CHAPTER

10

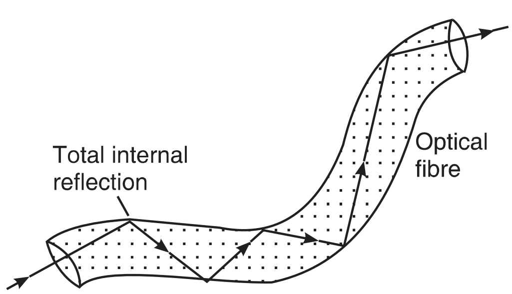
Optical Fibres

10.1 INTRODUCTION

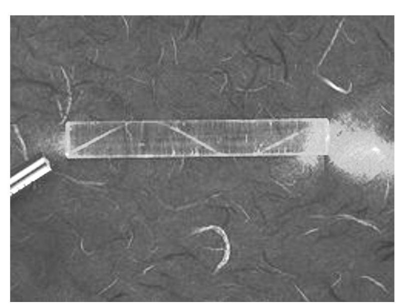
In 1870 John Tyndall, a British physicist demonstrated that light can be guided along the curve of a stream of water. Owing to total internal reflections light gets confined to the water stream and the stream appears luminous. A luminous water stream is the precursor of an optical fibre. In the 1950's, 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.

10.2 OPTICAL FIBRE



(a)



(b)

Fig. 10.1: Illustration of a transparent fibre guiding light along its length by total internal reflection.

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*).

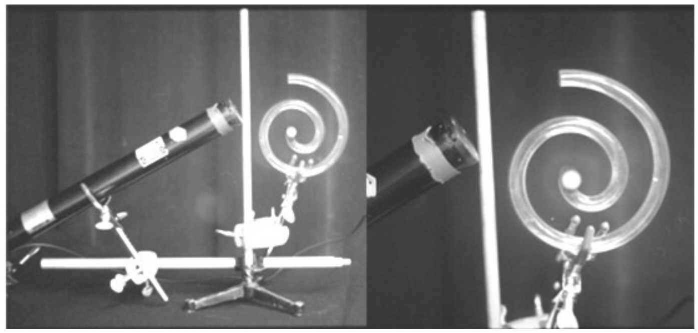


Fig. 10.1(c): A laser beam repeatedly bounces off the surface of the rod (by total internal reflection) as it makes its way around the plastic spiral and emerges out at the other end. The whole coil appears to glow red due to the scattering of light by the plastic. However, the path of light is seen clearly in the coil.

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. 10.1 (a). A small fraction of light may escape through sidewalls but a major fraction emerges out from the exit end of the fibre, as shown in Fig. 10.1 (b). Light can travel through fibre even if it is bent [Fig. 10.1(c)].

Structure:

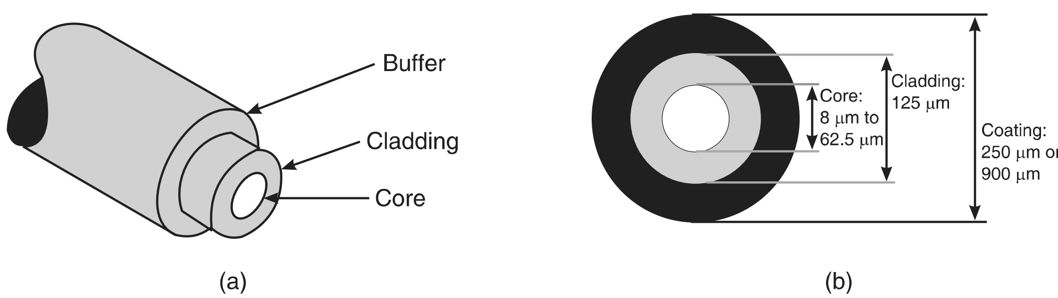


Fig. 10.2: Side view and cross sectional view of a typical optical fibre

A practical optical fibre is cylindrical in shape (Fig. 10.2a) and has in general three coaxial regions (Fig. 10.2b).

(*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.

10.2.1 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. For use in communications and 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.

10.2.2 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.

10.2.3 Optical Fibre Cable

Optical fibre cables are designed in different ways to serve different applications. More protection is provided to the optical fibre by the “cable” which has the fibres and strength members inside an outer covering called a “jacket”. We study here two typical designs: a single fibre cable or a multifibre cable.

- **Single Fibre Cable:** Around the fibre a tight buffer jacket of Hytrel is used (see Fig. 10.3). The buffer jacket protects the fibre from moisture and abrasion. A strength member is arranged around the buffer jacket in order to provide the necessary toughness and tensile strength. The strength member may be a steel wire, polymer film, nylon yarn or Kevlar yarn. Finally, the fibre cable is covered by a Hytrel outer jacket. Because of this arrangement fibre cable will not get damaged during bending, rolling, stretching or pulling and transport and installation processes. The single fibre cable is used for indoor applications.

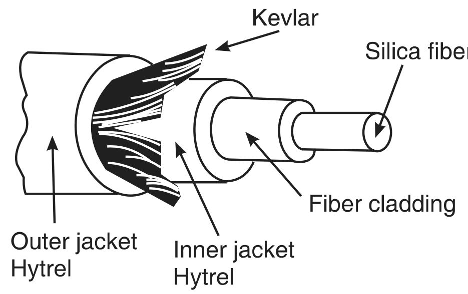


Fig. 10.3: Single fibre cable

- **Multifibre Cable:** A multifibre cable consists of a number of fibres in a single jacket. Each fibre carries light independently. The cross-sectional view of a typical telecommunication cable is shown in Fig. 10.4. It contains six insulated optical fibre strands and has an insulated steel cable at the center for providing tensile strength. Each optical fibre strand consists of a core surrounded by a cladding, which in turn is coated with insulating jacket. The fibres are thus individually buffered and strengthened. Six insulated copper wires are distributed in the space between the fibres. They are used for electrical transmission,

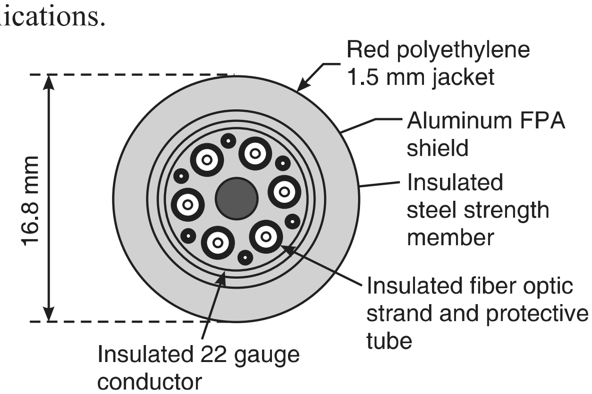


Fig. 10.4: Cross-sectional view of a typical multi fibre cable

if required. The assembly is then fitted with in a corrugated aluminium sheath, which acts as a shield. A polyethylene jacket is applied over the top.

10.3 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. 10.5a). Snell's law for this case may be written as

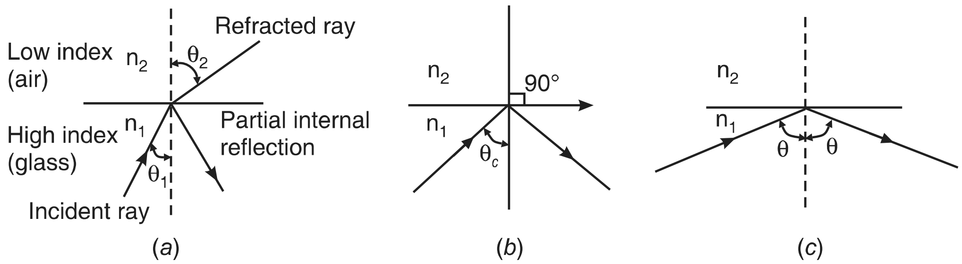


Fig. 10.5: Phenomenon of total internal reflection

$$\sin\theta_2 = \left(\frac{n_1}{n_2}\right)\sin\theta_1 \tag{10.1}$$

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 $n_1 > n_2$. 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. 10.5 (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. 10.5 c). 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 $\qquad \theta_1 = \theta_c, \quad \theta_2 = 90°.$

Therefore, from equ. (10.1), we get

$$n_1 \sin\theta_c = n_2 \sin 90° = n_2$$

$$\therefore \qquad \sin\theta_c = \frac{n_2}{n_1} \tag{10.2}$$

When the rarer medium is air, $n_2 = 1$ and writing $n_1 = n$, we obtain

$$\sin\theta_c = \frac{1}{n} \tag{10.3}$$

10.4 PROPAGATION OF LIGHT THROUGH AN OPTICAL FIBRE

The diameter of an optical fibre is very small and as such we cannot use bigger light sources for launching light beam into it. Light emitting diodes (LEDs) and laser diodes are the optical

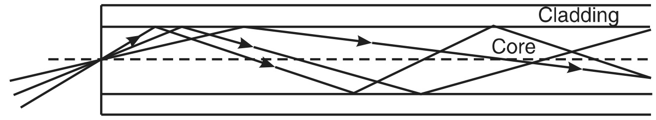


Fig. 10.6: Propagation of light rays through an optical fibre due to total internal reflection.

sources used in fibre optics. Even in case of these small sized sources, a focusing lens has to be used to concentrate the beam on to the fibre core. Light propagates as an electro-magnetic wave through an optical fibre. However, light propagation through an optical fibre can as well 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 less 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. Due to the cylindrical symmetry in the fibre structure, the rays reflected from an interface on one side of the fibre axis will suffer total internal reflections at the interface on the opposite side also. Thus, the rays travel forward through the fibre via a series of total internal reflections and emerge out from the exit end of the fibre (Fig. 10.6). Since each reflection is a total internal reflection, there is no loss of light energy and light confines itself within the core during the course of propagation. Because of the negligible loss during the total internal reflections, optical fibre can carry the light waves over very long distances. Thus, the optical fibre acts essentially as a wave-guide and is often called a **light guide** or **light pipe**. At the exit end of the fibre, the light is received by a photo-detector.

Total internal reflection at the fibre wall can occur and light propagates down the fibre, only if the following two conditions are satisfied.

1. The refractive index of the core material, n_1, must be slightly greater than that of the cladding, n_2.
2. At the core-cladding interface (Fig. 10.7), the angle of incidence ϕ between the ray and the normal to the interface must be greater than the critical angle ϕ_c defined by

$$\sin \phi_c = \frac{n_2}{n_1} \tag{10.4}$$

It is to be noted here that only those rays, that are incident at the core-clad interface at angles greater than the critical angle will propagate through the fibre. Rays that are incident at smaller angles are refracted into the cladding and are lost.

10.4.1 Critical Angle of Propagation

Let us consider a step index optical fibre into which light is launched at one end. The end at which light enters the fibre is called the **launching end**. Fig. 10.7 depicts the conditions at the launching end. In a step-index fibre, the refractive index changes abruptly form the core to the cladding. Now, we consider two rays entering the fibre at two different angles of incidence.

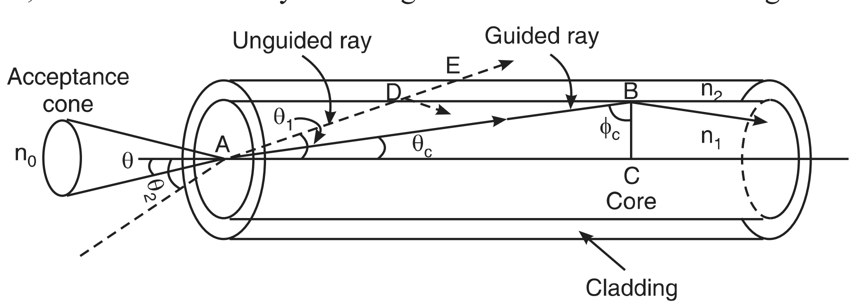


Fig. 10.7: Light rays incident at an angle smaller than critical propagation angle will propagate through the fibre.

The ray shown by the broken line is incident at an angle θ_2 with respect to the axis of the fibre. This ray undergoes refraction at point A on the interface between air and the core. The ray refracts into the fibre at an angle θ_1 ($\theta_1 < \theta_2$). The ray reaches the core-cladding interface at point D. At point D, refraction takes place again and the ray travels in the cladding. Finally, at point E, the ray refracts once again and emerges out of fibre into the air. It means that the ray does not propagate through the fibre.

Let us next consider the ray shown by the solid line in Fig. 10.7. The ray incident at an angle θ undergoes refraction at point A on the interface and propagates at an angle θ_c in the fibre. At point B on the core-cladding interface, the ray undergoes total internal reflection, since $n_1 > n_2$. Let us assume that the angle of incidence at the core-cladding interface is the *critical angle* ϕ_c, where ϕ_c is given by

$$\phi_c = \sin^{-1}(n_2/n_1) \tag{10.4a}$$

A ray incident with an angle larger than ϕ_c will be confined to the fibre and propagate in the fibre. A ray incident, at the core-cladding boundary, at the critical angle is called a **critical ray**. The critical ray makes an angle ϕ_c with axis of the fibre. It is obvious that rays with propagation angles larger than θ_c will not propagate in the fibre. Therefore, the angle θ_c is called the **critical propagation angle**. From the Δ^{le} ABC, it is seen that

$$\frac{AC}{AB} = \sin\phi_c. \quad \text{Also,} \quad \frac{AC}{AB} = \cos\theta_c$$

From the relation (10.4a), $\sin\phi_c = n_2 / n_1$.

$$\cos\theta_c = n_2 / n_1 \tag{10.5}$$

$$\therefore \quad \theta_c = \cos^{-1}(n_2 / n_1) \tag{10.6}$$

Thus, only those rays which are refracted into the cable at angles $\theta_r < \theta_c$ will propagate in the optical fibre.

Example 10.1: *In an optical fibre, the core material has refractive index 1.43 and refractive index of clad material is 1.4. Find the propagation angle.*

Solution:
$$\cos\theta_c = \frac{n_2}{n_1} = \frac{1.40}{1.43} = 0.979$$

Therefore, propagation angle $\theta_c = \cos^{-1}(0.979) = 11.8°$

Example 10.2: *In an optical fibre, the core material has refractive index 1.6 and refractive index of clad material is 1.3. What is the value of critical angle? Also calculate the value of angle of acceptance cone.*

Solution: Critical angle is given by

$$\sin\phi_c = \frac{n_2}{n_1} = \frac{1.3}{1.6} = 0.8125$$

$$\therefore \quad \phi_c = 54.3°$$

Acceptance angle
$$\theta_0 = \sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right] = \sin^{-1}\left[\sqrt{1.6^2 - 1.3^2}\right]$$

$$= \sin^{-1}(0.87)$$

$$= \mathbf{60.5°}$$

Angle of acceptance cone = $2\theta_0$ = **121°**

10.4.2 Acceptance Angle

Let us again consider a step index optical fibre into which light is launched at one end, as shown in Fig. 10.8. 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 θ_i to the axis of the fibre. The ray refracts at an angle θ_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.

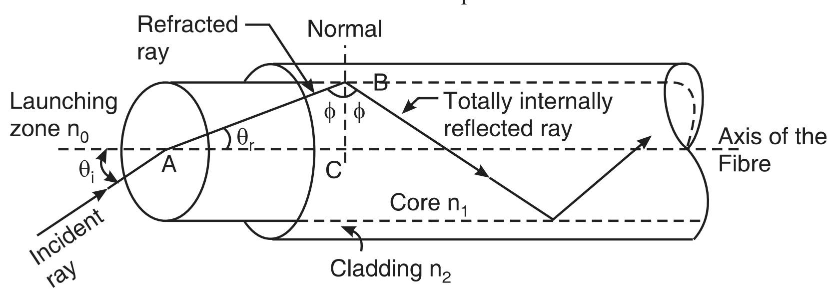


Fig. 10.8: Geometry for the calculation of acceptance angle of the fibre.

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

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_1}{n_0} \tag{10.7}$$

If θ_i is increased beyond a limit, ϕ will drop below the critical value ϕ_c and the ray escapes from the sidewalls of the fibre. The largest value of θ_i occurs when $\phi = \phi_c$.

From the Δ^{le} ABC, it is seen that

$$\sin \theta_r = \sin (90° - \phi) = \cos \phi \tag{10.8}$$

Using equation (10.8) into equation (10.7), we obtain

$$\sin \theta_i = \frac{n_1}{n_0} \cos \phi$$

When $\phi = \phi_c$,

$$\sin\left[\theta_{i_{\max}}\right] = \frac{n_1}{n_0} \cos \phi_c \tag{10.9}$$

But

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

$$\therefore \qquad \cos \phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \tag{10.10}$$

Substituting the expression (10.10) into (10.9), we get

$$\sin [\theta_i (\max)] = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \tag{10.11}$$

Quite often the incident ray is launched from air medium, for which $n_0 = 1$.

Designating $\theta_i (\max) = \theta_0$, equation (10.11) may be simplified to

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

$$\therefore \qquad \theta_0 = \sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right] \tag{10.12}$$

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.*

Thus, only those rays that are incident on the face of the fibre making angles less than θ_0 will undergo repeated total internal reflections and reach the other end of the fibre. Obviously, larger acceptance angles make it easier to launch light into the fibre.

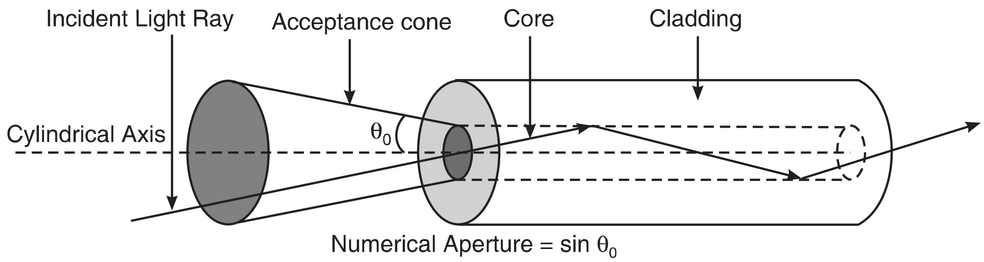


Fig. 10.9

In three dimensions, the light rays contained within the cone having a full angle $2\theta_0$ are accepted and transmitted along the fibre (see Fig. 10.9). Therefore, the cone is called the **acceptance cone**.

Light incident at an angle beyond θ_0 refracts through the cladding and the corresponding optical energy is lost.

Example 10.3: *Calculate the numerical aperture and acceptance angle of an optical fibre from the following data:*

n_1(core) = 1.55 and n_2(cladding) = 1.50

Solution: $\text{NA} = \sqrt{n_1^2 - n_2^2} = \sqrt{1.55^2 - 1.50^2} = \sqrt{0.153} = \mathbf{0.391.}$

Acceptance angle $\theta_0 = \sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right] = \sin^{-1}\left[\sqrt{1.55^2 - 1.50^2}\right] = \mathbf{23.02°}$

Example 10.4: *What is the numerical aperture of an optical fibre cable with a clad index of 1.378 and a core index of 1.546?*

Solution: $$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.546^2 - 1.378^2} = \sqrt{0.491} = 0.70$$

Example 10.5: *A fibre cable has an acceptance angle of 30° and a core index of refraction of 1.4. Calculate the refractive index of the cladding.*

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

$$\therefore \quad \sin^2\theta_0 = n_1^2 - n_2^2$$

$$n_2^2 = n_1^2 - \sin^2\theta_0 = (1.4)^2 - \sin^2 30° = 1.96 - 0.25$$

$$= 1.71$$

$$\therefore \quad n_2 = \mathbf{1.308}$$

Example 10.6: *Calculate the angle of acceptance of a given optical fibre, if the refractive indices of the core and the cladding are 1.563 and 1.498 respectively.*

Solution: $$\sin\theta_0 = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.563)^2 - (1.498)^2} = 0.4461$$

$$\theta_0 = \sin^{-1}(0.4461) = \mathbf{26.49°}$$

10.5 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