CHAPTER 16

Fibre Optics

16.1 Introduction

Light travels in straight lines. Devices such as cameras, binoculars, telescopes, microscopes can function only for light travelling in a straight line. But when one is to look around the corners of an object or illuminate or view something inside places not directly in front of our eyes such as inside a human body, we need a guiding medium.

Moreover, on transmitting information through open space from one place to another, light was found to be severely attenuated and distorted due to scattering and absorption by the vagaries of terrestrial atmosphere, for example, smoke, fog, rain, precisely because their size being of the order of wavelength of light. Thus a need of a guiding medium was felt.

This gave birth to a guiding medium in the form of an optical fibre. And, this led to the birth of a new subject called 'fibre optics'.

16.2 Optical Fibre

An optical fibre is a dielectric waveguide operating at optical wavelengths, guiding light within the fibre parallel to its axis.

The basic parts of a typical optical fibre (Figure 16.1) are as follows:

1. Core
2. Cladding, and
3. Jacket

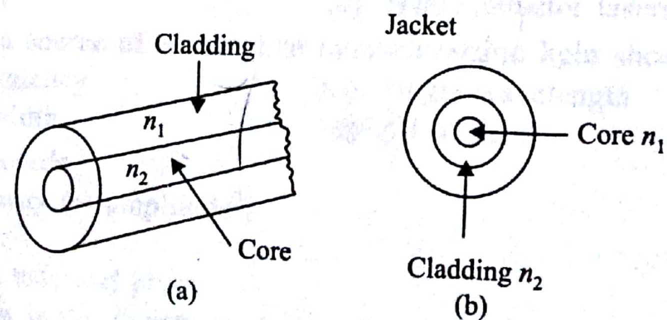


Figure 16.1 An optical fibre: (a) Side view and (b) End view.

Light is made to propagate through the core. Some part of the light, propagating through the core, may leak. The cladding (i) prevents light leaking from one fibre to the other, (ii) adds mechanical strength to the fibre and helps in checking it being distorted during supports, and (iii) reduces scattering losses occurring at the core surface.

In low- and medium-loss fibres, the core is of silica/glass and the cladding is made either of silica/glass or plastic. Glass fibres have a high tensile strength even comparable to the stainless-steel wires of the same diameter. In case of higher-loss fibres, core and cladding are of plastic. Plastic fibres, as compared to glass fibres, are more flexible and can withstand larger stresses.

The optical fibres do have an outer layer called jacket, which is made of polyvinyl chloride (PVC). The jacket (i) provides strength and flexibility to the fibre making easy handling and installation of the fibres, (ii) helps protect the fibre from damage due to microcracks, (iii) reduces scattering losses produced by microscopic bends.

16.3 Step-index Fibre

A step-index fibre has constant refractive index for both core n_1 and cladding n_2 such that $n_1 > n_2$. It is called a step-index fibre, as its index profile (n Vs r) resembles steps of a staircase (Figure 16.2).

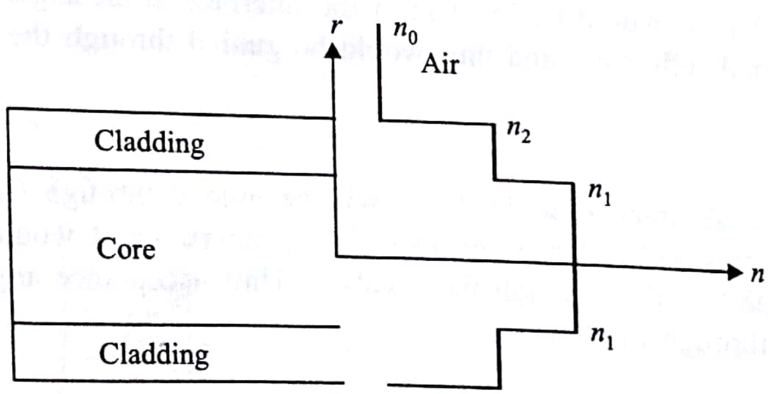


Figure 16.2 Step-index fibre and refractive index profile: Index n Vs distance r from the fibre axis.

16.4 Total Internal Reflection

Light is guided through an optical fibre using total internal reflection. To realise total internal reflection at a rarer–denser interface, following two conditions must be met:

1. Light be incident from the denser medium side
2. Angle of incidence i at the interface be greater than the critical angle i_c

Critical angle is the angle of incidence in the denser medium for which the angle of refraction is equal to 90° (Figure 16.3).

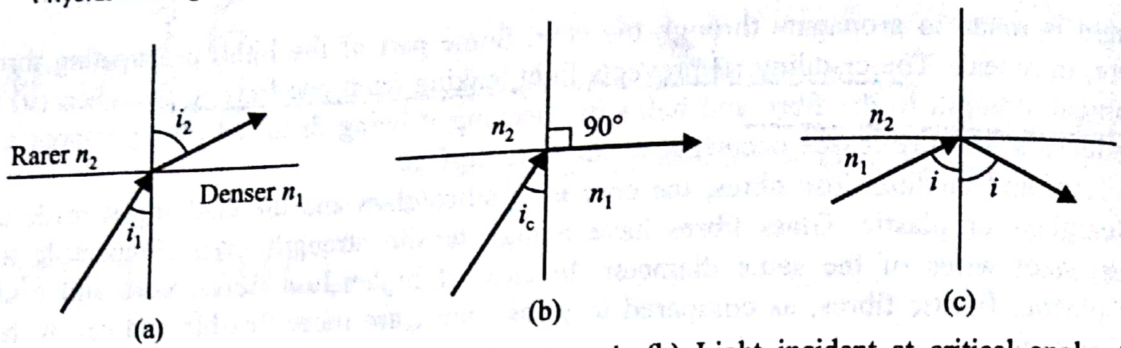


Figure 16.3 (a) Light incident at rarer interface $i_1 < i_c$, (b) Light incident at critical angle, i_c and (c) Light incident at $i > i_c$: Total internal reflection.

16.5 Acceptance Angle and Acceptance Cone

Consider a ray of light entering a step-index fibre from the left end (Figure 16.4). Let a ray M make an angle i_a with the fibre axis at the fibre end. This ray after refraction at the fibre end bends towards the fibre axis, and subtends an angle i_c (the critical angle), at the core–cladding interface. The refracted ray then grazes the interface. Another light ray A incident at the fibre end at an angle greater than i_a would make an angle smaller than i_c at the interface and, therefore, would enter the cladding and eventually gets lost by radiation. Ray B incident at an angle smaller than i_a would be incident at the interface at an angle greater than i_c, and will suffer total internal reflection, and thus would be guided through the fibre.

Acceptance angle

Angle i_a is called the acceptance angle. Light will be guided through the fibre only if it is incident at the fibre end within the acceptance angle, otherwise, it would be simply lost in the cladding or escape the fibre through the cladding. Thus acceptance angle is the maximum angle to guide light through the fibre.

Acceptance cone

The cone of light within which if light is incident gets guided through the fibre and is called the acceptance cone (Figure 16.4).

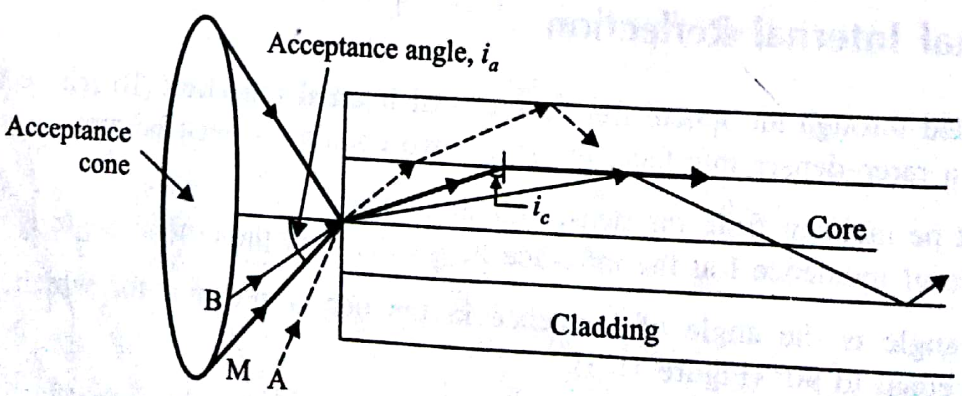


Figure 16.4 Acceptance angle and acceptance cone.

16.6 Numerical Aperture

Consider a beam of light incident at the fibre end at the acceptance angle [Figure 16.5(a)], and on applying Snell's law, respectively at the fibre end and the interface, we have

$$n_0 \sin i_a = n_1 \sin \theta \tag{16.1}$$

and

$$n_1 \sin \theta_c = n_2 \sin 90° \tag{16.2}$$

From Figure 16.5(a), as $\theta + \theta_c = 90°$ or $\theta_c = 90° - \theta$ Eq. (16.2) gives

$$n_1 \sin (90° - \theta) = n_2$$

or

$$\cos \theta = \frac{n_2}{n_1} \tag{16.3}$$

and

$$\sin \theta = \sqrt{1 - \cos^2 \theta} = \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} = \frac{\sqrt{n_1^2 - n_2^2}}{n^2} \tag{16.4}$$

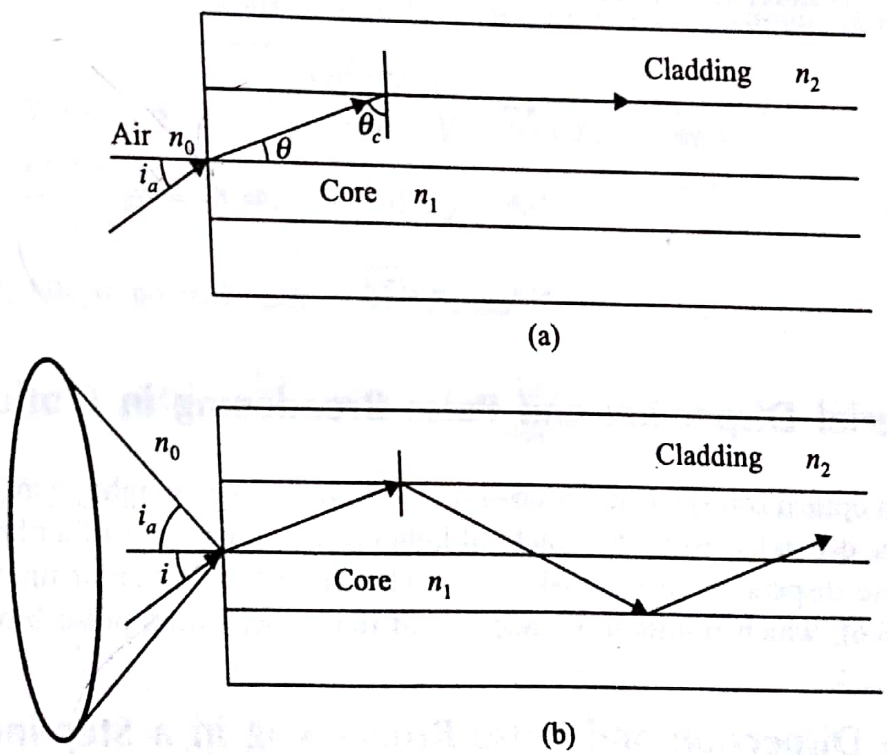


Figure 16.5 (a) Light incident at acceptance angle and (b) Light incident at an angle less than the acceptance angle, so, guided through the fibre.

Substituting for $\sin \theta$ in Eq. (16.1), we get

$$\sin i_a = \frac{n_1}{n_0} \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

or

$$\sin i_a = \sqrt{n_1^2 - n_2^2} \tag{16.5}$$

As $n_0 = 1$ (the surrounding medium being air).

By the definition of the acceptance angle i_a, light incident within this angle will be guided through the fibre [Figure 16.5(b)], therefore, we can say that i_a measures the light gathering power of an optical fibre. So, does $\sin i_a = \left(\sqrt{n_1^2 - n_2^2}\right)$.

Now, as numerical aperture of an optical fibre is equal to $n_0 \sin i_a$ or $\sin i_a$ (as $n_0 = 1$), it also measures the light gathering power of an optical fibre. Thus

$$\text{Numerical aperture} = \sqrt{n_1^2 - n_2^2} \tag{16.6}$$

16.7 Relative Refractive Index Difference

Relative refractive index difference Δ is a ratio of core–cladding index difference to core index, i.e., $(n_1 - n_2)/n_1$.

Further, $$\text{Numerical aperture (NA)} = \sqrt{n_1^2 - n_2^2} = \sqrt{(n_1 - n_2)(n_1 + n_2)}$$

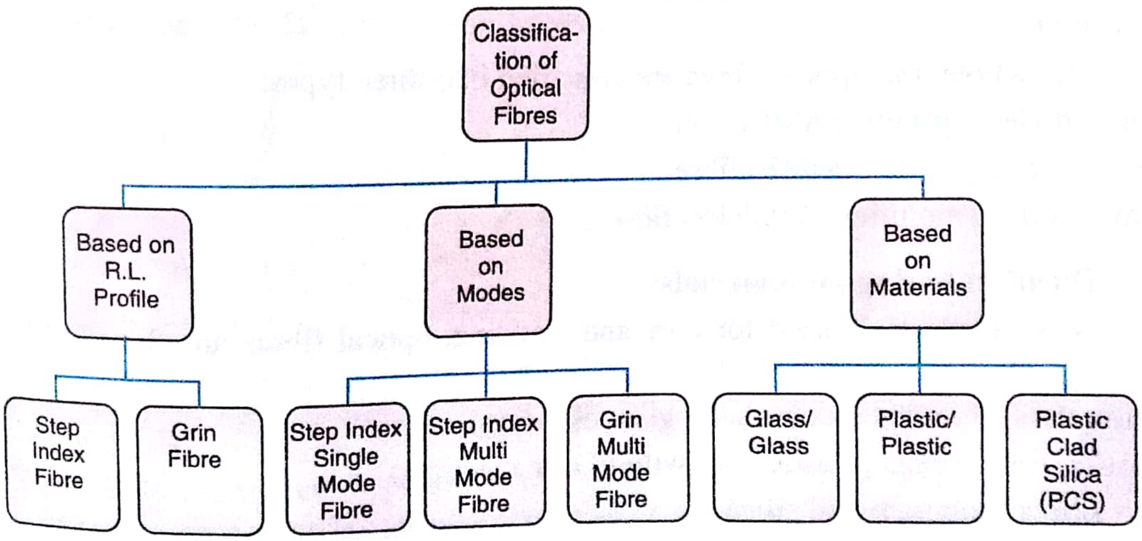
or $$\text{NA} = \sqrt{\frac{(n_1 - n_2)}{n_1}\ddot{u}_{\ddot{u}}(\quad + \quad)}$$

or $$\text{NA} = \sqrt{\Delta 2 n_1^2} \qquad (\text{as } n_1 \cong n_2)$$

Hence $$\text{NA} = n_1\sqrt{2\Delta}$$

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.**

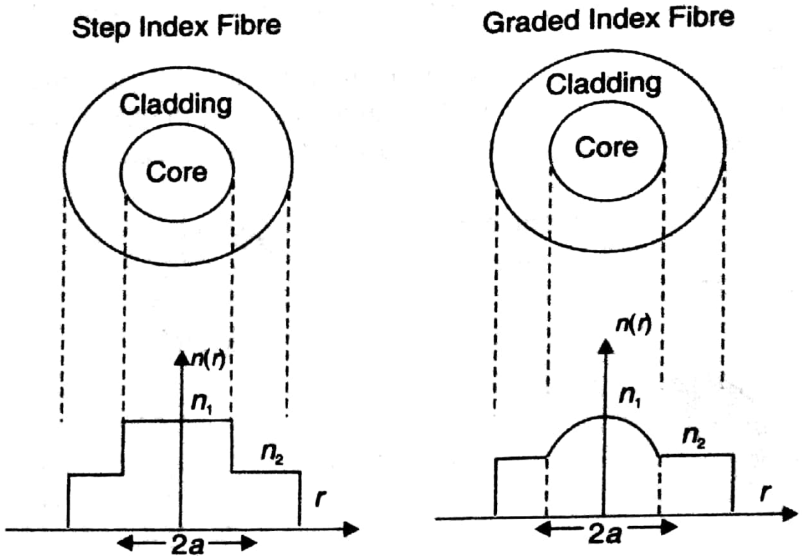


Fig. 24.14 : Classification of optical fibres based on R.I. profile (*a*) Step index fibre (*b*) GRIN fibre

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

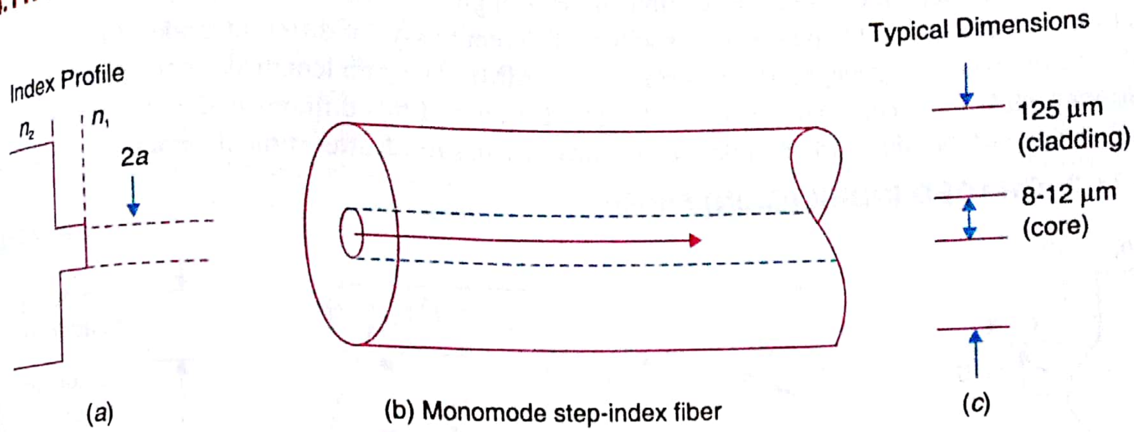


Fig. 24.15: Single mode step index fibre (a) R.I. profile (b) ray paths (c) typical dimensions

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

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

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

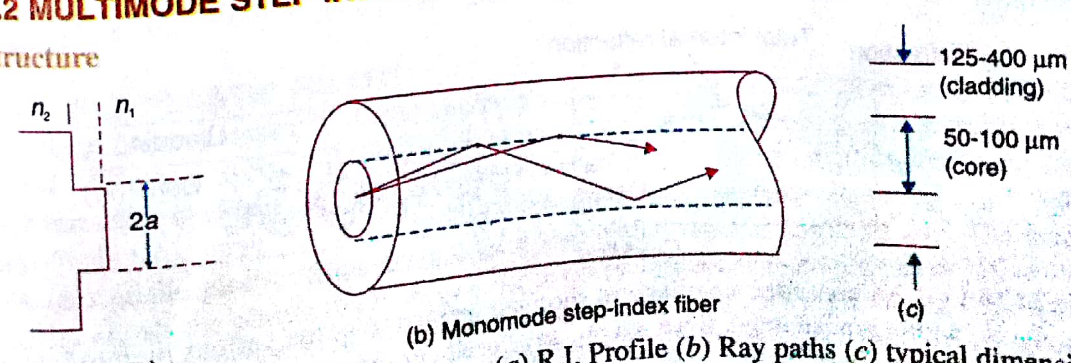


Fig. 24.16: Multimode step index fibre (*a*) R.I. Profile (*b*) Ray paths (*c*) typical dimensions.

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

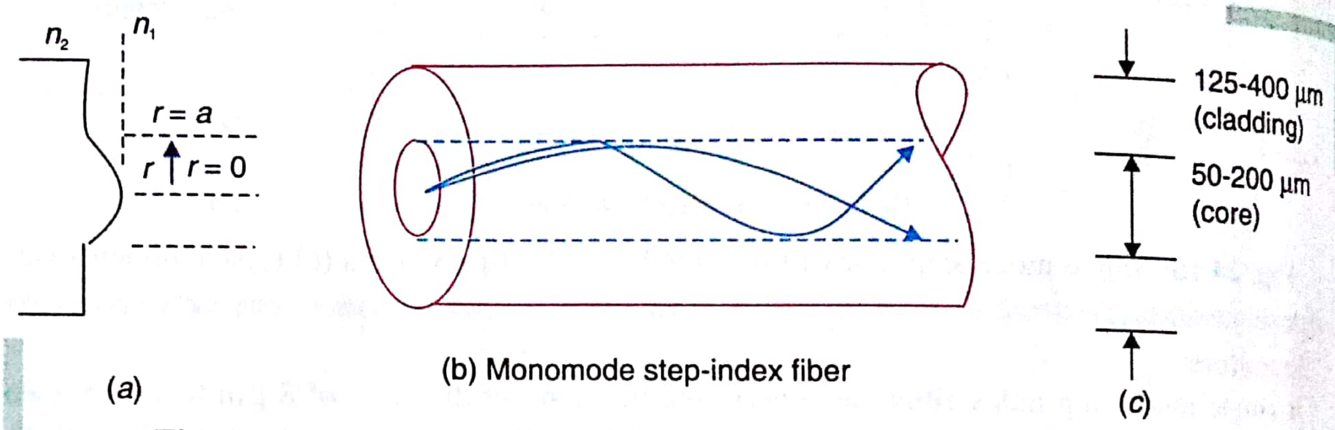


Fig. 24.17 : GRIN fibre (*a*) R.I. Profile (*b*) Ray paths (*c*) typical dimensions

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

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

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.

An optical fibre is characterized by one more important parameter, known as ***V*-number** which is more generally called normalized frequency of the fibre. It is given by the relation

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \qquad \text{...(11)}$$

where a is the radius of the core and λ is the free space wavelength. In terms of numerical aperture (NA), it is given as

$$V = \frac{2\pi a}{\lambda}\,(\text{NA}) \qquad \text{...(12)}$$

and

$$V = \frac{2\pi a}{\lambda}\, n_1 \sqrt{2\Delta} \qquad \text{...(13)}$$

The maximum number of modes supported by a step index fibre is determined by :

$$\boxed{N_{max} \simeq \frac{V^2}{2}} \qquad \text{...(14)}$$

For single mode fibre $V < 2.405$ and for multimode fibre $V > 2.406$.

The wavelength corresponding to the value of $V = 2.405$ is knwon as the *cut-off wavelength* (λ_c) of the fibre

$$\boxed{\lambda_c = \frac{\lambda V}{2.405}} \qquad \text{...(15)}$$

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).

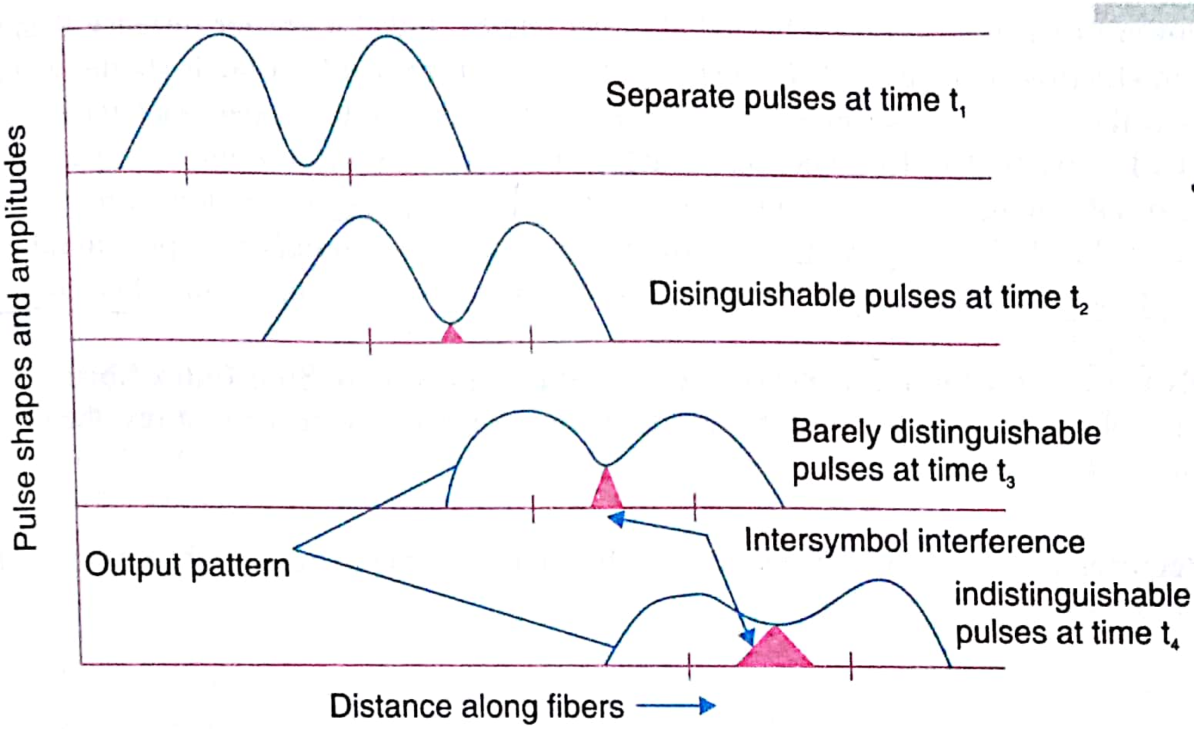


Fig. 24.25 : Distortion of the pulses traveling along a fibre

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

5.5 INTRAMODAL DISPERSION

Intramodel dispersion is pulse spreading that occurs with in a single mode. *This dispersion is due to the fact that group velocity of guided mode is a function of the wavelength.* The intramodal dispersion, also known as ***chromatic dispersion,*** *depends upon the wavelength and therefore, its effect on signal distortion increases with the spectral width of the optical source.* The spectral width of the optical source is defined as the band of wavelengths over which the optical source emits light. The dispersion that occurs due to the core material as a function of wavelength is called intramodal dispersion Fig. 5.9 shows the spectral width ($= \Delta\lambda$) and the peak emission wavelength, λ. In case of LEDs as an optical source the spectral width is approximately 5% of the central wavelength.

The intramodal dispersion has following two main regions :

(*a*) Material dispersion

(*b*) Wavelength dispersion.

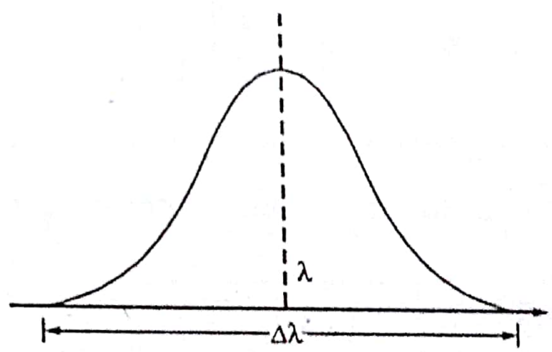


Fig. 5.9. Spectral width ($\Delta\lambda$) and the peak emission wavelength (λ).

(*a*) **Material dispersion :** *The refractive index of the core material depends upon the wavelength of the guided mode. As the group velocity of the given mode depends upon the refractive index of the core material of fibre, group velocity of an given mode depends upon the wavelength.* Material dispersion is sometimes referred to as ***spectral dispersion,*** since this is the same effect by which a prism spreads out a spectrum.

The pulse spreading occurs even when different wavelengths follow the same path.

To calculate material dispersion, we consider a plane wave propagating in an infinitely extended dielectric medium that has a refractive index $\eta(\lambda)$ equal to that of the fibre core.

The propagation constant β is thus given by :

$$\beta = k\, n(\lambda) \qquad i.e. \qquad \beta = \frac{2\pi}{\lambda}\, n(\lambda) \qquad ...(20)$$

... pure silica and 13.5 per cent GeO_2/86.5 percent SiO_2.

(*b*) **Wavelength dispersion :** *Wavelength dispersion causes the signal to broaden thereby limiting the data rate. The longer wavelength light travelling the same path as the shorter wavelength light will travel faster and, therefore, will arrive at its destination sooner.* **The difference between the time of arrival of the slowest moving wave and the fastest moving wave is equal to the pulse broadening.**

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24.16.1 INTERMODAL DISPERSION

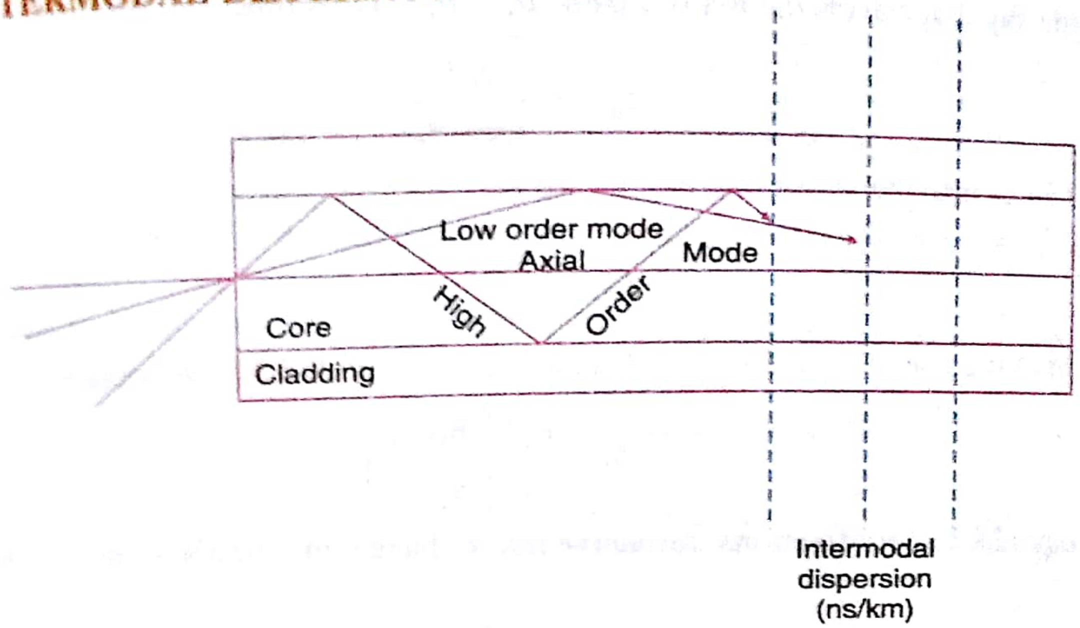

Fig. 24.26: Lower order modes reach the end of the fibre earlier while the high order modes reach after some time delay

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.

5.10 FIBRE LOSSES

The losses in optical fibres may be due to following causes :

1. Rayleigh Scattering Losses. The glass in optical fibres is an amorphous (non crystalline) solid that is formed by allowing the glass to cool from its molten state at high temperature until it freezes. During this forming process, some imperfections (defects) are caused in fibre which allow to scatter a small portion of the light passing through the glass, creating losses. It affects each wavelength differently. This scattering results in the following losses :

2.5 dB/km at 0.82 μm

0.24 dB/km at 1.3 μm

0.012 dB/km at 1.55 μm

Fig. 5.24 shows the intrinsic minimum Rayleigh scattering losses of silica fibres plotted against wavelength over the usable portion of the spectrum from 0.7 to 1.6 μm.

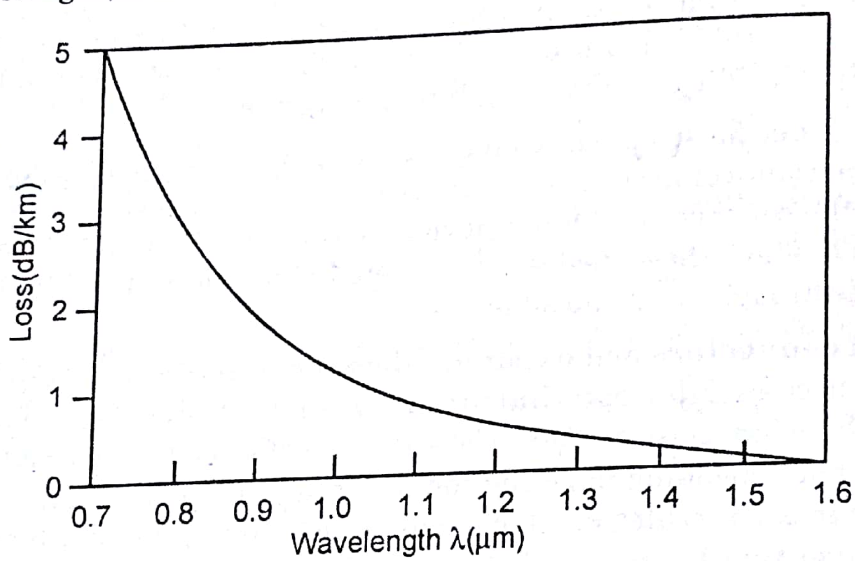

Fig. 5.24. Rayleigh scattering losses in silica fibres.

2. Absorption Losses. Three different mechanisms contribute to absorption losses in glass fibres. These are ultraviolet absorption, infrared absorption, and ion resonance absorption.

The oxygen ions in pure silica have very tightly bonded electrons, and only the ultraviolet light photons have enough energy to be absorbed. However, in silica light guide, the dopants and transitional metal impurities have electrons that can be excited in the visible and near-infrared light regions. These absorption trails are minimal between 1.2 and 1.3 μm wavelength (Fig. 5.25).

Infrared absorption takes place because photons of light energy are absorbed by the atoms within the glass molecules and converted to the random mechanical vibration type of heating.

During manufacture, some minute quantities of water molecules trapped in the glass contribute *hydroxyl ions* (OH^-) to the material. These ions also absorb energy at peaks of 0.95, 1.23 and 1.39 μm with the main peak at 1.39 μm as shown in Fig. 5.25.

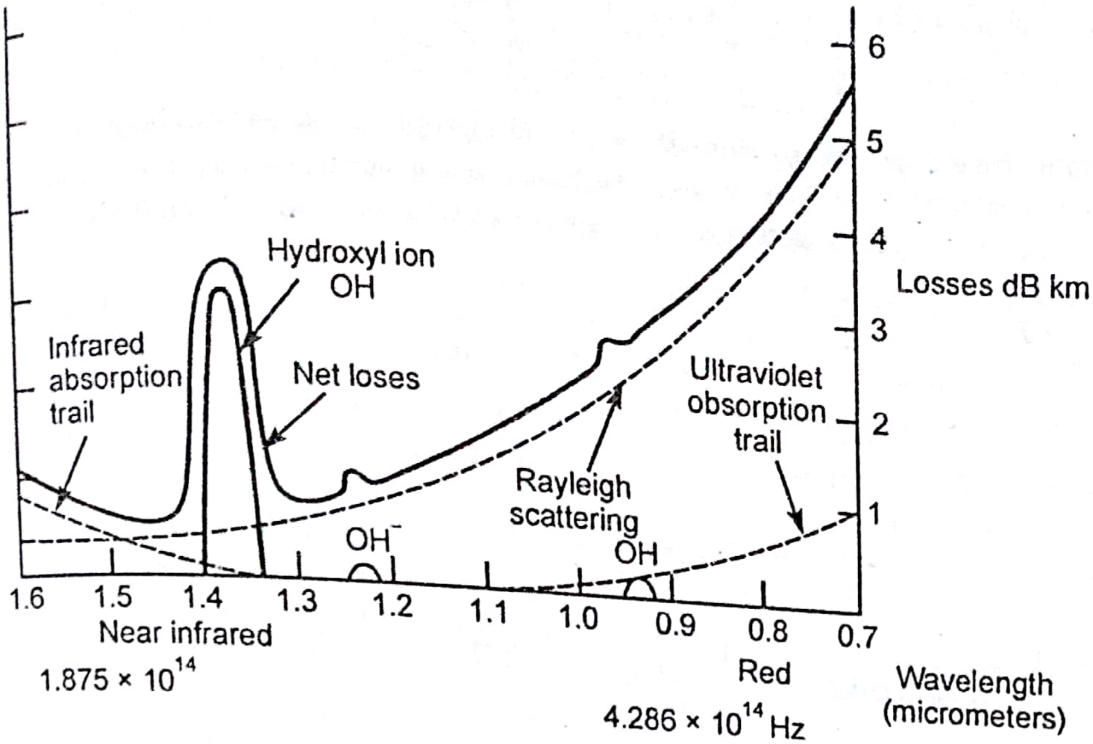

Fig. 5.25. Wavelength versus losses in typical fibre optic cables.

3. **Microbend loss,** due to small surface irregularities in the cladding, causes light to be reflected at angles where there is no further reflection.

4. **Macrobend** is a bend in the entire cable which causes certain modes not to be reflected and therefore causes loss to the cladding (Fig. 5.26).

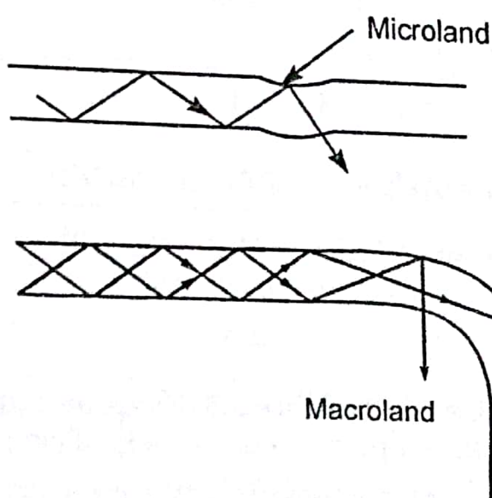

Fig. 5.26. Power loss due to microbend and macrobend.

5. A **temperature change** from 0° to – 60°C could add as much as 5 dB to the cable losses. *Stress* (strain and tension) could add another 10 dB.

Attenuation loss of an optical fibre is defined as the ratio of optical output power P_{out} from a fibre of length L to the optical input power P_{in}. In symbol α it expresses attenuation in decibel/kilometre.

$$\boxed{\alpha = \frac{10}{L}\log\left[\frac{P_{in}}{P_{out}}\right]} \quad ...(i)$$

In case a fibre is an ideal, then $P_{in} = P_{out}$, therefore $\alpha = 0$ which means that there will not be any attenuation loss. In actual practice, a low loss fibre may have $\alpha = 3$ decibel/km. This means that the optical power would decrease by 50% over a 1 km length.

5.11 ADVANTAGES/DISADVANTAGES OF OPTICAL FIBRES

Now knowing the basic facts about fibre optics, we will discuss the advantages and disadvantages of optical fibres.

Advantages

1. **Ceaper**. The main ingredient in glass is sand (SiO_2), and there is an almost unlimited supply of sand in the world compared to the supply of copper or aluminium.
2. **Safety.** Through optical fibres, photons of light move instead of an electrical current. Therefore, there is no chance of a spark flash, which could be dangerous.
3. **Radio Frequency Interference (RFI).** Since the fibre system carries no electrical current, the energy transmitted through the fibre cannot radiate *RF* interference, nor can it be contaminated by any external noise or *RF* fields.
4. **Security (Privacy).** Because of the absence of the flow of current through the fibre, criminal intrusion into the system is also prevented. Confidential information cannot be routed to unwanted receivers, nor can false information be fed into data stream.

5. **Low losses.** The transmission loss per unit length of an optical fibre is about 4 dB/km. Therefore, longer cable runs between repeaters are feasible. Examination of 46 fibre types revealed a range of losses from 2 to 385 dB/km, with an average loss of 27 dB/km.
6. **Wider bandwidth.** Within a totally closed system, the number of signals that can be modulated on a fibre optic light beam exceeds the number that can be modulated on a very high frequency *RF* carrier by a factor of about 1000.
7. **Deterioration.** Glass is immune to corrosive and oxide degradation and will stand up well in harsh environments. Moisture, toxic vapours and acids will not degrade the glass fibres.
8. **Small size and light weight.** The size of the core and clad of a single fibre conductor is much smaller than the diameter of a common copper wire conductor; however, when the insulation is included, the sizes are similar. Bundles of optical fibre cables are smaller by a factor of 10 and weigh less by a factor of 14 than an equal number of copper wire conductors.
9. **Temperature.** Excluding the protective insulation, the melting point of glass is much higher than copper, and that of copper is much higher than the plastics used for cores and clads.
10. **Long life.** The life expectancy of glass fibres is predicted to exceed 100 years. (This prediction is based on the history of glass and due to its immunity to harsh environment).

sadvantages

1. **Limited application.** All fibre optic systems are limited to fixed point-to-point ground installations. They cannot leave the ground nor be associated with a mobile communication station.
2. **Nuclear radiation.** Glass, when exposed to neutron bombardment, will darken. The harder the glass, the more quickly it will discolour.
3. **Low power.** Popular light-emitting sources are restricted to very low power devices. Though, higher power devices are available but they are very costly.
4. **Distance.** Because of the low-power sources, the distance between repeater amplifiers must be relatively short for the high date rates demanded in some system.
5. **Modulation.** There are limited ways in which the light source can be modulated.
6. **Fragility.** The other disadvantage with optical fibre is that these fibres are easily broken or damaged due to age and vibrations.

5.12 APPLICATIONS OF OPTICAL FIBRES

Due to the various advantages described in last section, optical fibres are widely used in many systems. Some of these are as follows :

1. The most important application of optical fibres is in the field of communications as information channel or transmission medium. Other telecommunication networks include telephone, cable TV, videophone, multimedia, desktop teleconferencing etc.

2. In military mobiles such as air-craft, ships, tanks etc., fibre guided missiles, short and long distance communication links.
3. Close circuit TV (CCTV) links for traffic controls, security etc.
4. In ophthalmology, a laser beam guided by the fibres is used to reattach detached retinas and to correct defects in vision.
5. In the fabrication of fibrescope in endoscopy for the visualization of internal portions of the human body.
6. In sensors and transducers.
7. The signal multiplexing and transmission in automotive electronics, centralized locking, door lamps, power windows, seat mechanism etc. in automobilies is under investigation.