Study Material – Sem. 6 – C13T

– Optical Fibres – Dr. T. Kar

Fibre Optics

24.1. INTRODUCTION

In 1870 John Tyndall, a British physicist demonstrated that light can be guided along the curve of a stream of water. Owing to total internal reflections light gets confined to the water stream and the stream appears luminous. A luminous water stream is the precursor of an optical fibre. In the 1950's, the transmission of images through optical fibres was realized in practice. Hopkins and Kapany developed the flexible fibrescope, which was used by the medical world in remote illumination and viewing the interior of human body. It was Kapany who coined the term fibre optics. By 1960, it had been established that light could be guided by a glass fibre. In 1966 Charles Kao and George Hockham proposed the transmission of information over glass fibre, but the fibres available at that time heavily attenuated light propagating through them. In 1970 Corning Glass Works produced low-loss glass fibres. The invention of solid state lasers in 1970 made optical communications practicable. Commercial communication systems based on optical fibres made their appearance by 1977. Apart from the use as communicational channel, optical fibres are widely used in other areas. Fibro-scopes made of optical fibres are widely used in a variety of forms in medical diagnostics. Sensors for detecting electrical, mechanical, thermal energies are made using optical fibres.

Fibre optics is a technology in which signals are converted from electrical into optical signals, transmitted through a thin glass fibre and reconverted into electrical signals.

24.2 OPTICAL FIBRE

Definition: *An optical fibre is a cylindrical wave guide made of transparent dielectric, (glass or clear plastic), which guides light waves along its length by total internal reflection*. It is as thin as human hair, approximately 70 μm or 0.003 inch diameter. (Note that a thin strand of a metal is called a *wire* and a thin strand of dielectric materials is called a *fibre*).

Optical Fibre.

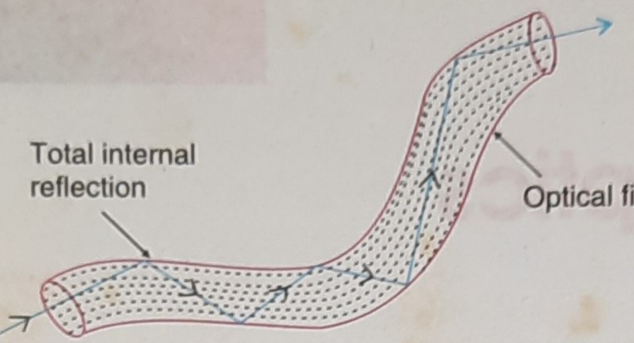
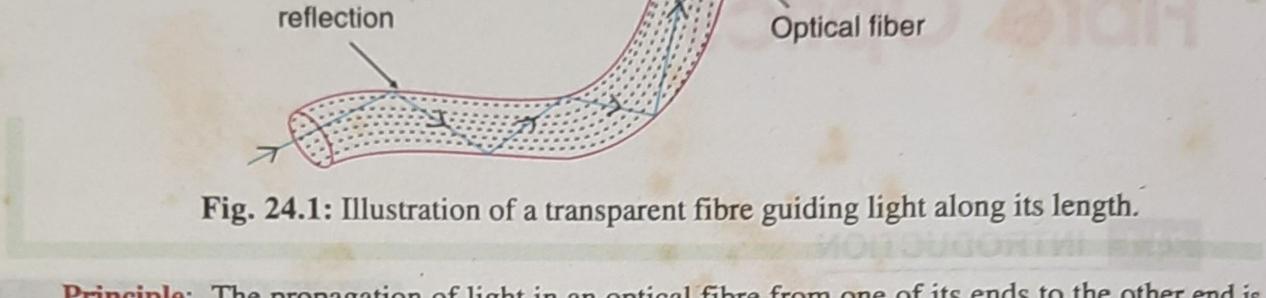


Fig. 24.1: Illustration of a transparent fibre guiding light along its length.

Principle: The propagation of light in an optical fibre from one of its ends to the other end is based on the principle of *total internal reflection*. When light enters one end of the fibre, it undergoes successive total internal reflections from sidewalls and travels down the length of the fibre along a zigzag path, as shown in Fig.24.1. A small fraction of light may escape through sidewalls but a major fraction emerges out from the exit end of the fibre, as illustrated in Fig. 24.1. Light can travel through fibre even if it is bent.

Structure:



(*a*) (*b*)

Fig. 24.2: Side view and cross sectional view of a typical optical fibre

A practical optical fibre is cylindrical in shape (Fig. 24.2a) and has in general three coaxial regions (Fig. 24.2b).

(*i*) The innermost cylindrical region is the light guiding region known as the **core**. In general, the diameter of the core is of the order of 8.5 μm to 62.5 μm.

(*ii*) 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 cladding (n_2) is always lower than that of the core (n_1). Light launched into the core and striking the core-to-cladding interface at an angle greater than critical angle will be reflected back into the core. Since the angles of incidence and reflection are equal, the light will continue to rebound and propagate through the fibre.

(iii) The outermost region is called the **sheath** or a **protective buffer coating.** It is a plastic coating given to the cladding for extra protection. This coating is applied during the manufacturing process to provide physical and environmental protection for the fiber. The buffer is elastic in nature and prevents abrasions. The coating can vary in size from 250 μm or 900 μm. To sum up

- Core is the inner light-carrying member.
- Cladding is the middle layer, which serves to confine the light to the core.
- Buffer coating surrounds the cladding, which protects the fibre from physical damage and environmental effects.

24.2.1 NECESSITY OF CLADDING

The actual fibre is very thin and light entering a bare fibre will travel along the fibre through repeated total internal reflections at the glass-air boundary. However, bare fibres are used only in certain applications. For use in communications and some other applications, the optical fibre is provided with a cladding. *The cladding maintains uniform size of the fibre, protects the walls of the fibre from chipping, and reduces the size of the cone of light that will be trapped in the fibre.*

- It is necessary that the diameter of an optical fibre remains constant throughout its length and is surrounded by the same medium. Any change in the thickness of the fibre or the medium outside the fibre (when the fibre gets wet due to moisture etc) will cause loss of light energy through the walls of the fibre.
- A very large number of reflections occur through the fibre and it is necessary that the condition for total internal reflection must be accurately met over the entire length of the fibre. If the surface of the glass fibre becomes scratched or chipped, the normal to the edge will no longer be uniform. As a result, the light traveling through the fibre will get scattered and escapes from the fibre. This also causes loss of light energy.
- Part of light energy penetrates the fibre surface. The intensity of the light decreases exponentially as we move away from the surface, as the light is able to penetrate only a very small distance outside the fibre. However, anytime the fibre touches something else, the light can leak into the new medium or be scattered away from the fibre. This effect causes a significant leakage of the light energy out of the fibre. Even a small amount of dust on the surface would cause a fair amount of leakage.
- If bare optic fibres are packed closely together in a bundle, light energy traveling through the individual fibres tends to get coupled through the phenomenon of *frustrated total internal reflection*. Cladding of sufficient thickness prevents the leakage of light energy from one fibre to the other.

  The fiber is provided with a cladding in order to prevent loss of light energy due to the above reasons.
- The cladding causes a reduction in the size of the cone of light that can be trapped in the fibre. Light entering the fibre at larger angles will strike the fibre walls at smaller angles (higher modes) and ultimately travel a longer distance. Such higher modes of a light signal will take longer time to reach the end of the fibre than the lower modes. Therefore, a pulse sent through optical fibre spreads out. The spreading would be larger, the larger the cone of acceptance. Such pulse spreading limits the rate of data transmission through the fibre. As fibers with a cladding have smaller cone of acceptance, they carry information at a much higher bit rate than those without a cladding.

Thus, the cladding performs the following important functions:

- Keeps the size of the fibre constant and reduces loss of light from the core into the surrounding air.
- Protects the fiber from physical damage and absorbing surface contaminants.
- Prevents leakage of light energy from the fibre through evanescent waves.
- Prevents leakage of light energy from the core through frustrated total internal reflection.
- Reduces the cone of acceptance and increases the rate of transmission of data.
- A solid cladding, instead of air, also makes it easier to add other protective layers over the fibre.

24.2.2 OPTICAL FIBRE SYSTEM

An optical fibre is used to transmit **light signals** over long distances. It is essentially a **light-transmitting medium**, its role being very much similar to a coaxial cable or wave-guide used in microwave communications. Optical fibre requires a **light source** for launching light into the fibre at its input end and a **photodetector** to receive light at its output end. As the diameter of the fibre is very small, the light source has to be dimensionally compatible with the fibre core. Light emitting diodes and laser diodes, which are very small in size, serve as the light sources. The electrical input signal is in general of digital form. It is converted into an optical signal by varying the current flowing through the light source. Hence, the intensity of the light emitted by the source is modulated with the input signal and the output will be in the form of light pulses. The light pulses constitute the signal that travels through the optical fibre. At the receiver end, semiconductor photodiodes, which are very small in size, are used for detection of these light pulses. The photodetector converts the optical signal into electrical form. Thus, a basic *optical fibre system* consists of a LED/laser diode, optical fibre cable and a semiconductor photodiode.

24.3 TOTAL INTERNAL REFLECTION

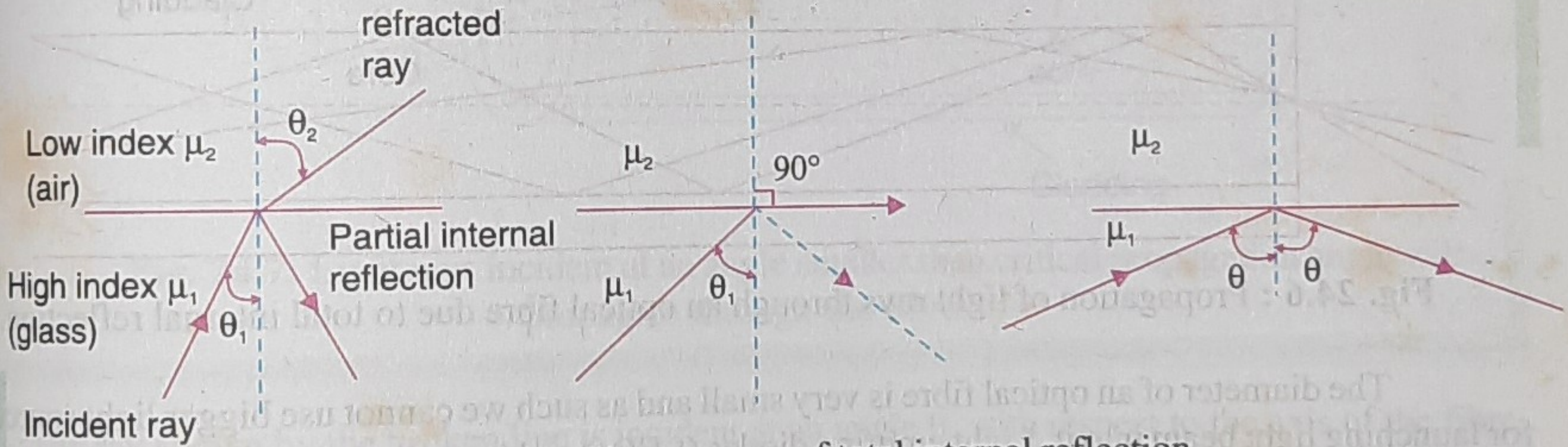


Fig. 24.5: Phenomenon of total internal reflection

A medium having a lower refractive index is said to be an optically **rarer medium** while a medium having a higher refractive index is known as an optically **denser medium**. When a ray of light passes from a denser medium to a rarer medium, it is bent away from the normal in the rarer medium (see Fig.24.5a). Snell's law for this case may be written as

$$\sin\theta_2 = \left(\frac{\mu_1}{\mu_2}\right)\sin\theta_1 \tag{24.1}$$

where θ_1 is the angle of incidence of light ray in the denser medium and θ_2 is the angle of refraction in the rarer medium. Also $\mu_1 > \mu_2$. When the angle of incidence, θ_1 in the denser medium is increased, the transmission angle, θ_2 increases and the refracted rays bend more and more away from the normal. At some particular angle θ_c the refracted ray glides along the boundary surface so that $\theta_2 = 90°$, as seen in Fig. 24.5(b). At angles greater than θ_c there are no refracted rays at all. The rays are reflected back into the denser medium as though they encountered a specular reflecting surface (Fig. 24.5c). Thus,

- If $\theta_1 < \theta_c$, the ray refracts into the rarer medium
- If $\theta_1 = \theta_c$, the ray just grazes the interface of rarer-to-denser media
- If $\theta_1 > \theta_c$, the ray is reflected back into the denser medium.

The phenomenon in which light is totally reflected from a denser-to-rarer medium boundary is known as **total internal reflection**. The rays that experience total internal reflection obey the laws of reflection. Therefore, the critical angle can be determined from Snell's law.

When $\theta_1 = \theta_c$, $\theta_2 = 90^o$.

Therefore, from equ.(24.1), we get

$$\mu_1 \sin\theta_c = \mu_2 \sin 90^o = \mu_2$$

$$\therefore \quad \sin\theta_c = \frac{\mu_2}{\mu_1} \tag{24.2}$$

When the rarer medium is air, $\mu_2 = 1$ and writing $\mu_1 = \mu$, we obtain

$$\sin\theta_c = \frac{1}{\mu} \tag{24.3}$$

A. Classification basing on refractive index profile:

Refractive index profile of an optical fibre is a plot of refractive index drawn on one of the axes and the distance from the core axis drawn on the other axis (see Fig. 24.14). Optical fibres are classified into the following two categories on the basis of refractive index profile.

1. Step index fibres and **2. Graded index (GRIN) fibres.**

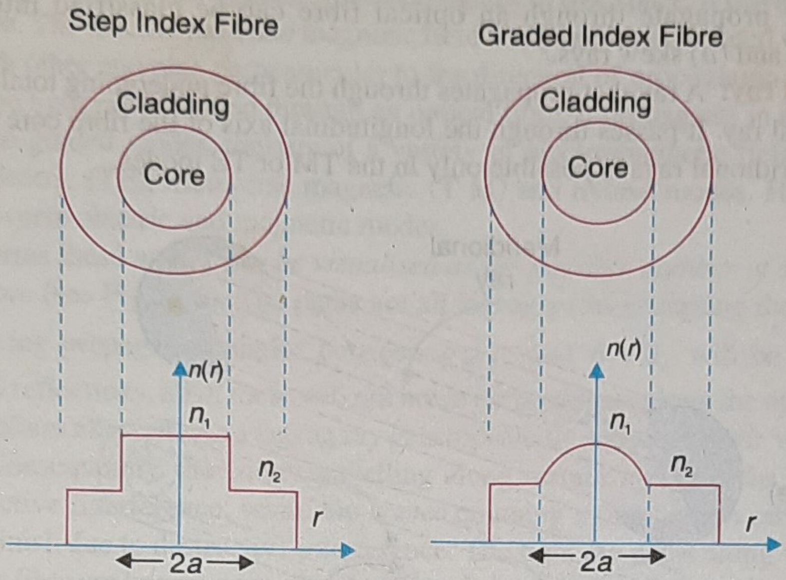


Fig. 24.14 : Classification of optical fibres based on R.I. profile (*a*) Step index fibre (*b*) GRIN fibre

Step index refers to the fact that the refractive index of the core is constant along the radial direction and abruptly falls to a lower value at the cladding and core boundary (see Fig.24.14a). In case of GRIN fibres, the refractive index of the core is not constant but varies smoothly over the diameter of the core (see Fig. 24.14b). It has a maximum value at the center and decreases gradually towards the outer edge of the core. At the core-cladding interface the refractive index of the core matches with the refractive index of the cladding. The refractive index of the cladding is constant.

B. Classification basing on the modes of light propagation:

On the basis of the modes of light propagation, optical fibres are classified into two categories as **1. Single mode fibres (SMF)** and 2. **Multimode fibres (MMF).**

A **single mode fibre** (SMF) has a smaller core diameter and can support only one mode of propagation. On the other hand, a **multimode fibre** (MMF) has a larger core diameter and supports a number of modes.

Thus, on the whole, the optical fibres are classified into three types:

- Single mode step-index (SMF) fibre
- Multimode step-index (MMF) fibre
- Graded index (multimode) (GRIN) fibre.

C. Classification basing on materials:

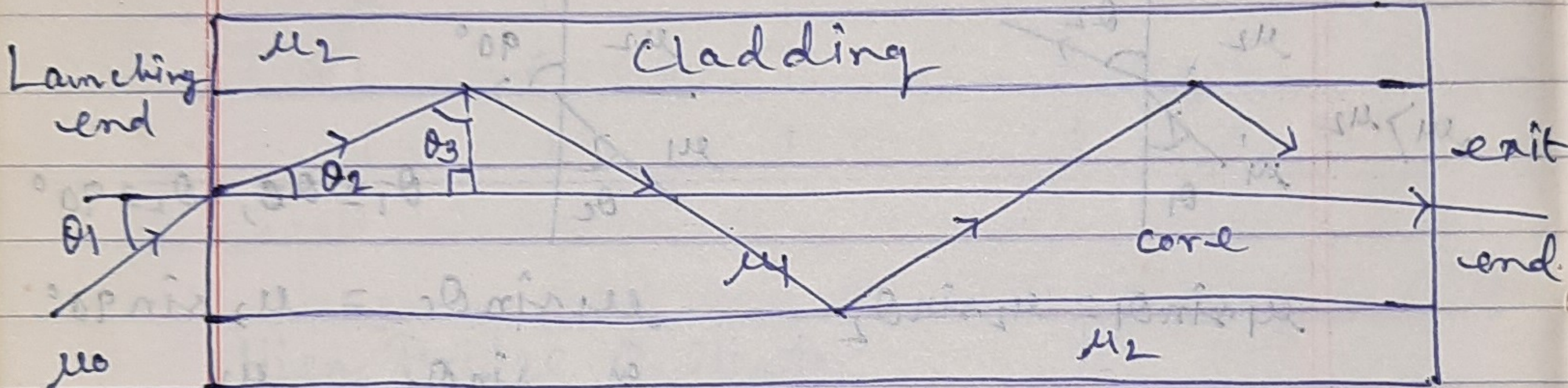
On the basis of materials used for core and cladding, optical fibres are classified into three categories.

1. Glass/glass fibres (glass core with glass cladding)
2. Plastic/plastic fibres (plastic core with plastic cladding)
3. PCS fibres (polymer clad silica)

Acceptance Angle and Numerical Aperture of optical fibre

We consider a step index optical fibre with its core and cladding having refractive indices μ_1 and μ_2 respectively. Let μ_0 be the refractive index of the outside medium. Let a ray is incident on the entrance end or launching end of the fibre at an angle θ_1 with the axis. If θ_2 be the angle of refraction, then from Snell's law —

$$\mu_0 \sin\theta_1 = \mu_1 \sin\theta_2 \longrightarrow (1)$$



In order to keep the light inside the core the angle of incidence θ_3 at the core-cladding interface must not be less than the critical angle θ_c.

from fig.,

$$\theta_2 + \theta_3 + \pi/2 = \pi$$

or, $\theta_2 + \theta_3 = \pi/2$ or, $\theta_3 = \frac{\pi}{2} - \theta_2 \longrightarrow (2)$

If θ_1 increases, θ_2 also increases, hence θ_3 decreases. So there is a maximum value of θ_1 (say θ_A) for which θ_3 is not less than θ_c and the ray undergoes total internal reflection at the core-cladding interface. This angle θ_A is known as acceptance angle. Thus the acceptance angle is maximum angle of incidence for which any ray is totally internally reflected at the interface and therefore transmitted without loss. To determine θ_A —

$$\mu_0 \sin\theta_1 = \mu_2 \sin\theta_2 = \mu_1 \sin(\pi/2 - \theta_3)$$
$$= \mu_1 \cos\theta_3 \longrightarrow (3)$$

for $\theta_1 = \theta_A$, $\theta_3 = \theta_c$, we have,

$$\mu_0 \sin\theta_A = \mu_1 \cos\theta_c \longrightarrow (4)$$

Now, $\sin\theta_c = \frac{\mu_2}{\mu_1}$

$$\therefore \cos\theta_c = \sqrt{1-\sin^2\theta_c} = \sqrt{1-\frac{\mu_2^2}{\mu_1^2}}$$

From eq. (4), we got,

$$\mu_0 \sin\theta_A = \mu_1 \cos\theta_c$$

$$= \mu_1 \left[1 - \frac{\mu_2^2}{\mu_1^2}\right]^{1/2}$$

$$= \left[\mu_1^2 - \mu_2^2\right]^{1/2} \longrightarrow (5)$$

The quantity $\mu_0 \sin\theta_A$ is known as numerical aperture (NA) of the optical fibre. It determines the light gathering ability of the fibre. It is a measure of the amount of light that can be accepted by the fibre. NA depends only on the refractive indices of core and cladding material and does not depend on the physical dimensions of the fibre. A large NA implies that a fibre will accept large amount of light from source.