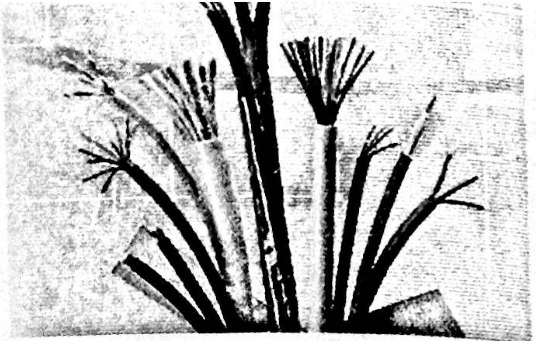
24.2 OPTICAL FIBRE

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.

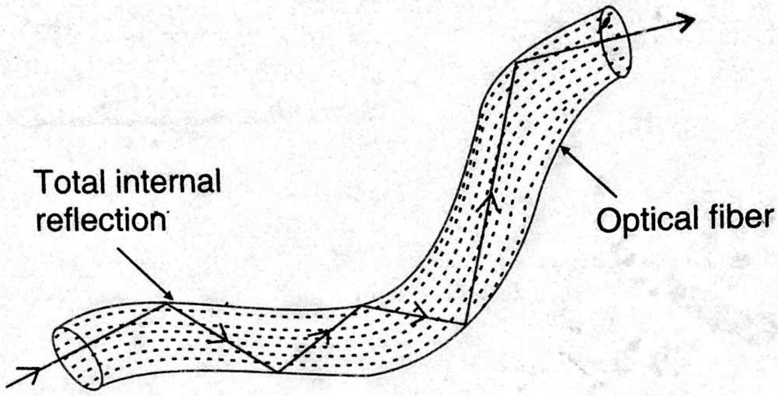
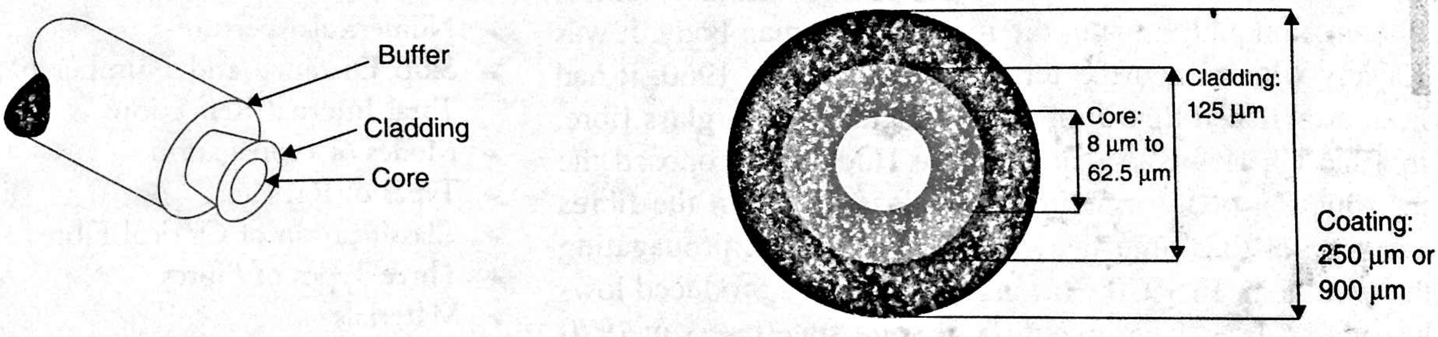


Fig. 24.1: Illustration of a transparent fibre guiding light along its length.

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.

24.2.3 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.

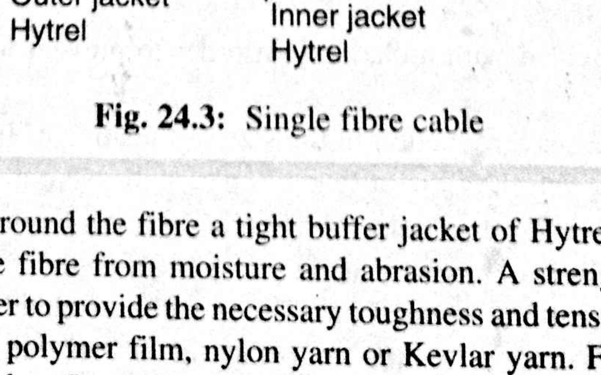


Fig. 24.3: Single fibre cable

- **Single Fibre Cable:** Around the fibre a tight buffer jacket of Hytrel is used (see Fig.24.3). 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.

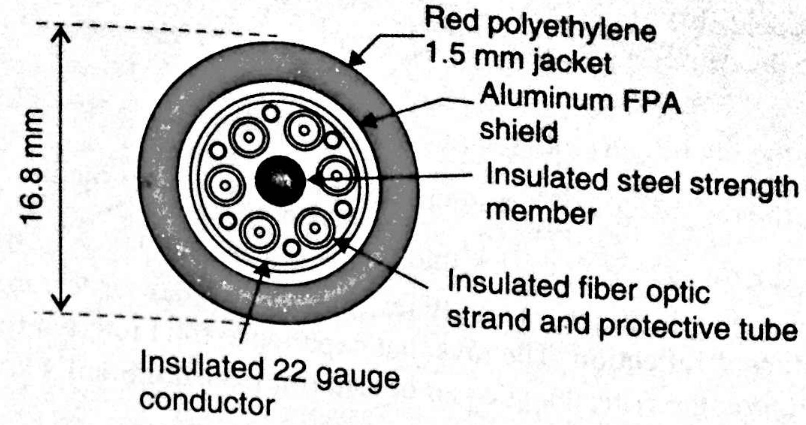


Fig. 24.4: Cross-sectional view of a typical multi fibre cable

• **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.24.4. 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, 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.

24.3 TOTAL INTERNAL REFLECTION

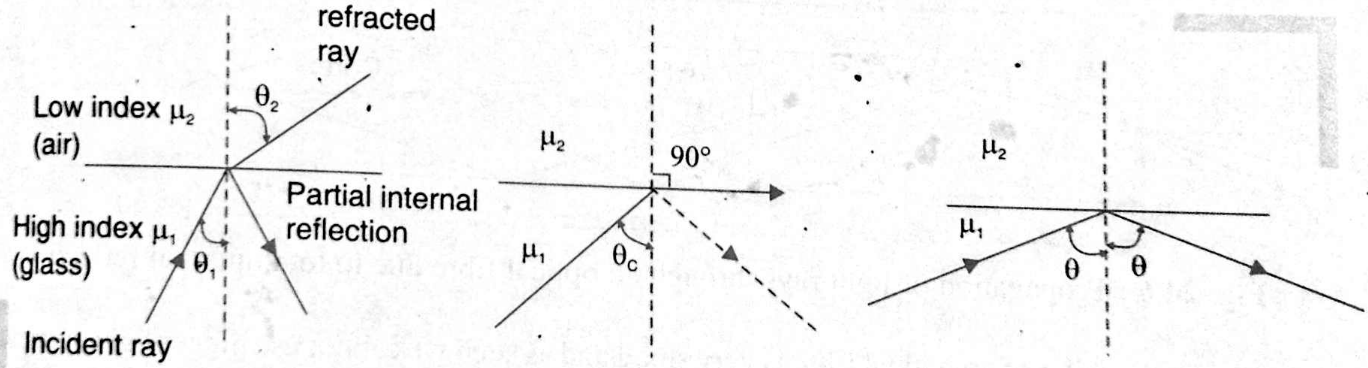


Fig. 24.5: Phenomenon of total internal reflection

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

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

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

24.4 PROPAGATION OF LIGHT THROUGH AN OPTICAL FIBRE

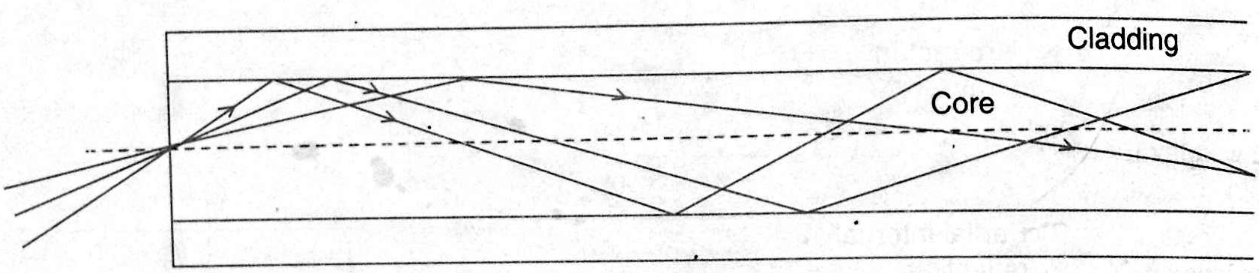


Fig. 24.6 : Propagation of light rays through an optical fibre due to total internal reflection.

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 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 electromagnetic 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.24.6). 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

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.24.7), 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

$$\sin\phi_C = \frac{n_2}{n_1} \quad (24.4)$$

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.

24.4.1 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. 23.7 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.

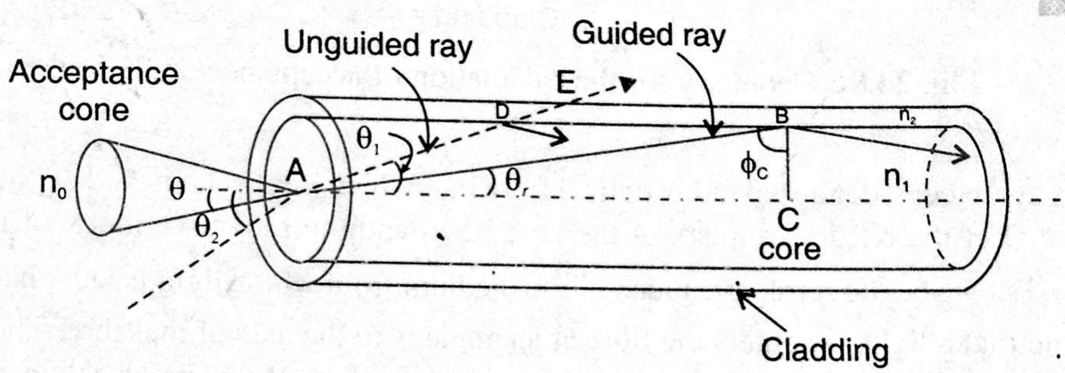


Fig. 24.7: Light rays incident at an angle smaller than critical propagation angle will propagate through the fibre.

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.24.7. 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

$$\phi_C = \sin^{-1}(n_2 / n_1) \quad (24.4a)$$

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 θ_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

$$\frac{AC}{AB} = \sin\phi_C . \qquad \text{Also, } \frac{AC}{AB} = \cos\theta_c$$

From the relation (24.4a), $\sin\phi_c = n_2 / n_1$.

$$\cos\theta_c = n_2 / n_1 \tag{24.5}$$

$$\therefore \qquad \theta_c = \cos^{-1}(n_2/n_1) \tag{24.6}$$

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

24.4.2 ACCEPTANCE ANGLE

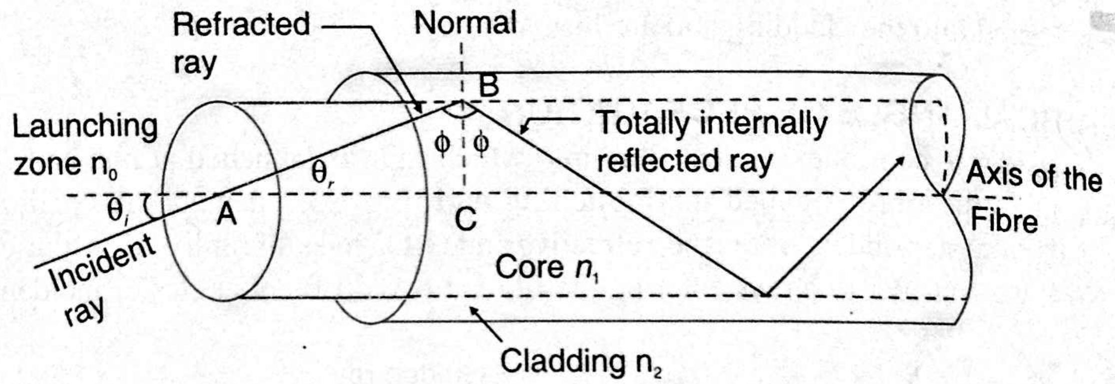


Fig. 24.8 : Geometry for the calculation of acceptance angle of the fibre.

Let us again consider a step index optical fibre into which light is launched at one end, as shown in Fig. 24.8. 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_o 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.

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

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0} \tag{24.7}$$

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

$$\sin\theta_r = \sin(90^\circ - \phi) = \cos\phi \tag{24.8}$$

Using equation (24.8) into equation (24.7), we obtain

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

When $$\phi = \phi_c, \quad \sin\left[\theta_{i_{max}}\right] = \frac{n_1}{n_o}\cos\phi_c \tag{24.9}$$

But $$\sin\phi_C = \frac{n_2}{n_1}$$

$$\therefore \quad \cos\phi_C = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \tag{24.10}$$

Substituting the expression (24.10) into (24.9), we get

$$\sin\left[\theta_i(\max)\right] = \left[\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right] \tag{24.11}$$

Quite often the incident ray is launched from air medium, for which $n_o=1$. Designating $\theta_i(max) = \theta_o$, equation (24.11) may be simplified to

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

$$\therefore \quad \theta_o = \sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right] \tag{24.12}$$

The angle θ_o 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_o 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.

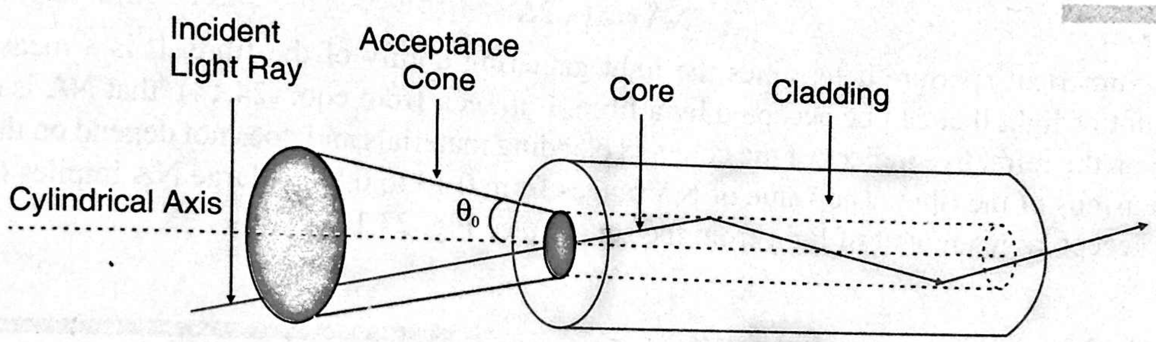


Fig. 24.9 Acceptance Cone

In three dimensions, the light rays contained within the cone having a full angle $2\theta_o$ are accepted and transmitted along the fibre (see Fig. 24.9). Therefore, the cone is called **the acceptance cone.**

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

24.5 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

$$\Delta = \frac{n_1 - n_2}{n_1} \tag{24.13}$$

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, $\Delta \ll 1$. Typically, Δ is of the order of 0.01.

24.6 NUMERICAL APERTURE

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 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,

$$NA = \sin \theta_o$$

where θ_o is the acceptance angle.

But

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

$$\therefore \quad NA = \sqrt{n_1^2 - n_2^2} \tag{24.14}$$

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

Approximating $\frac{n_1 + n_2}{2} \approx n_1$, we can express the above relation as $(n_1^2 - n_2^2) = 2n_1^2\Delta$. It gives

$$NA = \sqrt{2n_1^2\Delta}$$

$$\therefore \quad NA = n_1\sqrt{2\Delta} \tag{24.15}$$

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 equ. (24.14) 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 (see Fig. 23.10).

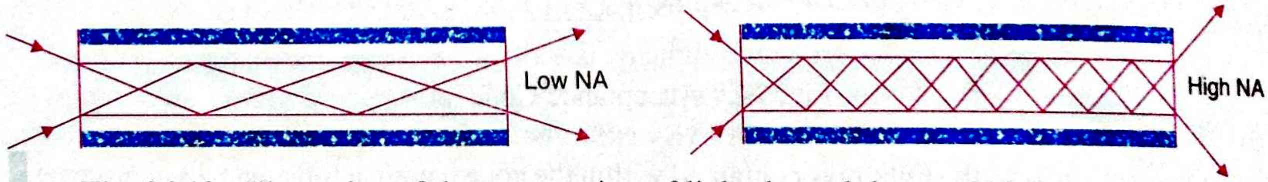


Fig. 24.10: Illustration of the propagation of light through low and high numerical aperture fibres.

24.7 SKIP DISTANCE AND NUMBER OF TOTAL INTERNAL REFLECTIONS

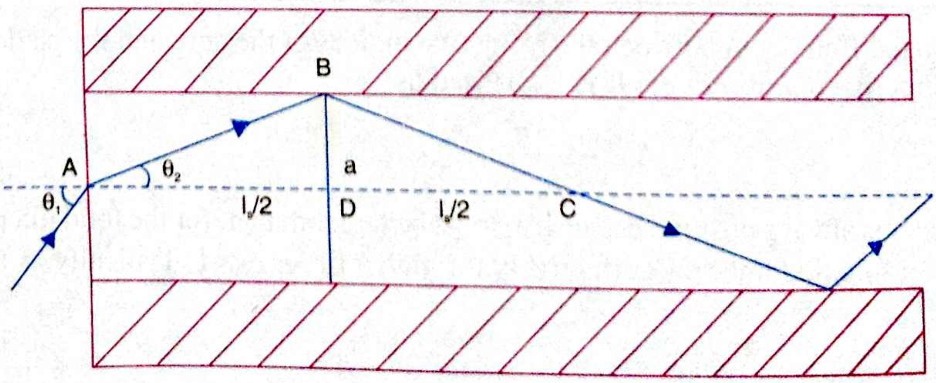
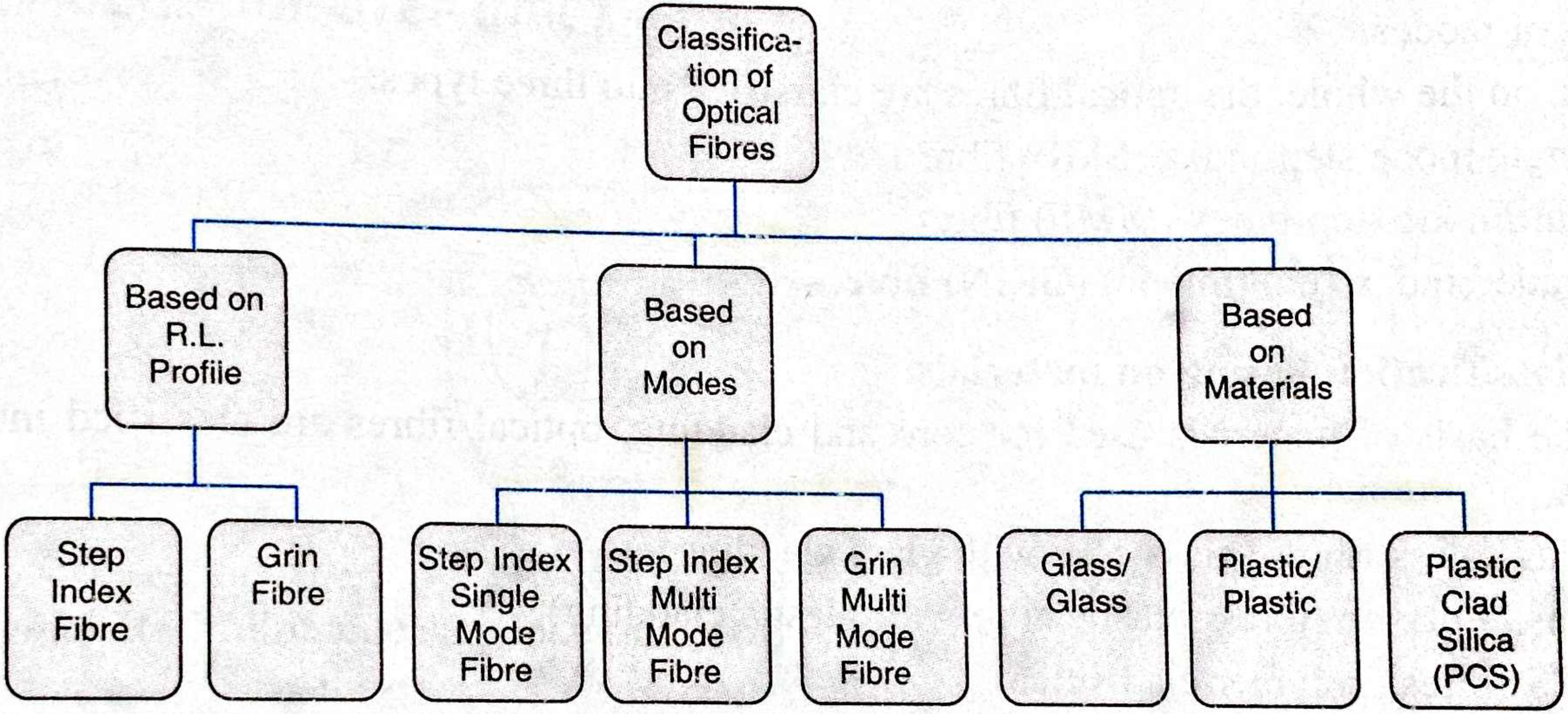


Fig. 24.11 : Skip Distance l_s

24.10 CLASSIFICATION OF OPTICAL FIBRES

Optical fibres are differently classified into various types basing on different parameters.



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.**

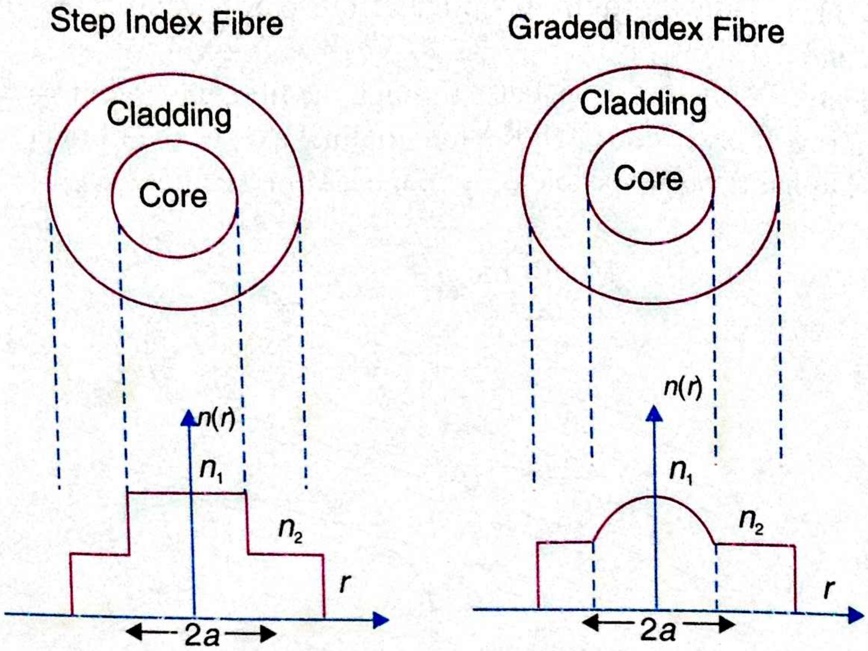


Fig. 24.14 : Classification of optical fibres based on R.I. profile (*a*) Step index fibre (*b*) GRIN fibre

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)

24.11 THE THREE TYPES OF FIBRES

We now study the detailed structure and characteristics of the three types of optical fibres.

24.11.1 SINGLE MODE STEP INDEX FIBRE

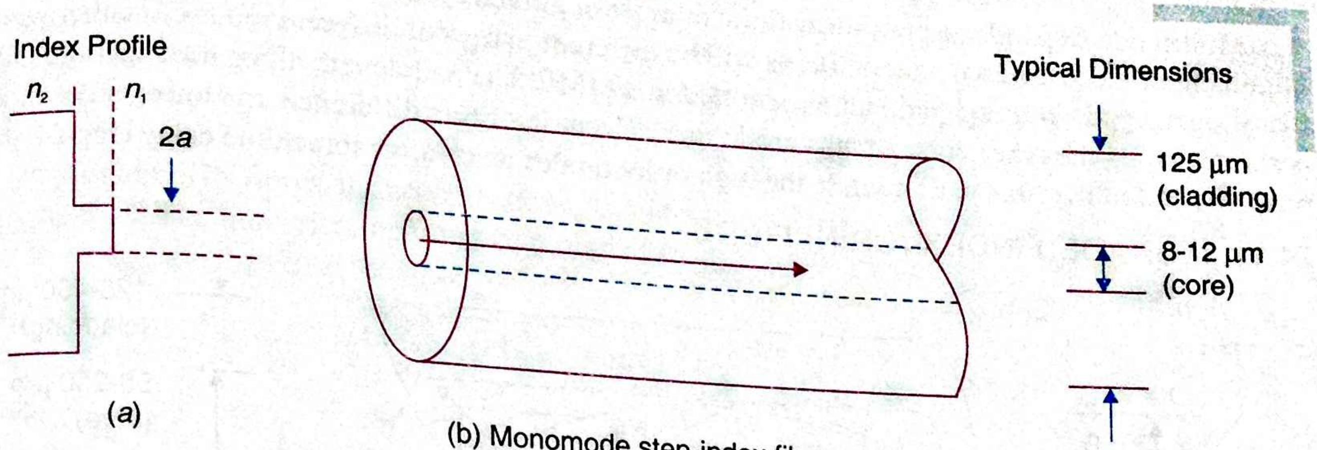


Fig. 24.15: Single mode step index fibre (a) R.I. profile (b) ray paths (c) typical dimensions

Structure

A single mode step index fibre has a very fine thin core of diameter of 8 μm to 12 μm (see Fig.24.15 c). It is usually made of germanium doped silicon. The core is surrounded by a thick cladding of lower refractive index. The cladding is composed of silica lightly doped with phosphorous oxide. The external diameter of the cladding is of the order of 125 μm. The fibre is surrounded by an opaque protective sheath. The refractive index of the fibre changes abruptly at the core-cladding boundary, as shown in Fig. 24.15 (a). The variation of the refractive index of a step index fibre as a function of radial distance can be mathematically represented as

$$n(r) = n_1 \; [r < a \quad \text{inside core}]$$
$$= n_2 \; [r > a \quad \text{in cladding}] \tag{24.19}$$

Propagation of light in SMF

Light travels in SMF along a single path that is along the axis (Fig.24.15b). Obviously, it is the zero order mode that is supported by a SMF. Both Δ and NA are very small for single mode fibres. This relatively small value is obtained by reducing the fibre radius and by making Δ, the relative refractive index change, to be small. The low NA means a low acceptance angle. Therefore, light coupling into the fibre becomes difficult. Costly laser diodes are needed to launch light into the SMF.

24.11.2 MULTIMODE STEP INDEX FIBRE

Structure

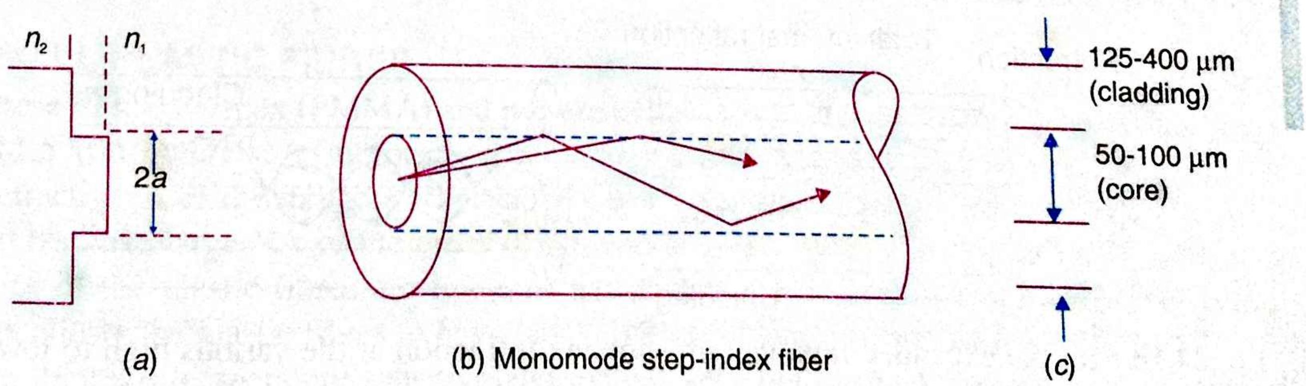


Fig. 24.16: Multimode step index fibre (*a*) R.I. Profile (*b*) Ray paths (*c*) typical dimensions.

A multimode step index fibre is very much similar to the single mode step index fibre except that its core is of larger diameter. The core diameter is of the order of 50 to 100 μm, which is very large compared to the wavelength of light. The external diameter of cladding is about 150 to 250 μm (Fig. 24.16 c).

Propagation of light in MMF

Multimode step index fibres allow finite number of guided modes. The direction of polarization, alignment of electric and magnetic fields will be different in rays of different modes. In other words, many zigzag paths of propagation are permitted in a MMF. The path length along the axis of the fibre is shorter while the other zigzag paths are longer. Because of this difference, the lower order modes reach the end of the fibre earlier while the high order modes reach after some time delay (Fig.24.16b).

24.11.3 GRADED INDEX (GRIN) FIBRE

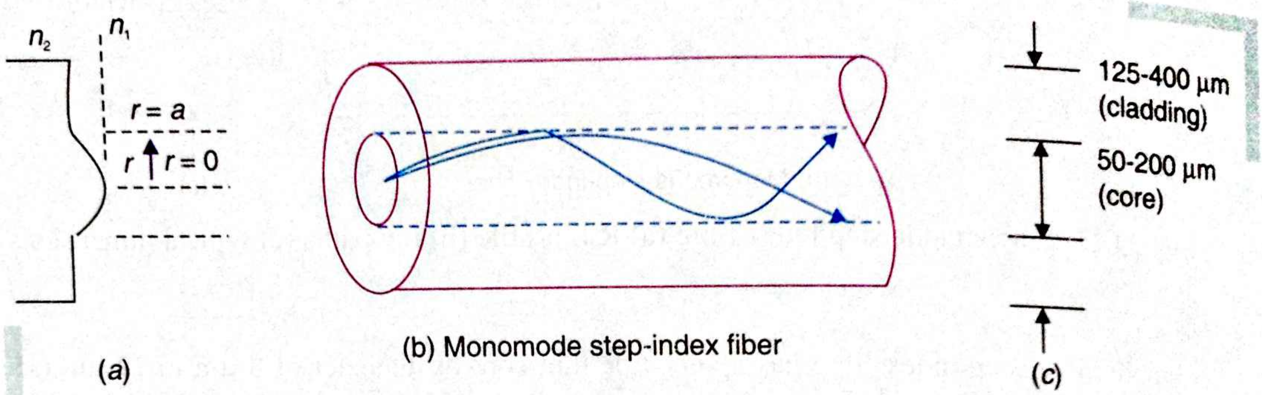


Fig. 24.17 : GRIN fibre (*a*) R.I. Profile (*b*) Ray paths (*c*) typical dimensions

A graded index fibre is a multimode fibre with a core consisting of concentric layers of different refractive indices. Therefore, the refractive index of the core varies with distance from the fibre axis. It has a high value at the centre and falls of with increasing radial distance from the axis. A typical structure and its index profile are shown in Fig. 24.17 (a). Such a profile causes a periodic focussing of light propagating through the fibre. The size of the graded index fibre is about the same as the step index fibre. The variation of the refractive index of the core with radius measured from the center is given by

$$n(r) = \begin{cases} n_1\sqrt{1-\left[2\Delta\left(\dfrac{r}{a}\right)^{\alpha}\right]}, & r < a \text{ inside core} \\ n_2, & r > a \text{ in cladding} \end{cases} \qquad (24.20)$$

where n_1 is maximum refractive index at the core axis, a the core radius, and α the grading profile index number which varies from 1 to ∞. When $\alpha = 2$, the index profile is parabolic and is preferred for different applications.

Propagation of light

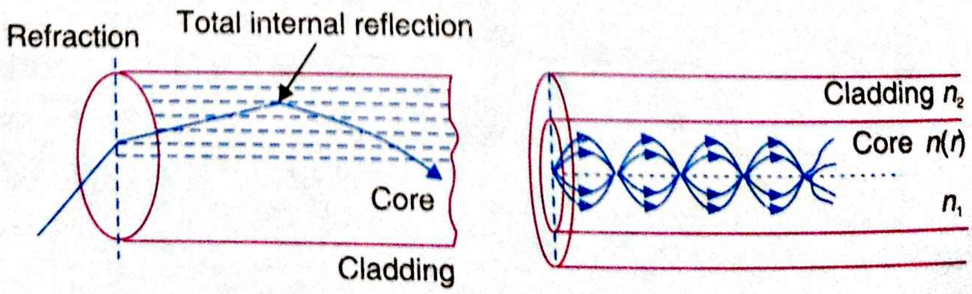


Fig.24.18 : (a) An expanded ray diagram showing refraction at the various high to low index interfaces within graded index fibre, giving an overall curved ray path. (b) Light transmission in a graded index fibre.

As a light ray goes from a region of higher refractive index to a region of refractive index, it is bent away from the normal. The process continues till the condition for total internal reflection is met. Then the ray travels back towards the core axis, again being continuously refracted (Fig.24.18a). The turning around may take place even before reaching the core-cladding interface. Thus, continuous refraction is followed by total internal reflection and again continuous refraction towards the axis. In the graded index fibre, rays making larger angles with the axis traverse longer path but they travel in a region of lower refractive index and hence at a higher speed of propagation. Consequently, all rays traveling through the fibre, irrespective of their modes of travel, will have almost the same optical path length and reach the output end of the fibre at the same time (see Fig. 24.18b).

In case of GRIN fibres, the acceptance angle and numerical aperture decrease with radial distance from the axis. The numerical aperture of a graded index fibre is given by

$$NA = \sqrt{n^2(r) - n_2^2} \approx n_1 (2\Delta)^{\frac{1}{2}} \sqrt{1 - \left(\frac{r}{a}\right)^2}$$

$$= n_1 \sqrt{2\Delta\left[1 - \left(\frac{r}{a}\right)^2\right]} \qquad (24.21)$$

24.12 MATERIALS

Optical fibres are fabricated from glass or plastic which are transparent to optical frequencies. Step index fibres are produced in three common forms – (*i*) a glass core cladded with a glass having a slightly lower refractive index, (*ii*) a silica glass core cladded with plastic and (*iii*) a plastic core cladded with another plastic. Generally, the refractive index step is the smallest for all glass fibres, a little larger for the plastic clad silica (PCS) fibres and the largest for all plastic construction.

24.12.1 ALL GLASS FIBRES

The basic material for fabrication of optical fibres is silica (SiO_2). It has a refractive index of 1.458 at $\lambda = 850\ nm$. Materials having slightly different refractive index are obtained by doping the basic silica material with small quantities of various oxides. If the basic silica material is doped with germania (GeO_2) or phosphorous pentoxide (P_2O_5), the refractive index of the material increases. Such materials are used as core materials and pure silica is used as cladding material in these cases. When pure silica is doped with boria (B_2O_3) or fluorine, its refractive index decreases. These materials are used for cladding when pure silica is used as core material. Examples of fiber compositions are

- SiO_2 core – $B_2O_3.SiO_2$ cladding
- $GeO_2.SiO_2$ core – SiO_2 cladding

The glass optical fibres exhibit very low losses and are used in long distance communications.

24.12.2 ALL PLASTIC FIBRES

In these fibres, perspex (PMMA) and polysterene are used for core. Their refractive indices are 1.49 and 1.59 respectively. A fluorocarbon polymer or a silicone 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 angles up to 77°. The main advantages of the plastic fibres are low cost and higher mechanical flexibility. The mechanical flexibility allows the plastic fibres to have large cores, of diameters ranging from 110 to 1400 μm. However, they are temperature sensitive and exhibit very high loss. Therefore, they are used in low cost applications and at ordinary temperatures (below 80°C). Examples of plastic fiber compositions are

24.15 LOSSES IN OPTICAL FIBRE

As a light signal propagates through a fibre, it suffers loss of amplitude and change in shape. The loss of amplitude is referred to as *attenuation* and the change in shape as *distortion*.

24.15.1 ATTENUATION

When an optical signal propagates through a fibre, its power decreases exponentially with distance. The loss of optical power as light travels down a fiber is known as **attenuation**. The attenuation of optical signal is defined as *the ratio of the optical output power from a fibre of length L to the input optical power.* If P_i is the optical power launched at the input end of the fibre, then the power P_o at a distance L down the fibre is given by

$$P_o = P_i\, e^{-\alpha L} \tag{24.34}$$

where α is called the **fibre attenuation coefficient** expressed in units of km^{-1}. Taking logarithms on both the sides of the above equation, we obtain

$$\alpha = \frac{1}{L} ln \frac{P_i}{P_o} \tag{24.35}$$

In units of dB / km, α is defined through the equation

$$\therefore \qquad \alpha_{dB/km} = \frac{10}{L} \log \frac{P_i}{P_o} \tag{24.36}$$

In case of an ideal fibre, $P_o = P_i$ and the attenuation would be zero.

24.15.2 DIFFERENT MECHANISMS OF ATTENUATION

There are several loss mechanisms responsible for attenuation in optical fibres. They are broadly divided into two categories: *intrinsic* and *extrinsic* attenuation. Intrinsic attenuation is caused by substances inherently present in the fiber, whereas extrinsic attenuation is caused by external forces such as bending.

A. Intrinsic Attenuation

Intrinsic attenuation results from materials inherent to the fiber. It is caused by impurities present in the glass. During manufacturing, there is no way to eliminate all impurities. When a light signal hits an impurity in the fiber, either it is scattered or it is absorbed. Intrinsic attenuation can be further characterized by two components:

- **Material absorption**
- **Rayleigh scattering**

Absorption by material

Material absorption occurs as a result of the imperfection and impurities in the fiber and accounts for 3-5% of fiber attenuation. The most common impurity is the hydroxyl (OH-) molecule, which remains as a residue despite stringent manufacturing techniques. These radicals result from the presence of water remnants that enter the fiber-optic cable material through either a chemical reaction in the manufacturing process or as humidity in the environment. The natural impurities in the glass absorb light signal, and convert it into vibrational energy or some other form of energy. Hydroxyl radical ions(OH), and transition metals such as copper, nickel, chromium, vanadium and manganese have electronic absorption in and near visible part of the spectrum. Their presence causes heavy losses.

Even a highly pure glass absorbs light in specific wavelength regions. Strong electronic absorption occurs at UV wavelengths, while vibrational absorption occurs at IR wavelengths.

Losses due to impurities can be reduced by better manufacturing processes. In improved fibres, metal ions are practically negligible. The largest loss is caused by OH ions. These cannot be sufficiently reduced. The absorption of light either through intrinsic or impurity process constitutes a transmission loss because that much energy is subtracted from the light propagating through the fibre. The absorption losses are found to be at minimum at around 1.3 μm.

Unlike scattering, absorption can be limited by controlling the amount of impurities during the manufacturing process.

Rayleigh Scattering

Rayleigh scattering accounts for the majority (about 96%) of attenuation in optical fiber. The local microscopic density variations in glass cause local variations in refractive index. These variations, which are inherent in the manufacturing process and cannot be eliminated, act as obstructions and scatter light in all directions (Fig.24.21). This is known as *Rayleigh scattering*. The Rayleigh scattering loss greatly depends on the wavelength. It varies as $1/\lambda^4$ and becomes important at lower wavelengths. Thus, Rayleigh scattering sets a lower limit, on the wavelengths that can be transmitted by a glass fibre at 0.8 μm, below which the scattering loss is very high.

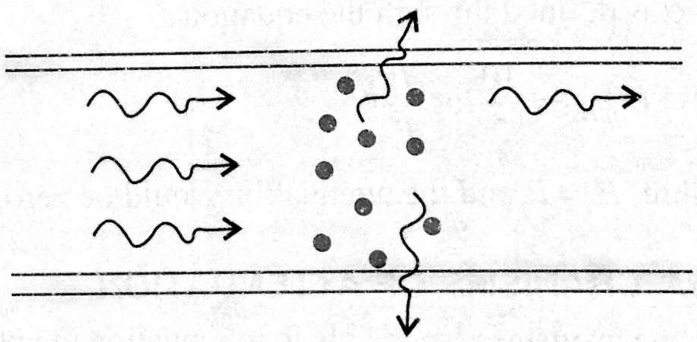


Fig. 24.21: Rayleigh scattering, showing attenuation of an incident stream of photons due to localized variations in refractive index.

Any wavelength that is below 800 nm is unusable for optical communication because attenuation due to Rayleigh scattering is high. At the same time, propagation above 1700 nm is not possible due to high losses resulting from infrared absorption.

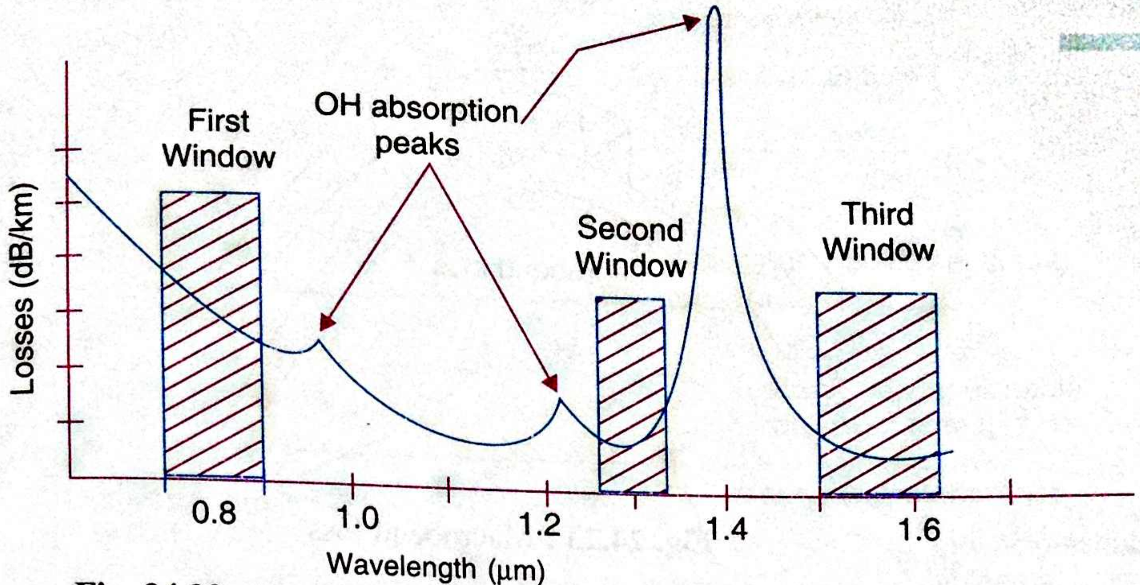


Fig. 24.22: A typical plot of fibre attenuation versus wavelength for a silica based optical fibre.

Fig. 24.22 shows the variation of attenuation with wavelength measured for a typical fiber-optic cable.

For better performance, the choice of wavelength must be based on minimizing loss and minimizing dispersion. Such windows are selected for communication purposes. It is seen from the attenuation curve that it has a minimum at around a particular band of optical wavelengths. The band of wavelengths at which the attenuation is a minimum is called **optical window** or **transmission window** or **low-loss window**. There are three **principal windows.** These correspond to wavelength regions in which attenuation is low and matched to the capability of a transmitter to generate light efficiently and a receiver to carry out detection.

λ (nm)	**Approx. loss (dB/km)**
820 - 880	2.2
1200 - 1320	0.6
1550 - 1610	0.2

From the above data it is seen that the range 1550 to 1610 is most preferable. From the point of view of dispersion, the low intramodal dispersion wavelength of about 1300nm is most suitable.

B. Extrinsic Attenuation or Bending losses

Extrinsic attenuation is caused by two external mechanisms: **macrobending** or **microbending.** Both of them cause a reduction of optical power. If a bend is imposed on an optical fiber, strain is placed on the fiber along the region that is bent. The bending strain affects the refractive index and the critical angle of the light ray in that specific area. As a result, the condition for total internal reflection is no longer satisfied. Hence, light traveling in the core can refract out, and loss occurs.

Macrobend losses

A **macrobend** is a large-scale bend that is visible. When a fibre is bent through a large angle, strain is placed on the fiber along the region that is bent. The bending strain will affect the refractive index and the critical angle of the light ray in that specific area. As a result, light traveling in the core can refract out, and loss occurs. (Fig. 24.23). To prevent macrobends, optical fiber has a *minimum bend radius* specification that should not be exceeded. This is a restriction on how much bend a fiber can withstand before experiencing problems in optical performance or mechanical reliability.

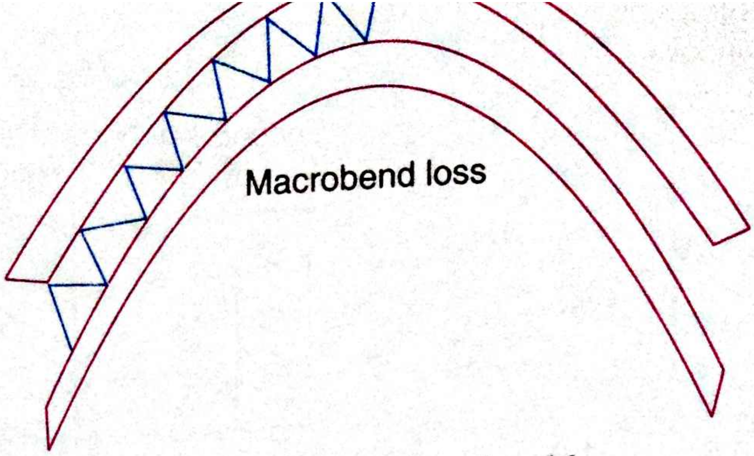


Fig. 24.23 : Macrobend loss

Microbend losses

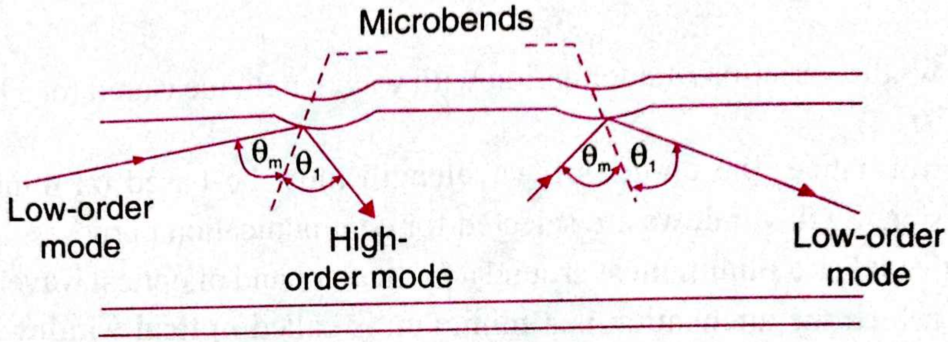


Fig. 24.24: Microbend losses

Microbend is a small-scale distortion. It is localized and generally indicative of pressure on the fiber. Microbending might be related to temperature, tensile stress, or crushing force. Microbending is caused by imperfections in the cylindrical geometry of fiber during the manufacturing process or installation processes. The bend may not be clearly visible upon inspection. Structural variations in the fibre, or fibre deformation, cause radiation of light away from the fibre (Fig. 24.24). Microbending may occur, for example, due to winding of optical fibre cable over spools. Light rays get scattered at the small bends and escape into the cladding. Such losses are known as microbend losses.

24.16 DISTORTION

In an optical fibre communication system, the information (signal) is coded in the form of discrete pulses of light, which are transmitted through the fibre. The light pulses are of a given width, amplitude and interval. The number of pulses that can be sent per unit time will determine the information capacity of the fibre. More information can be sent by optical cable when distinct pulses can be transmitted in more rapid succession. The pulses travel through the transmitting medium (i.e., optical fibre) and reach the detector at the receiving end. For the information to be retrieved at the detector, it is necessary that the optical pulses are well resolved in time. However, the light pulses broaden and spread into a wider time interval because of the different times taken by different rays propagating through the fibre. This phenomenon is known as **distortion** or **pulse dispersion**. Hence, even though two pulses may be well resolved at the input end, they may overlap on each other at the output end, as shown in Fig.24.25. It is obvious that the pulse broadening depends on the length of the travel of the pulses through the fibre. Hence, dispersion is expressed in units of **ns/km** (time/distance).

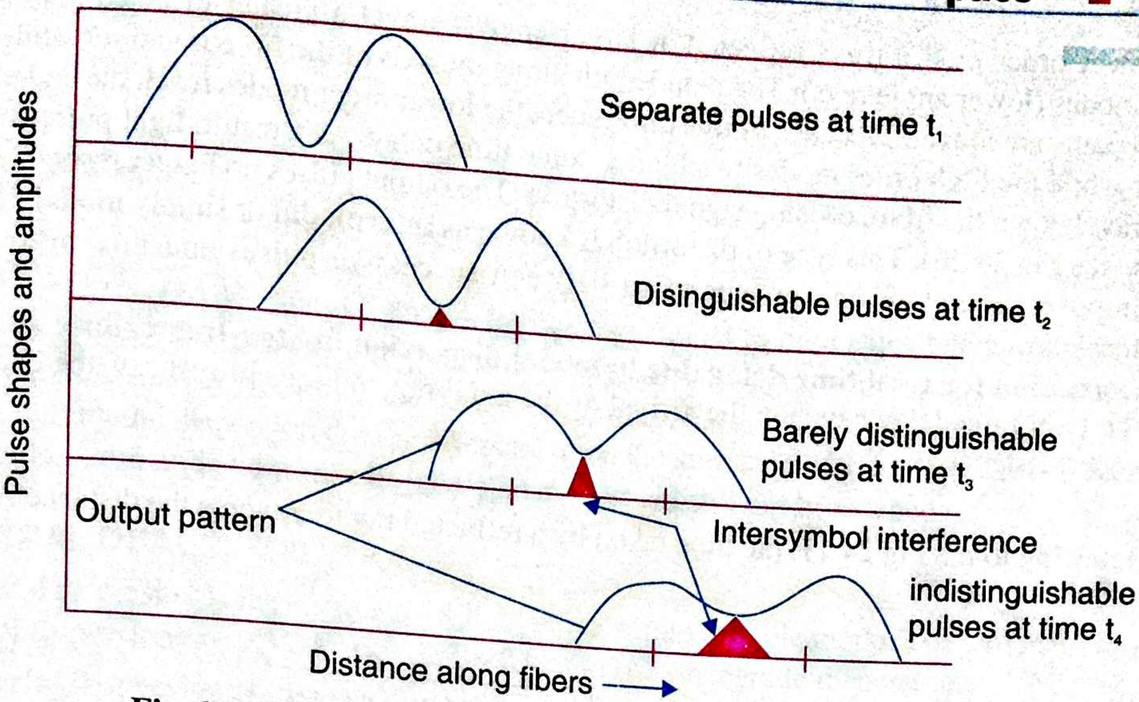


Fig. 24.25 : Distortion of the pulses traveling along a fibre

The following three different dispersion mechanisms determine the distortion of the signal in an optical fibre. They are

- Intermodal dispersion and
- Intramodal dispersion.

Intramodal dispersion is again divided into the following two types.

- Material dispersion
- Waveguide dispersion

24.16.1 INTERMODAL DISPERSION

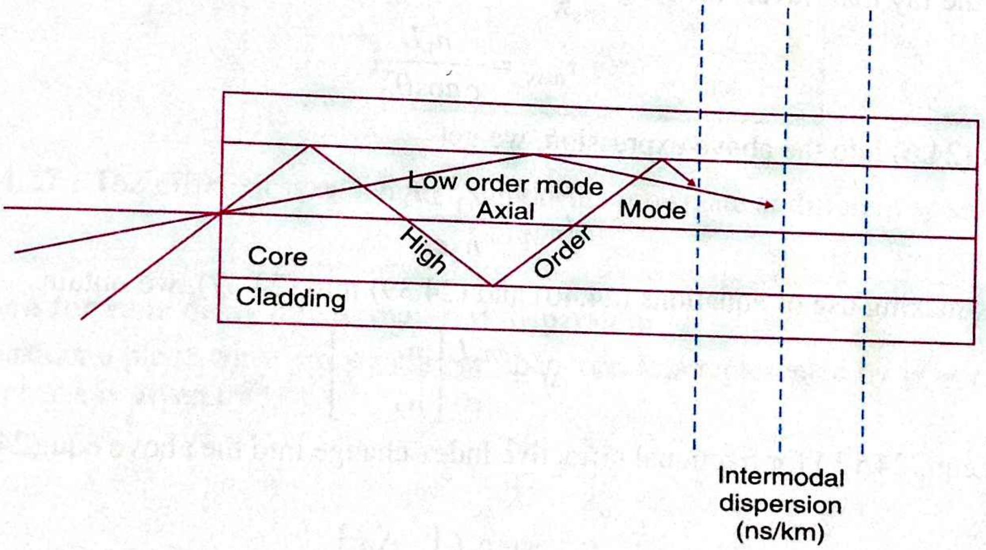


Fig. 24.26: Lower order modes reach the end of the fibre earlier while the high order modes reach after some time delay

Intermodal dispersion occurs as a result of the differences in the group velocities of the modes. For example, let us consider the propagation of a pulse through a multimode fibre. The power associated with the single pulse gets distributed into the various modes or paths guided by the fibre.

The lower order modes (rays reflected at larger angles) travel a greater distance than the higher order modes (lower angle rays). The path length along the axis of the fibre is shorter while the other zigzag paths are longer. Because of this difference, the lower order modes reach the end of the fibre earlier while the high order modes reach after some time delay. As a result, light pulses broaden as they travel down the fibre, causing signal distortion. The output pulses no longer resemble the input pulses (see Fig.24.26). This type of distortion is known as **intermodal** or simply **modal dispersion.** This imposes limitation on the separation between successive pulses and thereby reduces the transmission rate and capacity.

modal dispersion in Step-Index fibre:

or

It is seen

Therefore

dis

24.16.2 INTRAMODAL DISPERSION

Intramodal dispersion is the spreading of light pulse within a single mode. The two main causes of intramodal dispersion are (*a*) material dispersion and (*b*) waveguide dispersion.

a. **Material Dispersion:** Glass is a dispersive medium. A light pulse is a wave packet, composed of a group of components of different wavelengths. The different wavelength components will propagate at different speeds along the fibre (Fig. 24.27). The short wavelength components travel slower than long wavelength components, eventually causing the light pulse to broaden. This type of distortion is known as **material dispersion**. It is often called the **chromatic dispersion**. Obviously, the spectral width of the source determines the extent of material dispersion.

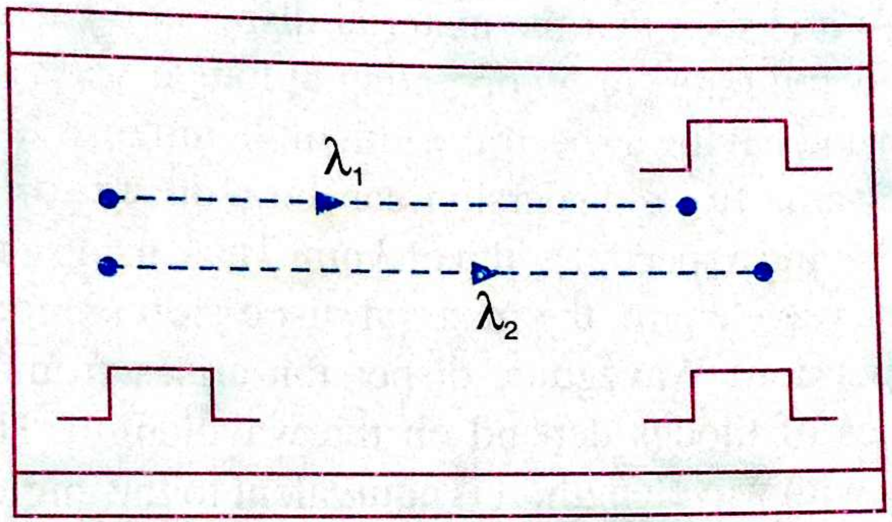


Fig. 24.27 : The different wavelength components propagate at different speeds along the fibre

source operating at higher wavelength, the material dispersion is reduced.

b. Wave-guide Dispersion: Waveguide dispersion arises from the guiding properties of the fibre. The group velocities of modes depend on the wavelength. Hence, the effective refractive index for any mode varies with wavelength. It is equivalent to the angle between the ray and the fibre axis varying with wavelength which subsequently leads to a variation in the transmission times for the rays and hence dispersion (see Fig.24.28). Waveguide dispersion is generally small in MMF, but it is important in SMF.

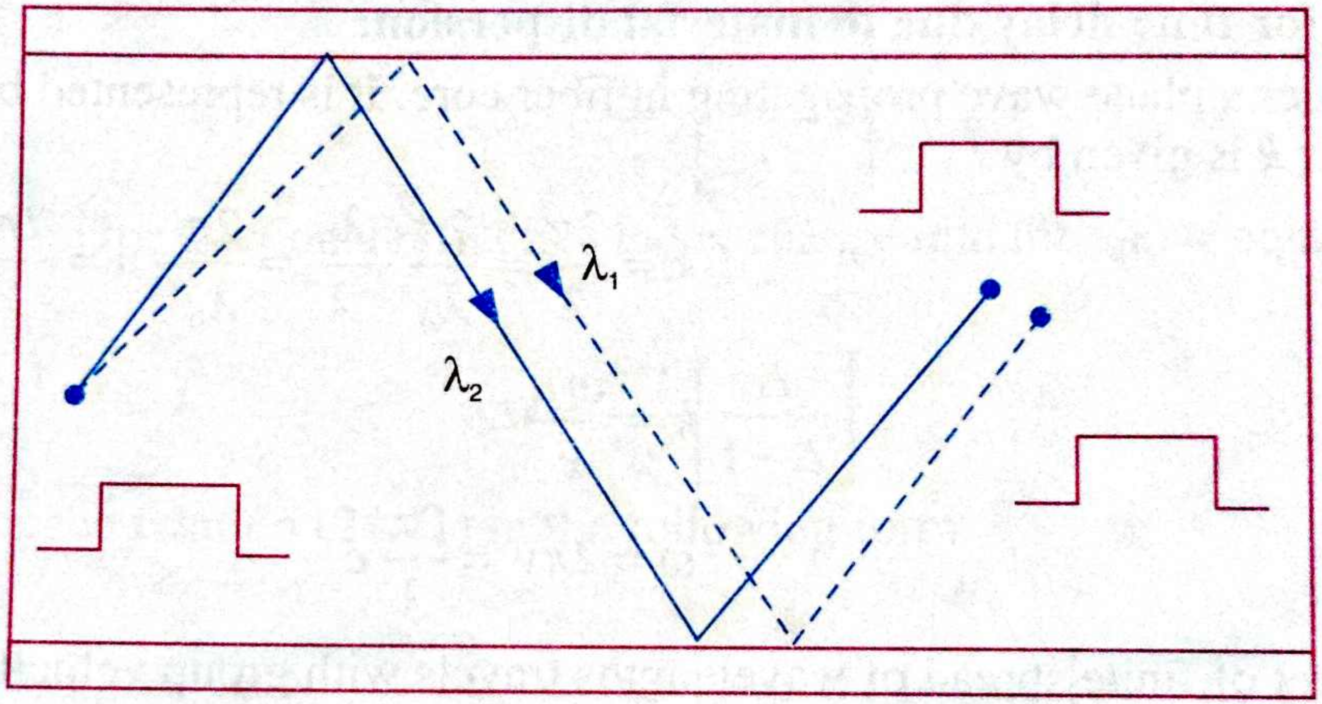


Fig. 24.28: Wave guide dispersion

The intermodal distortion can be reduced if graded index fibre is used. In case of a graded index fibre, the refractive index is larger at the center and it gradually decreases away from the center. A pulse traveling along the axis of the fibre, travels along a shorter path but it takes longer time to reach the end of the fibre since it is traveling through a medium of higher refractive index. On the other hand, the pulse traveling away from the axis travels a longer distance but takes lesser time since it is traveling through a medium of lower refractive index. As a result both the pulses reach the end of the fibre simultaneously. Thus, using a GRIN fibre can reduce the problem of intermodal dispersion. Low NA fibres exhibit smaller dispersion. Dispersion may be restricted by a careful selection of low NA fibre and a narrow spectral width fibre.

In a MMF, all three pulse spreading mechanism exist simultaneously. In case of SMF, only material and wave-guide dispersion exist.

24.16.3 TOTAL DISPERSION

All the above three dispersions contribute pulse spreading during signal transmission through an optical fibre. The total dispersion introduced by an optical fibre is given by the root mean square value of all the three dispersions. Thus,

$$(\Delta t)_T = \sqrt{(\Delta t)^2_{intermodal} + (\Delta t)^2_{mat} + (\Delta t)^2_{wg}} \qquad (24.49)$$

24.17 BANDWIDTH

It is learnt in the above section that various dispersion mechanisms cause broadening of the information signal in time domain. If the pulses spread more, they can interfere with the adjacent pulses resulting in *Inter Symbol Interference* or ISI in short and there can be so much of ISI that it becomes impossible to distinguish between the individual pulses. Therefore, for a given broadening, the pulses have to be separated by a minimum time interval in order to avoid overlapping of the pulses. This would determine the ultimate information-carrying capacity of the system. When the pulse separation is increased, the data transfer rate decreases. Thus, broadening of pulses puts an upper limit on the rate of pulse transmission. To a first approximation, it may be taken that the bandwidth in hertz is equal to the digital bit rate. Thus, $B_T = \frac{1}{\tau} = B$, where τ is the input pulse duration. In other words, the maximum allowable transmission rate is called **bandwidth**. In practice, the fibre bandwidth is expressed in terms of MHz.km, a product of frequency and distance. This is known as **bandwidth-distance** product, which specifies the usable bandwidth over a definite distance. With the increase in distance, different dispersion effects would increase in the optical fibre and as a result the usable bandwidth reduces. The attenuation per kilometer and the bandwidth-kilometer product are the important performance parameters of optical fibres.

24.18 CHARACTERISTICS OF THE FIBRES

A. Step-index single-mode fibre

- It has a very small core diameter, typically of about 10 μm.
- Its numerical aperture is very small.
- It supports only one mode in which the entire light energy is concentrated.
- A single mode step index fibre is designed to have a V number between 0 and 2.4.
- Because of a single mode of propagation, loss due to intermodal dispersion does not exist. With careful choice of material, dimensions, and wavelength, the total dispersion can be made extremely small.

- The attenuation is least.
- The single mode fibres carry higher bandwidth than multimode fiber.
- It requires a monochromatic and coherent light source. Therefore, laser diodes are used along with single mode fibres.

Advantages

- No degradation of signal
- Low dispersion makes the fibre suitable for use with high data rates. Single-mode fiber gives higher transmission rate and up to 50 times more distance than multimode.
- Highly suited for communications.

Disadvantages

- Manufacturing and handling of SMF are more difficult.
- The fibre is costlier.
- Launching of light into fibre is difficult.
- Coupling is difficult.

Applications

- Used as under water cables

B. Step-index multi-mode fibre

- It has larger core diameter, typically ranging between 50-100 μm.
- The numerical aperture is larger and it is of the order of 0.3.
- Larger numerical aperture allows more number of modes, which causes larger dispersion. The dispersion is mostly intermodal.
- Attenuation is high.
- Incoherent sources like LEDs can be used as light sources with multimode fibres.

Advantages

- The multimode step index fibre is relatively easy to manufacture and is less expensive.
- LED or laser source can be used.
- Launching of light into fibre is easier.
- It is easier to couple multi-mode fibres with other fibres.

Disadvantages

- Has smaller bandwidth.
- Due to higher dispersion data rate is lower and transmission is less efficient.
- It is less suitable for long distance communications.

Applications

- Used in data links.

C. Graded-index multi-mode fibre

- Core diameter is in the range of 50-100 μm.
- Numerical aperture is smaller than that of step-index multimode fibre.
- The number of modes in a graded index fibre is about half that in a similar multimode step-index fibre.
- Has medium attenuation.
- Intermodal dispersion is zero, but material dispersion is present.
- Has better bandwidth than multimode step-index fibre.

Advantages

- Either an LED or a laser can be used as the source of light with GRIN fibres.