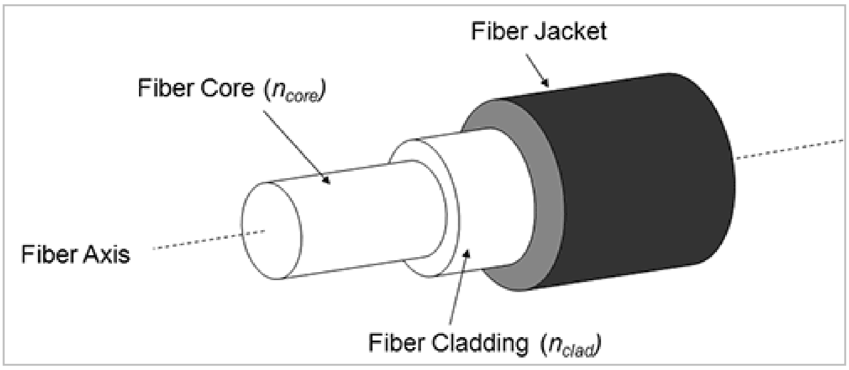
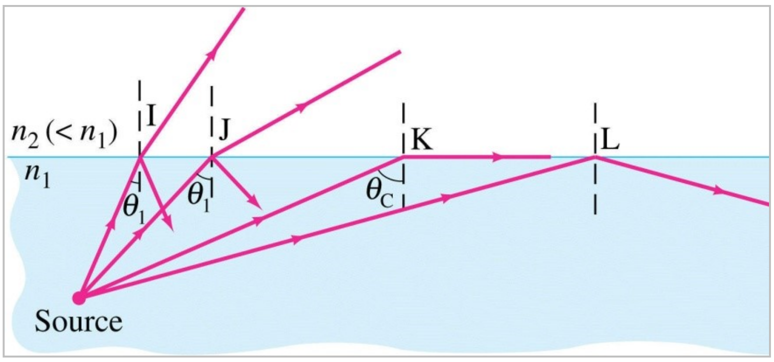
Optical Fibres

Construction: Optical fibre consists of mainly two parts. Inner cylindrical structure of refractive index n_1 is called **core** of the fibre. Outer concentric cylinder of refractive index n_2 is called **cladding ($n_2 < n_1$).** In addition, fibres are encapsulated in an elastic, abrasion resistant plastic material jacket called **sheath.**



Working: Basic principle of transmission of light through an optical fibre is **total internal reflection**.

- **Total Internal Reflection:** When light travels from denser to rarer medium and angle of incidence is greater than critical angle for the pair of media, the light gets reflected back in the denser medium. This phenomenon is known as total internal reflection.



- **Critical angle:** The angle of incidence in the denser medium for which angle of refraction in the rarer medium is 90º, is called critical angle for the pair of media.

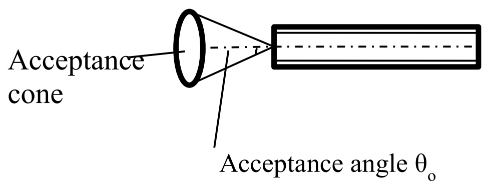
By Snell's law of refraction at critical incidence,

$$\mathbf{n_1 \sin \theta_c = n_2 \sin 90^o}$$

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

- **Acceptance angle (θ_o):** It is the maximum allowed angle that the incident ray can make with the fibre axis so that the light ray can pass through the fibre.

- **Acceptance cone:** It is the cone in which the light incident at acceptance angle or less than the acceptance angle can propagate through the fibre after total internal reflection.

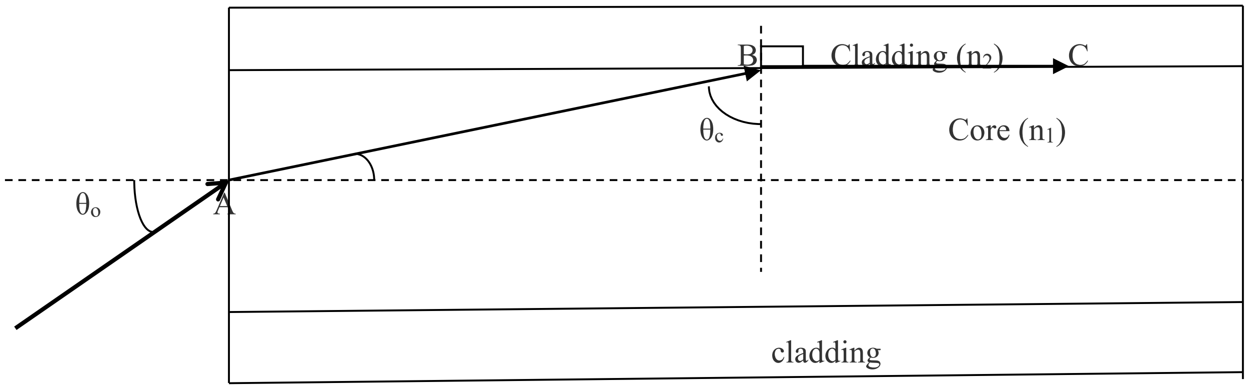


- **Numerical Aperture (NA):** It is a measure of light gathering capacity of the optical fibre. It is defined as the sine of acceptance angle.

  i.e. $\mathbf{NA = \sin \theta_o}$

- <u>**Expression for numerical aperture (NA):**</u>

  Let n_o, n_1 and n_2 be the refractive indices for surrounding medium, core and cladding respectively. Consider a ray of light OA incident at the on the fibre at acceptance angle θ_o. The refracted ray OB strikes core- cladding interface at an angle θ_c which is equal to critical angle for the pair of media and gets refracted along BC.



Applying Snell's law at point A,

$$n_o \sin \theta_o = n_1 \sin (90 - \theta_c) = n_1 \cos \theta_c \qquad \text{---------------- (1)}$$

Again applying Snell's law at point B,

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

$$\therefore \sin \theta_c = \frac{n_2}{n_1} \qquad \text{------------------ (2)}$$

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

Substituting $\cos \theta_c$ in eq. (1)

$$n_o \sin \theta_o = n_1 \sqrt{1 - \frac{n_2^2}{n_1^2}}$$

$$\sin \theta_o = \frac{\sqrt{n_1^2 - n_2^2}}{n_o}$$

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

If the surrounding medium is air, then $n_o = 1$

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

- **Condition of propagation:**

Light ray will propagate through the fiber if the angle of incidence $\theta_i \le \theta_o$

or $\sin \theta_i \le \sin \theta_o \le NA$

$\therefore$ $\theta_i \le \sin^{-1} (NA)$

- **Fractional index change (Δ):** It is the ratio of the refractive index difference between core and cladding to the refractive index of core of an optical fibre.

i.e. $$\Delta = \frac{n_1 - n_2}{n_1}$$

➢ **<u>Relation between NA and Δ:</u>**

$$\mathbf{NA} = \frac{\sqrt{n_1^2-n_2^2}}{n_o} = \frac{\sqrt{(n_1+n_2)(n_1-n_2)}}{n_o}$$

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

Since $\mathbf{n_1 \approx n_2}$, we can write $\mathbf{(n_1 + n_2) \approx 2n_1}$

Therefore $$\mathbf{NA}= \frac{\sqrt{2n_1.\Delta n_1}}{n_o} \approx \frac{n_1\sqrt{2\Delta}}{n_o}$$

- **Modes of propagation:** Modes can be visualized as the possible number of paths for light rays in an optical fibre.

- **V- number (or) Normalized frequency:** V-number of an optical fibre is defined as,

$$\mathbf{V}= \frac{\pi d}{\lambda}\,\mathbf{(NA)} = \frac{\pi d}{\lambda}\frac{\sqrt{n_1^2-n_2^2}}{n_o}$$

where d= core diameter, λ= the wavelength of light propagating in the fibre.

The number of modes supported by the fibre, $\mathbf{N} \cong \frac{V^2}{2}$

- **Refractive index profile:** The graph showing the variation of refractive index with respect to radial distance from the axis of fibre is called the refractive index profile.

➢ **Types of Optical Fibres:** Depending on refractive index profile, optical fibres can be classified as

(1) Step index fibre: In the step index fibres, the refractive index of the core is uniform throughout and undergoes an abrupt change at the core-cladding interface. Thus the refractive index profile takes the shape of a step.

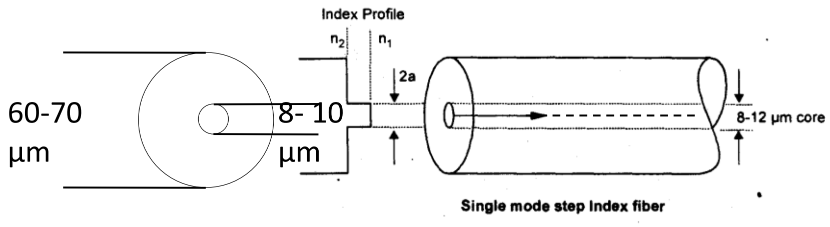
Variation of refractive index as a function of distance from the axis of fiber is given by,

$$\begin{aligned} \mathbf{n(r)} &= \mathbf{n_1} \;\; \textbf{for } r < a \\ &= \mathbf{n_2} \;\; \textbf{for } r \geq a \end{aligned}$$

Step index fibres can further be classified as single mode fibres and multimode fibres.

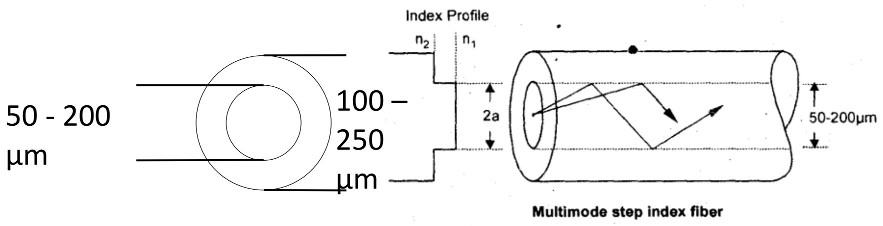
(i) Single mode fibres: In single mode fibres, the diameter of core is 8 to 10 µm and cladding diameter is 60 to 70 µm. It can guide just a single mode.

Applications: submarine cable system



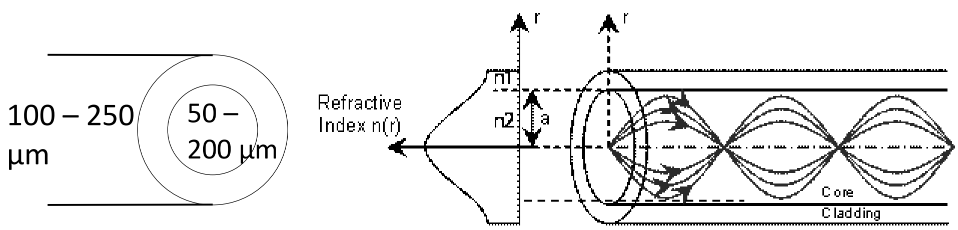
(ii) Step index multimode fibres: The diameter of core is 50 – 200 µm and of cladding 100 - 250 µm. It can support a large number of modes for propagation. The modes are zig-zag paths.

Applications: data links



(2) Graded index fibre (GRIN): In this fibre, the refractive index of core decreases in the outward direction from the axis and becomes equal to that of the cladding at the interface. The light paths are not zig- zag but they are like sinusoidal waves as shown in the figure.

Applications: telephone trunk between central offices.



The light rays travel along the region of lower refractive index faster as compared to light travelling in the region of high refractive index, hence all the pulses of signals will reach at the other end of fiber simultaneously. Thus the problem of intermodal dispersion can be reduced to a large extent and attenuation is less in graded index fiber.

Attenuation:

The loss of optical power suffered by a signal as it propagates through the fibre is called attenuation.

$$\textbf{Attenuation coefficient,}\quad \alpha = \frac{10}{L}\ \log\frac{Pi}{Po} \quad \text{dB km}^{-1}$$

where P_i = Input Power, P_o= Power output, L= length of the fibre in km.

- **Causes (or) mechanisms of attenuation:**

Attenuation in an optical fibre happens by several factors.

(1) Absorption losses: Absorption losses occur when signal photons interact with electrons in the core of fibre and excite them to higher energy levels.

Absorption losses are of two types.

(a) Intrinsic absorption: It occurs due to absorption by the core material itself. The vibrations of the constituent Si-O atoms absorb optical wavelengths. Intrinsic absorption is very strong in the ultraviolet portion of electromagnetic spectrum.

(b) Extrinsic absorption: Extrinsic absorption is caused by the presence of impurities like iron, cobalt, chromium, copper and OH ions in glass material. These impurities are incorporated during the fabrication process and it is very hard to eliminate them.

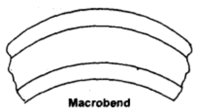
(2) Scattering losses: Scattering losses occur due to in-homogeneities and structural defects present in the fibre.

(a) Rayleigh Scattering: Rayleigh scattering is caused by in-homogeneities that are small compared to the wavelength of light. These in-homogeneities are formed due to density and compositional variation in the core and lead to local variations in the refractive index. Rayleigh scattering is inversely proportional to λ^4. Thus scattering losses are very high for shorter wavelengths.

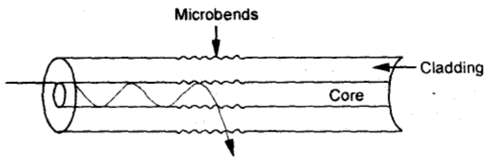
(b) Mie Scattering: Non perfect cylindrical structure of the fiber and imperfections like irregularities in the core-cladding interface, diameter fluctuations, strains and bubbles may cause scattering of light which is termed as Mie scattering.

(3) Bending losses: A bend in the fibre may result in the modification of the angle of incidence and leads to signal loss.

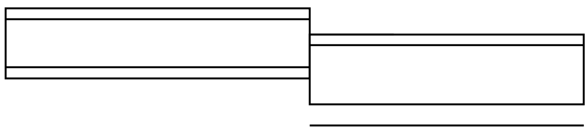
(a) Macro bending losses: Macro bends are the bends having radii that are large compared to the fiber diameter e.g. such bends occur when a fibre cable turns a corner.

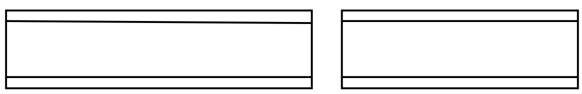


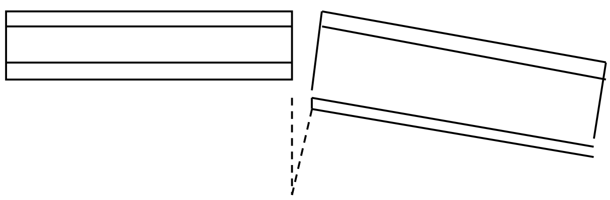
(b) Micro bending losses: These bends are repetitive small-scale fluctuations in linearity of the fibre axis or core-clad interface. They occur due to manufacturing defects or non-uniform lateral pressures created during the cabling of the fibre.



(4) Coupling Losses- For some applications, the optical fibres have to be laid over very large distances then it becomes necessary to interconnect two fibres which are usually of a kilometre length. When the fibres are interconnected, losses occur due to mechanical misalignment.


Lateral misalignment

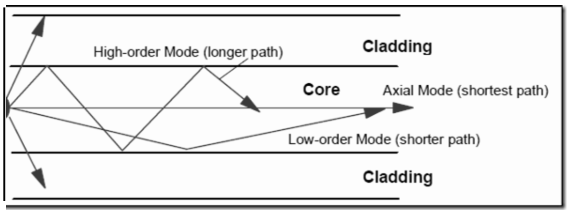

Longitudinal misalignment


Angular misalignment

➢ **<u>Dispersion in optical fibres</u>:**

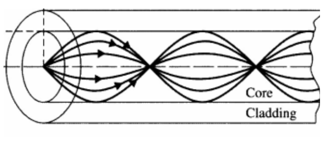
It is spreading of optical pulses as they travel down the fibre.

(1) Inter modal dispersion/ Modal dispersion: When light travels in the step-index multimode fibre, each ray of light is reflected many times. The higher order modes (rays reflected at high angles) travel a longer distance than the lower order modes to reach the end of the fibre. Hence the higher order modes arrive a little later than the lower order modes and hence pulses broaden causing signal distortion.



- **Elimination of Inter modal dispersion in Graded index fiber (GRIN):**

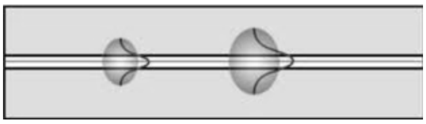
In graded index fiber (GRIN), light rays travel at different speeds in different parts of the fiber because refractive index varies across the core. The rays near the outer edge of core travel faster because of low refractive index than the rays in the centre of the core. As a result, both higher order and lower order modes arrive at the same time at the other end of the fiber, thus eliminating the inter modal dispersion. Light rays propagating through it are in the form of **skew rays** (or) helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical (or) spiral manner as shown in fig.



(2) Intra modal dispersion: It can further be classified as,

(a) **Material dispersion-** Light waves of different wavelengths travel at different speeds in a medium. The short wavelengths travel slower than long wavelengths. Consequently, pulses of light tend to broaden as they travel down the fibre. Material dispersion occurs in all type of fibres. This can be eliminated using monochromatic light sources like Laser.

(b) **Waveguide dispersion**- It is caused by the different refractive indices of the core and cladding of an optical fibre. Regardless of the nature of the light source and optical fibre, some light travels in the cladding as well. The light propagating in the cladding travels faster than the light confined to the core and hence broadening of pulses occurs.



- **<u>Optical communication system</u>:**

The block diagram shown below depicts the general form of point to point optical communication system.

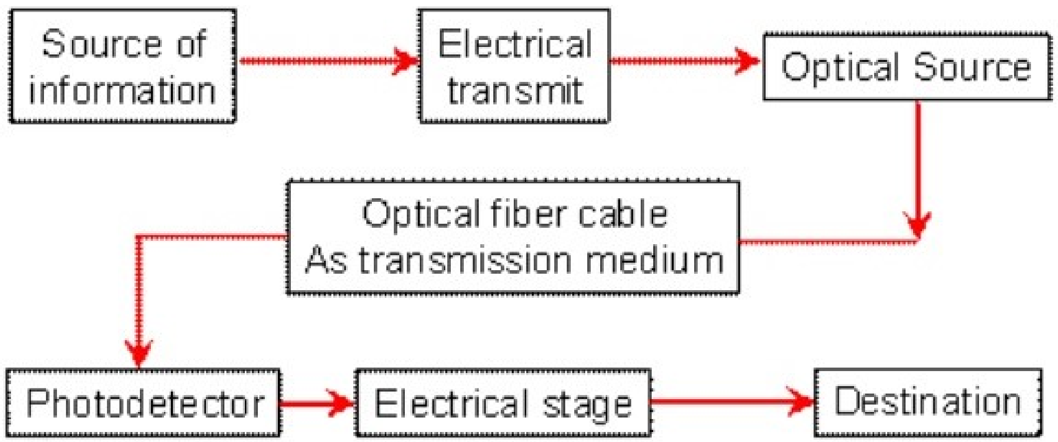


Figure: Basic Block Diagram of Optical Communication System

The electrical transmitter converts the message (information) into electrical signal. The optical source converts electrical signal into optical signal. The optical source may be a laser diode or light emitting diode (LED). This intensity modulated light signal is coupled in to an optical fibre. The optical fibre acts as a channel between transmitter and receiver. At the receiver end, the optical signal is detected by detectors such as PIN diode or photo diode. Now again the electrical transducer processes the signal and reconstructs the original message for delivering it to the user.

- **Advantages of optical fiber communication over electrical communication:**

  1. **Broad bandwidth:** Information band width of optical fibres is very high. A single optical fiber can carry over 3,000,000 full-duplex voice calls or 90,000 TV channels.
  2. **Immunity to electromagnetic interference:** Light transmission through optical fibers is unaffected by other electromagnetic radiation nearby. The optical fiber is electrically non-conductive, so it does not act as an antenna to pick up electromagnetic signals.
  3. **Low attenuation loss over long distances:** Attenuation loss can be as low as 0.2 dB/km in optical fiber cables, allowing transmission over long distances without the need for repeaters.
  4. **Electrical insulator:** Optical fibers do not conduct electricity, preventing problems with ground loops and conduction of lightning. Optical fibers can be strung on poles alongside high voltage power cables. There is no risk of short circuit in fibres.
  5. **Material cost and maintenance:** Optical fibres are small in size and light in weight and also they are cheaper than copper cables. Optical fibres are more reliable and easy to maintain.
  6. **Security of information passed down the cable:** Cross talk and internal noise is eliminated in optical fibres. Tapping of information from optical fibres is not possible.