Introduction

Fiber optics deals with the light propagation through thin glass fibers. Fiber optics plays an important role in the field of communication to transmit voice, television and digital data signals fro one place to another. The transmission of light along the thin cylindrical glass fiber by total internal reflection was first demonstrated by John Tyndall in 1870 and the application of this phenomenon in the field of communication is tried only from 1927. Today the applications of fiber optics are also extended to medical field in the form of endoscopes and to instrumentation engineering in the form of optical sensors.

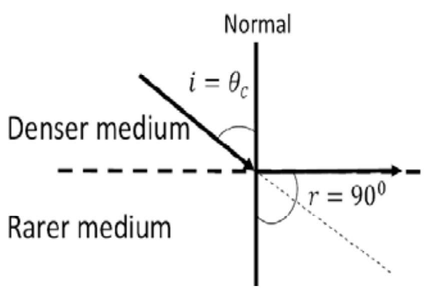
1. The Basic principle of optical fiber Or principle of total internal reflection

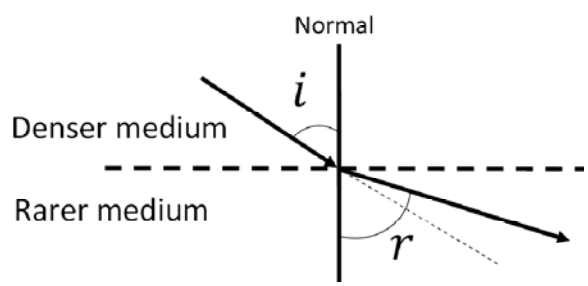
Principle:
The basic principle of optical fiber in the transmission of optical signal is total internal reflection.

Total internal reflection:-

When the light ray travels from denser medium to rarer medium the refracted ray bends away from the normal. When the angle of incidence is greater than the critical angle, the refracted ray again reflects into the same medium. This phenomenon is called ***total internal reflection.***

The refracted ray bends towards the normal as the ray travels from rarer medium to denser medium. The refracted ray bends away from the normal as it travels from denser medium to rarer medium.

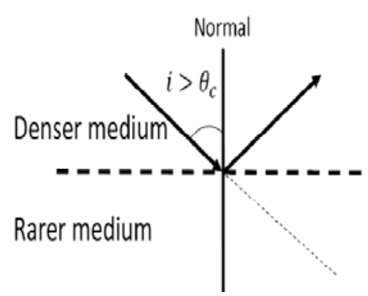




Let, a light ray traveling from denser medium (refractive index n_1) to rarer medium (refractive index n_2) with an angle of incidence i, then the angle of refraction r can be obtained by Snell's law.

$$n_1 \, Sin \, i = n_2 \, Sin \, r$$

When the angle of incidence is increased angle of reflection also increases and for a particular angle of incidence $(i = \theta_C)$ the refracted ray travels along the interface of two mediums. This angle of incidence is known as ***critical angle (θ_C).***



$$n_1 \, Sin \, \theta_C = n_2 \, Sin \, 90$$

$$n_1 \, Sin \, \theta_C = n_2 \;\Rightarrow Sin \, \theta_C = n_2 / n_1$$

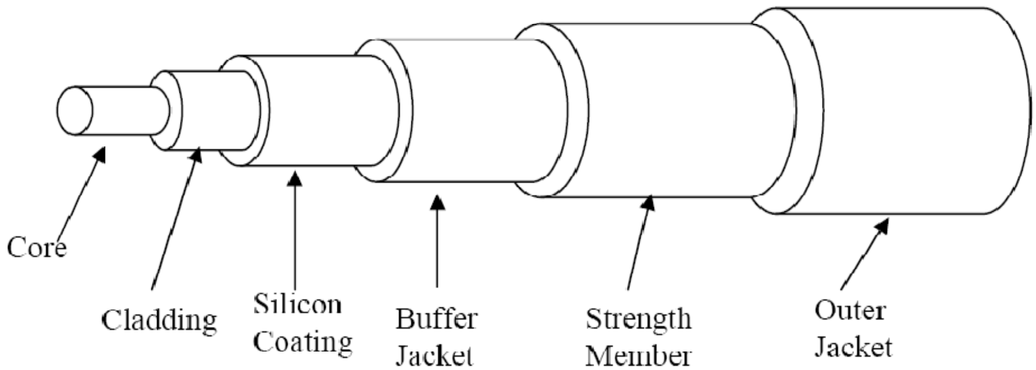
$$\theta_C = Sin^{-1}\left(\frac{n_2}{n_1}\right)$$

When the angle of incidence is greater than the critical angle $(i > \theta_C)$, the refracted ray again reflects into the same medium. This phenomenon is called total internal reflection

- When $(i < \theta_C)$, then the ray refracts into the secondary medium
- When $(i = \theta_C)$, then the ray travels along the interface
- When $(i > \theta_C)$, then the ray totally reflects back into the same medium

2. Construction of optical fiber:-

The optical fiber mainly consists the following six parts as shown in figure



Core:

A typical glass fiber consists of a central core material. Generally core diameter is $50\ \mu m$. The core is surrounded by cladding. The core medium refractive is always greater than the cladding refractive index.

Cladding

Cladding refractive index is lesser than the cores refractive index. The over all diameter of cladding is 125 μm to 200 μm.

Silicon Coating

Silicon coating is provided between buffer jacket and cladding. It improves the quality of transmission of light.

Buffer Jacket

Silicon coating is surrounded by buffer jacket. Buffer jacket is made of plastic and protects the fiber cable from moisture.

Strength Member

Buffer jacket is surrounded by strength member. It provides strength to the fiber cable.

Outer Jacket

Finally the fiber cable is covered by polyurethane outer jacket. Because of this arrangement fiber cable will not be damaged during pulling, bending, stretching and rolling through the fiber cable is made up of glasses.

3. Classification of fibers:-

Based on the refractive index of core medium, optical fibers are classified into two categories.

i. Step index fiber
ii. Graded index fiber

Based on the number of modes of transmission, optical fibers are classified into two categories

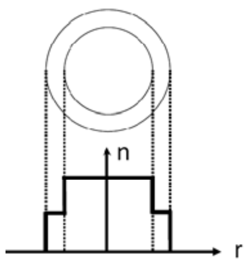
i. Single mode fiber
ii. Multi mode fiber

Based on the material used, optical fibers are may broadly classified into four categories

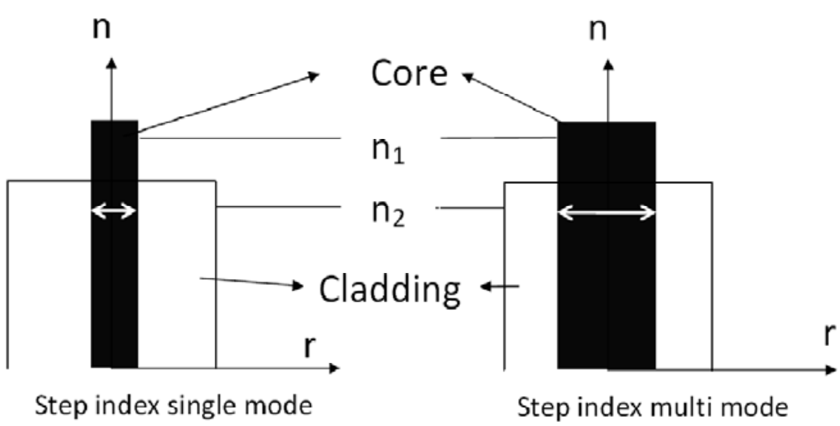
i. All glass fibers
ii. All plastic fibers
iii. Glass core with plastic cladding fibers
iv. Polymer clad silica fibers.

Step index fiber:-

In step index fibers the refractive index of the core medium is uniform and undergoes an abrupt change at the interface of core and cladding as shown in figure.



The diameter of core is about 10micrometers in case of single mode fiber and 50 to 200 micrometers in multi mode fiber.



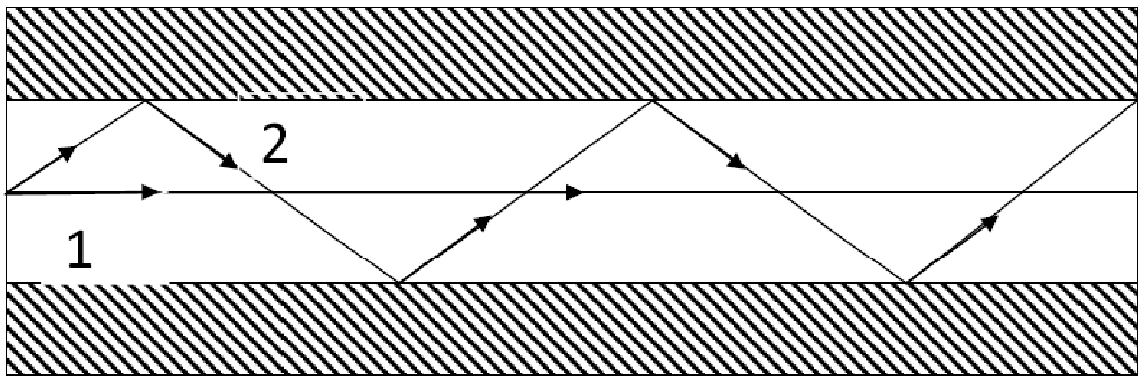
Attenuation is more for step index multi mode fibers but less in step index single mode fibers

Numerical aperture is more for step index multi mode fibers but it is less in step index single mode fibers

Transmission of signal in step index fiber

The transmitted optical signal will cross the fiber axis during every reflection at the core cladding boundary. The shape of propagation of the optical signal is in zigzag manner.

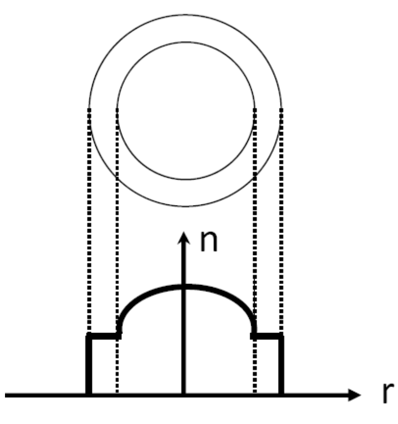
Generally the signal through the fiber is in digital form i.e. in the form of pulses representing 0s and 1s.



From figure the ray 1 follows shortest path (i.e. travels along the axis of fiber) and the ray 2 follows longer path than ray 1. Hence the two rays reach the received end at different times. Therefore, the pulsed signal received at other end gets broadened. This is called intermodal dispersion. This difficulty is over come in graded index fibers.

Graded index fiber:-

In graded index fibers, the refractive index of the core medium is varying in the parabolic manner such that the maximum refractive index is present at the center of the core.



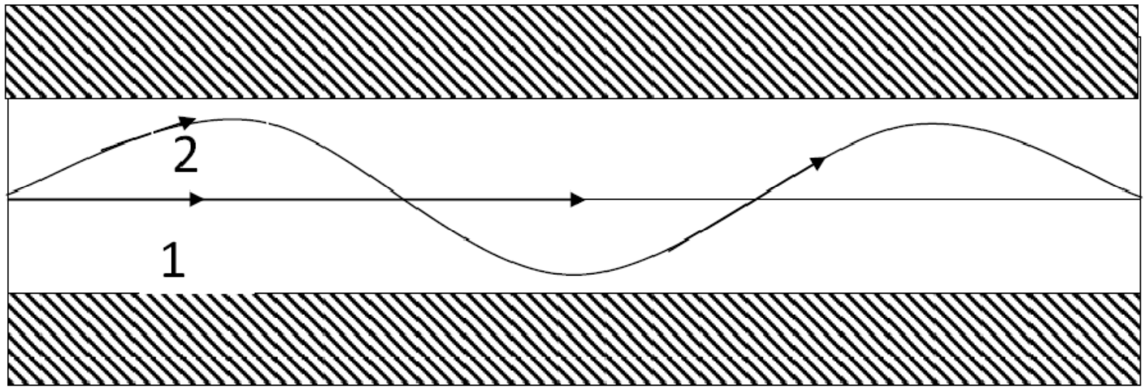
The diameter of the core is about 50 micro meters.

Attenuation is very less in graded index fibers

Numerical aperture is less in graded index fibers

Transmission of signal in graded index fiber:-

The shape of propagation of the optical signal appears in the helical or spiral manner.



As shown in figure, the ray 1 is traveling along the axis of the core and the other ray 2 traveling away from the axis undergoes refraction and bent. Since, ray 2 is traveling in the lesser refractive index medium, the two rays reach the other end simultaneously. Thus the problem of intermodal dispersion can be overcome by using graded index fiber.

Single mode optical fiber:-

- In single mode optical fibers only one mode of propagation is possible.
- In case of single mode fiber the diameter of core is about 10micrometers
- The difference between the refractive indices of core and cladding is very small.
- In single mode fibers there is no dispersion, so these are more suitable for communication.
- The single mode optical fibers are costly, because the fabrication is difficult.
- The process of launching of light into single mode fibers is very difficult.
- The condition for single mode operation is

$$V = \frac{2\pi}{\lambda} a\, NA$$

$$V = \frac{2\pi}{\lambda} a\, n_1 \sqrt{2\Delta}$$

Where a is the radius of the core of the fiber,

n_1 is the refractive of the core,

NA is the numerical aperture and

λ is the wave length of light traveling through the fiber

Multi mode optical fiber:-

- In multi mode optical fibers many mummer of modes of propagation are possible.
- In case of in multi mode fiber the diameter of core is 50 to 200 micrometers.
- The difference between the refractive indices of core and cladding is also large compared to the single mode fibers.
- Due to multi mode transmission, the dispersion is large, so these fibers are not used for communication purposes.
- The multi mode optical fibers are cheap than single mode fibers, because the fabrication is easy.
- The process of launching of light into single mode fibers is very easy.
- The condition for multi mode propagation is

$$N = 4.9\left(\frac{d \bullet NA}{\pi}\right)^2$$

Where d the radius of the core of the fiber and NA is is the numerical aperture.

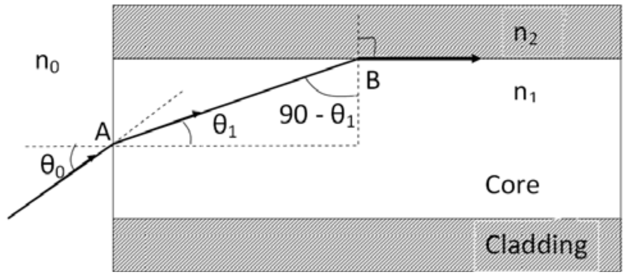
4. Acceptance angle:-

Definition:-

Acceptance angle is defined as the maximum angle of incidence at the interface of air medium and core medium for which the light ray enters into the core and travels along the interface of core and cladding.

Let n_0, n_1 and n_2 be the refractive indices of air, core and cladding media. Let a light ray OA is incident on the interface of air medium and core medium with an angle of incidence θ_0 then the light ray refracts into the core medium with an angle of refraction θ_1, and the refracted ray AB is again incidenting on the interface of core and cladding with an angle of incident $(90^0 - \theta_1)$.

If $(90^0 - \theta_1)$ is equal to the critical angle of core and cladding media then the ray travels along the interface of core and cladding along the path BC. If the angle of incident at the interface of air and core $\theta_1 < \theta_0$, then $(90^0 - \theta_1)$ will be greater than the critical angle. Therefore, the total internal reflection takes place.



According to Snell's law at point A

$n_0 \sin\theta_0 = n_1 \sin\theta_1$

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

According to Snell's law at point B

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

$n_1 \cos\theta_1 = n_2$

$\cos\theta_1 = \frac{n_2}{n_1}$

$\sin\theta_1 = \sqrt{(1-\cos^2\theta_1)}$

$\sin\theta_1 = \sqrt{\left(1-\frac{{n_2}^2}{{n_1}^2}\right)} = \frac{\sqrt{({n_1}^2-{n_2}^2)}}{n_1}$

$\sin\theta_0 = \frac{n_1}{n_0}\sin\theta_1 = \frac{n_1}{n_0}\frac{\sqrt{({n_1}^2-{n_2}^2)}}{n_1} = \frac{\sqrt{({n_1}^2-{n_2}^2)}}{n_0}$

$\sin\theta_0 = \frac{\sqrt{({n_1}^2-{n_2}^2)}}{n_0}$

$$\theta_0 = \sin^{-1}\left(\frac{\sqrt{({n_1}^2-{n_2}^2)}}{n_0}\right)$$

Acceptance angle $\theta_0 = \sin^{-1}\left(\frac{\sqrt{({n_1}^2-{n_2}^2)}}{n_0}\right)$

5. Numerical aperture:-

***Definition**: -*

Numerical aperture is defined as the light gathering capacity of an optical fiber and it is directly proportional to the acceptance angle.

Numerically it is equal to the sin of the acceptance angle.

$NA = \sin(acceptance\ angle)$

$$NA = Sin\left(Sin^{-1}\left(\frac{\sqrt{(n_1^2-n_2^2)}}{n_0}\right)\right)$$

$$NA = \frac{\sqrt{(n_1^2-n_2^2)}}{n_0}$$

If the refractive index of the air medium is equal to unity then

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

Fractional change in refractive index

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

$n_1\Delta = (n_1-n_2)$

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

$NA = \sqrt{n_1\Delta(n_1+n_2)}$ $\quad \because n_1\Delta = (n_1-n_2)$

$NA = \sqrt{n_1\Delta 2n_1}$ $\quad \because n_1 \approx n_2;\ \ n_1+n_2 = 2n_1$

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

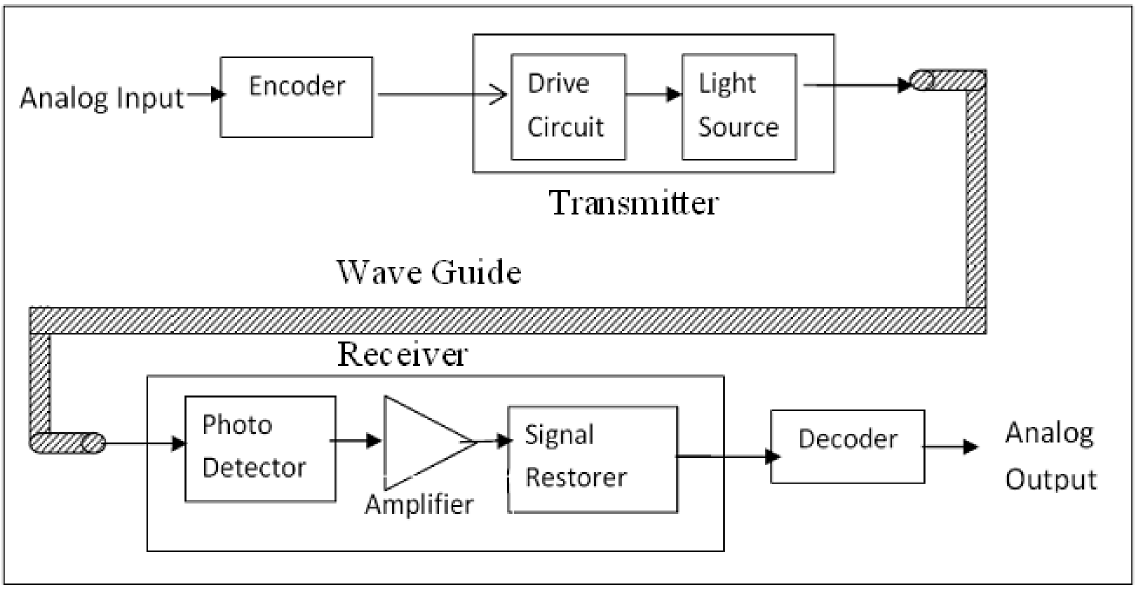
The above equation gives a relationship between numerical aperture and fractional change in relative refractive index.

6. Optical fiber communication system:-

Receiver

An optical fiber communication system mainly consists of the following parts as shown in figure.

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



1. **Encoder**

Encoder is an electronic system that converts the analog information like voice, figures, objects etc., into binary data.

2. **Transmitter**

It contain two parts, they are drive circuit and light source. Drive circuit supplies the electric signals to the light source from the encoder in the required form. The light source converts the electrical signals into optical form.

With the help of specially made connector optical signals will be injected into wave guide from the transmitter.

3. **Wave guide**.

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

4. **Receiver.**

It consists of three parts; they are photo detector, amplifier and signal restorer. The photo detector converts the optical signal into the equivalent electric signals and supply to hem to amplifier. The amplifier amplifies the electric signals as they become weak during the long journey through the wave guide over longer distance. The signal restorer deeps the electric signals in a sequential form and supplies to the decoder in the suitable way.

5. **Decoder**

It converts electric signals into the analog information.

7. Differences between step index fibers and graded index fibers:-

Step index fiber	Graded index fiber
1. In step index fibers the refractive index of the core medium is uniform through and undergoes an abrupt change at the interface of core and cladding.	1. In graded index fibers, the refractive index of the core medium is varying in the parabolic manner such that the maximum refractive index is present at the center of the core.
2. The diameter of core is about 10micrometers in case of single mode fiber and 50 to 200 micrometers in multi mode fiber.	2. The diameter of the core is about 50 micro meters.
3. The transmitted optical signal will cross the fiber axis during every reflection at the core cladding boundary.	3. The transmitted optical signal will never cross the fiber axis at any time.
4. The shape of propagation of the optical signal is in zigzag manner.	4. The shape of propagation of the optical signal appears in the helical or spiral manner
5. Attenuation is more for multi mode step index fibers but Attenuation is less in single mode step index fibers	5. Attenuation is very less in graded index fibers
6. Numerical aperture is more for multi mode step index fibers but it is less in single mode step index fibers	6. Numerical aperture is less in graded index fibers

8. Differences between single mode and multi mode fibers:-

Single mode fiber	Multi mode fiber
1. 1. In single mode optical fibers only one mode of propagation is possible	1. In multi mode optical fibers many mummer of modes of propagation are possible.
2. In case of single mode fiber the diameter of core is about 10micrometers	case of in multi mode fiber the diameter of core is 50 to 200 micrometers.
3. The difference between the refractive indices of core and cladding is very small.	2. The difference between the refractive indices of core and cladding is also large compared to the single mode fibers.
4. 3. In single mode fibers there is no dispersion, so these are more suitable for communication.	3. Due to multi mode transmission, the dispersion is large, so these fibers are not used for communication purposes.
5. 4. The process of launching of light into single mode fibers is very difficult	4. The process of launching of light into single mode fibers is very easy.
6. The condition for single mode operation is $V = \frac{2\pi}{\lambda} a\, NA$	5. The condition for multi mode propagation is $N = 4.9\left(\frac{d \bullet NA}{\pi}\right)^2$
7. 6. Fabrication is very difficult and the fiber is costly.	6. Fabrication is very easy and the fiber is cheaper.

9. Advantages of fiber optic communication:-

The optical fiber communication has more advantages than convectional communication.

1. Enormous bandwidth
2. low transmission loss
3. electric isolation
4. signal security
5. small size and less weight
6. low cost
7. immunity cross talk

1. Enormous bandwidth

The information carrying capacity of a transmission system is directly proportional to the frequency of the transmitted signals. In the coaxial cable (or convectional communication system) transmission the bandwidth range is up to around500MHZ. only. Where as in optical fiber communication, the bandwidth range is large as 10^5 GHZ.

2. Low transmission loss:-

The transmission loss is very low in optical fibers (i.e. $0.2\ dB/Km$) than compare with the convectional communication system. Hence for long distance communication fibers are preferred.

3. Electric isolation

Since fiber optic materials are insulators, they do not exhibit earth and interface problems. Hence communicate through fiber even in electrically danger environment.

4. Signal security

The transmitted signal through the fiber does not radiate, unlike the copper cables, a transmitted signal cannot be drawn from fiber without tampering it. Thus the optical fiber communication provides 100% signal security.

5. Small size and less weight

The size of the fiber ranges from $10\mu m$ to $50\mu m$, which is very small. The space occupied by the fiber cable is negligibly small compared to convectional electrical cables. Optical fibers are light in weight.

6. Low cost

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

7. Immunity cross talk

Since the optical fibers are dielectric wave guides, they are free from any electromagnetic interference and radio frequency interference. Since optical interference among different fibers is not possible, cross talk is negligible even many fibers are cabled together.

10. Applications of optical fibers

1. Optical fibers are extensively used in communication system.
2. Optical fibers are in exchange of information between different computers
3. Optical fibers are used for exchange of information in cable televisions, space vehicles, submarines etc.
4. Optical fibers are used in industry in security alarm systems, process control and industrial auto machine.
5. Optical fibers are used in pressure sensors in biomedical and engine control.
6. Optical fibers are used in medicine, in the fabrication in endoscopy for the visualization of internal parts of the human body.
7. Sensing applications of optical fibers are
   Displacement sensor
   Fluid level detector
   Liquid level sensor
   Temperature and pressure sensor
   Chemical sensors
8. Medical applications of optical fibers are
   Gastroscope
   Orthoscope
   Couldoscope
   Peritonescope
   Fiberscope

Question Bank

Principle of an optical fiber (total internal reflection)

1. Explain briefly 'basic principle of an optical fiber'.

   or

   Explain the principle of total internal reflection.

Acceptance angle and Numerical aperture

2. Explain the terms numerical aperture and acceptance angle.

   or

   Derive expressions for the numerical aperture and fraction change in refractive index change of an optical fiber.

Optical fiber communication system

3. Explain the advantages of an optical fiber communication system.
4. Draw the block diagram of fiber optic communication system and explain the function of each block

Applications of optical fibers

5. Write a note on the applications of an optical fiber.

Fibers classification

6. Explain how the optical fibers are classified.
7. Describe different types of fibers by giving the refractive index profiles and propagation details
8. Distinguish between
   Step index fiber graded index fiber
   Single mode and multimode optical fiber.

Construction of an optical fiber

9. With the help of suitable diagram explain the principle, construction and working of an optical fiber as a waveguide.

Problems

10. An optical fiber has a core material of refractive index of 1.55 and cladding material of refractive index of 1.50. The light is launched it in air. Calculate the its numerical aperture.
11. Calculate the angle of acceptance of a given optical fiber, if the refractive indices os the core and cladding are 1.563 and 1.498 respectively.
12. The numerical aperture of an optical fiber is 0.39. If the difference in the refractive indices of the material of its core and cladding is 0.05. Calculate refractive index of the core material.
13. Calculate fractional change in refractive for a given optical fiber if the refractive indices of the core and the cladding are 1.563 and 1.498 respectively.