FIBRE OPTICS

2.8 Introduction

Fibre optics is a technology in which information is transmitted from one place to another with the help of an optical signal propagating through optical fibres. Optical fibres are used to transmit light signals over long distances.

An optical fibre is defined as a dielectric waveguide that confines light energy to within its surface and guides it in a direction parallel to its axis.

2.9 Principle of Fibre Optics : Total Internal Reflection

- The optical beam is made to travel through the optical fibre not by the simple mode of transmission but by the principle of total internal reflection.
- Whenever a ray of light comes from a rarer medium (of refractive index μ_1) and enters a denser medium (of r.i., $\mu_2 > \mu_1$) it bends towards the normal as shown in

Fig. 2.19 (a). In this case, the angle of refraction, $\theta < i$, the angle of incidence and Snell's law is written as

$$\frac{\sin i}{\sin \theta} = \frac{\mu_2}{\mu_1} > 1 \quad \text{.................. (2.10-a)}$$

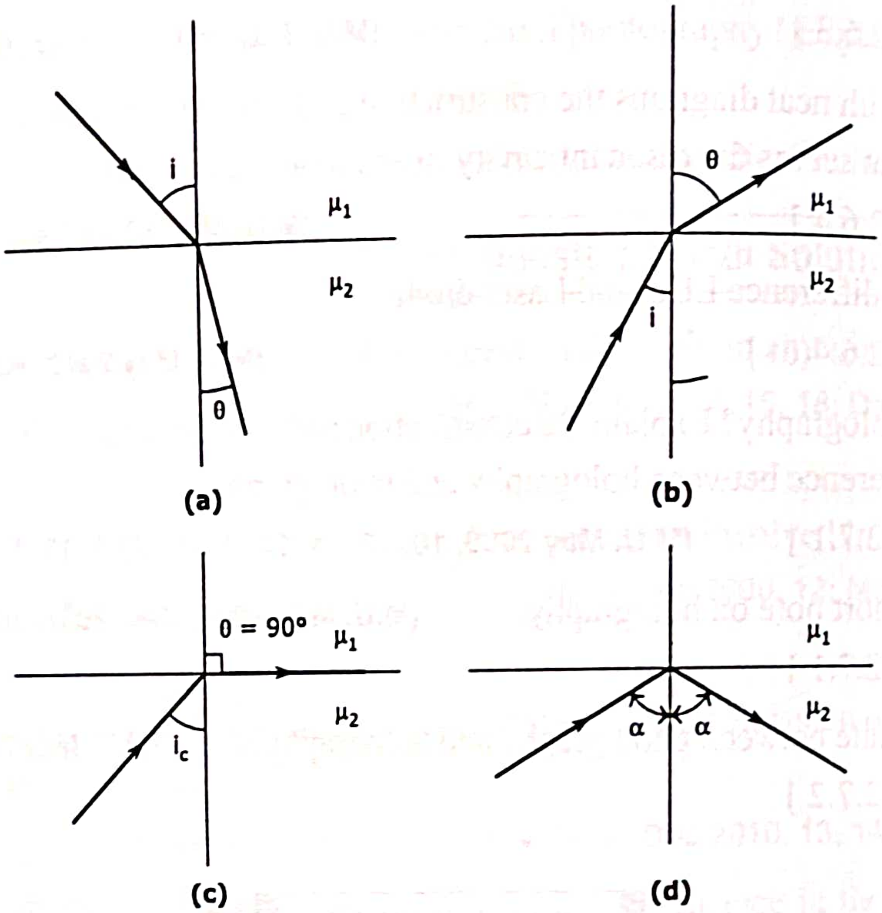


Fig. 2.19

- On the otherhand, if a ray of light falls on a denser surface after passing through a rarer medium, the refracted ray bends away from the normal on the interface [Fig. 2.19 (b)] In this case

$$\theta > i$$

and Snell's law becomes

$$\frac{\sin i}{\sin \theta} = \frac{\mu_1}{\mu_2} < 1 \quad \text{.................. (2.10-b)}$$

- Now, if the angle of incidence, i is gradually increased, the angle of refraction, θ also increases and a time comes when θ becomes equal to 90° [See Fig. 2.19 (c)]. The angle of incidence for $\theta = 90°$ is called the ***critical angle, i_c***. In this case, Snell's law is written as

$$\sin i_c = \frac{\mu_1}{\mu_2} < 1 \quad \text{.................. (2.10-c)}$$

- Finally, if a ray of light in denser medium is incident on the interface at an angle of incidence, $i > i_c$, the critical angle the light is reflected back into the denser medium [See Fig. 2.19 (d)]. This reflection is termed as ***total internal reflection***. The minimum angle of incidence for total internal reflection is

$$\alpha_{min} = i_c$$

and Snell's law becomes

$$\sin \alpha_{min} = \frac{\mu_1}{\mu_2} \qquad \text{.................... (2.10-d)}$$

- In ordinary reflection 4% of the incident energy is absorbed by the interface due to refraction and absorption at every incidence but in the case of total internal reflection total incident energy is reflected back to the medium.

  This is why, using the principle of total internal reflection, optical signals are transmitted through optical fibres without any significant loss of energy. The emergent beam is as intense as the incident beam.

- In a typical optical fibre about 2 m long, a ray undergoes about 45,000 reflections. Visible light can be transmitted successfully over a length of about 50 m through a single fibre.

  For long distance transmission couplers are used to join several fibre pieces.

2.10 Basic Construction of Optical Fibres

- The transmission properties of an optical fibre depends on its structural properties. In the most widely accepted structure, an optical fibre consists of an inner solid dielectric cylinder made up of high-silica-content glass known as the ***core*** of the fibre. The core is surrounded by a solid cylindrical dielectric shell, generally made up of law-silica-content glass or plastic. This is known as ***cladding*** as shown in Fig. 2.20.

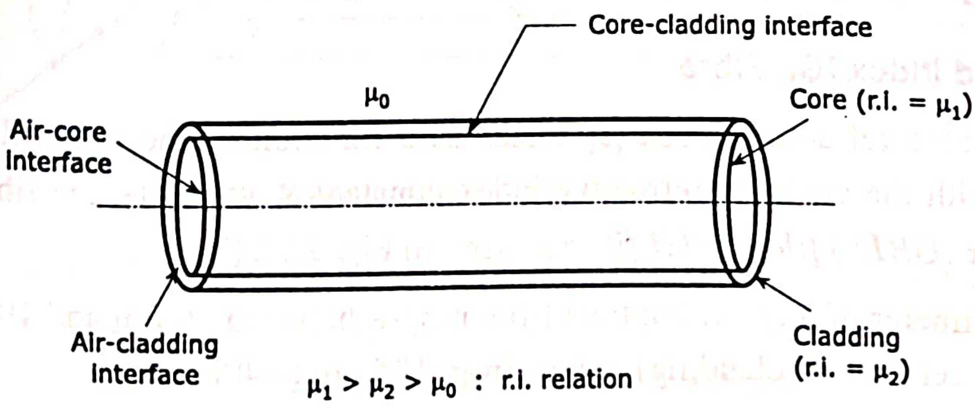
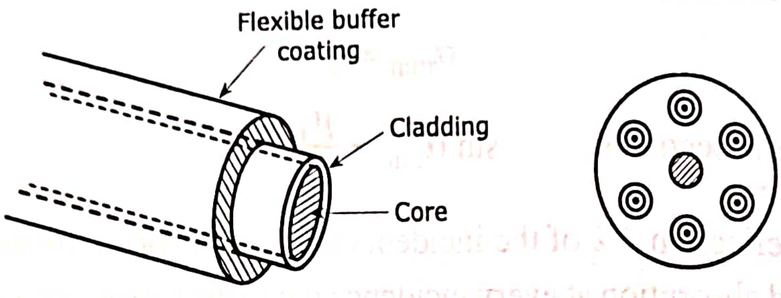


Fig. 2.20 : Structure of optical fibre

- The outermost region of an optical fibre is called the ***buffer coating***. It is a plastic coating given to the cladding for extra protection. The buffer is elastic in nature and prevents abrasions as shown in Fig. 2.21.



(a) Single optical fibre **(b)** Multi fibre cable

Fig. 2.21

- Hence, the function of the three regions of an optical fibre can be summarized as follows ;
  - (i) Core : used to carry light.
  - (ii) Cladding : confines the light to the core
  - (iii) Buffer coating : protects the fibre from physical damage and environmental effects.

2.10.1 : Step Index and Graded Index Fibres and their Refractive Index Profiles

Optical fibres may be classified in terms of their refractive index profiles as follows :

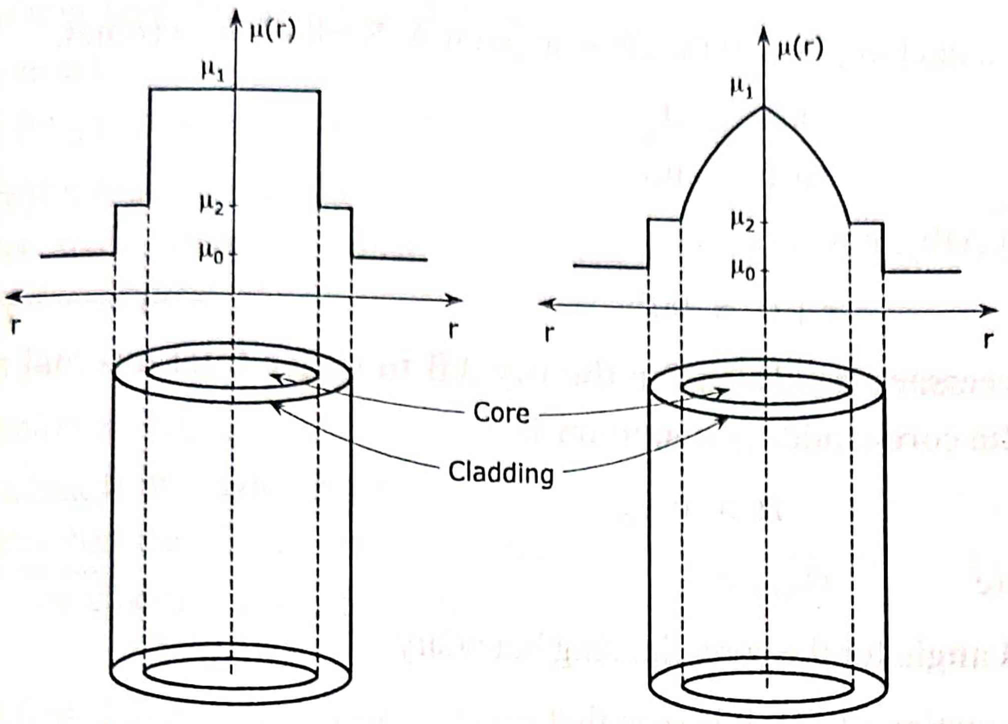
(A) Step Index (SI) Fibre

If the core refractive index remains constant at value μ_1 throughout the core region and abruptly drops to the cladding refractive index μ_2 at the core-cladding boundary it is known as ***step index fibre*** or ***SI fibre*** as shown in Fig. 2.22 (a).

(B) Graded Index (GI) Fibre

If the core refractive index μ_1 varies as a function of the radial distance 'r' as $\mu_1 = \mu_1(r)$ with the cladding refractive index constant at value μ_2, the fibre is called a ***graded index (GRIN) fibre*** or ***GI fibre*** as seen in Fig. 2.22 (b).

The diameter of a typical optical fibre ranges between 10 μm and 100 μm and the overall diameter (core + cladding) ranges from 125 μm to 400 μm.



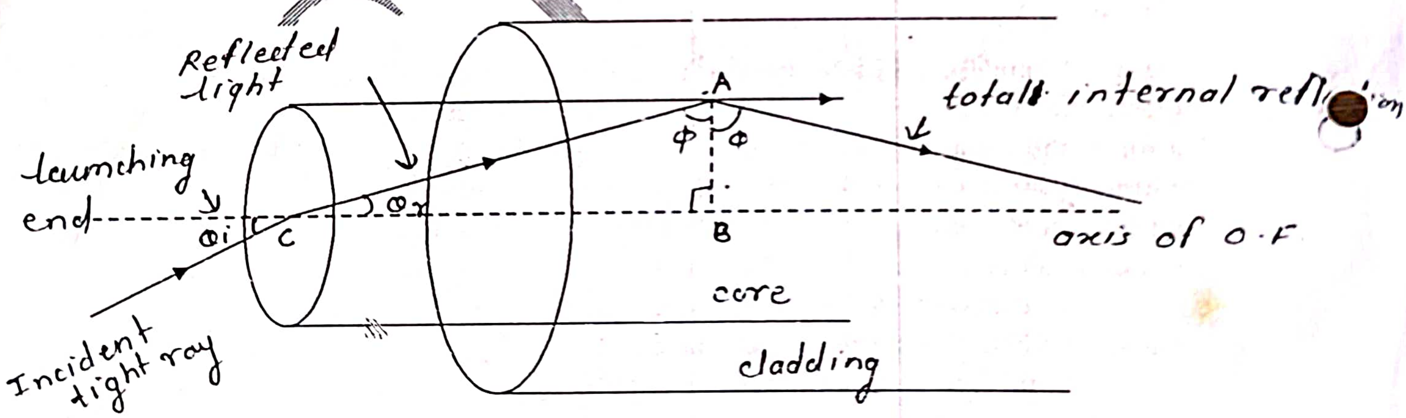
(a) Step index fibre

(b) Graded index fibre

Fig. 2.22 : Refractive index profile

Acceptance angle

Consider a step index optical fibre into which light is launched at one end, as shown in Fig. Let the refractive index of the core be n_1 and the refractive index of the cladding be n_2 ($n_2 < n_1$). Let n_0 be the refractive index of the medium from which light is launched into the fibre. Assume that a light ray enters the fibre at an angle 'i' to the axis of the fibre. The ray refracts at an angle 'r' and strikes the core-cladding interface at an angle ϕ. If ϕ is greater than critical angle ϕ_c the ray undergoes total internal reflection at the interface, since $n_1 > n_2$. As long as the angle ϕ is greater than ϕ_c, the light will stay within the fibre.



Applying Snell's law to the launching face of fiber, we get

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_1}{n_0} \qquad \text{....... (1)}$$

Where n_0 is the R.I. of air.

If i is increased beyond a limit i.e. i_{max}, ϕ will drop below the critical value ϕ_c and the ray escapes from the sidewalls of the fibre. The largest value of i occurs when $\phi = \phi_c$. From the ΔABC, it is seen that

$$\sin r = \sin(90° - \phi) = \cos(\phi) \quad \text{....... (2)}$$

Using equation (2) into equation (1), we obtain

$$\sin i = \frac{n_1}{n_0}\cos\phi \quad \text{........ (3)}$$

When $\phi = \phi_c$ (critical angle), for $i = i_{max}$

$$\sin i_{max} = \frac{n_1}{n_0}\cos\phi_c \quad \text{......... (4)}$$

But

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

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

$$\cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \quad \text{........ (5)}$$

From equation (4) & (5), we get

$$\sin i_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \quad \text{......... (6)}$$

The incident ray is launched from air medium, for which $n_0 = 1$.

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

$$i_{max} = \sin^{-1}\sqrt{n_1^2 - n_2^2} \quad \text{......... (7)}$$

The angle i_{max} 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 $2i_{max}$ are accepted and transmitted along the fibre. Therefore, the cone is called the **acceptance cone.**

Light incident at an angle beyond i_{max} refracts through the cladding and the corresponding optical energy is lost. It is obvious that the larger the diameter of the core, the larger the acceptance angle.

Fractional refractive index change

The fractional difference Δ between the refractive indices of the core and the cladding is known as ***fractional refractive index change.*** It is expressed as

$$\Delta = \frac{n_1 - n_2}{n_1} \quad \text{........ (8)}$$

This parameter is always positive because n_1 must be larger than n_2 for the total internal reflection condition. In order to guide light rays effectively through a fibre, $\Delta <<< 1$. typically, Δ is of the order of 0.01.

Numerical aperture (N.A):

The main function of an optical fibre is to accept and transmit as much light from the source as possible. The light gathering ability of a fibre depends on two factors, namely core size and the numerical aperture. The acceptance angle and the fractional refractive index change determine the numerical aperture of fibre.

The numerical aperture (NA) is defined as the sine of the acceptance angle. Thus

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

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

$$n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2)$$

$$= \left(\frac{n_1 + n_2}{2}\right)\left(\frac{n_1 - n_2}{n_1}\right)(2n_1)$$

Approximating $\frac{n_1+n_2}{2} \cong n_1$ we can express the above relation as

$$n_1^2 - n_2^2 = 2n_1^2\Delta$$

It gives

$$NA = n_1\sqrt{2\Delta} \quad \text{.........} (9)$$

Numerical aperture determines the light gathering ability of the fibre. It is a measure of the amount of light that can be accepted by a fibre. It is seen from eq^n (9) that NA is dependent only on the refractive indices of the core and cladding materials and does not depend on the physical dimensions of the fibre. The value of NA ranges from 0.13 to 0.50. A large NA implies that a fibre will accept large amount of light from the source.

Types of optical fiber

	Step index fiber		Graded index fiber
1	Refractive index of the core- cladding is	1	Refractive index of the core is not

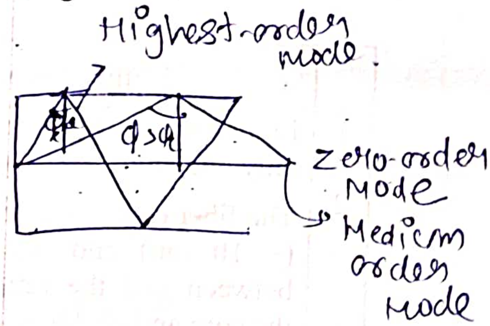
	uniform.		uniform. But, the refractive index of the cladding is uniform.
2	Since there is an abrupt change in the refractive index at the core and cladding interface, the refractive index profile takes the shape of a step. Hence, called step index fiber.	2	In this fiber, the refractive index of the core is maximum at the centre and decreases gradually (parabolic manner) with distance towards the outer edge. Hence, called graded index fiber.
3	Pulse dispersion is more in multi- mode step index fiber.	3	Pulse dispersion is reduced by a factor of 200 in comparison to step index.
4	Attenuation is less for single mode step index fiber and more for multimode step index fiber.	4	Attenuation is less.
5	Number of modes of propagation for a multimode step index fiber is given by $M_N = \frac{V^2}{2}$	5	Number of modes of propagation for a multimode graded index fiber is given by $M_N = \frac{V^2}{4}$ Thus, the number of modes is half the number supported by a MMSI fiber.

Normalized frequency (V – Number)

An optical fibre is characterized by one more important parameter, known as V-number. Which is more generally called **normalized frequency** of the fibre. The normalized frequency is a relation among the fibre size, the refractive indices, and the wavelength. It is given by

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

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



Where 'a' is the radius of the core

And λ is the free space wavelength.

As $\quad n_1\sqrt{2\Delta} = N.A$

We can write

$$V = \frac{2\pi a}{\lambda}(NA) \quad \ldots\ldots (11)$$

The V-number determines the number of modes that can propagate through a fibre. From above equation, the number of modes that propagate through a fibre increases with increase in the numerical aperture. However, the intermodal dispersion is proportional to the square of the N.A., and therefore, more modes imply more dispersion.

The maximum number of modes M_N supported by a multimode SI fibre is given by

$$M_N = \frac{V^2}{2}$$

While the number of modes in a GRIN fibre is about half that in a similar step-index fibre,

Given by
$$M_N = \frac{V^2}{4}$$

The axial modes are called zero order modes. The modes that propagate with $\phi = \phi_c$ are highest order modes.

The modes with $\phi > \phi_c$ are medium order modes.

2.13.1 : Fibre Optic Communication System

- Communication may be defined as the transfer of information from one place to another. For this a communication system is necessary.
- Within a communication system the information signal is superimposed on a carrier wave and the carrier wave is modulated by the information signal. The modulated carrier wave is then transmitted through the communication channel to the destination where it is received and demodulated to extract the original information.

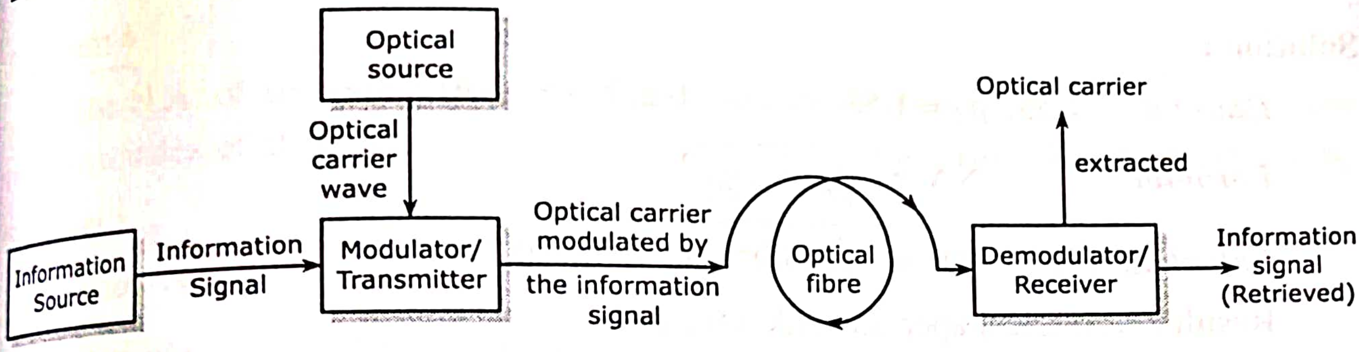


Fig. 2.29 : Optical fibre communication system

- The carrier waves are electromagnetic waves . Earlier there has been a frequent use of either the radio waves (frequency ~ 3 kHz to 300 GHz), the microwaves (frequency ~ 3 GHz to 30 GHz) or the millimeter waves (frequency ~ 30 GHz to 300 GHz), as a carrier wave.
- It has been found theoretically that the greater the carrier frequency, the larger is the transmission bandwidth and thus the information carrying capacity of the communication system.
- After the advent of laser in 1960, communication has become possible with an electromagnetic carrier selected from the optical range of frequencies.
- At higher optical frequencies (~ 10^{15} Hz) a large frequency bandwidth (~ 10^4 times the bandwidth available with a microwave carrier signal) and a high information carrying capacity (~ 10^5 times the information carrying capacity of a microwave carrier signal) are available.
- However, light energy gets dissipated in open atmosphere by inverse square law,

$$I \propto \frac{1}{d^2}$$

where 'I' is the intensity of the light beam and 'd' is the distance travelled. This dissipation is caused by the diffraction and scattering of light by dust particles, water vapour etc. and due to absorption in the medium.

- Hence, to transmit an optical carrier signal over a long distance a guiding channel is required. This is done by sending an optical beam or pulse through an optical fibre.