Optical Fibre

An optical fiber is a waveguide made of dielectric material which guides light waves along its length by total internal reflection. It has a central core in which the light is guided, embedded in an outer cladding of slightly lower refractive index than that of core which is shown in Fig. 1. Light rays incident on the core-cladding boundary at angles greater than the critical angle undergo total internal reflection and are guided through the core without refraction. The diameter of the core is few order of μm.

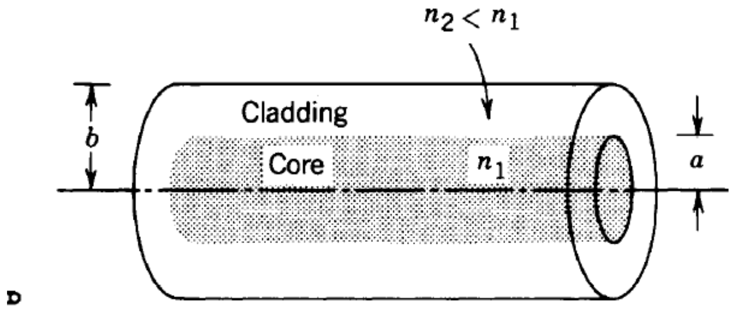


Fig. 1: An optical fibre is a dielectric waveguide.

Principles of optical fibre: The propagation of light in an optical fibre from one end to its other end is based on the principle of total internal reflection. When light enters one end of the fibre it undergoes successive total internal reflection from the sidewalls and travels down the length of the fibre along a zigzag path.

When an electromagnetic wave travels from a denser to a rarer medium, it is bent away from the normal in the rarer medium which is shown in Figure 2 (a). When the incident angle is greater than the critical angle, total internal reflection occurs, as shown in Fig. 2(c).

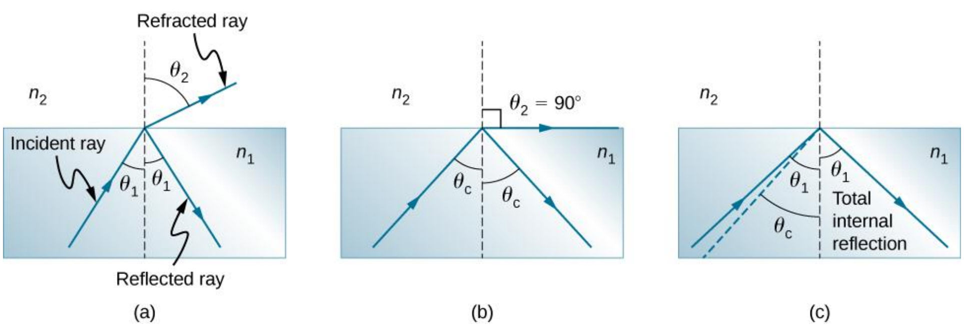


Fig.2: Phenomenon of total internal reflection. Here $n_1 > n_2$

Structure: A practical optical fibre is cylindrical in shape and composed primarily of three coaxial regions. These are the core, cladding, and a protective buffer layer.

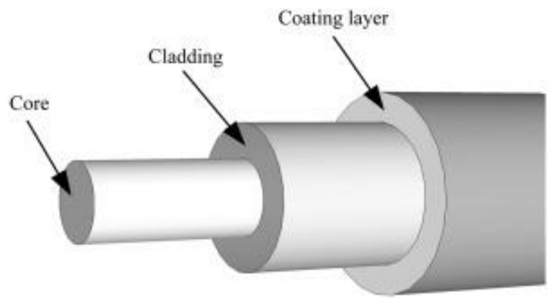


Fig. 2: Structure of an optical fiber.

Core: The innermost cylindrical region is the light-guiding region known as the core. Typically, the diameter of the core is of the order of 8.5 µm to 62.5 µm.

Cladding: It is surrounded by a coaxial middle region known as the cladding. The diameter of the cladding is of the order of 125 µm. The refractive index of the cladding should be lower than the core. The primary object of the cladding is to confine the light inside the core to propagate through the fibre.

Protective buffer coating: The outermost region is called protective buffer layer. It is plastic coating applied during the manufacturing process to provide physical and environmental protection for the fibre.

Propagation of Light in Optical Fibre:

Light propagates as an electromagnetic wave through an optical fibre. However, the light propagation through an optical fibre can also be understood on the basis of ray model. According to the ray model, light rays entering the fibre strike the core-clad interface at different angles. As the refractive index of the cladding is lower than that of the core, majority of the rays undergo total internal reflection at the interface and the angle of reflection is equal to the angle of incidence in each case. Thus the rays travel forward direction through the fibre via a series of total internal reflections and emerge out from the exit end of the fibre, which is shown in Fig. 3. Since there is minimal loss of energy due to total internal reflection, optical fibre can carry the light waves over very long distances.

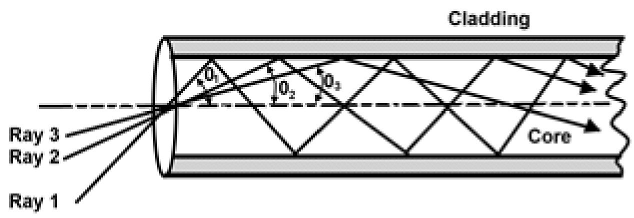


Fig. 3: Propagation of light rays through an optical fibre due to total internal reflection.

Therefore, light propagation through an optical fibre can occur only if the following two conditions are satisfied.

- The refractive index of the core material (n_1) must be little greater than that of the cladding (n_2).
- At the core cladding interface, the angle of incidence must be greater than the critical angle. Therefore, the rays incident at angles smaller than the critical angle are refracted into the cladding and are lost.

Acceptance angle and numerical aperture: Let us consider a step index optical fibre into which light is launched at one end as shown in Fig.4. Let the refractive indices for core and cladding be n_1 and n_2, respectively (n_1>n_2). Let n_0 be the refractive index of launching medium and θ_0 be the incident angle at the launching medium. The ray refracts at an angle θ and strikes the core cladding interface at angle φ. If $\varphi > \varphi_c$ (critical angle) then light rays undergo total internal reflection at the interface.

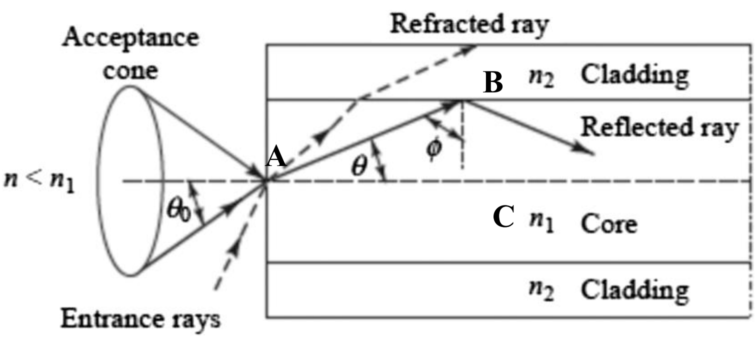


Fig. 4: Geometry for calculation of acceptance angle and numerical aperture of the fibre.

Applying Snell's law at the launching face of the fibre, we get

$$\frac{\sin\theta_0}{\sin\theta} = \frac{n_1}{n} \tag{3}$$

The largest value of θ_0 occurs when $\varphi=\varphi_c$

From ΔABC, It is seen that

$$\sin\theta = \sin(90^0 - \phi) = \cos\varphi \qquad (4)$$

Using equation (4) in (3), we get

$$\sin\theta = \frac{n_1}{n}\cos\phi$$

when $\varphi=\varphi_c$

$$\sin\theta_{0\max} = \frac{n_1}{n}\cos\phi_c$$

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

$$\cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

$$\sin\theta_{0\max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \qquad (5)$$

$$\theta_{0\max} = \sin^{-1}\frac{\sqrt{n_1^2 - n_2^2}}{n_0} \qquad (6)$$

If the launching medium is air, then $n_0=1$

Then $\theta_{0max} = sin^{-1}\sqrt{n_1^2 \_ n_2^2}$ (7)

The angle θ_0 is called the acceptance angle of the fibre.

Acceptance angle is the maximum angle that a light ray can have relative to the axis of the fibre and propagate down the fibre.

In three dimensions, the light rays contained within the cone having a full angle $2\theta_0$ are accepted and transmitted along the fibre (shown in Fig 4). Therefore, the cone is called acceptance cone.

Numerical Aperture (NA):

The sin of acceptance angle is the numerical aperture. The light gathering ability or capacity of a fibre is determined by the NA. More NA means more efficient fiber. Thus

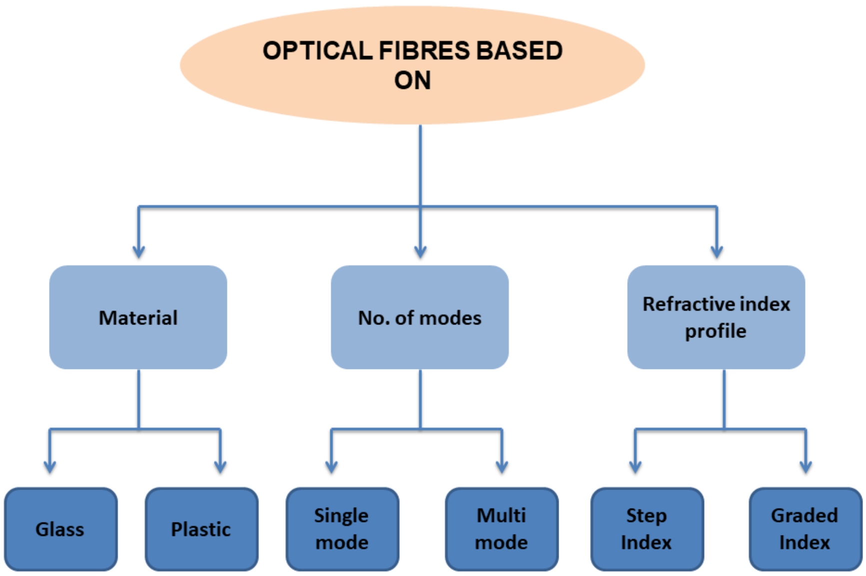
$$NA = \sin\theta_0$$

$$\sin\theta_0 = \sqrt{n_1^2 - n_2^2}$$

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

It is seen that NA is dependent only on the refractive indices of the core and cladding material and does not depend on the physical dimension of the fibre. A large NA implies that a fibre will accept large amount of light from the source.

Classification of Optical Fibre:



Classification Based on Material: On the basis of materials used for core and cladding, optical fibres are classified into three categories.

(a) Glass/glass fibres (glass core with glass cladding)

The basic material for fabrication of optical fibres is silica (SiO_2). Material having slightly different refractive index is obtained by doping the basic silica material with small quantities of various oxides. For example, if the basic silica material is doped with Germania oxide (GeO_2) or phosphorous pentoxide (P_2O_5), the refractive index of the material increase. Such material are used as core material and pure silica as used as cladding material. The glass optical fibres exhibit very low losses and are used in long distance communications.

(b) Plastic/plastic fibres (plastic core with plastic cladding)

Poly(methyl methacrylate) (PMMA) and polystyrene are used for core. A fluorocarbon polymer or silicon resin is used as a cladding material. A high refractive index difference is achieved between the core and the cladding materials. Therefore plastic fibres have large NA of the order of 0.6 and large acceptance angle up 70^0. The main advantages of the plastic fibre are low cost and higher mechanical flexibility. However, they're temperature sensitive and exhibit very high loss. Therefore, they are used in low cost application and at temperature bellow 80^0C.

(c) **PCS (Polymer clad silica)**

The plastic clad silica fibres are composed of silica cores and surrounded by a low refractive index transparent polymer as cladding. The core is made from high purity quartz. The cladding is made of silicon resin having a refractive index of 1.338. The plastic cladding is less expensive but has high losses. Therefore, they are mainly used in short distance communication.

Classification of Fibre based on propagation mode:

Single mode Fibre: In single-mode fibre, light can travel in a single path that is along the axis of the fibre. In the case of single mode fibre, we can have waves with different frequencies but of the same mode.

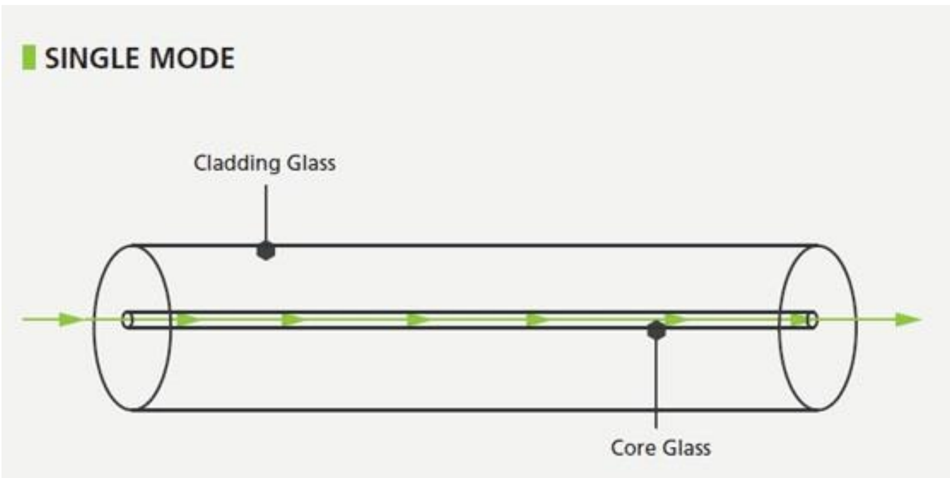


Fig. 5: Light propagation in a single mode fibre

Multimode Fibre: In this case light follows a number of paths to propagate through the fibre. The core size of multimode fibre is much larger than that in single mode fibre as shown in Fig.6

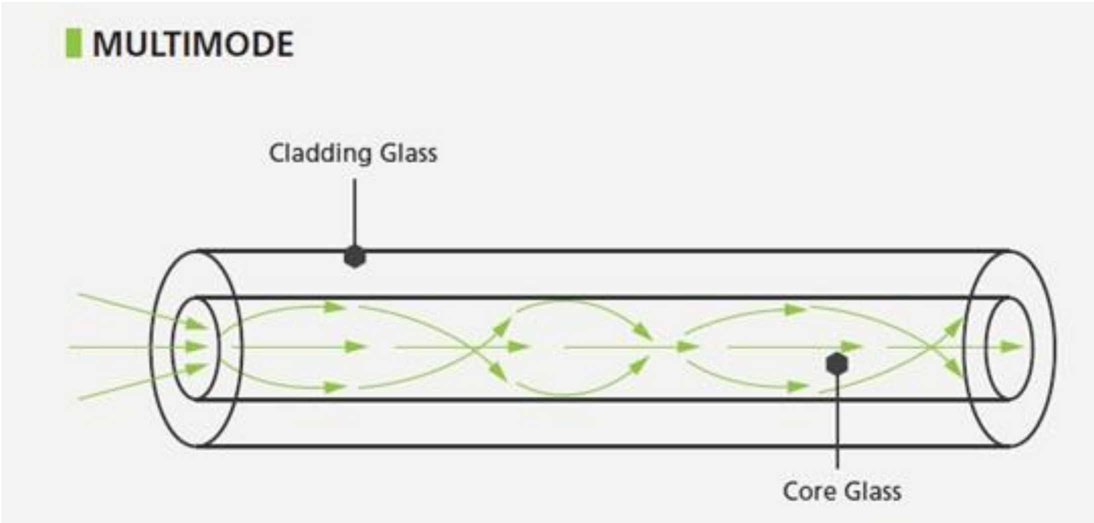


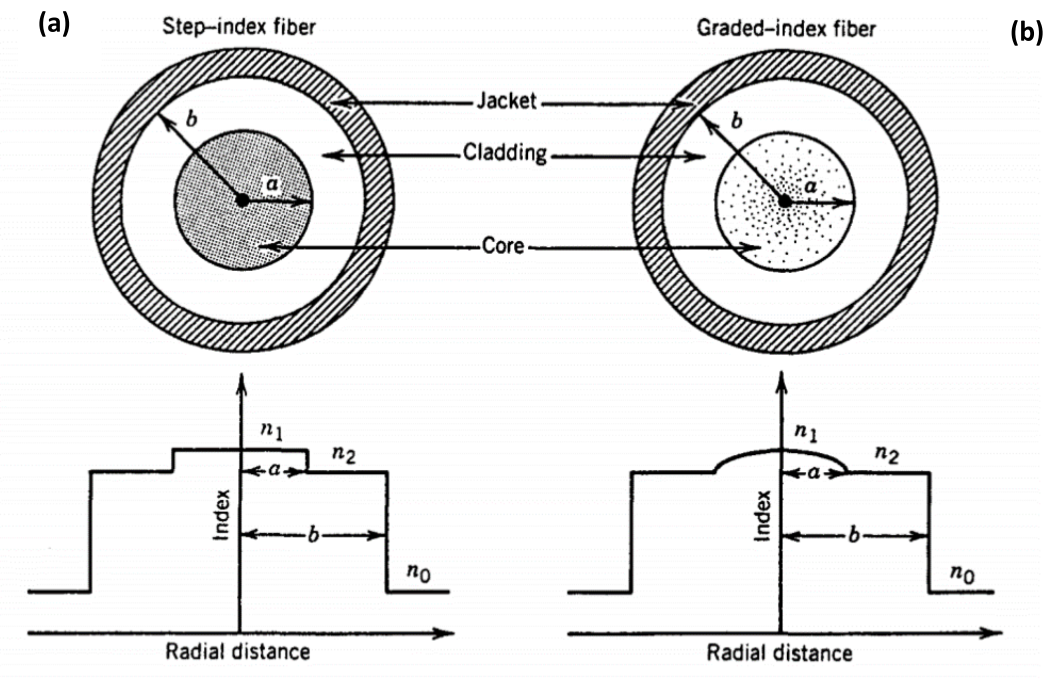
Fig. 6: Light propagation through multimode fibre.

Classification based on refractive index profile:

Refractive index profile of an optical fibre is basically a plot of refractive index in one axis and the distance from the core axis drawn on the other axis. Optical fibre is divided into two categories based on the refractive index profile.

(a) **Step index fibre:** In this fibre, the refractive index of the core is constant along the radial direction and abruptly falls to a lower value at the core-cladding boundary which is shown in Fig. 6(a)

(b) **Graded index fibre (GRIN):** In GRIN Fibres, the refractive index of the core is not constant but varies smoothly over the diameter of the core. It has a maximum value at the center and decreases gradually towards the core-cladding boundary. The refractive index of cladding is constant as shown in Fig. 6(b)



Cross section and refractive-index profile for step-index and graded-index fibers.

Fig. 6: Refractive index profile of (a) step index fibre (b) graded index fibre (GRIN)