13. FIBER OPTICS

Introduction: In 1870 John Tyndall demonstrated that light follows the curve of a stream of water pouring from a container; it was this simple principle that led to the study and development of application of the fiber optics. The transmission of information over fibers has much lower losses than compared to that of cables. The optical fibers are most commonly used in telecommunication, medical, military, automotive and in the area of industry. In fibers, the information is transmitted in the form of light from one end of the fiber to the other end with min.losses.

Advantages of optical fibers:

- Higher information carrying capacity.
- Light in weight and small in size.
- No possibility of internal noise and cross talk generation.
- No hazards of short circuits as in case of metals.
- Can be used safely in explosive environment.
- Low cost of cable per unit length compared to copper or G.I cables.
- No need of additional equipment to protect against grounding and voltage problems.
- Nominal installation cost.
- Using a pair of copper wires only 48 independent speech signals can be sent simultaneously whereas using an optical fiber 15000 independent speeches can be sent simultaneously.

Basic principle of Optical fiber:

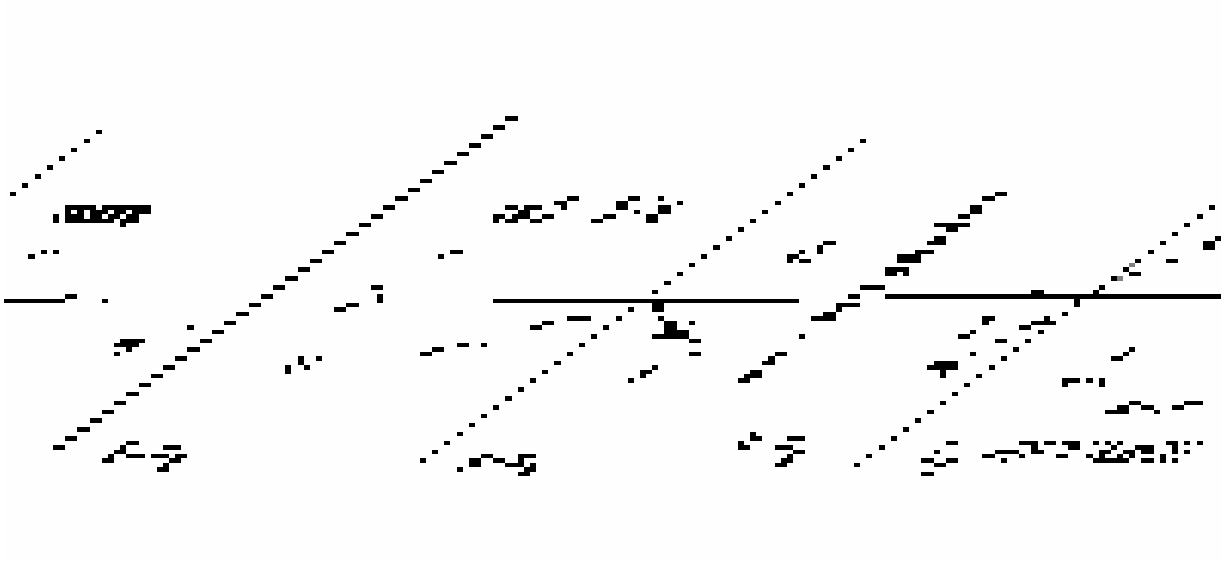
The mechanism of light propagation along fibers can be understood using the principle of geometrical optics. The transmission of light in optical fiber is based on the phenomenon of total internal reflection.

Let n_1 and n_2 be the refractive indices of core and cladding respectively such that $n_1 > n_2$.Let a light ray traveling from the medium of refractive index n_1 to the refractive index n_2 **be incident** with an angle of incidence "i" and the angle of refraction "r". By Snell's law

$$n_1 \sin i = n_2 \sin r \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The refractive ray bends towards the normal as the ray travels from rarer medium to denser medium .On the other hand ,the refracted ray bends away from normal as it travel from denser medium to rarer medium. In the later case , there is a possibility to occur total internal reflection provided, the angle of incidence is greater than critical angle(θ_c). This can be understood as follows.

1. When $i < \theta_c$,then the ray refracted is into the second medium as shown in below fig1.
2. When $i = \theta_c$, then the ray travels along the interface of two media as shown in fig2.
3. When $i > \theta_c$ then the ray totally reflects back into the same medium as shown in fig3.



Suppose if $i = \theta_c$ then $r = 90^o$,hence

$$n_1 \sin \theta_c = n_2 \sin 90^o$$

$$\sin \theta_c = n_2 / n_1 \qquad (\text{since } \sin 90^o = 1)$$

$$\theta_c = \sin^{-1}(n_2 / n_1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

thus any ray whose angle of incidence is greater than the critical angle ,total internal reflection occurs ,when a ray is traveling from a medium of high refractive index to low refractive index.

Construction of optical fiber:

The optical fiber mainly consists of the following parts.
i .Core ii .Cladding iii .Silicon coating iv .Buffer jacket
v .Strength material vi . Outer jacket

- A typical glass fiber consists of a central core of thickness 50μm surrounded by cladding.
- Cladding is made up of glass of slightly lower refractive index than core's refractive index, whose over all diameter is 125μm to 200μm.

Of course both core and cladding are made of same glass and to put refractive index of cladding lower than the refractive index of core, some impurities like Boron, Phosphorous or Germanium are doped.

- Silicon coating is provided between buffer jacket and cladding in order to improve the quality of transmission of light.
- Buffer jacket over the optical fiber is made of plastic and it protects the fiber from moisture and abrasion.
- In order to provide necessary toughness and tensile strength, a layer of strength material is arranged surrounding the buffer jacket.

- Finally the fiber cable is covered by black polyurethane outer jacket. Because of this arrangement fiber cable will not be damaged during hard pulling ,bending ,stretching or rolling, though the fiber is of brittle glass.



Acceptance angle and Numerical aperture of optical fiber:

When the light beam is launched into a fiber, the entire light may not pass through the core and propagate. Only the rays which make the angle of incidence greater than critical angle at the core –cladding interface undergoes total internal reflection. The other rays are refracted to the cladding and is lost. Hence the angle we have to launch the beam at its end is essential to enable the entire light to pass through the core .This maximum angle of launch is called acceptance angle.

Consider an optical fiber of cross sectional view as shown in figure no, n1and n2 are refractive indices of air ,core and cladding respectively such that $n_1>n_2>n_o$.let light ray is incidenting on interface of air and core medium with an angle of incidence α .This particular ray enters the core at the axis point A and proceeds after refraction at an angle α_r from the axis .It then undergoes total internal reflection at B on core at an internal incidence angle θ.

To find α at A:-
In triangle ABC, $\alpha r = 90- \theta$ ……. (1)

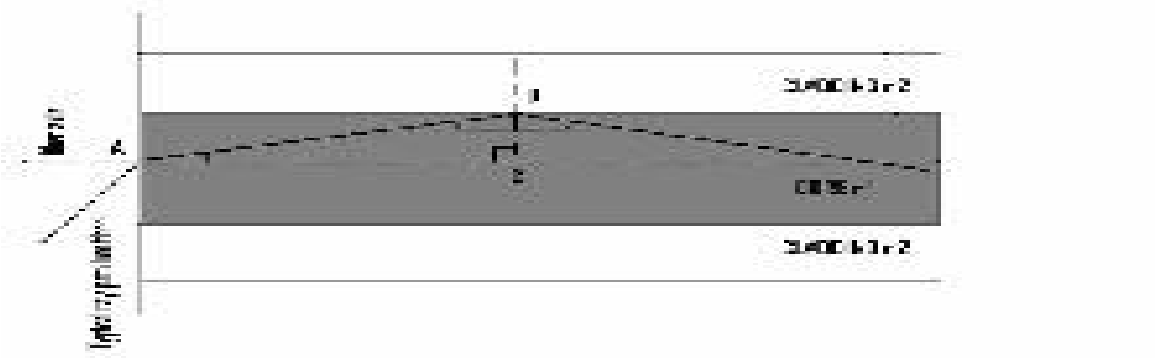
From snell' s law ,

$$n_0 \sin \alpha = n_1 \sin \alpha r \text{…….(2)}$$

$$\sin \alpha = n_1/n_0 \sin \alpha_r \text{ .....(3)}$$

From equations 1, 3

$$\sin \alpha = n_1/n_0 \sin(90- \theta) \Rightarrow \sin \alpha = n_1/n_0 \cos \theta \text{……(4)}$$



If $\theta < \theta_c$, the ray will be the lost by refraction. Therefore limiting value for the beam to be inside the core, by total internal reflection is θ_c. Let α (max) be the maximum possible angle of incident at the fiber end face at A for which $\theta = \theta_c$. If for a ray α exceeds α (max), then $\theta < \theta_c$ and hence at B the ray will be refracted.

Hence equation 4 can be written as

$$\sin \alpha(max) = n_1/n_0 \cos \theta_c \text{……..(5)}$$

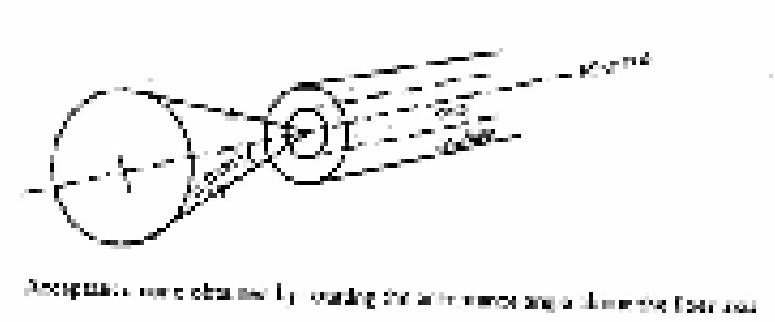
We know that

$$\cos \theta_c = \sqrt{(1-\sin^2 \theta_c)} = \sqrt{(1- n_2^2/n_1^2)}$$
$$= \sqrt{(n_1^2 - n_2^2)}/ n_1 \text{……(6)}$$

Therefore

$$\sin \alpha(max) = \sqrt{(n_1^2 - n_2^2)}/n_o$$

$$\alpha(max) = \sin^{-1}\sqrt{(n_1^2 - n_2^2)}/n_o$$



This maximum angle is called acceptance angle or acceptance cone angle. Rotating the acceptance angle about the fiber axis gives the acceptance cone of the fiber. Light launched at the fiber end within this acceptance cone alone will be accepted and propagated to the other end of the fiber by total internal reflection. Larger acceptance angles make launching easier.

Numerical aperture:-

Light collecting capacity of the fiber is expressed in terms of acceptance angle using numerical aperture. Sine of the maximum acceptance angle is called the numerical aperture of the fiber.

$$\text{Numerical aperture} = NA = \text{Sin } \alpha \text{ (max)} = \sqrt{(n_1^2 - n_2^2)}/n_o \text{…….(7)}$$

Let $\Delta = (n_1^2 - n_2^2)/2n_1^2$…… (8)

For most fiber $n_1 \approx n_2$

Hence $\Delta = (n_1 + n_2)(n_1 - n_2)/2n_1^2 = 2n_1(n_1 - n_2)/2n_1^2$

$\Delta =$ $(n_1 - n_2)/n_1$ (fractional difference in refractive indices)……(9)

From equation (8) $n_1^2 - n_2^2 = \Delta\ 2n_1^2$

Taking under root on both sides

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

Substituting this in equation (7) we get

$$NA \approx \sqrt{2}\ \Delta\ n_{1/}n_o \ldots\ldots\ldots(10)$$

For air $n_o = 1$, then the above equation can changed as

$$NA \approx \sqrt{2}\ \Delta\ n_1$$

Numerical aperture of the fiber is dependent only on refractive indices of the core and cladding materials and is not a function of fiber dimensions.

Types or classification of optical fibers:

Optical fibers are classified as follows:

Depending upon the refractive index profile of the core, optical fibers are classified into two categories

Step index Graded index

Depending upon the number of modes of propagation, optical fibers are classified into two categories, they are

Single mode Multi mode

Based on the nature of the material used, optical fibers are classified into four categories.

- Glass fiber
- Plastic fiber
- Glass Core with plastic cladding
- PCS Fibers(Polymer-Clad Silica fiber)

Step index fibers:-

In step index fibers the refractive index of the core is uniform through out the medium and undergoes an abrupt change at the interface of core and cladding.The diameter of the core is about 50-200μm and in case of multi mode fiber.And 10 μm in the case of single mode fiber.The transmitted optical signals travel through core medium in the form of meridonal rays, which will cross the fiber axis during every reflection at the core-cladding interface. The shape of the propagation appears in a zig-zac manner.

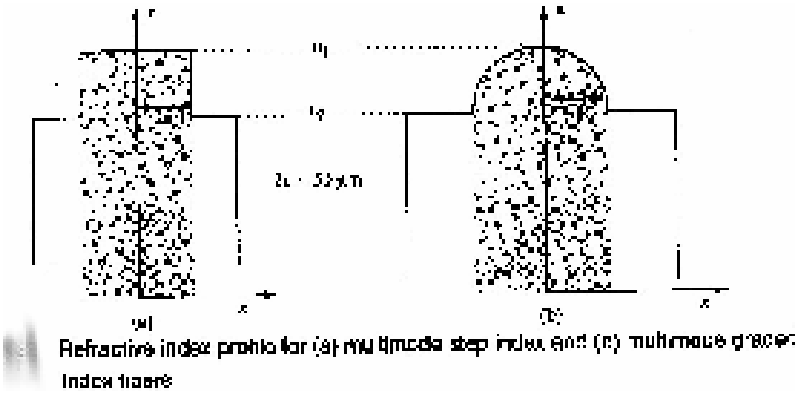




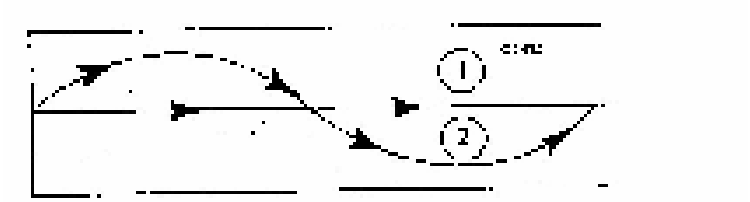
Fig. Signal transmission in step index fiber

Graded index fiber:-

In these fibers the refractive index of the core varies radially.As the radius increases in the core medium the refractive index decreases. The diameter of the core is about 50μm.The transmitted optical signals travel through core medium in the form of helical rays, which will not cross the fiber axis at any time.



Refractive index profile for (a) multimode step index and (b) multimode graded index fibers



Propagation of different mode rays inside graded index fiber

Attenuations in optical fiber (or losses):

While transmitting the signals through optical fiber some energy is lost due to few reasons. The major losses in fibers are 1.Distotrion losses 2.Transmission losses 3.Bending losses.

1. **Distortion losses:-**

When a pulse is launched at one end of the fiber and collected at the other end of the fiber, the shape and size of the pulse should not be changed. Distortion of signals in optical fiber is an undesired feature. If the out put pulse is not same as the input pulse, then it is said that the pulse is distorted .If the refractive index of the core is not uniform most of the rays will travel through the medium of lower refractive index region. Due to this the rays which are travel in fiber will become broadened. Because of this the out put pulses will no longer matches with the input pulses.

The distortion takes place due to the presence of imperfections, impurities and doping concentrations in fiber crystals.Disperion is large in multi mode than in single mode fiber.

2. **Transmission losses (attenuation):-**

The attenuation or transmission losses may be classified into two categories i) Absorption losses ii) scattering losses

i) Absorption losses:-

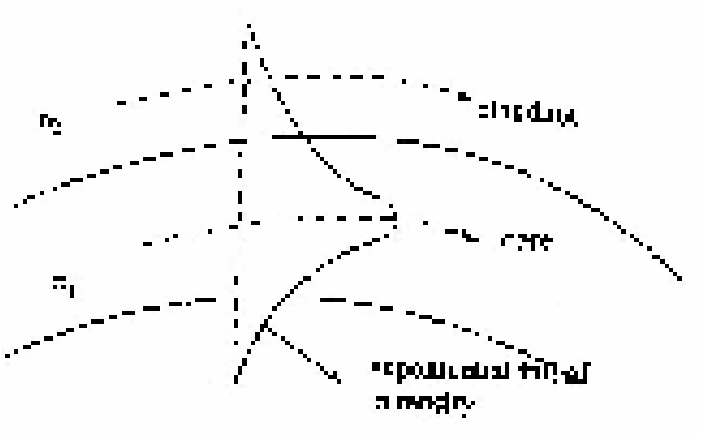
Absorption is a characteristic possessed by all materials every material in universe absorb suitable wavelengths as they incident or passed through the material. In the same way core material of the fiber absorbs wavelengths as the optical pulses or wavelengths pass through it.

ii) Scattering losses:-

The core medium of the fiber is made of glass or silica .In the passage of optical signals in the core medium if crystal defects are encountered, they deviate from the path and total internal reflection is discontinued, hence such signals will be destroyed by entering into the cladding however attenuation is minimum in optical fibers compared to other cables.

ii) Bending losses:-

The distortion of the fiber from the ideal strait line configuration may also result in fiber .Let us consider a way front that travels perpendicular to the direction of propagation. In order to maintain this, the part of the mode which is on the out side of the bend has to travel faster than that on the inside. As per the theory each mode extends an infinite distance into the cladding though the intensity falls exponentially. Since the refractive index of cladding is less than that of the core ($n_1 > n_2$), the part of the mode traveling in the cladding will attempt to travel faster. As per Einistein's theory of relativity since the part of the mode cannot travel faster the energy associated with this particular part of the mode is lost by radiation.



Attenuation loss is generally measured in terms of decibels (dB), which is a logarithmic unit.

Loss of optical power = $-10 \log (P_{out} / P_{in}) \text{ dB}$

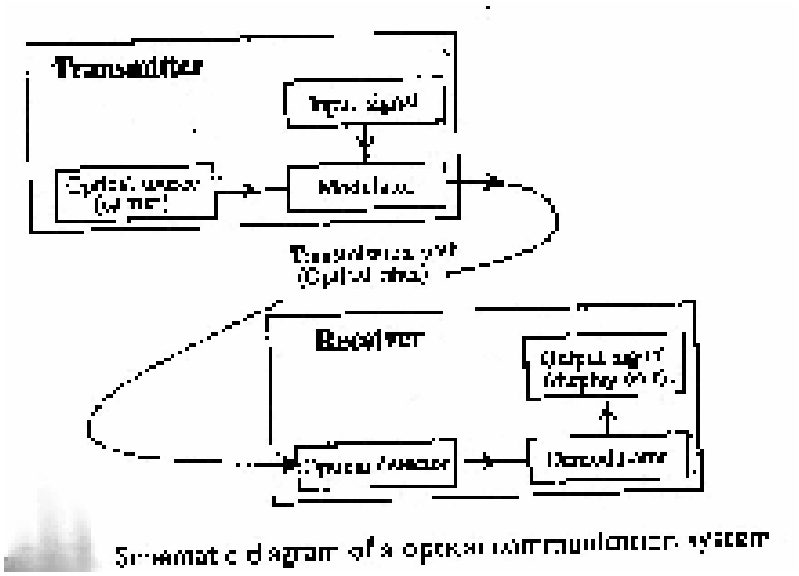
Where P_{out} is the power emerging out of the fiber

P_{in} is the power launched into the fiber.

Optical fiber in communication systems as a wave guide:

An efficient optical fiber communication system requires high information carrying capacity fast operating speed over long distances with minimum number of repeaters .An optical fiber communication system mainly contains

1. Encoder
2. Transmitter
3. Wave guide
4. Receiver
5. Decoder.



Encoder:-

It is an electronic system that convert the analog information like voice, figure, objects etc into binary data. This binary data contain a series of electrical pulses.

Transmitter:-

It consist of two parts namely drive circuit and light source .Drive circuit supplies electric signals to the light source from the encoder in the required form. In the place of light source either an LED or A diode Laser can be used ,which converts electric signals into optical signals. With the help of specially made connecter optical signal will be injected into wave guide from the transmitter.

Wave guide:-

It is an optical fiber which carries information in the form of optical signals over long distances with the help of repeaters. with the help of specially made connector optical signal will be received by the receiver from the wave guide.

Receiver:-

It consists of three parts namely photo detector, amplifier and signal restorer. The photo detector converts the optical signals into equivalent electric signals and supply them to amplifier. The amplifier amplifies the electric signals as they become weak during the journey trough the wave guide over a long distances. The signal restorer keeps all the electric signals in sequential form and supplies to decoder in suitable way.

Decoder:-

It convert the received electric signals into the analog information.

Advantages of optical fiber communication:

- Enormous Band width:-

In the coaxial cable transmission the band width is up to around 5000MHz only where as in fiber optical communication it is as large as 10^5 GHz. Thus the information carrying capacity of optical fiber system is far superior to the copper cable system.

- Electrical isolation:-

Since fiber optic material are insulators unlike there metallic counterpart, they do not exhibit earth loop and interface problems. Hence communication through fiber even in electrically hazarders environment do not cause any fear of spark hazards.

- Immunity to interference and cross talk:-

Since optical fibers are dielectric waveguides, they are free from any electromagnetic interference (EMI) and radio frequency interference (RIF).
Hence fiber cable do not require special shielding from EMI. Since optical interference among different fiber is not possible ,unlike communication using electrical conductors cross talk is negligible even when many fibers are cabled together.

- Signal security:-

Unlike the situation with copper cables a transmitted optical signal can not be drawn fiber with out tampering it. Such an attempt will affect the original signal and hence can easily detected.

- Small size and weight:-

Since fibers are very small in diameter the space occupied the fiber cable is negligibly small compare to metallic cables. Optical cables are light in weight , these merits make them more useful in air crafts and satellites.

- Low transmission loss:-

Since the loss in fibers is as low as 0.2dB/Km , transmission loss is very less compare to copper conductors. Hence for long distance communication, fibers are preferred. Number of repeaters required is reduced.

- Low cost:-

Since fibers are made up of silica which is available in nature ,optical fibers are less expensive.

Applications of optical fibers:

- Optical fibers are used as sensors
- These are used in Endoscopy
- These are used in communication system
- For decorative peaces in home needs.
- These are used in defence areas for the sake of high security.
- These are used in electrical engineering.