Unit-II
Fiber Optics

Principle and construction of optical fiber, Acceptance Angle and Numerical Aperture. Based on refractive index profile classification of Optical Fibers: Single mode & Multimode mode Step index fibers, Single mode & Multimode mode graded index fibers. Attenuation in Optical Fibers (scattering, absorption and bending losses), optical Fiber communication system, Fiber Optic Sensors-Temperature sensor, Pressure sensor and Medical Endoscopy.

Introduction

'Fiber Optics is a technology related to transportation of optical energy (light energy) in guiding media specifically glass fibers.

Optical fiber is a long thin transparent dielectric material which carries EM waves of visible and IR frequencies with negligible loss of energy from one end to the other end of the fiber by means of TIR.

NOTE: Glass or Plastic is used as Dielectric material.

Optical fibers works as Wave guides in optical television signals, digital data to transmit voice television signals from one end to the other end of the fiber.

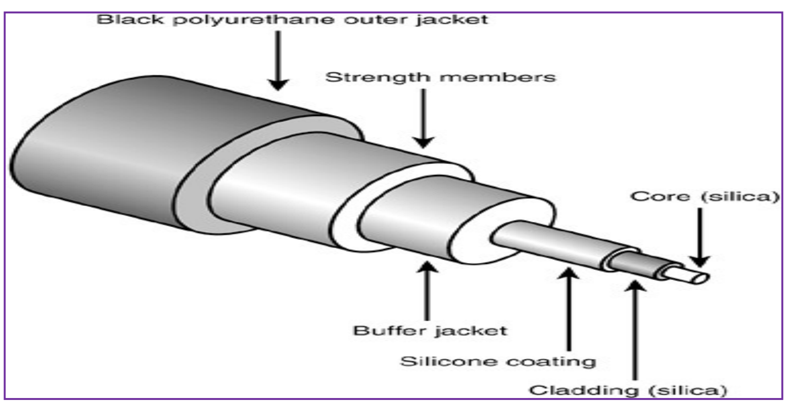
It has become popular because of the following reasons:

1). Higher information carrying capacity.
2). Light in weight, small in size, low cost.
3). No hazards of short circuits and can safely used in explosive environments.
4). No possibility of internal noise and cross talk generation.
5). Using an optical fiber, 15,000 independent speeches can be sent simultaneously where as using a pair of copper wires, only 48 independent speech signals can be sent.

Construction of Optical fiber:

The optical fiber mainly consists of the following three parts.

i) Core ii) Cladding iii) Silicon coating iv) Buffer Jacket v) Strength members and vi) Outer jacket.



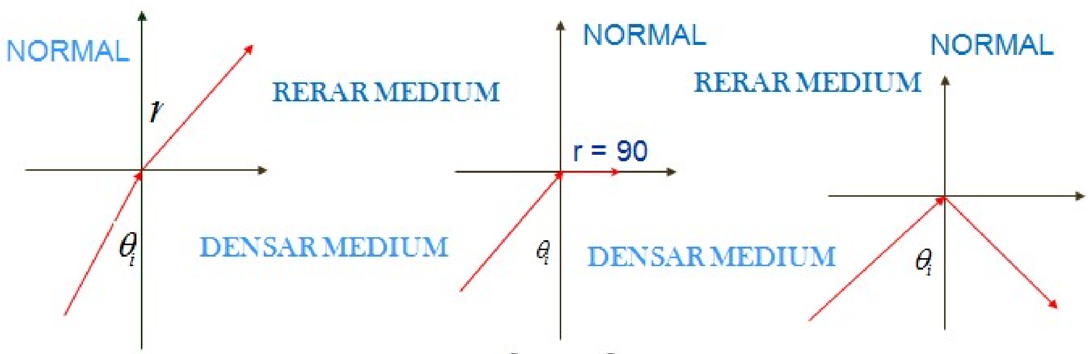
i) **Core:** A typical glass fiber consists of a central core of thickness 50µm surrounded by a cladding.
ii) **Cladding:** Cladding is of a glass of slightly lower refractive index than core's refractive index, which is overall diameter of 125 to 200µm. Both the core and cladding are made of same glass (SiO_2) and to put refractive index of cladding lower than refractive index of core by addition of some impurities like Boron, Phosphorus and Germanium.
iii) **Silicon coating:** It is provided between buffer jacket and cladding to improve the quality of transmission of light.
iv) **Buffer jacket:** Buffer jacket over the optical fiber is made of plastic and protects the fiber from moisture and abrasion.

v) **Strength members:** In order to provide necessary toughness and tensile strength a layer of strength member (Kelvar material) is arranged surroundings the buffer jacket.

vi) **Outer jacket:** Finally the fiber cable is covered by black poly urethane outer jacket. Because of this arrangement, fiber cable will not be damaged during hard pulling, bending, stretching, or rolling through the fiber is made up of brittle glass.

Principle of Optical Fiber:

- Optical fiber works on the principle of TIR. Once light ray enters into core, it propagates by means of multiple TIR' s at core-cladding interface.
- Total internal reflection at the fiber wall can occur only if the following two conditions are met.
  i) The refractive index of the core material 'n_1' must be slightly higher than that of the cladding '$\mathbf{n_2}$' surrounding it. ($\mathbf{n_1 > n_2}$)
  ii) At the core-cladding interface, the angle of incidence '$\boldsymbol{\theta_i}$' must be greater than critical angle '$\boldsymbol{\theta_c}$' . ($\boldsymbol{\theta_i > \theta_c}$)



$$\theta_i < \theta_c \qquad \theta_i = \theta_c \qquad \theta_i > \theta_c$$

$$according\ to\ law\ of\ refraction$$

$$n_1 \sin\theta_i = n_2 \sin r$$

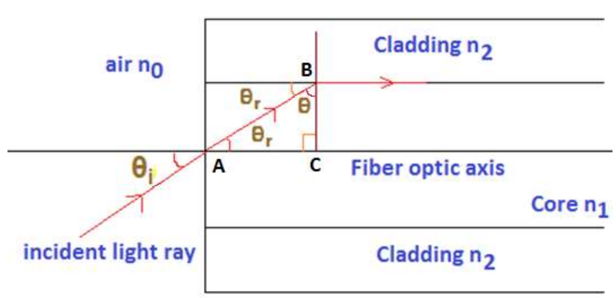
$$\theta_i = \theta_c \rightarrow r = 90^0$$

$$\sin\theta_c = \frac{n_2}{n_1}\sin 90^0$$

$$\sin\theta_c = \frac{n_2}{n_1}$$

Acceptance Angle:

The maximum angle of incidence at the end face of an Optical fiber for which the light ray can be propagated along Core-Cladding interface is known as maximum Acceptance angle. It is also called Acceptance cone half angle.



Applying Snell's law at the Air-Core interface

$$n_0 \sin\theta_i = n_1 \sin\theta_r \ldots\ldots\ldots\ldots(1)$$

from the right angle triangle ABC

$$\theta_r + \theta = 90^0$$

$$\theta_r = 90^0 - \theta$$

$$n_0 \sin\theta_i = n_1 \sin(90^0 - \theta)$$

$$n_0 \sin\theta_i = n_1 \cos\theta$$

$$\sin\theta_i = \frac{n_1}{n_0}\cos\theta \ldots\ldots\ldots(2)$$

$$when\ \ \theta = critical\ \ angle\,(\theta_c) \rightarrow \theta_i = \theta_m$$

$$\sin\ \theta_m = \frac{n_1}{n_0}\cos\ \theta_c \ldots\ldots\ldots\ \ldots\ldots(3)$$

according to law of refraction

$$n_1 \sin\ \theta_i = n_2 \sin\ \theta_r$$

$$\theta_i = \theta_c \rightarrow \theta_r = 90^0$$

$$\sin\ \theta_c = \frac{n_2}{n_1}\sin\ 90^0$$

$$\sin\ \theta_c = \frac{n_2}{n_1}$$

$$\cos\ \theta_c = \sqrt{1 - \sin^2\theta_c} = \sqrt{1 - (\frac{n_2}{n_1})^2}$$

$$\cos\theta_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \ldots\ldots\ldots\ldots(4)$$

substitute equation (4) *in* (3)

$$\sin\theta_m = \frac{n_1}{n_0}\frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

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

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

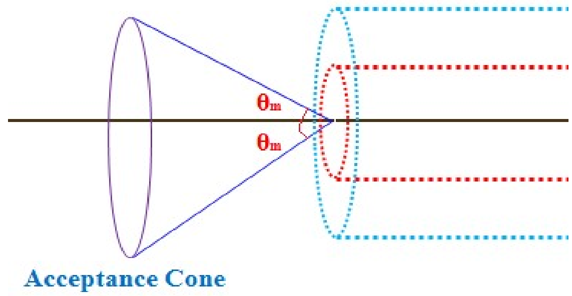
$$\theta_{\max} = \sin^{-1}\sqrt{n_1^2 - n_2^2}$$

This maximum angle is called the acceptance angle or the acceptance cone-half angle.

Acceptance Cone:

Rotating the Acceptance angle about the fiber axis describes 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.



Numerical Aperture:

The light gathering capacity of an optical fiber is known as Numerical Aperture and it is proportional to Acceptance Angle.

It is numerically equal to sine of minimum Acceptance Angle.

$$NA = \sin\theta_{max}$$

$$\sin\theta_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

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

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

The ratio between the differences in RI's of Core and Cladding to that of RI of core is called the fractional change.

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

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

$$n_1 \approx n_2$$

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

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

TYPES OF OPTICAL FIBER

- On the basis of variation of RI of core, the optical fibers are mainly classified into following types. i.e.,

  1.Step Index fiber 2. Graded Index fiber

- Based on Mode of propagation,

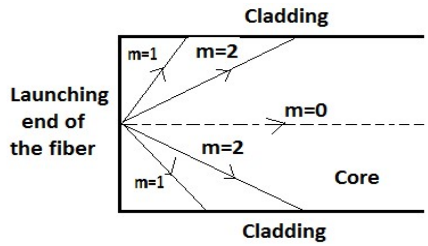
  the fibers are further divided into **Single Mode** and **Multi Mode.**

- Based on the nature of material used, the optical fibers are mainly classified into following types. i.e.,

i) All glass fibers (glass core with glass cladding) ii) All plastic fibers(plastic core with plastic cladding) iii) Glass core with plastic cladding fibers and iv) Polymer – clad – silica fibers (PCS) fibers

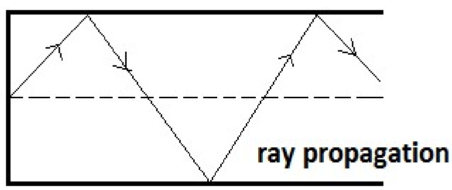
Mode:

Light launched at one end of the fiber within the acceptance cone alone propagates through the fiber by total internal reflection. But not all the light within the acceptance cone propagates but only specified directions are allowed which satisfy conditions for constructive interference. The rays travelling in these specified directions are called **modes.**



Single mode optical fibers:

- In this mode, only one mode of propagation is possible.
- The fibers have smaller core diameter.
- The difference between refractive indices of core and cladding is also very small.
- Here, no degradation of signal during travelling through the fibers. Therefore, more suitable for communication.
- Single mode optical fibers are costly because the fabrication method is very difficult and Joining of two fibers is not that easy.
- The process of launching of light into fibers is also very difficult.



The condition for single mode operation is given by the 'V' number

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

$$= \frac{2\pi}{\lambda} n_1 a \sqrt{2\Delta} \quad \text{such that} V \leq 2.405$$

Where

a = radius of the core

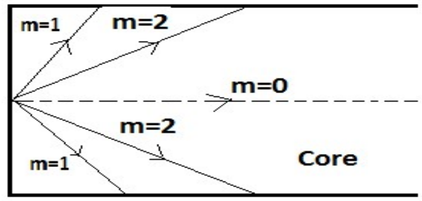
n_1= refractive index of the core.

NA = numerical aperture

λ = wavelength of the light travelling through the fiber.

Multi mode optical fibers:

- In this mode, many modes of propagation is possible.
- These fibers have larger core diameter.
- The difference between refractive indices of core and cladding is large.
- Due to multimode transmission dispersion is large. Hence, these are less suitable for communication.
- Multi mode optical fibers are not costly because the fabrication method is less difficult.
- The process of launching of light into fibers is easy.
- Joining of two fibers is easy.



The condition for multi mode operation is given by the 'N' number

$$N = \frac{V^2}{2} = 4.9\left(\frac{d \times NA}{\lambda}\right)^2 = 4.9\left(\frac{n_1 d\sqrt{2\Delta}}{\lambda}\right)^2$$

Where

D = diameter of the core of the fiber

n_1= refractive index of the core.

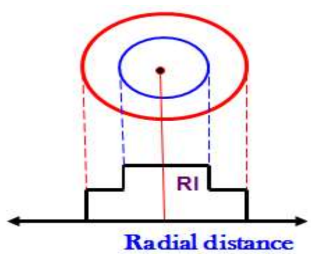
NA = numerical aperture

λ = wavelength of the light travelling through the fiber.

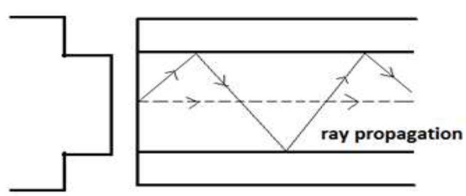
Step index fibers:

- The refractive index of the core medium is uniform throughout and undergoes an abrupt change at the interface of the core and cladding.
- Since the index profile is in the form of a step, these fibers are called step index fibers.
- The diameter of the core is about **50 – 200µm** for **multimode** and **8 – 10µm** for **single mode fibers**.
- The transmitted optical signal is in the form of meridional rays.
- The shape of the propagation appears in a zig – zag manner.
- **In the optical fiber communication system**, information is transmitted in the form of pulses.
- The rays making larger angles with the fiber axis travel longer distance where as the rays making shorter angles with the fiber axis travel shorter distance.

Intermodal dispersion: The optical power in the pulsed wave distribution over the mode of light through the fiber decreases during the propagation; these changes are known as intermodal dispersion.



Refractive index profile of step index fiber



Transmission of signal

- Due to this, optical signals get broadened as they travel through the fiber. This phenomenon of pulses broadening is called as dispersion.
- This imposes limitation on the separation between pulses there by reducing the transmission rate and capacity.
- The amount of dispersion made by a ray travelling through 'L' units of distance is given by

$$\Delta T = \frac{n_1 L}{c}\left[\frac{n_1}{n_2} - 1\right]$$ Where **c** is velocity of light

Note:

- Attenuation is more for multimode step index fibers but for single mode is less.
- Numerical aperture is more for multimode but less for single mode step index fibers.

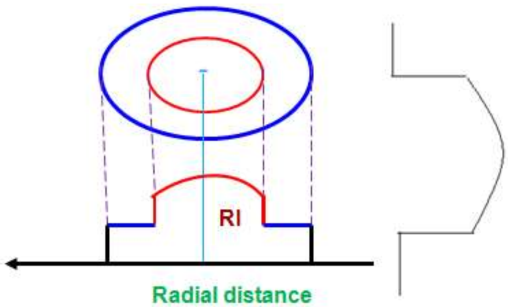
Graded index fibers:

- The refractive index of the core medium is made to vary parabolic manner such that the maximum refractive index present at the center of the core and minimum at core – cladding interface.
- Refractive index gradually falls with increase of radius and at the core – cladding interface matches with the refractive index of the cladding.
- The variation of refractive index of the core(n) with radius(x) measured from the center of the core is given by

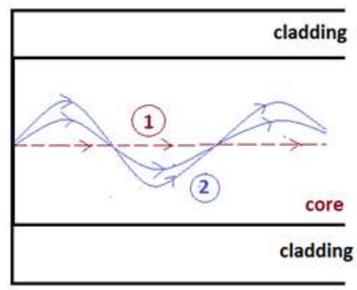
$$n(x) = n_1\left[1 - 2\Delta\left(\frac{x}{a}\right)^p\right]^2$$

Where p is the grading profile index number.

- The transmitted optical signals are in the form of **skew** or **helical** rays.



REFRACTIVE INDEX PROFILE OF GRADED INDEX FIBER



Transmission of signal

Transmission of signal in graded index fibers:

- The transmitted optical signals is in the form of **skew** or **helical** rays.
- According to Snell's law, a ray entered into the fiber bends towards the fiber axis as refractive index of the core lowers.
- The velocity of light is inversely proportional to the refractive index.
- Consider a signal pulse travelling through graded index fiber in two different paths 1 & 2.
- The pulse 1 travelling along the axis of fiber with shorter distance and with low velocity through a medium of higher refractive index.
- The other pulse 2, travelling away from the axis undergo refraction and bend. Though it travel longer distance with high velocity along the path possessing relatively lesser refractive index.
- This will keep the signal in the output without any distortion.
- Thus the problem of inter modal dispersion can be overcome by using graded index fiber.
- Attenuation and numerical aperture is less in graded index fibers.

Note: Let $\mathbf{N_{SI}}$ be the number of modes excited in step index fiber and $\mathbf{N_{GI}}$ be the number of modes excited in graded index fiber, both having similar core and cladding diameters, then $N_{GI}=N_{SI}/2$

Attenuation in optical fibers:

Attenuation is defined as the reduction in the signal strength or power when it is transmitted (or guided) through an optical fiber.

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

The decibel loss of optical power in a fiber is given as

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

Where $\mathbf{P_{out}}$ = power emerging out of the fiber

$\mathbf{P_{in}}$ = power launched into the fiber

The loss per kilometer (or dB/km) is a standard unit for describing attenuation loss in all fiber designs

Loss/km = $\mathbf{-(10/L) \log (P_{out}/P_{in})}$ **dB/km**

Where **L** is the length of the fiber tested

While transmitting the signals through the optical fibers, some energy will be lost due to few reasons. The major losses are

I) Transmission losses and II) Distortion losses

I) Transmission losses:

The mechanism of attenuation during transmission broadly classified into two categories.

i) Absorption losses

ii) Scattering losses

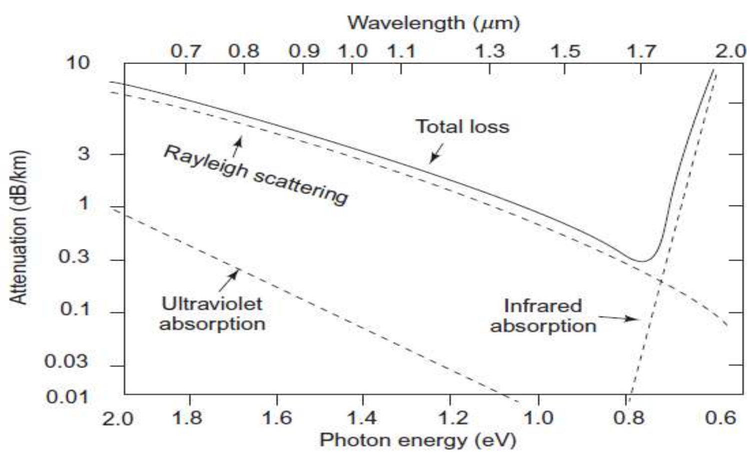
i). Absorption losses:

Core material of a fiber absorbs few wavelengths as optical pulses or wavelengths pass through it. Absorption of light is caused by the following three different mechanisms. These are Ultraviolet absorption, Infrared absorption and Ion resonance absorption.

In pure fused silica, Ultraviolet absorption around 0.14µm results in ionization of valence electrons into conduction band.

Absorption of Infrared photon by atoms within the glass molecules results in increase of random mechanical vibrations and hence heating. Absorption peaks corresponding to silicon at 3.2, 3.8 and 4.4µm.

OH- ions are present in the material due to trapping of water molecules during manufacturing. These ions absorb energy at peaks of 0.95, 1.25 and 1.39µm.

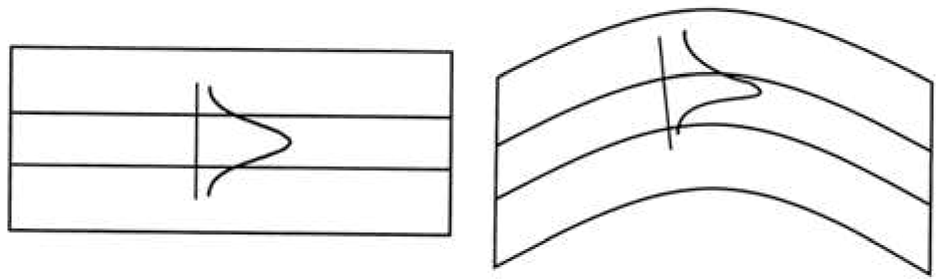


ii). Scattering losses:

Scattering is another parameter for optical attenuation. Such losses in glass arise due to microscopic variation in material density, random variation in refractive index, and structural in homogeneities or defects occurring during fiber manufacturing. These inhomogenities act as reflecting and refracting facts to scatter a small portion of light through the core into cladding contributing for the losses. This type of scattering is known as Rayleigh scattering.

iii). Distortion or Bending losses:

The distortion of the fiber from the ideal straight line configuration may also result in losses in fibers. Tight bends cause some of the light not to be internally reflected but to propagate into the cladding and be lost.



Mode Field distributions in straight and bent fibers

Applications of Optical Fiber:

Optical fiber Communication System:

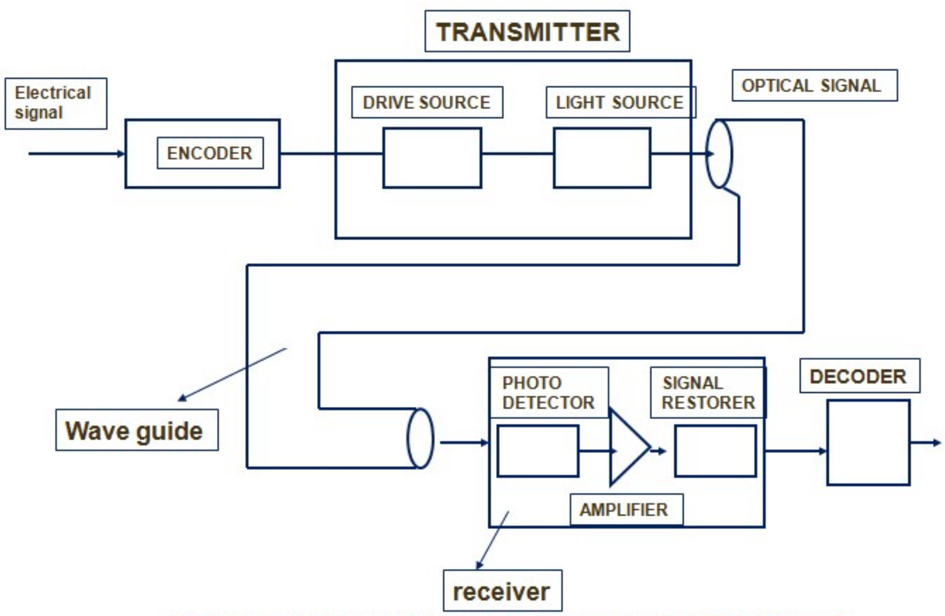
An efficient optical fiber communication system requires high information carrying capacity such as voice signals, video signals over long distances with a minimum number of repeaters. It essentially consists of following parts.

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

1.Encoder: It converts electric signal corresponding to analog information such as voice, figures, objects etc into binary data. This binary data comes out in the form of stream of electrical pulses.

2.TRANSMITTER: It mainly consists of a drive circuit and a light source. Drive circuit supplies the electric pulses to the light source from the encoder.

NOTE: LED or diode laser is used as light source and it converts electrical signals are injected into optical signals. These optical signals are injected into wave guide.



OPTICAL FIBER COMMUNICATION SYSTEM BLOCK DIAGRAM

3.Wave Guide: It carries the information through the desired distance in the form of optical signal.

4.Receiver: It consists of a photo detector, amplifier, signal restorer.

Photo Detector: It converts optical signal into electrical signal. This signal may become weak since it travels through very long distance.

Amplifier: Such weak signal from photo detector is amplified. This is allowed into signal restorer.

Signal Restorer: The function of signal restorer is to put the signals In order which are received from wave guide subsequently from photo detector.

5.Decoder: Finally, signals will be decoded and sent in the original form.

Fiber Optic Sensors:

Sensors are devices used to measure or monitor quantities such as displacement, pressure, temperature, flow rate, liquid level, chemical composition etc. The measurement techniques developed using fibers are more sensitive and reliable.

A smoke detector and pollution detector can be made from fibers.

The high sensitivity of fiber to external influences, like phase sensitivity, micro-bending losses and modal noise is utilized to develop new sensors.

There are two types of fiber optic sensors.

1) **Intrinsic or active sensors**
2) **Extrinsic or passive sensor**

1) Intrinsic or active sensors:

In active sensors the quantity to be measured acts directly on the fiber itself. Fiber itself acts as a transducing element and modifies the light passing through it.

Based on the modification occurring in the fiber, the active sensors are

i)**Intensity modulated sensors:** which are based on the change in absorption or transmission of light, refractive index, temperature etc.

ii)**Phase modulated sensors:** which involve the interference between signal and reference in the interferometer, leading to a shift in the interference fringes. These will have high sensitivity.

iii) **Polarization modulated sensors:** which involve the change in polarization state of the guided signal by the variable.

iv)**Wavelength modulated sensors:** which involve the spectral dependent variation of absorption and emission by the variable.

2) Extrinsic or passive sensor:

In passive sensors the quantity to be measured acts directly on the transducing material which modifies light.

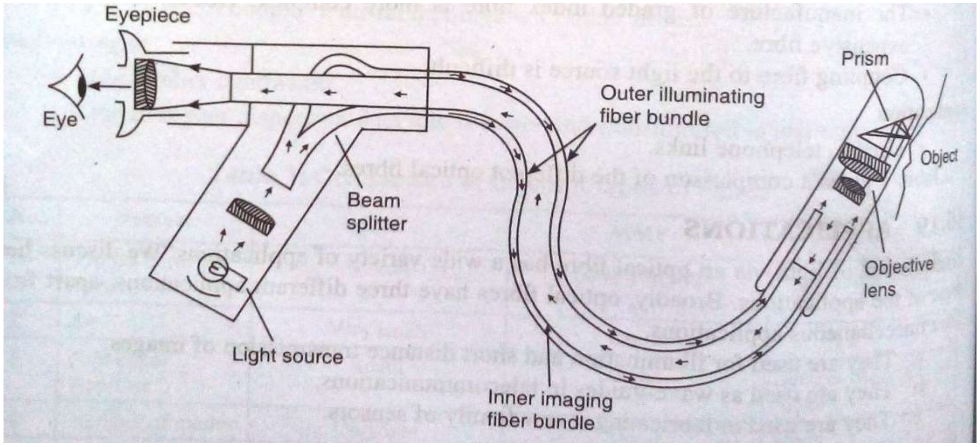
The modified light is collected through another fiber to reach the detector to sense the modification. Thus the fiber merely acts as a convenient transmission channel for the light.

Measured Parameter	Modulation effect in optical fiber
1)Temperature	1. Thermoluminescence
2) Magnetic field	2. Magneto-optic effect
3) Pressure	3. Piezo-optic effect
4) Mechanical force	4. Stress birefringence
5) Electric current	5. Electroluminescence
6) Electric field	6. Electro-optic effect
7) Density	7. Triboluminescence
8) Nuclear radiation	8. Radiation induced luminescence

Medical Endoscopy:

Endoscopy is an optical instrument which facilitates visual inspection of internal parts of a human body. It is also called a fiberoscope.

It requires about 10,000 fibers forming a bundle of 1mm diameter and it can resolve objects with a separation of 70μm. By allowing direct viewing of what was formerly hidden, a fiberoscope has become a vital diagnostic tool for industry and medicine.



- The above Fig. shows the schematic diagram of a flexible endoscope.
- The endoscopes are designed using low quality, large diameter and short silica fibers.
- There are two bundles in an endoscope.
- One of them is used to illuminate the interior of the body.
- The other is used to collect the reflected light from the illuminated area.
- A telescope system is added in the internal part of endoscope for obtaining a wider field of view and better image quality.
- At the object end, there is an assembly of objective lens and prism which are kept in a transparent glass cover and at the viewing end, there is an eye lens.
- The input end of the endoscope contains a powerful light source.
- The light rays are focused and coupled to the illuminating fiber bundle.
- The light rays are finally incident on the surface of the object under study.
- The light rays reflected from the object surface are received by the objective lens through a prism and are transmitted through the imaging fiber bundle to the viewing end of the scope.
- Here eye piece reconstruct the image of the object and one can view the image of the surface of the object.
- Endoscope pictures can be recorded on a videotape recorder.

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