UNIT II PART-B

OPTICAL FIBERS

INTRODUCTION:

The first experimental proof that light could be guided was given by John Tyndall nearly 120 years ago. The first glass fabrics were made in the 1920's. But the concept of cladding is introduced in 1950. Optical fiber communication is mainly because of the invension of lasers by Maiman in 1960. The optical frequencies are of the order of 5×10^{14} Hz as compared to electrical communication frequencies which are about 10^{10} Hz. So there is an increase in the signal strength. At the early time some of the best optical glasses had attenuations of the order of several thousands dB/km. For practical applications, communication is possible only when the attenuation could be of the order of 20 dB/km or less.

By 1970, the workers of corning glass works produced the first optical fiber with loss under 20 dB/km. By 1979, the fiber loss was brought down to just 0.2 dB/km.

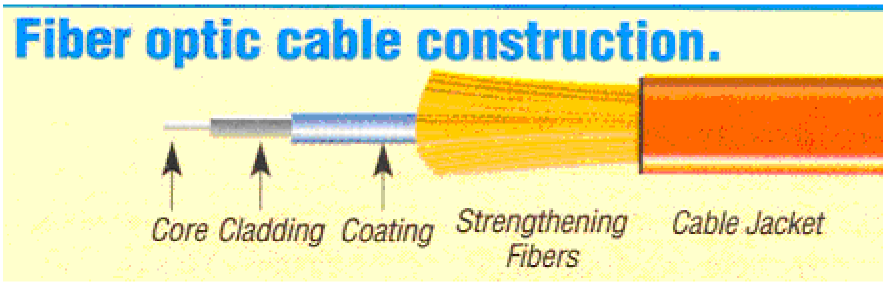
The first fiber optical communication was installed in Chicago, in 1977. A 24 – fiber optical cable less than 2.5 cm diameter in size was employed to carry 16,000 voice circuits to serve them. Around 1980, in USA alone more than 3 million kilometers of optical fibers were laid to replace electrical communication across the country and the decade 1980 is referred to as decade of glass.

The fiber optics communication is also known as light wave communication or photonics.

Photonics is the enabling technology for optical fiber communication to improve its performance and to reduce its cost.

Optical fibers construction:

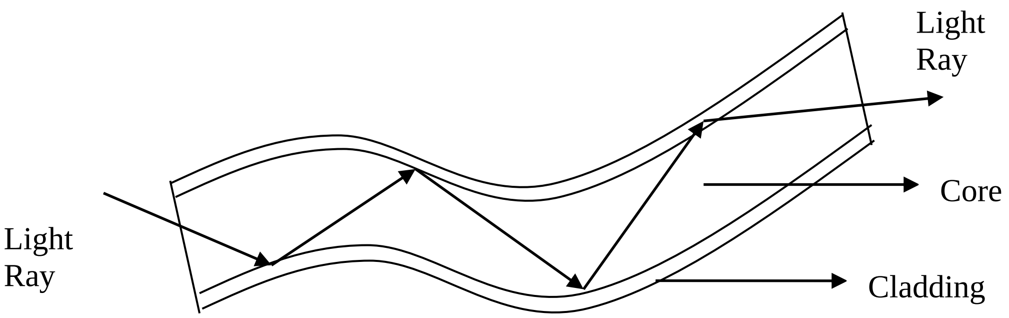
Optical fibers are essentially light guides used in optical communications as wave guides. They are transparent dielectrics and able to guide visible and infrared light over long distances.



An optical fiber is made of mainly two parts. One is the inner cylindrical material made of glass or plastic called the core. The outer part is called the cladding which envelops the inner core as a concentric cylinder. The cladding is also made of similar material but of lesser refractive index. There is a material continuity between core and cladding. The cladding is enclosed in polyurethane jacket.

Optical fibers as waveguides:

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 wave guide or fiber light guide.



The cladding has always lower refractive index than that of core. The light signal which enters into the core can strike the interface of the core and cladding only at larger angle of incidence. The light signal undergoes multiple reflections. 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 wave guide.

If the fiber has sharp bends, then there is no total internal reflection occurs, so signal fails to come out from the fiber.

Total internal reflection:

When a light travels from denser medium to rarer medium and the angle of incidence is greater than critical angle, the total internal reflection takes place.

From Snell's law

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

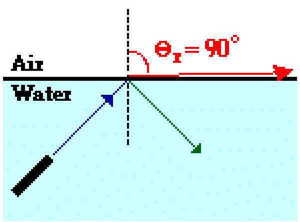
At critical angle $\theta_1 = \theta_c$ and $\theta_2 = 90°$

$\therefore n_1 \sin \theta_c = n_2 \sin 90 = n_2$

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

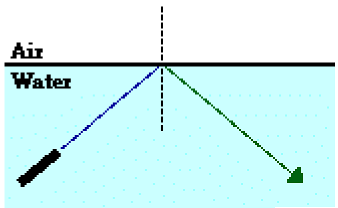
In case of total internal reflection, there is absolutely no absorption of light energy at the reflecting surface.

Reflection and Refraction



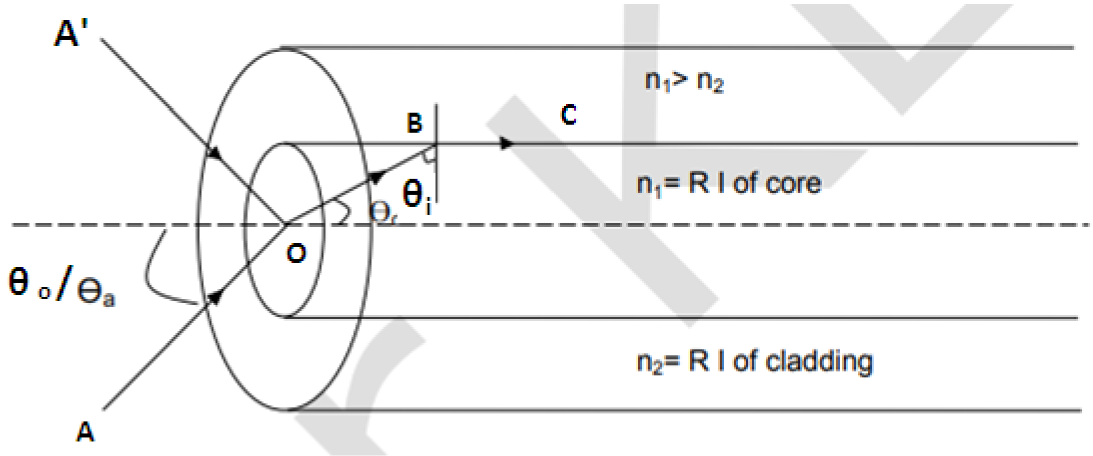
When the angle of incidence equal the critical angle, the angle of refraction is 90-degrees.

Total Internal Reflection



When the angle of incidence is greater than the critical angle, all the light undergoes reflection.

<u>Numerical aperture and Ray propagation in the fiber:</u>



Let us consider the special case of a ray which suffers critical incidence at the core cladding interface. Let 'AO' be the incident ray, entering to the core at an angle 'θ_o' with the fiber axis. Let it be refracted along OB at an angle θ_1 in the core, and further proceed to fall at critical angle of incidence $(90 - \theta_1)$ at B on the interface between core and cladding. Since it is a critical angle of incidence, the ray is refracted at 90° to the normal drawn to the interface i.e., it grazes along BC.

If the angle of incidence is less than 'θ_o' then, the ray will undergo total internal reflections. And the rays with incidence are greater than 'θo' will not undergo total internal reflection. Therefore the incident rays which are within the cone AOA' will undergo total internal reflections.

The angle 'θ_o' is called the waveguide acceptance angle or the acceptance cone half – angle, and '$\sin\theta_o$' 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_o, 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,

$$n_o \sin\theta_o = n_1 \sin \theta_1$$

At the point B on the interface, the angle of incidence = $90 - \theta_1$.

$\therefore$ 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 $\cos\theta_1 = \dfrac{n_2}{n_1}$ --------------------(2)

from (1), $\sin\theta_o = \dfrac{n_1}{n_0}\sin\theta_1 \quad = \dfrac{n_1}{n_0}(1-\cos^2\theta_1)^{1/2}$

or $\sin\theta_o = \dfrac{n_1}{n_0}\sqrt{1-\dfrac{n_2^2}{n_1^2}} = \dfrac{n_1}{n_0}\sqrt{\dfrac{n_1^2-n_2^2}{n_1^2}} = \dfrac{\sqrt{n_1^2-n_2^2}}{n_o}$

If the medium surrounding the fiber in air, then $n_o = 1$

Or $\quad \sin\theta_o = \sqrt{n_1^2 - n_2^2}$

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

If $\theta_i < \theta_o$ or $\sin\theta_i < \sin\theta_o$

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

Thus the condition for propagation is $\sin\theta_i < NA$

Fractional index change (Δ):

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

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

Relation between N A and Δ:

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

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

As Δ increases, N.A. increases and thus enchances the light gathering capacity of the fiber. But we cannot increase 'Δ' to a very large value. Since it leads to 'intermodal dispersion', which causes signal distortion.

Types of optical fibers and modes of transmission:

In any optical fiber, the whole material of the cladding has a uniform refractive index value. But the refractive index of the core materials may either remains 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 refractive index profile. The optical fibers are classified under three categories based on geometry, refractive index profile and the number of modes that the fiber can guide.

a) single mode fiber
b) step-index multimode fiber
c) Graded index multimode fiber.

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

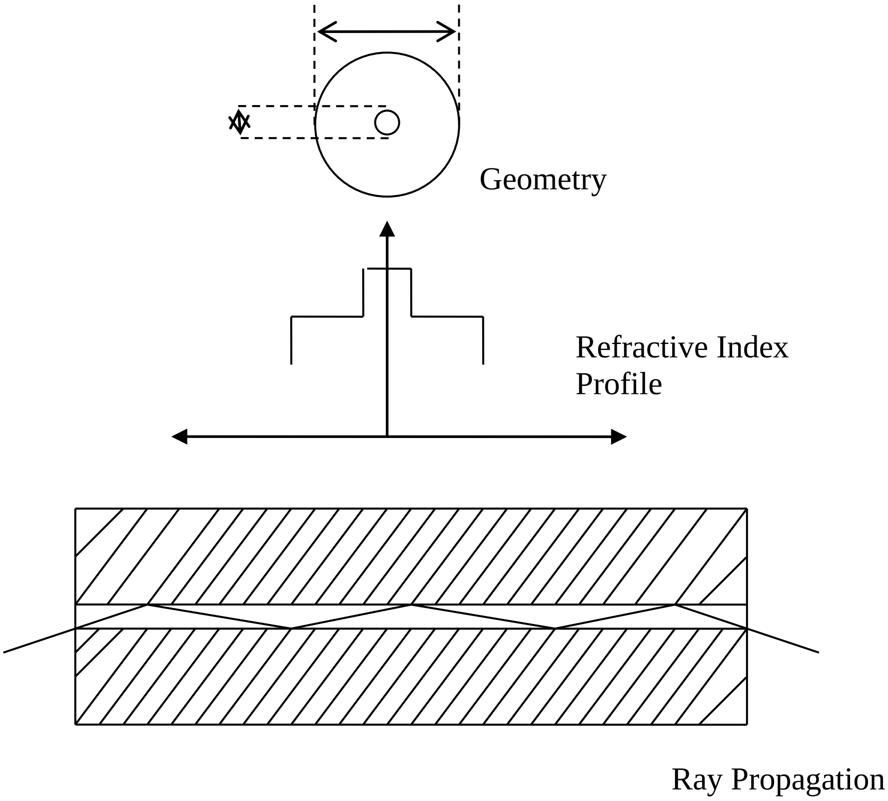


Fig: single mode fiber

Single mode fibers are the most extensively used ones and they constitute 80% of all 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 (join) them. They find particular application in submarine cable system.

b) Step – index multimode fiber:

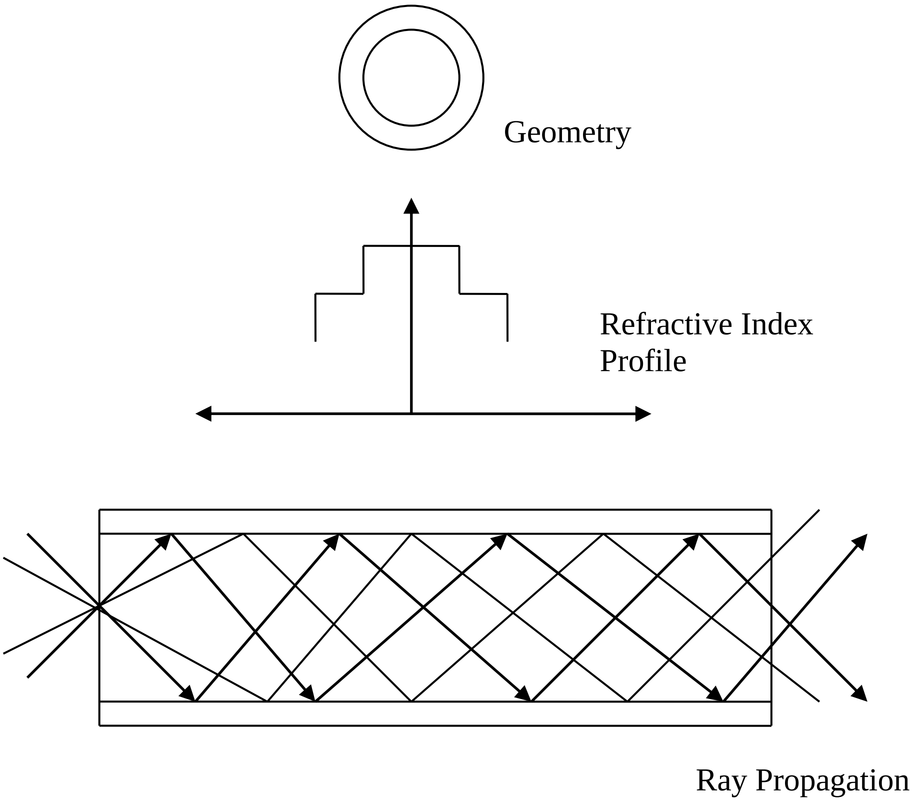


Fig. Step index multi mode fiber

Here core has larger diameter, so it is possible to propagate a large number of modes as shown in fig. Its refractive index profile is similar to that of a single mode fiber but with a larger plane regions 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 band width requirements.

c) Graded – index multimode fiber:

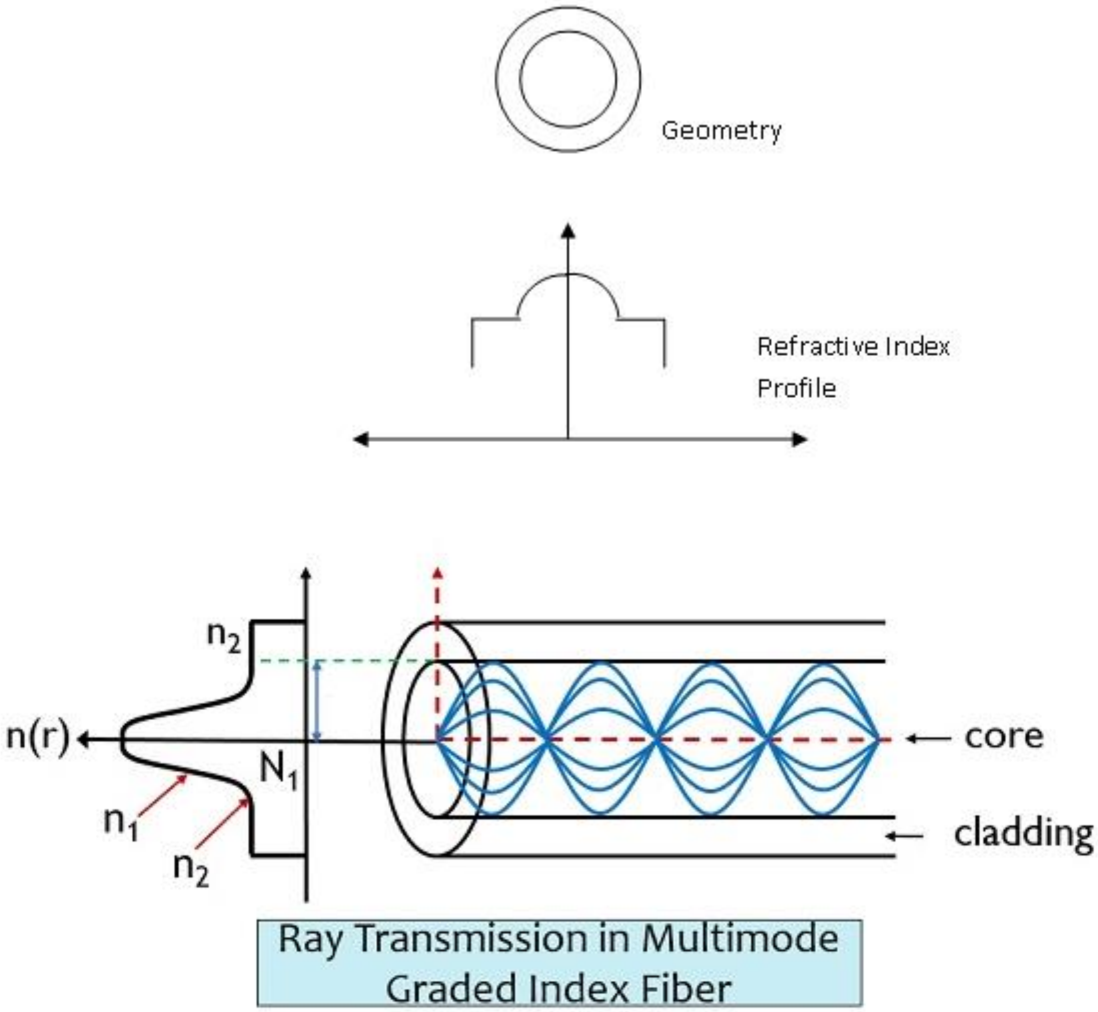


Fig.: Graded index multi mode fiber

It is also called GRIN. The geometry of GRIN 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 cladding remains constant. Either a Laser or LED can be the source for the GRIN multimode fiber. It is most expensive of all. Its splicing could be done with some difficulty. Its typical application is the telephone trunk between central offices.

Modes of propagation:

V – number:

The number of modes supported for propagation in the fiber is determined by a parameter called V – number and is given by

$$V = \frac{\pi d}{\lambda} n_o \sqrt{n_1^2 - n_2^2} \qquad \text{or} \qquad V = \frac{\pi d}{\lambda} n_o (N.A)$$

for v >>1, the number of modes supported by the fiber (approximately) is given by

number of modes $\approx \frac{V^2}{2}$

here d $\Rightarrow$ core diameter

$\lambda \Rightarrow$ wavelength of light propagating in the fiber.

Attenuation:

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

The three mechanism through which attenuation takes place are

1. Absorption 2. Scattering 3. Radiation losses

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

Where L is in km

1. Absorption:

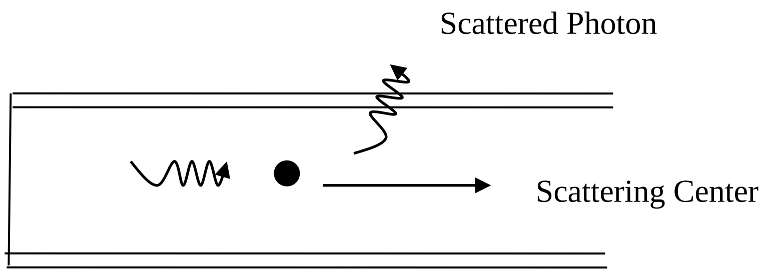
In this case, the loss of signal power occurs due to absorption of photons associated with signal. Photons are absorbed.

a) By impurities in the silica glass of which the fiber is made of.

b) By intrinsic absorption by the glass material itself.

2. Scattering Losses:

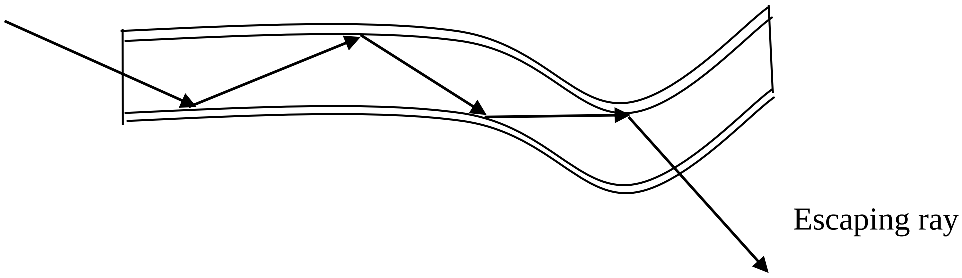
While the signal travels in the fiber, the photons may be scattered because of sharp changes in refractive index values inside the glass (non – crystalline) over long distances. The sharp variation in refractive index value inside the fiber glass is induced by localized structural in-homogeneity in the material.



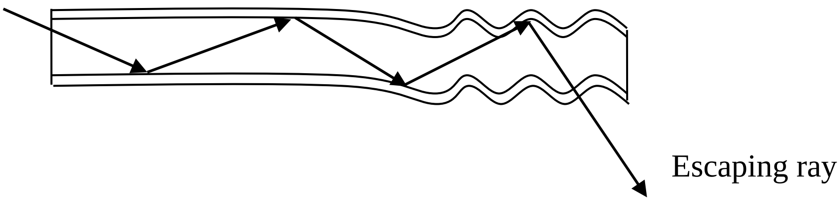
3. Radiation losses:

Radiation losses occur due to bending of fiber. There are two types of bends.

a) **Macroscopic bends:** This refers to bends having radii that are large as compared to the fiber diameter, such as ones which occur while turning it around a corner.



b) **Microscopic bends:** These are repetitive small scale fluctuations in the linearity of the fiber axis. Microscopic bending occurs due to non-uniformities in the manufacturing of the fiber or by non-uniform lateral pressures created during the cabling of the fiber.



Advantages of optical communication system:

1. Optical fibers can carry very large amounts of information in either digital or analog form.
2. The raw materials used to make optical fibers are easily available at low cost.
3. Because of their compactness and light weights, fibers are much easier to transport.
4. Optical fibers are totally protected from interference between different communication channels.
5. There is no signal disturbance in optical fibers.
6. The common grounding is irrelevant in optical fibers.
7. There is no energy radiation from a fiber.
8. Optical fibers are protected from corrosive and flammable environments.
9. Cost / meter/ channel for fiber would be lesser than that of metallic cable.

Limitations of optical communication system:

a. The optical connectors which are used to connect (splicing) two fibers are highly expensive.
b. The fibers will not bent to smaller radius of curvature, which leads to breaking of fiber.
c. The fibers undergo expansion and contraction with temperature, which leads to loss in signal power.
d. Optical fibers facing maintenance costs.

Applications of fiber optics:

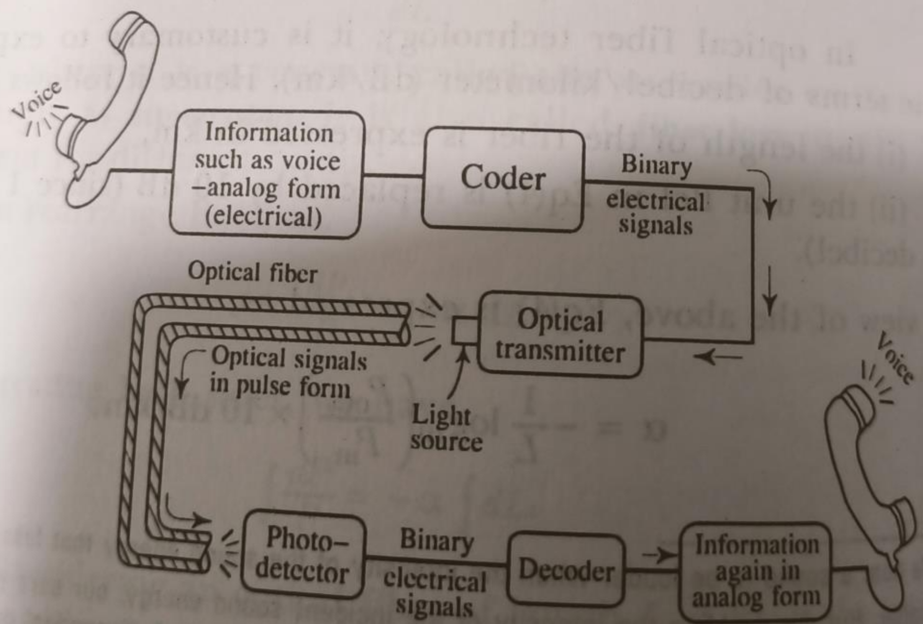
1. Optical fibers used for long distance transmission or communication of sound signals.
2. Optical fibers are used in Fiber – optic endoscope.
3. Optical fibers are used as sensing device.
4. Optical fibers are used for data link purpose.
5. Optical fibers are used as a communication device in Local Area Networks (LAN).

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.



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 funnelled 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.

Other Applications :

To mention a few other applications, the following could also be listed.

1. *Sensing Device* :

Optical fibers can be used as sensing devices wherein they are employed to sense parameters such as pressure, voltage or current, and the information is then fed to a processor from which the information is secured.

2. *Data link* :

A data link is a communication over a distance which is much shorter than what is required for a telecommunication trunk, but the required reliability is normally much higher. In such applications, the communication made using metal cables suffer from problems such as cross talk, impedance mismatching, *etc.*, which reduce the reliability. All such problems are overcome by employing optical fibers as means of communication.

3. *Local Area Networks* :

Optical fibers provide more efficient communication facilities in local area networks wherein the information is required to be exchanged between terminals which are located at different places.
