# Unit-3

# Fibre Optics

Syllabus:

Fibre Optics: Light guidance through optical fibre, types of fibre, numerical aperture, V-Number, Fibre dispersion (through ray theory in step index fibre), block diagram of fibre optic communication system

# Fibre Optics:

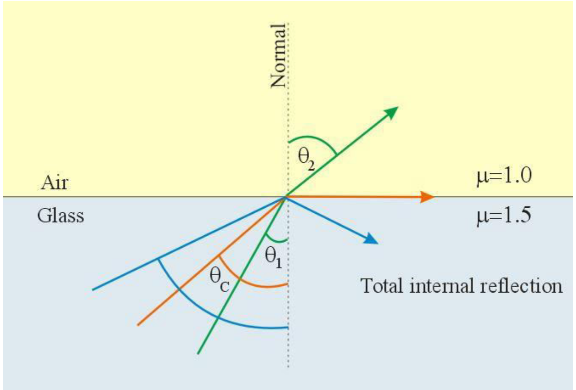
Fiber optics is the technology in which signals are converted from electrical into optical signals transmitted through a thin glass-fiber and re-converted into electrical signals.

**Definition:**

An optical fiber is a transparent medium as thin as human hair, made of glass or clear plastic designed to guide light waves along its length.

**Total Internal Reflection:**

When light waves goes into denser medium through rare medium then they goes away from the normal. If the angle of incidence exceeds the critical angle then the refracted ray comes back in to the same medium, this phenomenon is called the total internal reflection.




Figure(1):Total internal reflection

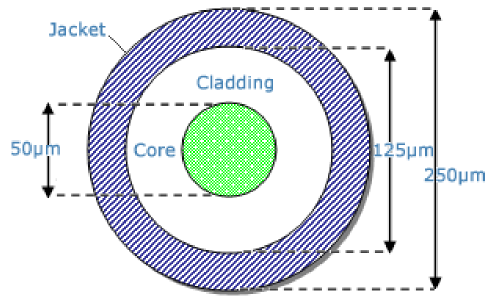
**Principle of optical fiber cable:**

The propagation of light in the optical fiber from one end to another end is based on the principal of total internal reflection (TIR). When light enters through one end it suffers successive TIR from side walls and travels along the fiber length in a zigzag path.

**Construction:**

An optical fiber is cylindrical in shape and has three co-axial regions. The inner most region is the light guiding region known as core, whose diameter is of the order of $50\mu m$. It is surrounded by a co-axial middle region known as cladding. The diameter of cladding is of the order of $125\mu m$, the refractive index of cladding is always lower than that of the core. The purpose of the cladding is to make the light to be confined to the core. Light launched into the core and striking the core cladding interface at an angle greater than critical angle will be reflected back into the core. The outermost region is called sheath or jacket, which is made up of plastic or polymer. The sheath protects the cladding and core from abrasion and the harmful contamination of moisture and also increases the mechanical strength of the fiber. Optical fiber is used to transmit light signal over long distance. Optical fiber requires a light source for launching light into the fiber at its input and a photo detector to receive light at its output end

. As the diameter of the optical fiber is very small, LEDs and laser diodes are used as light source. At the receiver end semiconductor photodiodes are used for detection of light pulses and convert the optical signals into electrical form.



Figure(2):Optical fiber cable

# Light Propagation in the Fibber:

Let us consider the light propagation in the optical fiber. The end at which the light enters the fiber is called the launching end. Let the refractive index of the core is $\mu_1$ and that of cladding is $\mu_2$ as $(\mu_2 < \mu_1)$. Let the outside medium from which the light is launched have the refractive index $\mu_0$. Let the light ray enters the fiber at an angle $\theta_r$ with the axis and strikes core-cladding interface at an angle $\phi$. If $\phi > \phi_c$ the ray will suffer total internal reflection and remains within the fiber.

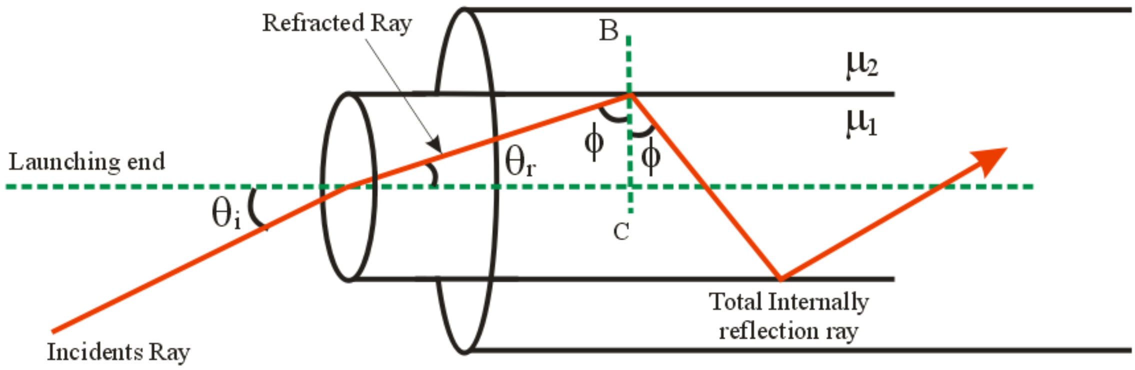



Figure (3): Propagation of light through optical fiber cable.

## Fractional Refractive Index:

It is the ratio of the difference of the refractive index of core and cladding to refractive index of core. It is denoted by Δ and is expressed as

$$\Delta = \frac{\mu_1 - \mu_2}{\mu_1}$$

Where $\mu_1$ = refractive index of the core

$\mu_2$ = refractive index of cladding

It has no dimension and its order is 0.01 this parameter is always positive because $\mu_1 > \mu_2$ In order to guide light effectively through the fiber $\Delta \ll 1$ typically of the order of 0.01

## Acceptance Angle:

Applying Snell's law at the launching end

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{\mu_1}{\mu_0}$$

$$\sin \theta_i = \frac{\mu_1}{\mu_0} \sin \theta_r \quad \ldots\ldots\ldots\ldots \quad (1)$$

Now In $\Delta ABC \quad \phi_c + \theta_r + 90 = 180$

$$\Rightarrow \quad \theta_r = 90 - \phi_c$$

So putting in equation (1)

$$\sin\theta_i = \frac{\mu_1}{\mu_0}\sin(90 - \phi_c)$$

$$\sin\theta_i = \frac{\mu_1}{\mu_0}\cos\phi_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Now $\theta_i = \theta_{max}$ when $\phi = \phi_c$

Applying Snell's law

$$\mu_1 \sin\phi_c = \mu_2 \sin 90$$

$$\sin\phi_c = \frac{\mu_2}{\mu_1}$$

$\because \sin 90 =$

But $$\cos\phi_c = \sqrt{1 - \sin^2\phi_c}$$

$$\cos\phi_c = \sqrt{1 - \left(\frac{\mu_2}{\mu_1}\right)^2}$$

$$\cos\phi_c = \sqrt{\frac{\mu_1^2 - \mu_2^2}{\mu_1^2}}$$

$$\cos\phi_c = \frac{\sqrt{\mu_1^2 - \mu_2^2}}{\mu_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Therefore, putting the value in equation (2) we get

$$\sin\phi_{max} = \frac{\mu_1}{\mu_0} \times \frac{\sqrt{\mu_1^2 - \mu_2^2}}{\mu_1}$$

$$\sin\phi_{max} = \frac{\sqrt{\mu_1^2 - \mu_2^2}}{\mu_0}$$

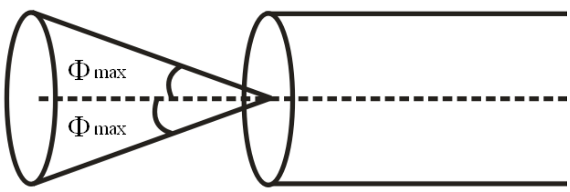
Let air be the medium at launching end so $\mu_0 = 1$

Then $$\sin\phi_{max} = \sqrt{\mu_1^2 - \mu_2^2}$$

$$\phi_{max} = \sin^{-1}\left(\sqrt{\mu_1^2 - \mu_2^2}\right)$$

The angle $\phi_{max}$ is called the acceptance angle of the fiber. Acceptance is the maximum angle that are light rays can have relative to the axis of the fiber and propagate down the fiber.

In 3D the light rays contained within the cone having a fall angle $2\phi_{max}$ are accepted and transmitted along the fiber. Therefore the cone is called the acceptance cone.




Figure(4): Acceptance cone=$2\phi_{max}$

## Numerical Aperture:

Numerical aperture determines the light gathering ability of the fiber. This is defined as the *sine* of the angle of acceptance angle.

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

But $\sin \phi_{max} = \sqrt{\mu_1^2 - \mu_2^2}$, so

$$NA = \sqrt{\mu_1^2 - \mu_2^2}$$

## Relation between $NA$ and $FRI$

We know that numerical aperture is given as

$$NA = \sqrt{\mu_1^2 - \mu_2^2}$$

$$NA = \sqrt{(\mu_1 + \mu_2)(\mu_1 - \mu_2)}$$

$$NA = \sqrt{(\mu_1 + \mu_2)(\mu_1 - \mu_2) \times \frac{2\mu_1}{2\mu_1}}$$

$$NA = \sqrt{\left(\frac{\mu_1+\mu_2}{2}\right)\left(\frac{\mu_1-\mu_2}{\mu_1}\right) 2\mu_1}$$

But $\frac{\mu_1+\mu_2}{2} \approx \mu_1$ and $\frac{\mu_1-\mu_2}{\mu_1} = \Delta$

so

$$NA = \sqrt{\mu_1 \, \Delta \, 2\mu_1}$$

$$NA = \mu_1\sqrt{2\Delta}$$

# Normalized frequency (V-number)

Optical fiber is characterized by a parameter caused V-number or normalized frequency. Normalized frequency is the relation between refractive indices and wavelength, and is given by

$$V = \frac{2\pi a}{\lambda}\sqrt{\mu_1^2 - \mu_2^2}$$

Where $a$ = radius of core

$\lambda$ = free space wavelength

But we know that

$$\sqrt{\mu_1^2 - \mu_2^2} = NA = \mu_1\sqrt{2\Delta}$$

so

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

$$V = \frac{2\pi a}{\lambda}\mu_1\sqrt{2\Delta}$$

$$V = \frac{\pi d}{\lambda}\mu_1\sqrt{2\Delta}$$

Where $2a = d$

V- number helps in determining the number of modes that can propagates through a fiber from above relation number of modes that can propagates through a fiber increase with increase in $NA$.

Maximum number of modes in multi-mode step index fiber is given by $N = \frac{V^2}{2}$ maximum number of mode in multi-mode graded index fiber is given by

$$N = \frac{V^2}{4}$$

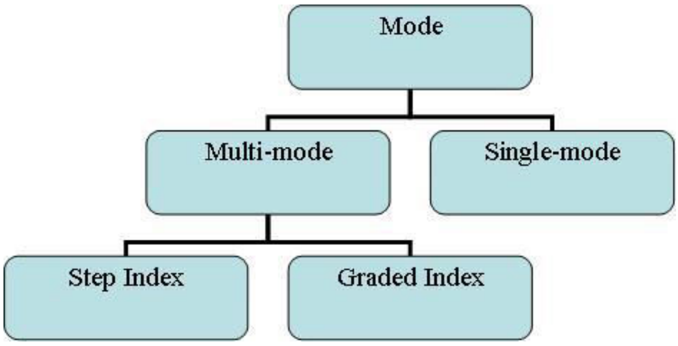
Also

For single mode fiber, $V < 2.405$

For multi-mode fiber, $V > 2.405$

The corresponding wavelength is called cut-off wavelength.

# Mode of Propagation:




Figure(5): Mode of Propagation

The total possible number allowed path in an optical fiber is known as modes.

When light propagates at an angle close to the critical angle are high order modes and when modes propagates with angles longer than critical angle are low order mode. The zero order rays travels along the axis are known as axial ray. On the basis of modes of light propagation optical fiber are of two types:

1) Single mode fiber: - It supports only one mode of propagation.
2) Multi-mode fiber: - It supports number of modes for propagation.

### Refractive Index Profile:

It is a plot of refractive index drawn on one of the axis (say-X) and the distance from axis of the core other axis (say-Y). On the basis of refractive index profile, there are two types of fibers-

1) Steps index fiber: In this refractive index of the core is constant throughout the core.
2) Graded Index Fiber: In this the refractive index of core varies smoothly over the diameter of the core.

# Types of the optical fiber:

Based on the profile and modes of propagation optical fiber are of three types-

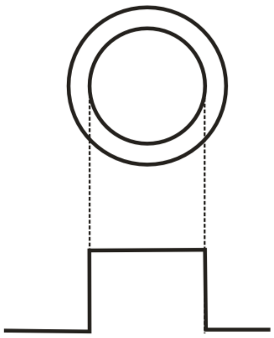
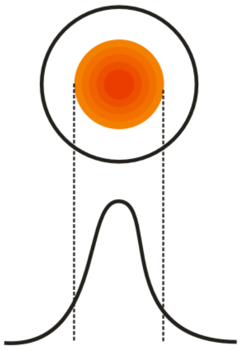
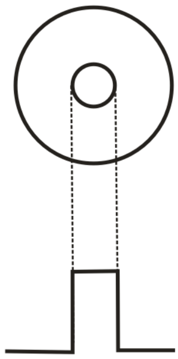
1) Single mode step index fiber: The diameter of typical SMSIF is about $5 - 10\ \mu m$ which is of the order of wavelength of light used. SMSIF has a very thin fiber, the refractive index changes abruptly at the core-cladding interface for which it is called step index fiber. In this fiber light travels along the axis of the fiber. The $NA$ (i.e. numerical aperture) and $\Delta$ (i.e. fractional refractive index) have very small values for single mode fiber and thus have very low acceptance. Therefore the light occupying in fiber becomes difficult. Costly laser diodes are used to launch the light into the fiber. A single mode fiber has very small value of $\Delta$ and allows only one mode to propagates through them therefore intermodal dispersion does not exists in single mode fiber and thus have high data transfer rate.
2) Multi-mode step index fiber: This fiber is similar to single mode fiber only it has a large diameter of

the order of $100 - 970\,\mu m$ large compared to the wavelength of light. In multi mode fiber the light follows a zigzag path. It allows more than one but finite number of modes to propagate through them. The NA is larger because of large core diameter the signal having path length along the axis of the fiber is shorter while the other zigzag path longer resulting in higher intermodal dispersion which means lower data rate and less efficient transmission. LEDs or laser source can be used for launching of light in this kind of fiber. This kind of fiber. This kind of fiber is used for short range communication.

3) Multi-mode Graded Index fiber: Multimode fiber have a core having refractive index at the center is very high and decreases as we move towards the cladding, such profile causes a periodic focusing of light propagation to the fiber. It allows more than one mode to propagate through them and the core diameter ranges from $50 - 85\,\mu m$ the acceptance angle and $NA$ decreases with distance from the axis. The number of modes in this fiber is half that of multimode step index fiber. Therefore gives lower dispersion. Since the $NA$ of this fiber is less than multimode step index fiber, it makes coupling fiber to the source more difficult. Hence LEDs or laser light source can be used for launching the light in them; these are used in medium range communication.

Refractive index profile:

Index profile is the refractive index distribution across the core and cladding of fibre. Some fibre has a step index profile, in which the core has one uniformly distributed index. Other optical fibre has a graded index profile, in which refractive index varies gradually as a function of radial distance from the axis of the fibre.

| | Multimode Step Index (MMSI OFC) | Multimode Graded Index (MMGI OFC) | Single mode Step Index (SMSI OFC) |
|---|---|---|---|
| Fibre cross-section |  |  |  |
| $NA$ | Large | Gradually decreases with distance from axis | Very small |
| $\Delta$ | Large | | Very small |
| Acceptance angle $(\theta)$ | Large acceptance angle | Gradually decreases with distance from axis | Low acceptance angle |
| Number of modes | Allow finite number of modes $(N = V^2/2)$ | Number of mode are half of MMSI OFC i.e. $(N = V^2/4)$ | Only single mode is possible |
| Range | Short range communication | Medium range communication | Long range communication |
| Data rate | Lower data rate | Lower data rate | Higher data rate |
| Efficiency | Lower efficient | Lower efficient | Highly efficient |

| | | | |
|---|---|---|---|
| Light source | LED | LED | Costly LASER diode |
| Coupling | Comparatively easy | Very difficult | difficult |

# Pulse Dispersion:

High pulse launched into a fiber decrease in amplitudes as it travels along the fiber decrease in amplitude as it travels along the fiber due to laser. It also spreads during travel so its output pulse become wider than input pulse these are of three types:

1) Intermodal Dispersion: It is due to difference in propagation time in different modes.
2) Intramodal Dispersion: It results due to difference in wavelength, since fiber light consists of groups of waves.
3) Wave guided dispersion: It happens due to wave guiding properties of fiber.

# Fiber Losses:

The losses in optical fiber may be due to following causes:

1. **Rayleigh scattering losses**: The glass in optical fiber is an amorphous solid that is formed by allowing the glass to cool from its molten state at high temperature, until it freezes. During the forming process, some defects are causes in fiber which allows scattering a small portion of light passing through the glass, creating losses. It affects each wavelength differently.
2. **Absorption Losses:** The ultraviolet absorption, infrared absorption and ion resonance absorption these three mechanisms contribute to absorption losses in glass fiber. The oxygen ions in pure silica have very tightly bounded and only the ultraviolet light photons have enough energy to be observe. Infrared absorption takes place because photons of light energy are absorbers by the atoms within the glass molecules and converted to the random vibration.
3. **Micro bend Losses:** Due to small irregularities in the cladding, causes light to be reflected at angle where there is no further reflection.
4. **Macro bend Losses:** It is a bend in the entire cable which causes certain modes not to be reflect and therefore causes losses to the cladding.

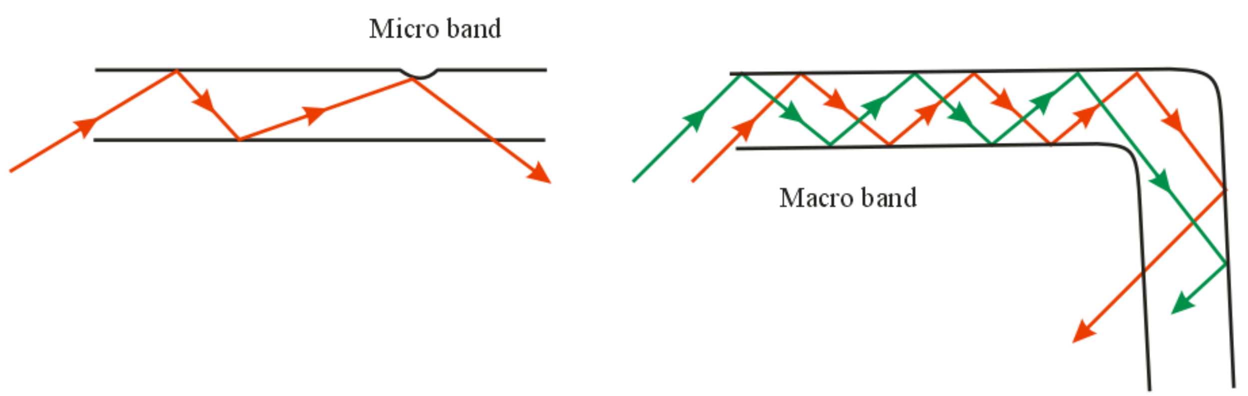



Figure (6): Macro and micro band losses in optical fiber cable.

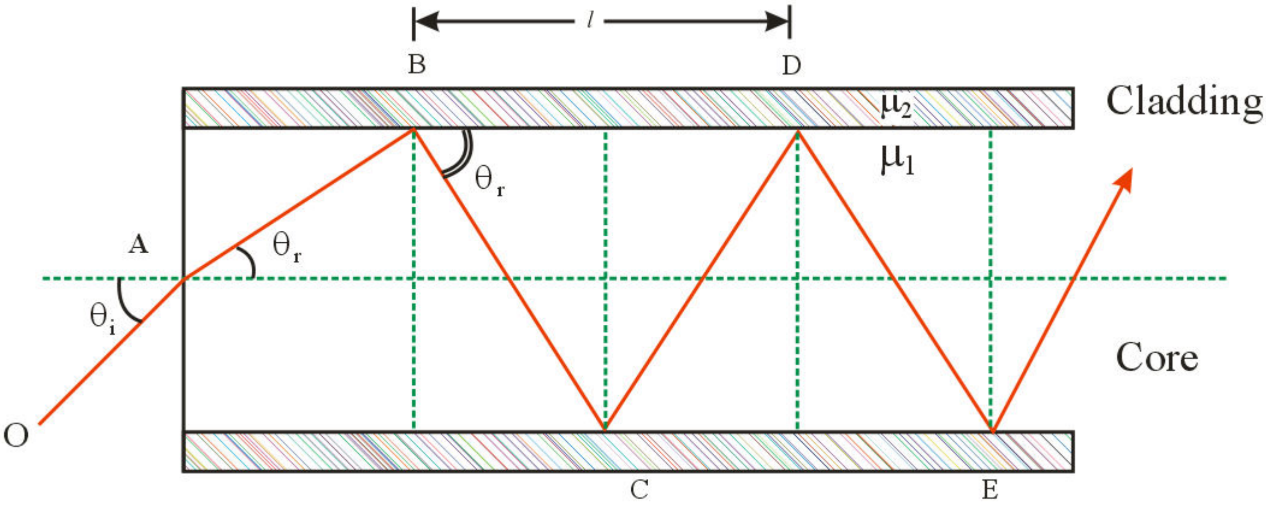
5. **Temperature Changes:** A temperature change from 0 to 60 ℃ could add as much as $5\ dB$ to the cable losses. Stress (Strain and tension) could add another $10\ dB$.

6. **Attenuation Losses:** Attenuation losses of an optical fiber is defined as the ratio of optical output power $P_{out}$ from a fiber of length $L$ to the output power $P_{in}$. In symbol $\alpha$ is expressed attenuation in $decibel/km$.

$$\alpha = \frac{10}{L}\log\left[\frac{P_{in}}{P_{out}}\right]$$

In case a fiber is an ideal when $P_{in} = P_{out}$, therefore $\alpha = 0$ which means that there will no attenuation loss. In actual practice, a low loss fiber may have $\alpha = 3\ dB/km$

# Calculation of dispersion for step indeed fiber:




Figure(7): Propagation of light through the optical fiber cable

$t$ is the time taken by ray to travel $BC + CD$ by velocity $v$ then

$$t = \frac{BC+CD}{v} \quad \text{..............................................} \quad (1)$$

If $\mu_1$ be the refractive index of core and $c$ is speed of light in vacuum, then

$$\mu_1 = \frac{c}{v}$$

$$v = \frac{c}{\mu_1}$$

From the figure in $\Delta ACG$

$$\frac{BC}{CG} = \sec \theta_r$$

$$\Rightarrow \quad BC = BG \sec \theta_r$$

and $$\frac{CD}{GD} = \sec \theta_r$$

$$\Rightarrow \quad CD = GD \sec \theta_r$$

Putting the values in equation (1) we get

$$t = \frac{(BG \sec \theta_r + GD \sec \theta_r)}{\left(\frac{c}{\mu_1}\right)}$$

$$= \frac{\mu_1 (BG + GD) \sec \theta_r}{c}$$

$$= \frac{\mu_1 l \sec \theta_r}{c} \quad \text{.............(2)}$$

As the ray in the fiber propagates by a series of total internal reflection at the interface, the time taken by the ray in traversing an axial length $l$ of the fiber will be

$$\tau = \frac{\mu_1 l}{c.\cos\theta_r} \quad \text{.......................................} \quad (3)$$

Time taken by rays making zero angle with fiber axis will be minimum i.e.

$$\tau_{min} = \frac{\mu_1 l}{c.\cos 0} = \frac{\mu_1 l}{c} \quad \text{........................} \quad (4)$$

The maximum time is given by

$$\tau_{max} = \frac{\mu_1 l}{c.\cos\theta_r} \quad \text{.......................................} \quad (5)$$

Now by Snell's law

$$\frac{\sin\theta_c}{\sin\theta_r} = \frac{\mu_2}{\mu_1}$$

But $\theta_r = 90$ for $\theta_i = \theta_c$ (i.e. critical angle)

$$\frac{\sin\theta_c}{\sin 90} = \frac{\mu_2}{\mu_1}$$

$$\sin\theta_c = \frac{\mu_2}{\mu_1} \quad \text{.............................................} \quad (6)$$

From the figure is clear that

$$\theta_c + \theta_r + 90 = 180$$

$$\theta_c = 90 - \theta_r$$

So by equation (8)

$$\sin(90 - \theta_r) = \frac{\mu_2}{\mu_1}$$

$$\cos\theta_r = \frac{\mu_2}{\mu_1} \quad \text{......................................} \quad (7)$$

Putting the value of $\cos\theta_r$ in equation (5)

$$\tau = \frac{\mu_1 l}{c.\left(\frac{\mu_2}{\mu_1}\right)}$$

$$\tau = \frac{\mu_1^2 l}{c.\mu_2}$$

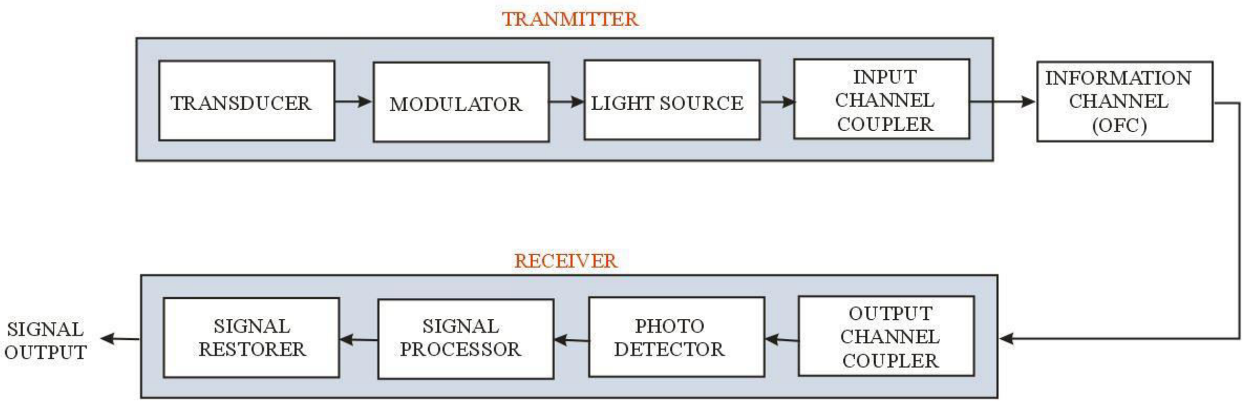
# Fibre Optics communication System:

The optical fibers are widely used for communication purpose. The fiber optics communication system is almost similar to ordinary communication system. Simply the systems consist of transmitter, information channel and recover.

## Transmitter:

The transmitter converts electrical signals (Information signal) into optical signals. Mainly transmitter consists of

1) Transducer: If input signal is other than the electrical signals, we use a transducer which consists a non-electrical message into electrical signal.
2) Modulator: The output of transducer is connected as the input of modulator, with the help of modulator electrical messages are converted into the desired form. There are two kinds of modulators; digital and analog.
3) Light source: The function of light source is to generate carrier waves on which the information signal is impressed and transmitted. The light sources used are light emitting diodes (LEDs) or LASER diodes. These are known as optical oscillators.
4) Input channel coupler: It transfers the signals to information channel i.e. optical fiber in a proper manner.
5) Information Channel: It is a link between transmitter and receiver.




Figure(8): The optical fiber communication system

## Receiver:

Receiver converts the signals into electrical signals; it consists of-

1) Output channel coupler: its main function is to direct the light emerging from optical fiber into the photodetector.
2) Photodetector: The photodetector converts the light wave into an electric current. The detector output includes the message, which is separated from the carrier in next step.

3) Signal processor: the information from the carrier wave is separated by signal processor includes amplifiers and filters. The optical signal, if needed, amplified and undesired frequencies are filtered by the processor.
4) Signal restorer: while traveling through the optical fiber the signal progressively attenuated and distorted due to various laser and dispersion occurring in the fiber. Thus the signal should be amplified and restorers are used for this purpose.