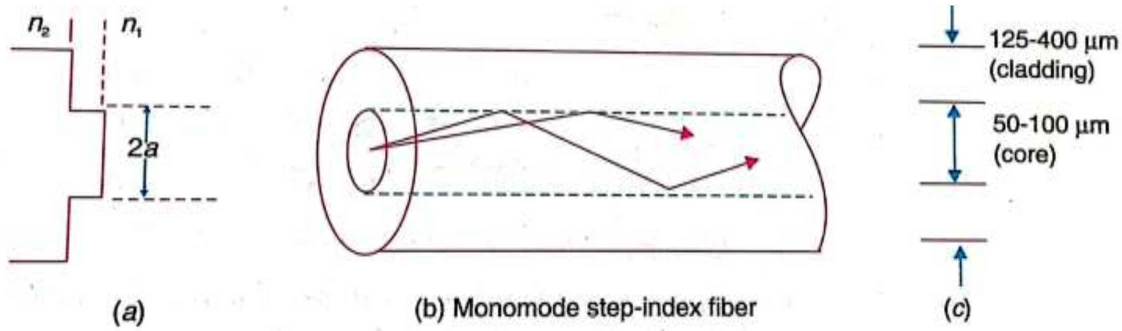


Figure: 14. Multimode step index Fiber

(a) R.I. Profile (b) Ray paths (c) Typical dimensions

Structure:

The figure 14 shows the Multimode step index Fiber, (a) its R.I. profile, (b) Ray paths (c) Typical dimensions.

A multimode step index Fiber is very much similar to the single mode step index Fiber except that its core is of larger diameter. The core diameter is of the order of 50 to 100um, which is very large compared to the wavelength of light. The external diameter of cladding is about 150 to 250um. See figure 14.

Propagation of light in MMF:

Multimode step index Fiber allows finite number of guided modes. The direction of polarization, alignment of electric and magnetic fields will be different in rays of different modes. We can also say that many zigzag paths of propagation are permitted in a MMF.

The path length along the axis of the Fiber is shorter while the other zigzag paths are longer. Because of this difference, the lower order modes reach the end of the Fiber earlier while the high order modes reach after some time delay see figure 14b.

(iii) Graded index (GRIN) Fiber:

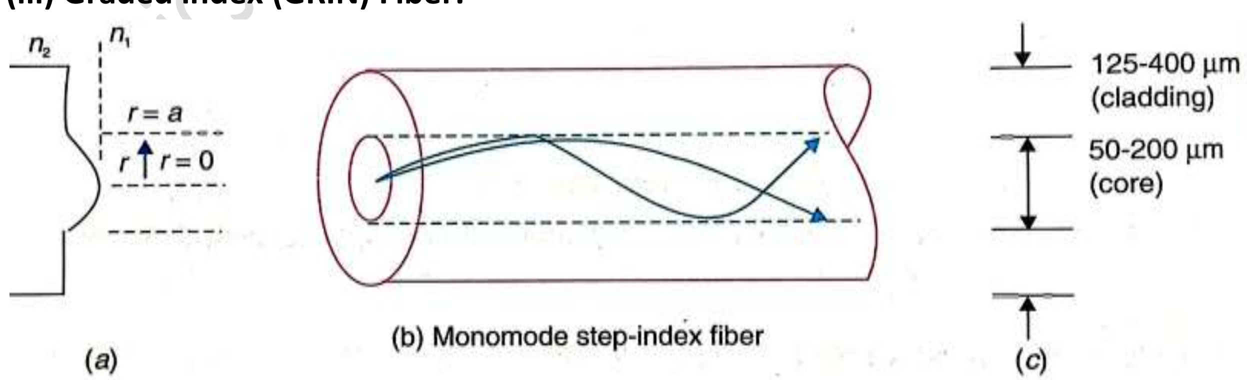


Figure: 15. Graded index (GRIN) Fiber

(a) R.I. Profile (b) Ray paths (c) Typical dimensions

The graded index Fiber is a multimode Fiber with a core consisting of concentric layers of different refractive indices. Therefore, the refractive index of the core varies with distance from the Fiber axis. A typical structure and its index profile are shown in the figure 15a. The size of the graded index Fiber is about the same as the step index Fiber. The variation of the refractive index of the core withy radius measured from the centre is given by

$$n(r) = \begin{cases} n_1\sqrt{1-\left[2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]} & r > a \text{ inside core} \\ n_2 & r < a \text{ in cladding} \end{cases} \qquad \text{.............1}$$

Where n_1 is maximum refractive index at the core axis, $\boldsymbol{a}$ is the core radius and $\boldsymbol{\alpha}$ the grading profile index number which varies from 1 to ∞, when $\boldsymbol{\alpha}$ =2, the index profile is parabolic and is preferred for different applications.

Propagation of light:

Consider figure 16 here 16a show the ray diagram of refraction at the various high and low index interfaces within graded index Fiber, giving an overall curved ray path. The figure 16b shows the light transmission in a graded index Fiber.

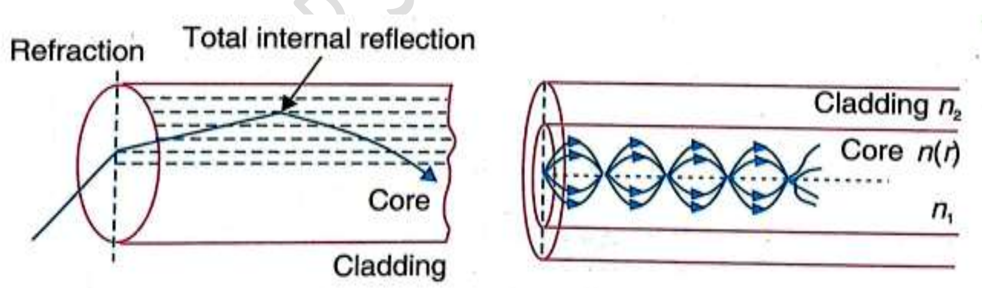


Figure: 16. (a) An expanded ray diagram showing refraction at the various high to low index interfaces within graded index fiber, giving an overall curved ray path. (b) Light transmission in a graded index fiber.

As light ray goes from a region of higher refractive index to a region of low refractive index, it is bent away from the normal the process continues till the condition for total internal reflection is met. Then the ray travels back towards the core axis, again being continuously refracted see figure 16a. The turning around may take place even before reaching the core-cladding interface. Thus, continuous refraction is followed by total internal reflection and again continuous refraction towards the axis.

In the graded index Fiber, rays making larger angles with the axis traverse longer path but they travel in a region of lower refractive index and hence at a higher speed of propagation. Consequently, all rays traveling through the Fiber, irrespective of their modes of travel, will have almost the same optical path length and reach the output end of the Fiber at the same time see figure 16b.

In case of GRIN Fibers, the acceptance angle and numerical aperture decreases with radial distance from the axis. The numerical aperture of a graded index Fiber is given by

$$N.A. = \sqrt{n^2(r) - {n_2}^2} \approx n_1 (2\Delta)^{1/2} \sqrt{\left(1 - \frac{r}{a}\right)^2}$$

$$= \sqrt{2\Delta\left[\left(1 - \frac{r}{a}\right)^2\right]}$$

Materials:

Optical Fibers are fabricated from glass or plastic which are transparent to optical frequencies. Step index Fibers are produced in three forms:

(a) A glass core cladded with a glass having a slightly lower refractive index,

(b) A silica glass core cladded with plastics and

(c) A plastic core cladded with another plastic. Generally the refractive index Step is the smallest for all glass Fibers, a little 1arger for the plastic clad Silica PCS (Fibers) and the largest for all plastic.construction.

(1) All Glass Fibers:

The basic material for fabrication, of optical Fibers is silica (SiO_2). It has a refractive index of 1.458 at λ=850nm. The materials of different refractive index are obtained by doping silica material with various oxides. If the silica is doped with Germania (GeO_2) or phosphorous pentoxide (P_2O_s), the refractive index of the material increases. Such materials are used as core materials and pure silica is used as cladding material in these cases, when pure silica is doped with boria (B_2O_3) or fluorine, its refractive index decreases. These materials are used for cladding when pure silica is used as core material.

The examples for Fiber compositions are

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

(2) All Plastic Fibers:

In these Fibers, Perspex (PMMA) and polystyrene 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. A high refractive index difference is achieved between the core and the cladding materials. Therefore, plastic Fibers have large NA of the order of 0.6 and large acceptance angles up to 77. The main advantages of the plastic Fibers are low cost and higher mechanical flexibility. The mechanical flexibility allows the plastic Fibers to have large cores, of diameters ranging from 110 to 1400μm. They are temperature sensitive and exhibit very high loss. Therefore, they are used in low cost applications and at ordinary temperatures (below 80°C).

Examples of plastic Fiber compositions are

- Polystyrene core $n_1 = 1.60$ N.A. = 0.60
  --Methyl methacrylate cladding $n_2 = 1.49$
- Polymethyl methacrylate core $n_1 = 1.49$ N.A. = 0.50
  --cladding made of its copolymer $n_2 = 1.40$

(3) PCS Fiber:

The plastic clad silica (PCS) Fibers 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 per fluorinated ethylene propylene (Teflon) having a refractive index of 1.338. Plastic claddings are used for step-index Fiber only. The PCS Fibers are less expensive but have high losses. Therefore, they are mainly used in short distance applications.

Characteristics of Fibers:

1. Step index single mode fiber:

- It has a very small core diameter, typically of about10μm.
- Their numerical aperture is very small
- It supports only one mode in which the entire light energy is concentrated.
- A single mode step index fiber is designed to have a V number between 0 and 2.4
- Because of a single mode of propagation; loss due to intermodal dispersion does not exist.
- With careful choice of material, dimensions, and wavelength, the total dispersion can be made extremely small.
- The attenuation is least.
- The single mode Fiber carries higher bandwidth than multimode Fiber.

- It requires a monochromatic and coherent light source. Therefore, laser diodes are used along with single mode Fiber.

Advantages:

- No degradation of signal
- Low dispersion makes the fiber suitable for use with high data rates. Single-mode fiber gives higher transmission rate and up to 50 times more distance than multimode.
- Highly suited for communications.

Disadvantages:

- Manufacturing and handling of SMF are more difficult.
- The fiber is costlier.
- Launching of light into fiber is difficult.
- Coupling is difficult.

Applications:

- Used as under water cables

Step-index multi-mode fiber:

- It has larger core diameter, typically ranging between 50-100um.
- The numerical aperture is larger and it is of the order of 0.3
- Larger numerical aperture allows more number of modes, which causes larger dispersion. The dispersion is mostly intermodal.
- Attenuation is high.
- Incoherent sources like LEDs can be used as high sources with multimode fibers.

Advantages:

- The multimode step index fiber is relatively easy to manufacture and is less expensive
- LED or laser source can be used.
- Launching of light into fiber is easier.
- It is easier to couple multi-mode fibers with other fibers.

Disadvantages:

- It has smaller bandwidth.
- Due to higher dispersion data rate is lower 'and transmission is less efficient.
- It is less suitable for long distance communications.

Applications:

- ❖ Used in data links.

3. Graded-index multi-mode fiber:

- ❖ Core diameter is in the range of 50-100um.
- ❖ Numerical aperture is smaller than that of step-index multimode fiber.
- ❖ The number of modes in a graded index fiber is about half that in a similar multimode step-index fiber.
- ❖ It has minimum attenuation.
- ❖ Intermodal dispersion is zero, but material dispersion is present.
- ❖ It has better bandwidth than multimode step-index fiber.

Advantages:

- ❖ Either an LED or a laser can be used as the source of light with GRIN Fibers.

Disadvantages:

- ❖ The manufacture of graded index fiber is more complex. Hence, it is the most expensive fiber.
- ❖ Coupling fiber to the light source is difficult.

Applications:

- ❖ Used in telephone links.

Merits of Optical Fiber:

Optical fibers have many advantageous than conducting wires. The important advantages are given as follows:

1. **Cheaper:**

   Optical fibers are made from silica (SiO_2) which is one of the most abundant materials on the earth. The overall cost of a fiber optic communication is lower than that of an equivalent cable communication system.

2. Smaller in size, lighter in weight, flexible and strong:

The cross section of an optical fiber is about a few hundred microns. Hence, the fibers are less bulky. Typically, a RG-19/U coaxial cable weights about 1100kg/km while a PCS fiber cable weights 6kg/km only. Optical fibers are quite flexible and 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 fiber links since fiber links are made of insulating materials.

4. Immune to EMI and RFI:

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

5. No cross talk:

The light waves propagating along the optical fiber are completely trapped within the fiber and cannot leak out. Further, light cannot couple into the fiber from sides. In view of these features, possibility of cross talk is minimized when optical fiber is used. Therefore, transmission is more secure and private.

6. Wider bandwidth:

Optical fibers have ability to carry large amounts of information. While a telephone cable composed of 900 pairs of wire can handle 10,000 calls, a 1mm optical fiber can transmit 50,000 calls.

7. Low loss per unit length:

The transmission loss per unit length of an optical fiber is about 4dB/km. Therefore, longer cable-runs between repeaters are feasible. If copper cables are used, the repeaters are to be spaced at intervals of about 2km. In case of optical fibers, the interval can be as large as 100km and above.

Disadvantages:

Installation and maintenance of optical fibers requires a new set of skills. They require specialized and costly equipment like optical time domain reflectometers etc. All this means heavy investment.