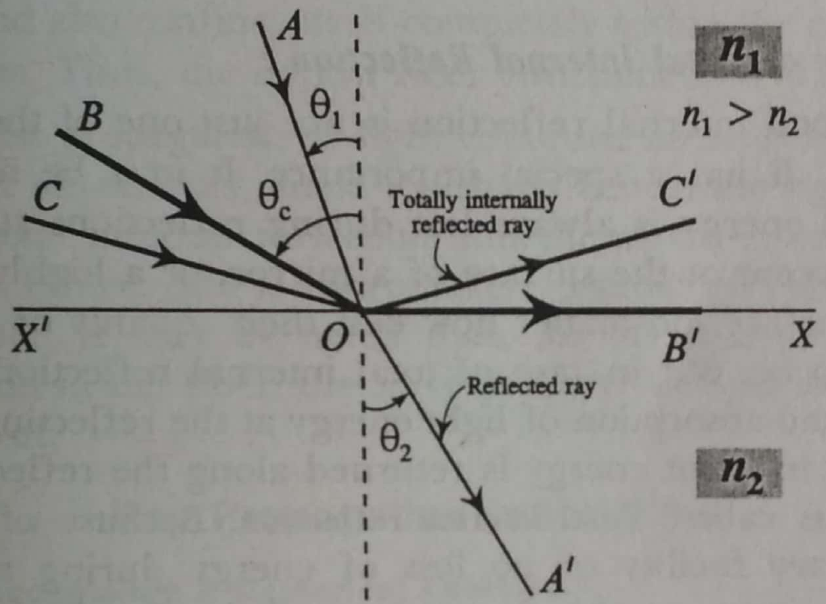
Total Internal Reflection :

The physical principle based on which the optical fiber works is total internal reflection which is a well known optical phenomenon in Physics. The same is recalled here in the following.

Consider a ray *AO* (Fig. 2), travelling in a medium of refractive index n_1. Let XX' be the boundary of this medium separating it from another medium of lower refractive index n_1.



TOTAL INTERNAL REFLECTION
Fig. 2

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

If θ_2 is the angle made by the refracted ray with the normal, then $\theta_2 > \theta_1$. If θ_1 is increased then for certain value of $\theta_1 = \theta_c$, called the **critical angle,** $\theta_2 = 90°$, *i.e.*, the refracted ray just grazes along the boundary of separation along *OB'* while the incident ray is along *BO*. For any angle of incidence θ_1 which is greater than θ_c, the incident ray like *OC* always gets reflected back into the medium in which it is incident on the boundary, as per the laws of reflection.

For refraction, we have the Snell's law,

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

For total internal reflection,

$$\theta_1 = \theta_c, \text{ and } \theta_2 = 90° .$$

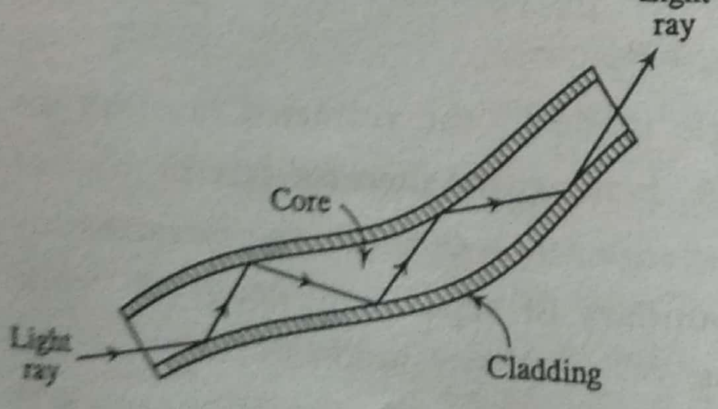
$$\therefore \quad n_1 \sin \theta_c = n_2 \sin 90 = n_2 \text{ (since, } \sin 90 = 1).$$

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

Importance of Total Internal Reflection :

Total internal reflection is not just one of the kinds of reflections. It has a special importance. It may be noted that, some light energy is always lost during reflections such as the ones that occur at the surface of a mirror, or a highly polished metallic surface, no matter how best their quality of reflection happens to be. But in case of total internal reflection, there is absolutely no absorption of light energy at the reflecting surface. The entire incident energy is returned along the reflected light. Hence, it is called **Total internal reflection.** Because of such an extraordinary facility of no loss of energy during reflection, the optical fibers are able to sustain the light signal transmission over very long distances in spite of virtually infinite number of reflections that occur within the fiber. Even if there were to be minute amount of losses during reflections, fiber optics communication would have been impossible.

Propagation mechanism (or Working principle) :



FIBER AS A WAVEGUIDE
Fig. 3

A waveguide is a tubular structure through which energy of some sort could be guided in the form of waves. Since light waves can be guided through a fiber, it is called light-guide. It is also called fiber waveguide or fiber light-guide.

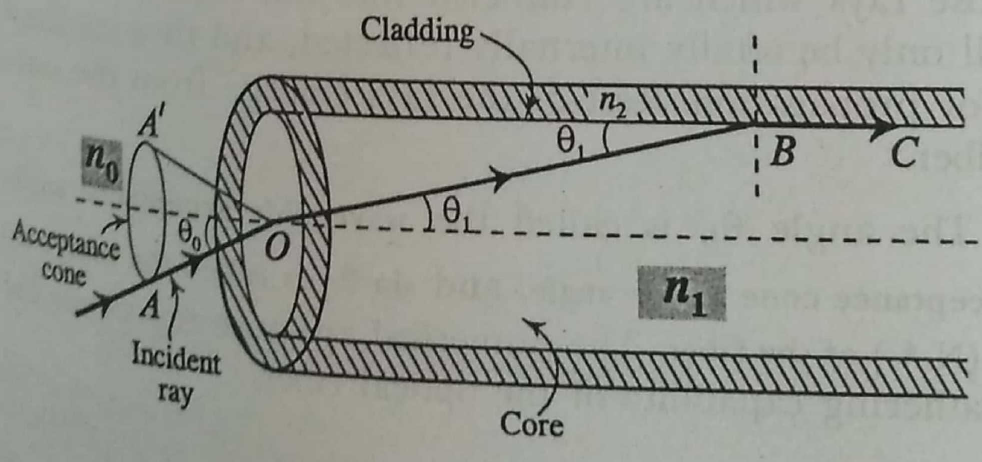
The guiding mechanism (*i.e.*, the principle on which the light propagation takes place through the optical fiber) can be described as follows.

In any optical fiber, the refractive index of cladding is always lesser than that for its core. The light signal which enters into the core can strike the interface of the core and cladding only at large angles of incidence because of the ray geometry shown in Fig. 3. The signal undergoes reflection after reflection at the points wherever it is incident on the interface. Since each reflection is a total internal reflection, the signal sustains its strength and also confines itself completely within the core during propagation. Thus, the optical fiber functions as a waveguide.

The propagation of light continues as long as the fiber is not bent too sharply, since for sharp bends, the light fails to undergo total internal reflection and the signal strength drops drastically. Hence, care is always taken to avoid very sharp bends in the fiber. It may by noted that, for all analysis of signal propagation in the fiber, the wave property of light is primarily made use of.

Ray Propagation in the Fiber

Angle of Acceptance & Numerical Aperture :



ACCEPTANCE CONE

Fig. 4

Let us consider the special case of a ray which suffers critical incidence at the core cladding interface.

The ray, to begin with travels along *AO* (Fig. 4) entering into the core at an angle θ_0 to the fiber axis. Then it is refracted along OB at an angle θ_1 in the core and further proceeds to fall at critical angle of incidence (equal to $90 - \theta_1$) at B on the interface between core and cladding. Since we are considering the incidence as critical angle of incidence, the ray is refracted at 90° to the normal drawn to the interface *i.e.*, it grazes along BC.

It is clear from the figure that, any ray that enters into the core at an angle of incidence less than θ_0, will have refractive angle less than θ_1 because of which its angle of incidence ($= 90 - \theta_1$) at the interface, will become greater than the critical angle of incidence and hence undergoes total internal reflection.

On the other hand, any ray that enters at an angle of incidence greater than θ_0 at O, will have to be incident at the interface at an angle less than the critical angle because of which, it gets refracted into the cladding region. Then it travels across the cladding thickness and emerges into the surroundings and thus will be lost.

Now if OA is rotated around the fiber axis keeping θ_0 same, then it describes a conical surface. We can therefore say that if a beam converges at a wide angle into the core, then those rays which are funneled into the fiber within this cone will only be totally internally reflected, and thus confined within for propagation. Rest of the rays emerge from the sides of the fiber.

The angle θ_0 is called the **waveguide acceptance angle, or the acceptance cone half – angle,** and **sin θ_0 is called the numerical aperture (N.A.) of the fiber.** The numerical aperture represents the light – gathering capability of the optical fiber.

Condition for Propagation :

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

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

$$n_0 \sin \theta_0 = n_1 \sin \theta_1 . \qquad \text{......(1)}$$

At the point B on the interface,

$$\text{the angle of incidence} = 90 - \theta_1.$$

Again applying Snell's law, we have,

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

Or,
$$n_1 \cos\theta_1 = n_2,$$

or,
$$\cos\theta_1 = \frac{n_2}{n_1}. \qquad \text{......(2)}$$

Rewriting Eq(1), we have,

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

$$= \frac{n_1}{n_0}\sqrt{\left(1 - \cos^2\theta_1\right)}.$$

Substituting for $\cos\theta_1$ from Eq.(2), we have,

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

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

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

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

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

if
$$\theta_i < \theta_0.$$

Or, if,
$$\sin\theta_i < \sin\theta_0.$$

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

This is the condition for propagation.

i.e.,
$$\sin\theta_i < N.A.$$

Fractional Index Change (Δ) :

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

$$\therefore \qquad \Delta = \frac{(n_1 - n_2)}{n_1}, \qquad \text{......(3)}$$

Relation between N.A. and Δ :

From Eq(3), $\qquad (n_1 - n_2) = n_1 \Delta. \qquad$ ......(4)

We have,

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

$$= \sqrt{(n_1 + n_2)(n_1 - n_2)},$$

$$= \sqrt{(n_1 + n_2)\, n_1 \Delta} \qquad \text{[from Eq(4)].}$$

Since, $\qquad n_1 = n_2, \quad (n_1 + n_2) = 2n_1 .$

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

or,

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

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

Modes of Propagation :

On the basis of geometrical optics, though it is expected that all such rays which enter into the core at an angle less than the angle of acceptance should travel in the core, it is not so even theoretically. The application of Maxwell's equation shows that, out of the light that enters into the core within the waveguide acceptance angle, only the light waves in terms of certain number of modes will be sustained for propagation in the fiber. However, symbolically, the modes are represented as though they are light rays in the figures. Thus a single ray propagation is shown in single mode fiber, and so on.

V-number :

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

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

where, d is the core diameter,

n_1 is the refractive index of the core

n_2 is the refractive index of the cladding,

λ is the wavelength of light propagating in the fiber.

Or, $$V = \frac{\pi d}{\lambda}(\mathrm{NA}).$$

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

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

For $V \gg 1$, the number of modes supported by the fiber (approximately) is given by,

$$\text{number of modes} \cong \frac{V^2}{2}.$$

Types of Optical Fibers

In any optical fiber, the whole material of the cladding has a uniform refractive index value. But the refractive index of the core material may either remain constant or subjected to variation in a particular way. The curve which represents the variation of refractive index with respect to the radial distance from the axis of the fiber is called the **refractive index profile.**

The optical fibers are classified under 3 categories, namely,

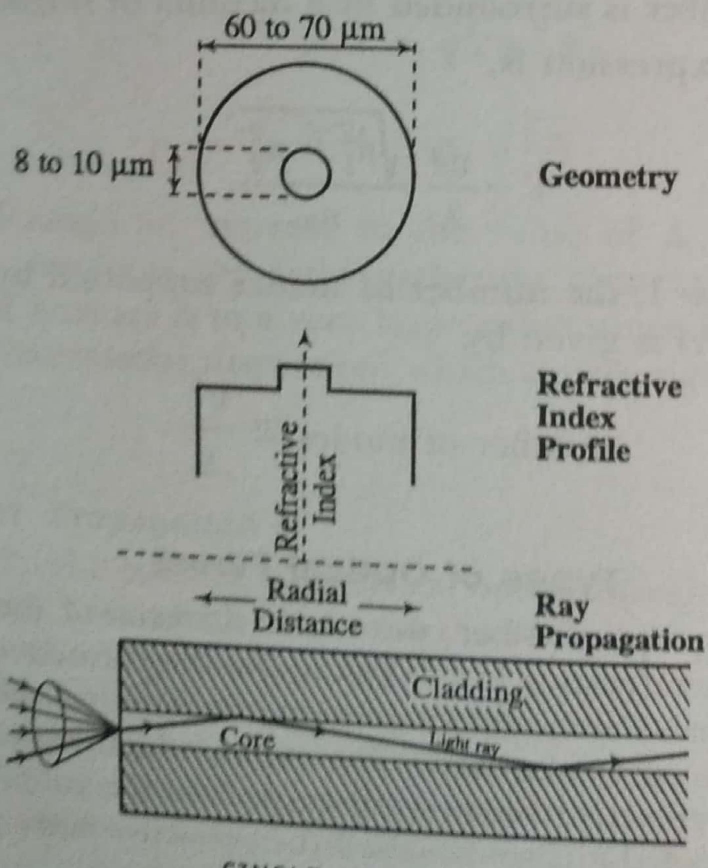
a) single mode fiber,
b) step index multimode fiber, and
c) graded index multimode fiber.

This classification is done depending on the refractive index profile, and the number of modes that the fiber can guide.

a) Single Mode Fiber :

A single mode fiber has a core material of uniform refractive index value. Similarly cladding also has a material of uniform index but of lesser value. This results in a sudden increase in the value of refractive index from cladding to core. Thus its refractive index profile takes the shape of a step. The diameter value of the core is about 8 to 10 μm and external diameter of cladding is 60 to 70 μm.

Because of its narrow core, it can guide just a single mode as shown in Fig. 5. Hence it is called single mode fiber.

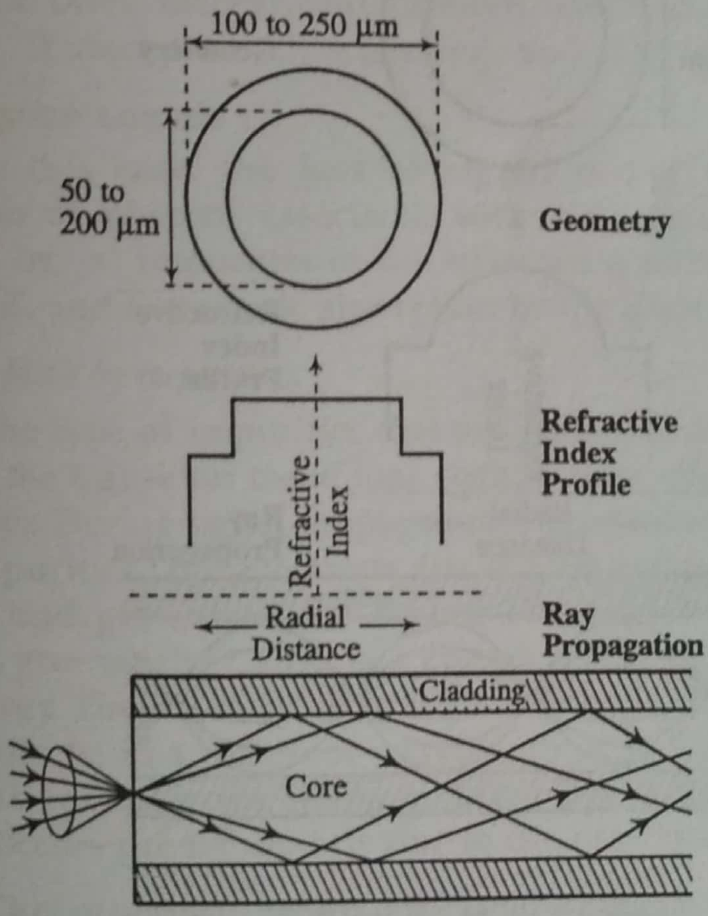


SINGLE MODE FIBER
Fig. 5

Single mode fibers are the most extensively used ones and they constitute 80% of all the fibers that are manufactured in the world today. They need lasers as the source of light. Though less expensive, it is very difficult to splice* them. They find particular application in submarine cable system.

b) Step-index Multimode Fiber :

The geometry of a step – index multimode fiber is as shown in Fig. 6. Its construction is similar to that of a single mode fiber but for the difference that, its core has a much larger diameter by the virtue of which it will be able to support propagation of large number of modes as shown in the figure.



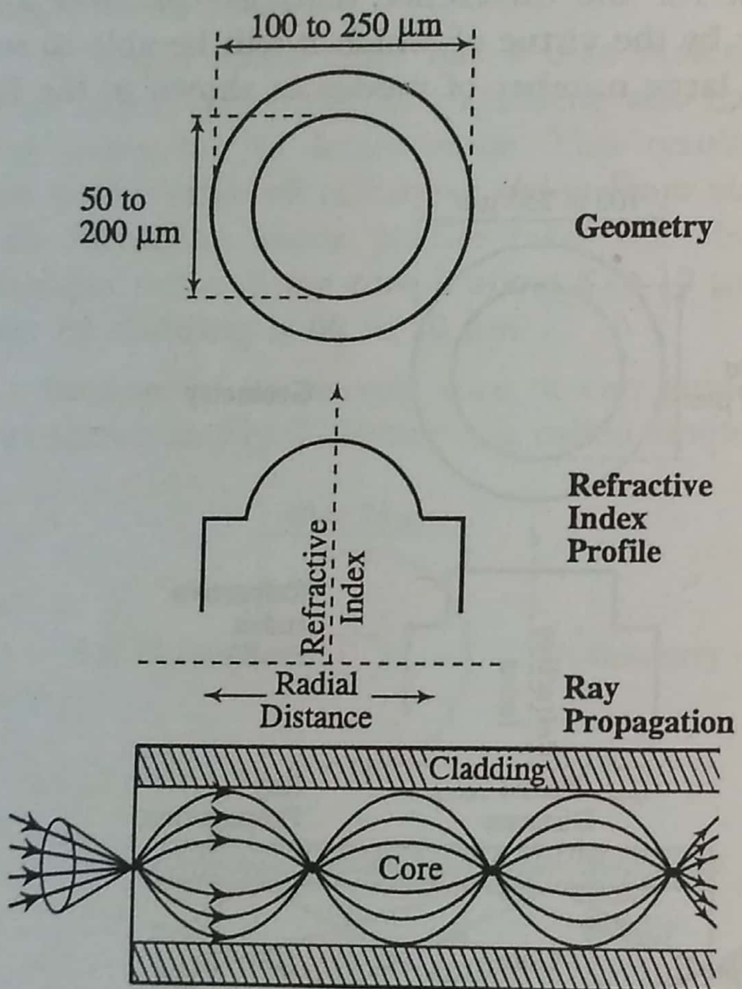
STEP - INDEX MULTIMODE FIBER
Fig. 6

*Splicing means joining the strands of one optical fiber to the strands of another. It cannot be done the way we do for copper cables by twisting and soldering. The splicing is done by fusing the ends of the respective strands or by employing certain aids called mechanical splices, which involves precise alignment of tiny fibers.

Its refractive index profile is also similar to that of a single mode fiber but with a larger plane region for the core.

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

c) Graded-Index Multimode Fiber :



GRADED – INDEX MULTIMODE FIBER
Fig. 7

Graded index multimode fiber is also denoted as GRIN. The geometry of the GRIN multimode fiber is same as that of step index multimode fiber. Its core material has a special feature that its refractive index value decreases in the radially outward direction from the axis, and becomes equal to that of the cladding at the interface. But the refractive index of the cladding remains uniform. Its refractive index profile is also shown in Fig. 7. Either a laser or LED can be the source for the GRIN multimode fiber. It is the most expensive of all. Its splicing could be done with some difficulty. Its typical application is in the telephone trunk between central offices.

ATTENUATION

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

Causes of attenuation

The three mechanisms through which attenuation takes place are, 1) absorption, 2) scattering, and, 3) radiation losses.

1. Absorption Losses :

In this case, the loss of signal power occurs due to absorption of photons associated with the signal. Photons are absorbed by, a) impurities in the silica glass of which the fiber is made of, and b) intrinsic absorption by the glass material itself.

a) Absorption by impurities :

The type of impurities that are generally present in fiber glass are the transition metal ions such as iron, chromium, cobalt and copper. During signal propagation when photons interact with these impurities, the electrons (in the impurities) absorb the photons and get excited to higher energy level. Later these electrons give up their absorbed energy either as heat energy or light energy. The re–emission of light energy is of no use since it will usually be in a different wavelength or at least in different phase with respect to the signal. Hence it is a loss. The absorption in fiber occurs predominantly due to the presence of impurities.

The other impurity which would cause significant absorption loss is the OH (hydroxy) ion, which enters into the fiber constitution at the time of fiber fabrication (due to hydrolysis reaction between the oxyhydrogen flame and the starting materials). But the technological breakthrough in the fiber manufacturing has made it possible to restrict the OH content to less than 1 part per billion (ppb), and has reduced the absorption remarkably.

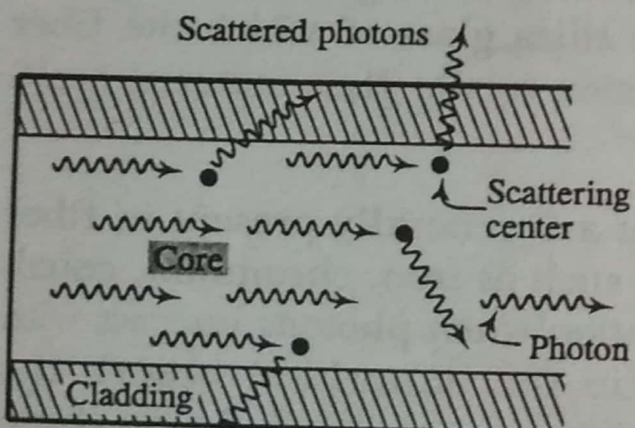
b) Intrinsic absorption :

The fiber itself as a material, has a tendency to absorb light energy however small it may be. **The absorption that takes place in the fiber material assuming that there are no impurities in it and that the material is free of all inhomogeneities, is called intrinsic absorption.** It sets the lowest limit on absorption for a given material.

2. Scattering Losses :

a) Rayleigh scattering :

While the signal travels in the fiber, the photons may be scattered because of sharp changes in refractive index values inside the glass over distances that are small compared to wavelength of light (Fig. 8). The sharp variation in refractive index value inside the fiber glass is induced by the localized structural inhomogeneity. The structural inhomogeneities are set into the glass constitution during its solidification from molten state. This type of scattering is same as Rayleigh scattering. Rayleigh scattering occurs whenever a light wave travels through a medium having scattering objects whose dimensions are smaller than a wavelength. Thus it becomes a loss.



RAYLEIGH SCATTERING
Fig. 8

Since the Rayleigh scattering has a characteristic λ^{-4} dependence, it increases enormously with decreasing wavelength*. The inhomogeneities in glass cannot be removed by any processing techniques. Thus the loss which depends upon the inhomogeneities becomes a fundamental lower limit on the attenuation.

b) *Others :*

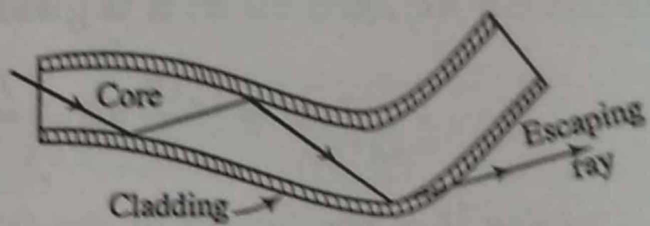
There are defects in the fiber in the form of trapped gas bubbles, unreacted starting materials, and some crystallized region in the glass. But the latest manufacturing methods make these losses negligible compared to the Rayleigh scattering.

3. Radiation Losses :

Radiative losses occur due to

a) macroscopic and, b) microscopic bends.

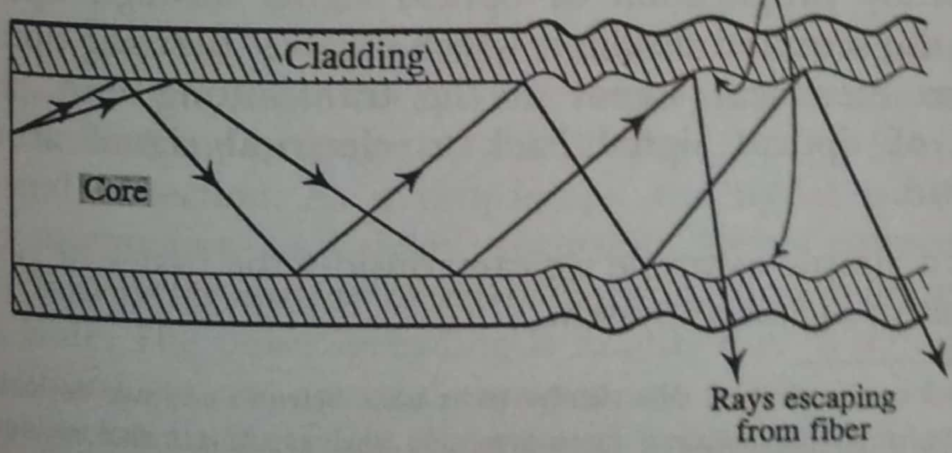
Macroscopic bends : They are the bends with radii much larger compared to the fiber diameter. These bends occur while wrapping the fiber on a spool or turning it around a corner.



RADIATION LEAKS
Fig. 9

The loss will be negligible for small bends but increases rapidly until the bending reaches a certain critical radius of curvature. Any bend of radius less than this threshold, makes the losses suddenly become extremely large (Fig. 9) which indicates the absence of total internal reflection.

Microscopic bends : This type of bends are repetitive small-scale fluctuations in the linearity of the fiber axis (Fig. 10). They occur due to non–uniformities in the manufacturing of the fiber or by nonuniform lateral pressures created during the cabling of the fiber. The microbends cause irregular reflections and some of



MICROSCOPIC BENDING LOSS
Fig. 10

them then leak through the fiber. Microbending losses could be minimized by extruding a compressible jacket over the fiber. The jacket will then be able to withstand the stresses while keeping the fiber relatively straight.

Attenuation Coefficient :

When light travels in a material medium, there will always be a loss in its intensity with distance travelled. The loss of intensity is expressed in terms of a quantity called attenuation coefficient denoted as 'α'. α is given as,

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

where, L is the length of the fiber through which the optical signal travels and is expressed in terms of kilometer,

P_{in} is the initial intensity with which the light is launched into the fiber, and

P_{out} is the intensity of the signal received as output at the other end of the fiber.

P_{in} & P_{out} are expressed in watt.

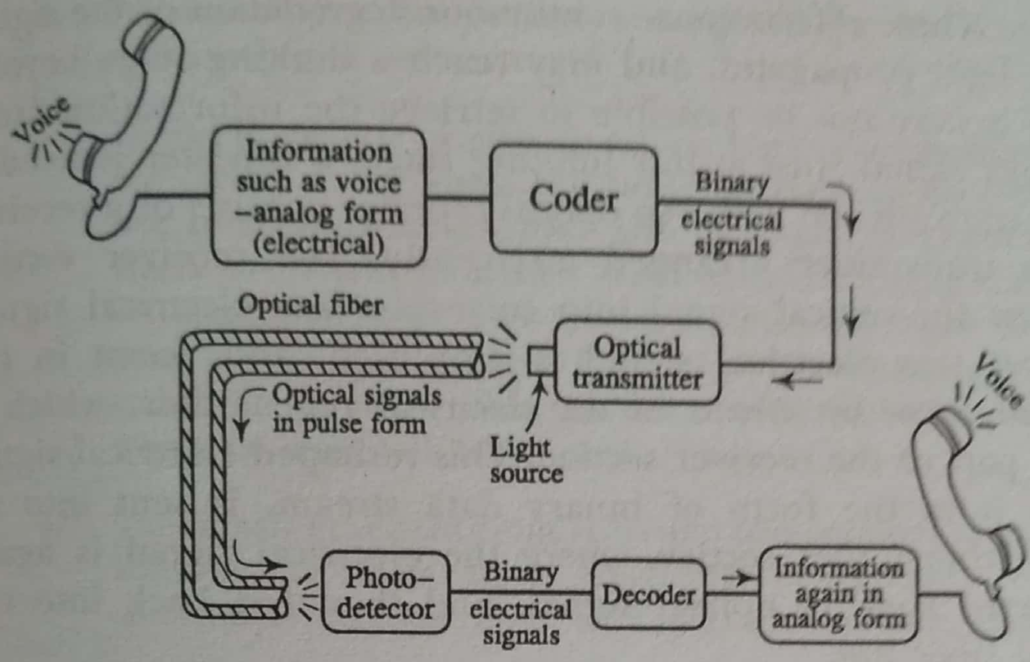
APPLICATION OF FIBER OPTICS

Basics of Point to Point Communication System using Optical Fibers :

Optical fiber communication is the transmission of information by propagation of optical signal through optical fibers over the required distance, which involves deriving optical signal from electrical signal at the transmitting end, and conversion of optical signal back to electrical signal at the receiving end.

As a simple example we can consider the basics of point to point communication* system.

*In point



TYPICAL POINT-TO-POINT FIBER OPTIC COMMUNICATION SYSTEM
Fig. 11

In a typical point to point communication system, we have analog information such as voice of a telephone user. The voice gives rise to electrical signals in analog form coming out of the transmitter section of the telephone. The analog signal is converted to binary data with the help of an electronic system called coder. The binary data comes out as a stream of electrical pulses from the coder. These electrical pulses are converted into pulses of optical power by modulating the light emitted by an optical source (such as an LED or laser diode) in the binary form. This unit is called an optical transmitter (Fig. 11) from which the optical power is fed into the fiber.

Out of the incident light which is funneled into the core within the half angle acceptance cone, only certain modes will be sustained for propagation within the fiber by means of total internal reflection. As it propagates, the signal is subjected to both attenuation and delay distortion. Delay distortion is the reduction in the quality of signal because of spreading of pulses with time. The pulse spreading is mainly due to the variation in velocity of various spectral components of the pulse during its propagation in the fiber. Because of such an effect, the pulses which are initially separated, start overlapping in time.

These effects cause continuous degradation of the signal as the light propagates, and may reach a limiting stage beyond which it may not be possible to retrieve the information from the light signal. Just at this limiting stage, a repeater is needed in the transmission path. An optical repeater consists of a receiver and a transmitter arranged adjacently. The receiver section converts the optical signal into corresponding electrical signal. Further, this electrical signal is amplified, and recast in the original form by means of an electrical regenerator, which is also a part of the receiver section. This reshaped electrical signal which is in the form of binary data stream, is sent into an optical transmitter section where the electrical signal is again converted back to optical signal, and then fed back into the optical fiber line.

Finally, at the receiving end, the optical signal is fed into a photodetector where it is transformed into pulses of electric current which is then fed to decoder which converts the sequence of binary data stream into an analog signal which will be the same information such as voice, which was there at the transmitting end.