8 Fibre Optics

(1) INTRODUCTION

Communication may be defined as transfer of information from one place to other. A communication system is set up, which can convey information to any distance. Generally the information is sent by the communication system by modulating it with a suitable electromagnetic wave, which acts as a carrier for the information. The modulated carrier is received back at the destination and signal is reproduced from it by demodulation. The carrier frequencies used for this purpose extend from radio frequencies to optical frequencies. The communication using carrier waves of optical frequencies is called optical communication.

Optical communication through the atmosphere has a number of limitations *e.g.* light transmission is restricted to line of sight (*i.e.* if an obstacle comes in between transmitter and receiver, then communication through atmosphere is not possible). Also light transmission through atmosphere is severely affected by disturbances such as rain, snow, fog, dust and atmospheric disturbances etc. The low frequency carrier waves like radio waves and micro waves are least affected by atmospheric conditions. But the problem of using these waves is the small transmission band width. Because of this information carrying capacity of these waves is very less. On the other hand if we use optical frequency carriers, then band width increases by a factor of 10^4. However as said above for optical communication, atmosphere is not suitable transmission medium. Hence we have to use optical fibres for this purpose.

Then a new problem of launching enormous amount of optical power into the fibre appeared. This problem was solved by the invention of Laser.

(2) ADVANTAGES OF OPTICAL FIBRE COMMUNICATION

The communication of information via optical fibre has many advantages. For example the information carrying capacity is much more than conventional copper or co-axial cables. The loss of signal is much more in copper cables, which restricts the transmission to a few kilometers of distance. On the other hand, the loss of signal in optical fibre is very less, which makes them most suitable for long distance transmission. Optical fibre have very small diameters (comparable to diameter of a hair). Even after covering with protective coatings, these are much lighter in weight and smaller in size compared to corresponding copper wires. This feature makes them suitable for use in mobiles like satellites. The material used for optical fibres is glass or a polymer plastic. These materials are electrical insulators. Hence these fibres are free from external electromagnetic disturbances. This property makes these fibres suitable for communication in electrically hazardous environments. Further light wave from optical fibres donot radiate significantly. This provides high signal security and makes optical fibres an ideal way of communication in millitary applications, banking etc. Optical fibres require less intermediate repeaters, which enchances system reliability. The optical components have predicted life time of 20 to 30 years, which reduces cost of maintenance.

(3) OPTICAL FIBRES

"An optical fibre is a thin flexible medium having cylindrical shape, consisting of three sections (*i*) core (*ii*) clad (*iii*) outer jacket called sheath". Core is the inner most section and is made from glass or plastic. Signal propagation takes place via this section of the fibre. Core is surrounded by another layer of glass or plastic called cladding. The refractive index of clad is slightly lesser than that of core. The outer layer of sheath is made from plastic or polymer and other materials and is provided for protection against moisture, crushing and other environmental damages. The core acts as a continuous layer of parallel mirrors. The signal is first encoded into a light beam, which is then passed in between the two boundaries and propagated as a result of multiple total internal reflections.

(4) PROPAGATION OF LIGHT WAVE IN AN OPTICAL FIBRE

Fig. (1) shows the longitudinal cross section of an optical fibre. The core has uniform refractive index n_1 and clad has refractive index n_2, where $n_1 > n_2$. When a ray of light strikes at any point A on the core clad interface, making an angle i, greater than the critical angle then it suffers total internal reflection back into core. The ray then strikes at same angle i with the normal at point B and hence suffers total internal reflection. The process continues and light ray travels along the length of fibre. Hence propagation of light signal through optical fibre is based on the principle of total internal reflection.

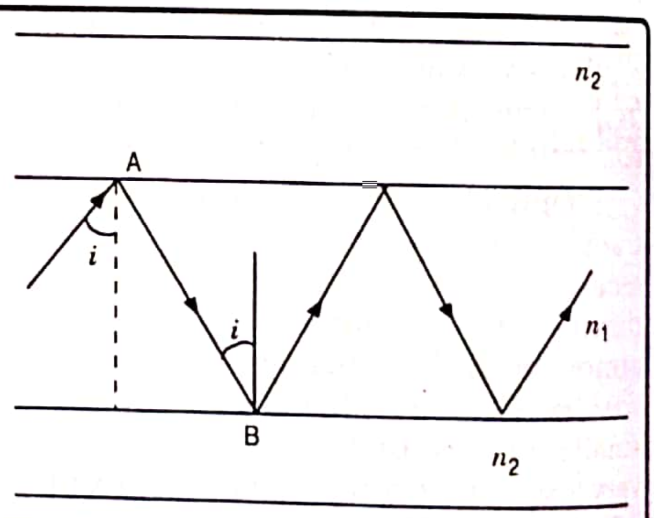


Fig. 1

In figure (1) we have shown a single ray passing through fibre. If a large number of light rays travel as a parallel beam through the fibre then all these rays in the beam will suffer equal number of reflections from one end to the other end of the fibre and hence will take same time to travel through it. "All parallel paths of light rays, consisting of same number of reflections are said to constitute a Mode". The fibre through which a single beam of parallel waves/rays can travel is called Single mode (or mono mode) fibre.

Figure (2) shows three non parallel rays 1, 2, 3 entering in a fibre at point 'A' simultaneously. It is clear from the figure that the paraxial ray 1 (travelling almost zero angle with axis of core) suffers less reflections than marginal rays 2 & 3 (making large angle with axis of fibre). Thus these rays suffer different number of reflections and hence take different times to travel the fibre length. The rays 1, 2, 3 thus define three different modes. In general if there are three different parallel beams 1, 2, 3 (instead of single rays) then beam 1 will take less time to travel through fibre length than beam 2 and 3. Thus a fibre through which more than one non parallel light beams can travel is called Multimode Fibre. Different modes take different times to travel same length of optical fibre. This is called Transit Time Dispersion. This dispersion sets up an upper limit on the rate at which light can be modulated by an analog or digital signal. As a result of this distortion, the variations of successive pulses of light may overlap each other and thereby causing distortion of the information being carried. However this defect can be minimised by taking diameter of the core of same order as the wavelength of the light wave to be propagated.

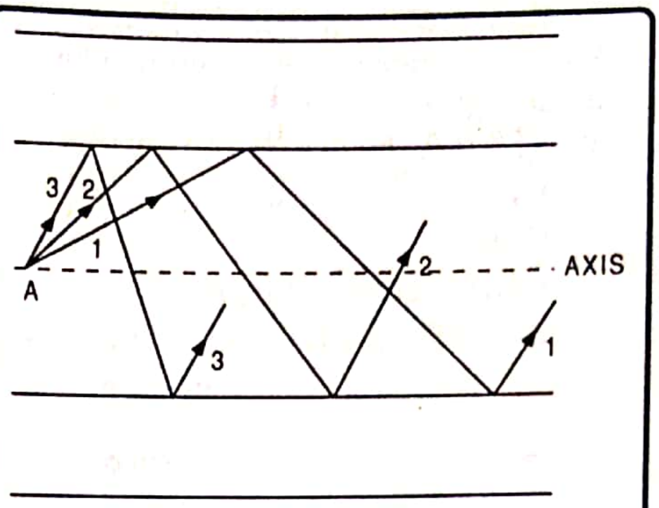


Fig. 2

(5) ACCEPTANCE ANGLE AND ACCEPTANCE CONE

Fig. (3) shows a number of light rays entering the optical fibre at left end (called Launching End). Let n_0, n_1, n_2 be the refractive index of surrounding, core and clad respectively where $n_0 < n_2 < n_1$. Let a ray of light (named as ray number 1) enters the fibre making an angle θ_i with axis of fibre. It refracts into the core at angle θ_r and then travels along path DA. At point A, it strikes core clad interface and angle of incidence at A is ϕ. If ϕ is greater than critical angle (ϕ_c) then ray will suffer total internal reflection and hence can propagate through fibre.

Apply Snell's level at point D we get

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

In right angled ΔAED, we have

$$\theta_r + \phi = 90°$$

$$\Rightarrow \quad \theta_r = 90 - \phi$$

$$\Rightarrow \quad \sin\theta_r = \cos\phi \qquad \text{...(2)}$$

Substitute in (1), we get

$$n_0 \sin\theta_i = n_1 \cos\phi \qquad \text{...(3)}$$

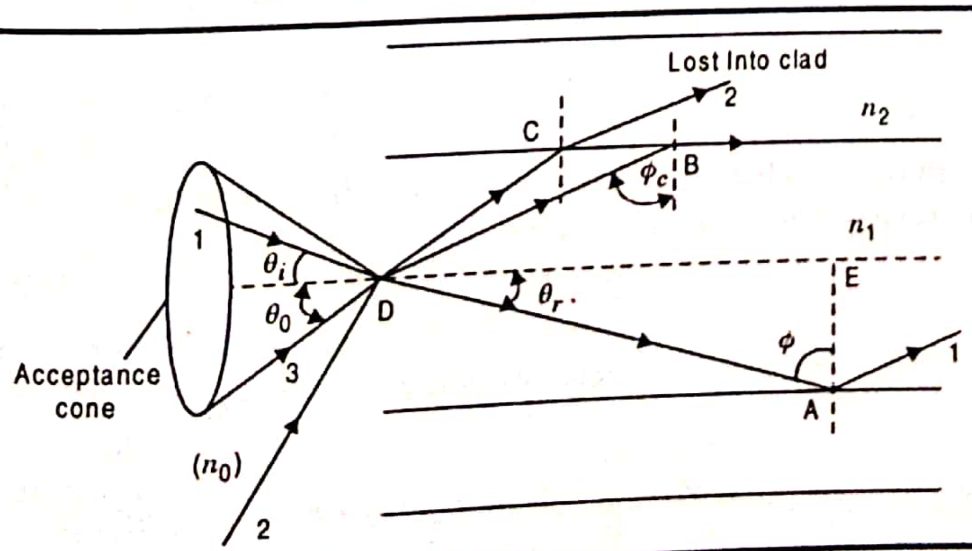


Fig. 3

We know that as ϕ decreases $\cos\phi$ will increase (for $0 \le \phi \le \pi$). Thus from (3), we see that $\sin\theta_i$, and hence θ_i is maximum, when ϕ is minimum. The minimum value of ϕ is equal to critical angle ϕ_c, so that ray just suffers total internal reflection at core clad interface. Let largest value of θ_i is θ_0. Hence we can say that

When $\phi = \phi_c = \text{minimum}$

then $\theta_i = \theta_0 = \text{maximum}$

Hence equation (3) gives $n_0 \sin\theta_0 = n_1 \cos\phi_c$ ...(4)

By Snell's law, the critical angle is given by

$$n_1 \sin\phi_c = n_2 \sin 90° \text{ (see point B in figure)}$$

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

Hence

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

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

Substitute this value in equation (4), we get

$$n_0 \sin\theta_0 = \sqrt{n_1^2-n_2^2}$$

or

$$\sin\theta_0 = \frac{1}{n_0}\sqrt{n_1^2-n_2^2}$$

or

$$\boxed{\theta_0 = \sin^{-1}\left(\frac{1}{n_0}\sqrt{n_1^2-n_2^2}\right)} \quad \text{...(5)}$$

Equation (5) gives the maximum value of angle of incidence at the launching end of the optical fibre, such that the ray is just propagated in the core of the fibre. This angle is called Acceptance angle.

The light rays contained within a cone having semi vertical angle θ_0 are accepted or transmitted along the fibre. This cone is called Acceptance cone.

(6) NUMERICAL APERTURE

Numerical aperture of an optical fibre is defined as the sine of the angle of acceptance. Thus

$$NA = \sin\theta_0$$

or

$$NA = \frac{1}{n_0}\sqrt{n_1^2-n_2^2} \quad \text{...(6) (using 5)}$$

Numerical aperture is also called figure of merit of the optical fibre.

Generally n_2 is very close to n_1. We define

$$\Delta = \frac{n_1-n_2}{n_1} \quad \text{...(7)}$$

as fractional change in refractive index between core and cladding.

From (7), we have

$$NA = \frac{1}{n_0}\sqrt{(n_1-n_2)(n_1+n_2)}$$

$$\approx \frac{1}{n_0}\sqrt{(n_1-n_2)(2n_1)}$$

$$= \frac{1}{n_0}\sqrt{\frac{(n_1-n_2)}{n_1}(2n_1^2)}$$

$$\Rightarrow \qquad \text{NA} \approx \frac{n_1}{n_0}\sqrt{2\Delta} \qquad \text{...(8)}$$

The numerical apertures for fibres used in short distance communication are in the range of 0.4 to 0.5. Whereas for long distance transmission NA lies in the range 0.1 to 0.3.

(7) TYPES OF OPTICAL FIBRES

Optical fibres are classified in two categories :

(*i*) Step Index Fibre (*ii*) Graded Index Fibre

Each type is further divided into two catagories namely (*a*) Single Mode Fibre (SMF) (*b*) Multimode Fibre (MMF). Thus we can have step index SMF or step index MMF or graded index SMF or graded index MMF.

Step Index Fibre

In case of step index fibre the refractive index of core has uniform value n_1 every where. In crossing from core to clad normal to the fibre axis, there is an abrupt decrease in the refractive index from n_1 to n_2. The refractive index is again uniform every where in the clad, having value n_2. If a graph is plotted between refractive index of the material of the fibre and the distance from the axis of the fibre (this graph is named as index profile of the fibre), then shape of the profile is similar to a step. Hence the name of fibre.

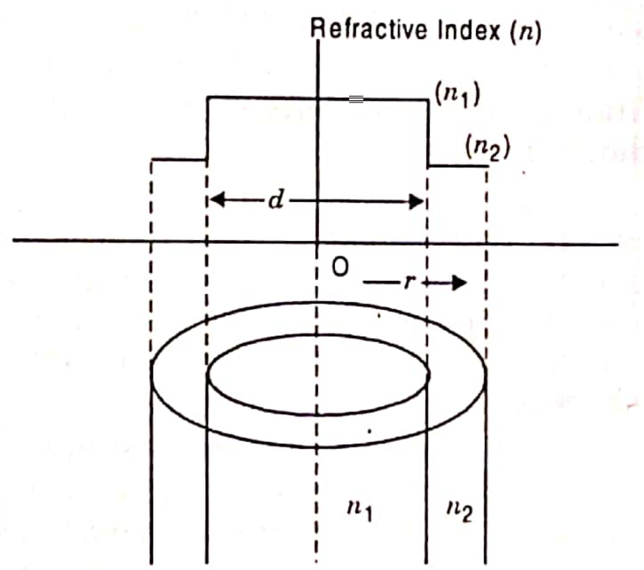


Fig. 4

The outer clad may be made from plastic or glass. However in plastic clad fibres the signal loss is much more than glass clad. Further glass clading fibres can be fabricated with small core diameters without sacrificing the mechanical strength. If the diameter of core is very large then a number of modes can propagate simultaneously through the fibre and each mode will have different value of transit time. If diameter d of the fibre satisfies the condition

$$d \geq \frac{0.766\lambda}{\text{NA}} \qquad \text{...(9)}$$

then a number of modes existing through the light pipe become possible . Such a fibre is called step index multi mode fibre. On the other hand if d is less than $\frac{0.766\lambda}{\text{NA}}$, then only a single mode can propagate through fibre. This type of fibre is called step index single mode fibre. Single mode fibres (SMF) are characterised by very small core diameter, low numerical aperture, low attenuation and very high band width. Inspite of all these qualities, the use of very thin cores creates mechanical difficulties in manufacturing, handling and splicing the fibres. Hence this type of fibre is very expensive. Single mode fibre is used under sea cables.

Graded Index Fibre

In these fibres the refractive index of the core is maximum at the centre and it decreases with distance from centre of core towards clad. The refractive index of core changes with distance r from centre of core according to the expression.

$$n_1(r) = n_1(0)\sqrt{1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}} \qquad \ldots(10)$$

Where $\Delta = \dfrac{n_1(0) - n_2}{n_1(0)}$

a = core radius

$n_1(0)$ = refractive index of core at the centre.

α is called index parameter. Value of α is decided by fibre manufacturer.

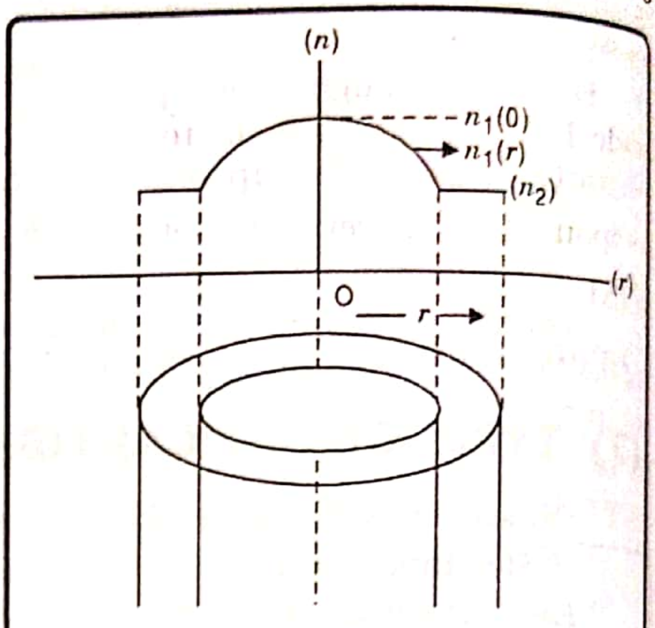


Fig. 5

Typically $\alpha = 2$ and corresponding index profile is parabolic in nature, as shown in figure (5). This profile is also called Index Profile.

The propagation of light through a Graded index multimode fibre (MMF) is shown in figure (6).

Light ray 1 travels along the axis of core and ray 2 travels obliquely to it. However ray 2 is continuously entering in a medium of lower refractive index thus it starts bending away from normal and simultaneously its velocity increases.

Ultimately ray 2 suffers total internal reflection and starts approaching the centre of core again. The ray 1 on the other hand travels along the axis of the core, where the refractive index is maximum. Thus this ray is slowest.

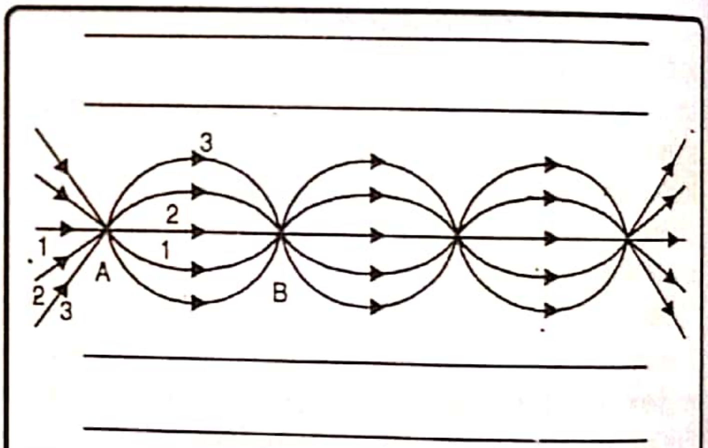


Fig. 6

Although ray 1 travels minimum distance from point A to B, but its velocity is also minimum. While distance travelled by oblique rays is large, but their velocity is also large than axial ray. Hence the rays will reach from point A to B in same time independent of the path followed. Thus practically there is no transit time dispersion in graded index fibres.

(8) MODES OF PROPAGATION

In optical fibres, light propagates in same way as electromagnetic wave propagates. Thus variation of electric field (E) and magnetic field (H) in the wave guide (optical fibre) takes place in a number of distinct ways. The plane passing through the instantaneous direction of electric field $\vec{E}$ and magnetic field $\vec{H}$ at a point is called Frontal Plane.

(*i*) In free space light propagates as TEM mode (Transverse Electric & Magnetic). In this mode both $\vec{E}$ & $\vec{H}$ are perpendicular to the direction of propagation (Z-axis) *i.e.* neither electric nor magnetic field has any component along direction of propagation of light (called longitudinal component) *i.e.* $E_l = H_l = 0$. This is shown in fig. (7) (*a*), where propagation of light is assumed along Z-axis.

However through a wave guide (propagation medium), light may not travel as TEM mode. It can have various different modes. A few modes are shown in fig. (7). In TE mode, the electric field vibration is perpendicular to the direction of propagation (*i.e.* $E_l = E_z$ = longitudinal component = 0), however magnetic field $\vec{H}$ is not perpendicular to the direction of propagation. In TM mode, $\vec{H}$ is perpendicular to the direction of propagation. Hence in this case $H_l = 0$, but $E_l \neq 0$. In the hybrid EH mode, neither $\vec{E}$, nor $\vec{H}$ is perpendicular to direction of propagation, but transverse component of $\vec{E}$ is stronger than transverse component of $\vec{H}$. While in case of HE mode, we have H_t stronger than E_t. The frontal planes corresponding to some modes are shown as shaded in fig. (7).

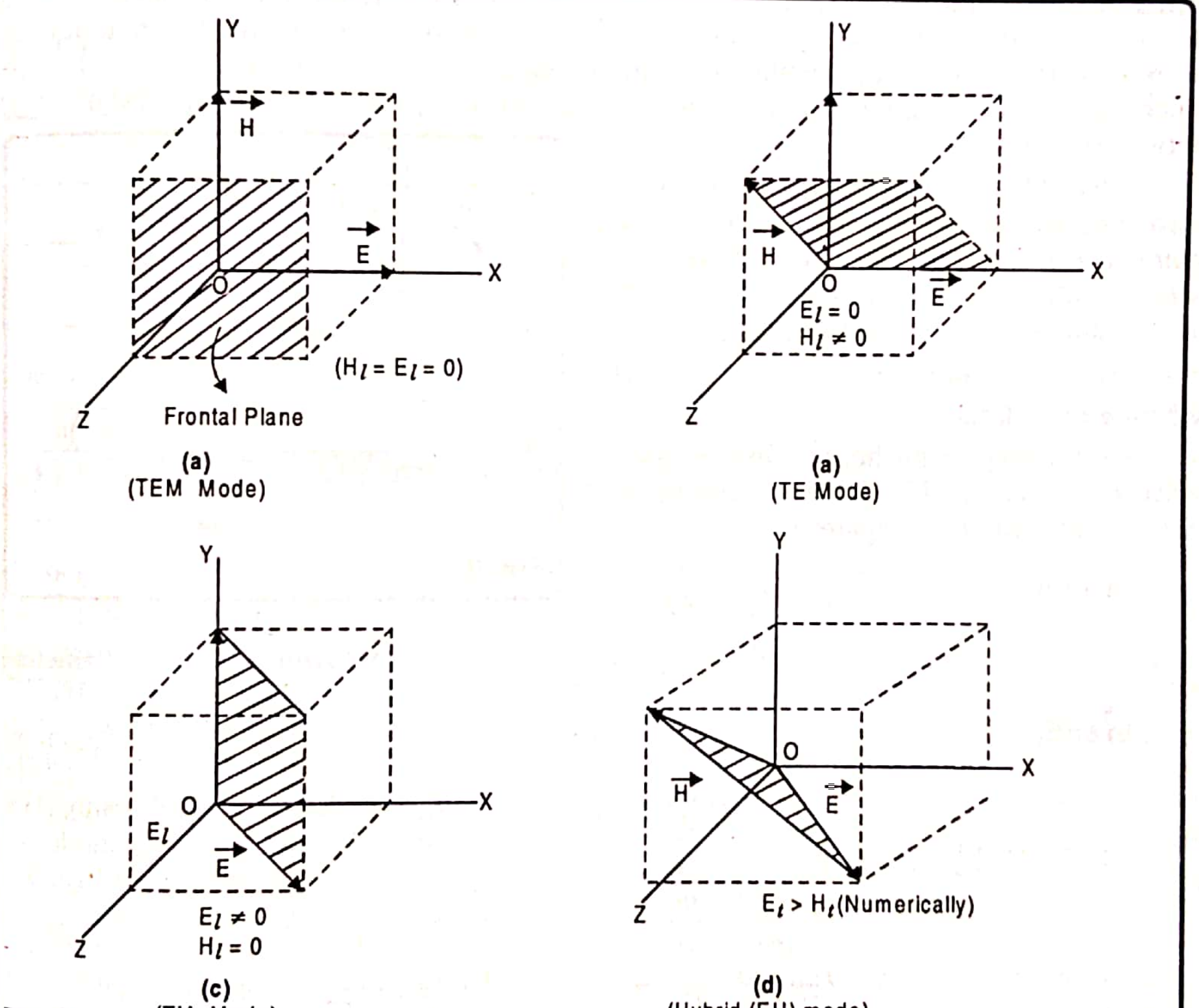


Fig. 7

(9) MERIDIONAL AND SKEW RAYS

A ray of light is said to be Meridional if it propagates in a single plane from one end to the other end of the fibre. The propagation of meridional rays is possible only in TE and TM mode. These rays are completely guided.

A ray of light whose plane of propagation changes with successive reflections is said to be skew ray. Its path in the fibre is a sort of spiral path. The propagation of skew rays takes place entirely in hybrid HE or EH mode. But some of these modes produce losses due to leakage and radiation.

(10) NUMBER OF MODES

According to ray theory of light, it appears that all rays which are incident on core clad interfrace and making angle with normal greater than the critical angle are propagated along the fibre. However, when the interference effect due to phase of the plane wave associated with the ray is taken into account, it is seen that only waves at certain discrete angles greater than or equal to critical angle are capable of propagating along the fibre.

Fig. (8) shows a monochromatic light ray of wavelength λ incident at an angle of glance θ on the core clad interface at point A. It suffers total internal reflection at A and reaches at point B, such that angle of glance at B is also θ (law of reflection). AD is a plane drawn at point A normal to the incident ray (1), while BE is another plane drawn normal to reflected ray 1'' at B. Since these rays are parallel, so the planes AD & BE are also parallel and let shortest distance between them is BD.

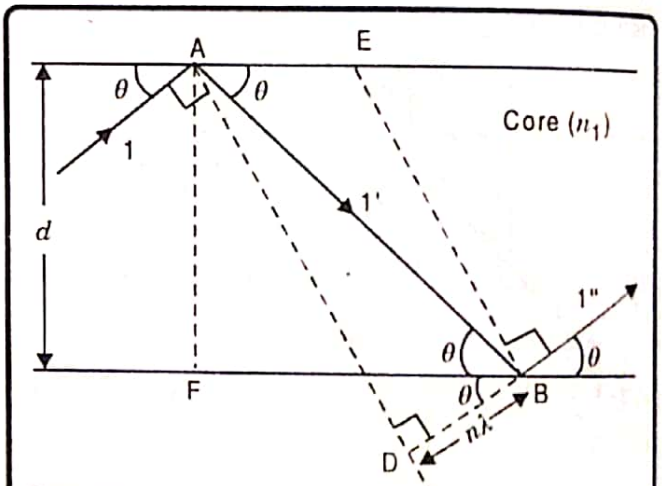


Fig. 8

Infact AD & BE represent two consecutive wave fronts for two consecutive reflections at points A & B. Now parallel wave fronts can be formed only when separation between them is an integral multiple of wavelength λ.

i.e. $\quad BD = n\lambda \quad$ ...(11)

where $n = 1, 2, 3, 4,......$

$n = 0$ is not possible because in that case ray will oscillate back and forth between point A & B of core and cannot propagate at all.

In ΔAFB
$$\sin\theta = \frac{AF}{AB} = \frac{d}{AB} \quad \text{...(12) (where } d \text{ is core diameter)}$$

In ΔABD
$$\cos 2\theta = \frac{BD}{AB} = \frac{n\lambda}{AB} \quad \text{...(13) (using (11))}$$

Divide (13) by (12), we get
$$\frac{\cos 2\theta}{\sin\theta} = \frac{n\lambda}{d}$$

or
$$\frac{d\cos 2\theta}{\lambda \sin\theta} = n \quad \text{...(14)}$$

Equation (14) tells us that $\frac{d\cos 2\theta}{\lambda \sin\theta}$ should always be an integer for a ray of light to propagate through fibre. This means that for a given value of d & λ, there are only certain specific angles θ (or directions or paths) in the core along which propagation of light is possible. Hence number of modes propagated in fibre are limited.

The number of allowed modes through a multimode fibre are determined by an important parameter called V-number or Normalized frequency or cut off frequency. It is a dimensionless parameter and is defined by the following relation.

$$V = \frac{\pi d n_0}{\lambda} (NA) \qquad ...(15)$$

Where d = core diameter, n_0 = refractive index of surroundings and $NA = \frac{1}{n_0}\sqrt{n_1^2 - n_2^2}$ represents numerical aperture.

For a step index multimode fibre the number of allowed modes is given roughly as

$$N \approx \frac{V^2}{2} \qquad ...(16)$$

provided the number of propagated modes is more than 10.

For a single mode fibre the value of V is less than/equal to 2.405. If $V > 2.405$ then fibre is multimode.

In case of graded index multimode fibre, the number of modes are given approximately as

$$N_{graded} = N_{step\ index}\left(\frac{\alpha}{\alpha+2}\right)$$

Normally $\alpha = 2$

$$\therefore \qquad N_{graded} \approx \left(\frac{V^2}{2}\right)\left(\frac{2}{2+2}\right)$$

$$= \frac{V^2}{4}$$

(11) LOSS OF POWER IN OPTICAL FIBRE

There are many reasons, which can cause the loss of optical power, as light propagates through the fibre. Some of these are discussed below :

1. Material Loss : In the fabrication of various types of fibres, we use GeO_2, P_2O_5, B_2O_3 etc. as dopants in silica in order to modify its refractive index. These dopants have property of absorbing light waves corresponding to wavelength range 800 nm to 1300 nm. Since optical carrier wavelengths also fall in this range, thus these materials cause loss of optical power by absorbing a portion of it.

2. Rayleigh Scattering Loss : During the manufacturing process of fibre, a large number of inhomogeneities appear in the material, due to fluctuation in density and presence of impurity atoms. These inhomogeneites act as scattering centres as their dimensions are comparable to the carrier wave length. This loss of signal is called Rayleigh Scattering Loss, because the intensity loss due to this effect varies inversely as fourth power of wavelength.

3. Absorption Loss : This kind of loss is caused by the very nature of core. We know that when light falls on a transparent medium, a part of it is reflected, some part is absorbed and remaining light is transmitted. The absorption of light by core material can take place via three different mechanisms namely ultraviolet absorption, infrared absorption and Ion resonance. During the manufacturing process, minute quantities of water molecules are trapped in glass fibre. These water molecules contribute OH^- ions to the material. A concentration of OH^- ions of 1 part in billion can cause $1 dB/km$ loss at 950 nm. So dehydration of the material during manufacturing can be employed to keep OH^- ions at minimum.

4. Leaky Modes : We know that propagation of light through fibre can take place via meridional rays or skew rays. The skew rays suffer only partial reflection while meridional rays are completely guided. Thus the modes allowing propagation of skew rays are called leaky modes. Some optical power is lost into the clad due to these modes.

5. Mode coupling loss : It is not possible to manufacture a single fibre of infinite length. Thus we often have to connect two or more fibres to increase length. Further, these have to be tapped at a large number of points, when there are multi users of the transmitted signal. The devices used to connect two fibres are called connectors or splicers depending upon nature of joint (whether temporary or permanent). These devices may not be able to transmit all the power to the next fibre segment due to improper matching of the cores etc. Such kind of loss of optical power is called mode coupling loss.

6. Geometric or Bending loss : In fig. (1), the basic diagram of optical fibre is shown. Here core is shown to be of uniform diameter, so that a ray of light will suffer total internal reflections repeatedly. However, it is not possible to make core of uniform diameter. The diameter of core may be varying slightly at certain locations. These locations are called microbends. When ray of light strikes at this microbend then by chance the angle of incidence may become less than critical angle. Hence ray will leak into the clad. This kind of loss is called Microbending loss. It is demonstrated in fig. (9) (*a*).

A macrobend is the bend in entire cable, which causes certain modes, not to be reflected and therefore causes the loss of the signal into the cladding.

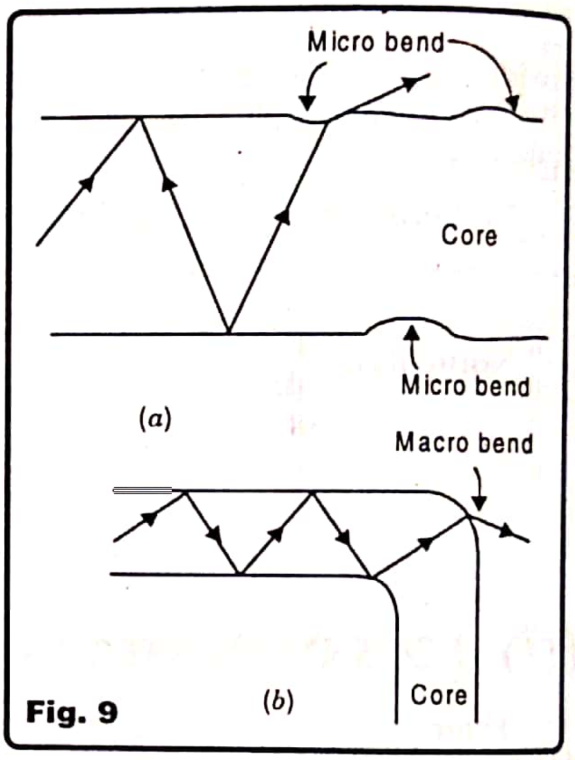


Fig. 9

7. Radiation Induced Loss : When material of glass interacts with the electrons, neutrons, gamma rays and X-rays, the structure of the glass molecules is altered and fibre darkens. This results in additional loss of optical power. This loss is called Radiation induced loss. It is more prevalent in nuclear reactors and other regions where energetic radiations are present.

8. Temperature Dependent Losses : If the temperature of fibre is less than –10°C, then differential thermal expansion between polymer coating and glass causes stress, which creates a microbend and results in loss of power.

Total Attenuation. Combining all the loss phenomena, except the cabling, the resulting attenuation curve obtained is shown in fig. (10). From figure, it is clear that the power loss in optical fibre (glass core) is minimum corresponding to wavelength ranges 800-900 nm, 1200-1300 nm and 1500-1600 nm. These three ranges are known as three 'optical windows'.

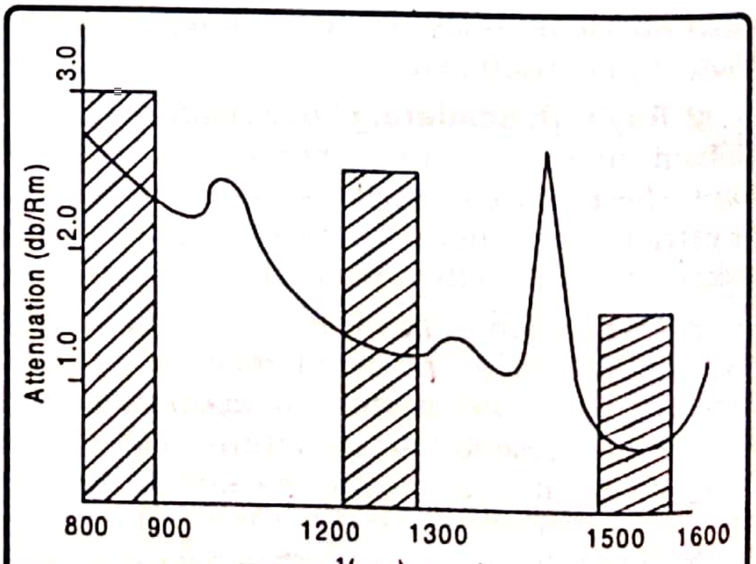


Fig. 10

"The decrease in intensity of propagated light along the length of optical fibre is called Attenuation." Let P_0 is optical power launched into the fibre.

P = Optical power at distance x from launching end of fibre.

$$-\frac{dP}{dx} = \text{rate of decrease of optical power w.r.t. distance}$$

It is observed that rate of decrease of power (Power Gradient) at a point is directly proportional to optical power at that point.

i.e. $$-\frac{dP}{dx} \propto P$$

or $$-\frac{dP}{dx} = \alpha_p P$$ (where α_p = constant of proportionality)

$$\Rightarrow \quad \frac{dP}{P} = -\alpha_p \, dx$$

$$\Rightarrow \quad \int_{P_0}^{P} \frac{dP}{P} = -\alpha_p \int_0^x dx$$

$$\Rightarrow \quad \ln\left(\frac{P}{P_0}\right) = -\alpha_p \, x$$

$$\Rightarrow \quad \frac{P}{P_0} = e^{-\alpha_p x}$$

$$\Rightarrow \quad P = P_0 \, e^{-\alpha_p x} \qquad \text{...(17)}$$

Thus optical decreases exponentially w.r.t. distance along the length of fibre. The constant α_p is called 'Attenuation Coefficient'. Its unit is of $(km)^{-1}$. The units of quantity $2\alpha_p x$ is called Nepers.

For simplicity in calculating the optical signal attenuation in a fibre, the common procedure is to express attenuation coefficient in units of decibels per kilometer. For accomplishing this task, we define a new parameter α called 'Fibre Loss' or 'Fibre Attenuation' as follows :-

$$\alpha = \frac{10}{x} \log_{10}\left(\frac{P_0}{P}\right)$$

unit of α is dB/km

We can find a relation between α_p & α. For that it should be noted that $\log_{10}(y) = \frac{1}{2.303} \ln(y)$

Hence above equation becomes

$$\alpha = \frac{10}{2.303\,x} \ln\left(\frac{P_0}{P}\right)$$

$$= \frac{4.343}{x} \ln\left(\frac{P_0}{P}\right)$$

$$\Rightarrow \quad \frac{\alpha x}{4.343} = \ln\left(\frac{P_0}{P}\right)$$

$$\Rightarrow \quad P = P_0 \, e^{\frac{-\alpha x}{4.343}} \qquad \text{...(18)}$$

Comparing equation (17) and (18), we get

$$\frac{\alpha}{4.343} = \alpha_p$$

$$\Rightarrow \qquad \alpha = 4.343\,\alpha_p \qquad ...(19)$$

Equation (19) gives a relation between fibre loss and attenuation coefficient. Fibre attenuation is a function of several parameters like bonds in the fibre, wavelength of light, temperature etc.

We can define α_p from equation (17) as follows :-

If we put $\alpha_p = \frac{1}{x}$ then we see from equation (17) that

$$P = P_0 e^{-1}$$

or

$$P = \frac{1}{e} P_0$$

Thus attenuation coefficient of optical fibre for a given wavelength is reciprocal of the length of fibre, which reduces optical power to $\frac{1}{e}$ times the input optical power.

(12) PULSE DISPERSION

When light pulses propagate through the fibre, it suffers various dispersion effects. "The spreading of the output pulse in the time domain and change in the shape of pulse is called Pulse Dispersion". It is illustrated in fig. (11). In fig (*b*) the shape of the pulses has changed. However pulses are still well resolved. In fig. (*b*), the over lapping of pulses is shown. Here the initial coded information 101 is lost and we are getting distorted signal giving us coded information 111. Here 1 means maximum pulse amplitude and 0 means absence of light pulse.

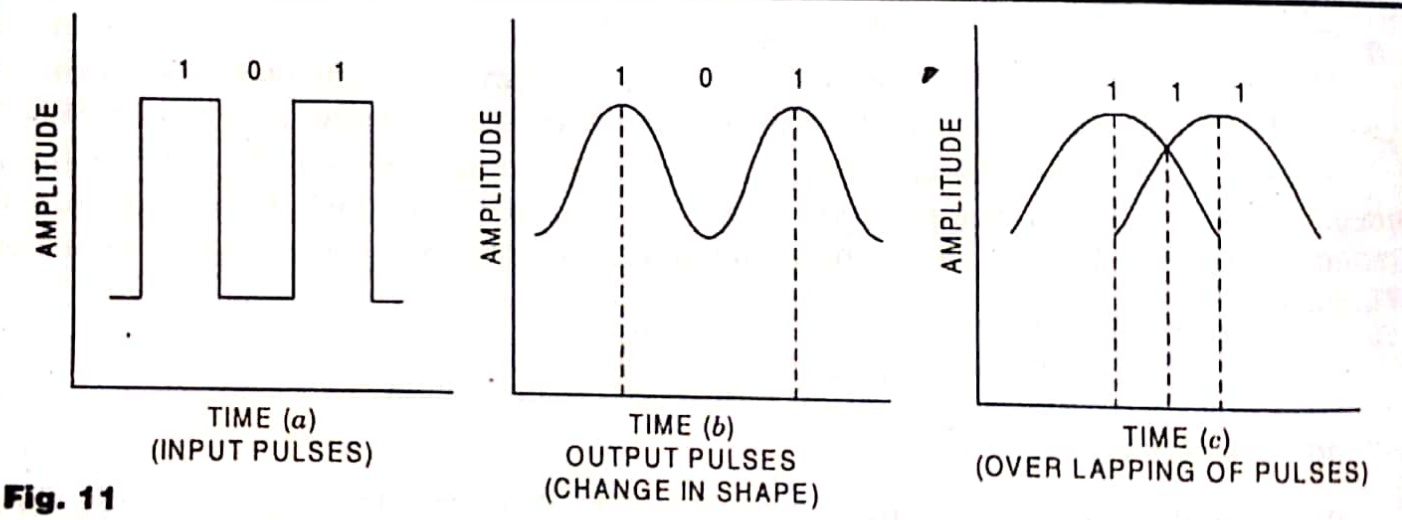


Fig. 11

Pulse dispersion can be of two types :

1. Intermodal Dispersion : This dispersion in also called Modal dispersion. It arises due to the difference in time taken by various modes to travel along given length of fibre. This dispersion does not depend on the wave length of light, but depends on the angle at which ray of light strikes core clad interface of the multimode fibre.

Fig. (12) shows plane section of step index multimode fibre of diameter *d*.

Ray of light 1 travels along straight line path AB. It strikes at angle of incidence *i*, greater than critical angle i_c and thus suffers total internal reflection.

Let n_1, n_2 be refractive index of core & clad respectively.

Let $\qquad AB = x =$ distance travelled by ray of light

In ΔABD $\sin i = \frac{z}{x}$

or $x = \frac{z}{\sin i}$

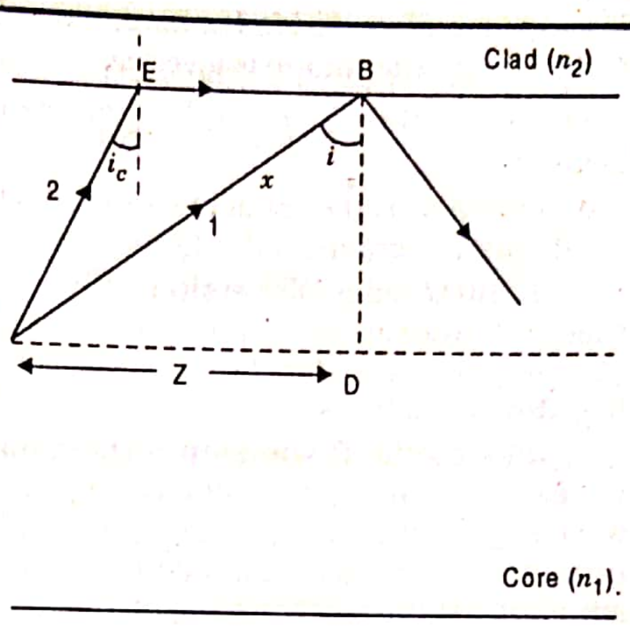


Fig. 12

Here z is the linear distance travelled by ray of light along the axis of fibre. If L is length of fibre, then the length of the path (x) travelled by ray of light is given by

$$x_{total} = \frac{L}{\sin i} \quad ...(20)$$

Clearly x_{total} is maximum when i is minimum and minimum allowed value of i is critical angle i_c.

Thus $x_{max} = \frac{L}{\sin i_c}$

$$= \frac{Ln_1}{n_2} \quad ...(21) \left(\because \quad \sin i_c = \frac{n_2}{n_1}\right)$$

The value of x_{total} will be minimum when i is maximum

That is $i = 90°$. The ray for which $i = 90°$ is axial ray.

Thus $x_{min} = \frac{L}{\sin 90°}$

$$= L \quad ...(22)$$

Thus maximum difference in actual path lengths of the rays reaching the other end of fibre is

$$(\Delta x)_{max} = x_{max} - x_{min}$$

$$= L\left(\frac{n_1}{n_2} - 1\right)$$

$$= \frac{L\Delta}{1-\Delta} \quad \left(\text{where} \quad \Delta = \frac{n_1 - n_2}{n_1}\right)$$

Let V = Velocity of a mode in the core, then

$$\frac{C}{V} = n_1$$

$\Rightarrow$ $V = \frac{C}{n_1}$ (where C = velocity of light in vacuum)

Thus maximum time delay between the highest and lowest mode is given as

$$\tau_{int} = \frac{(\Delta x)_{max}}{V}$$

$$\tau_{int} = \frac{L\,n_1\Delta}{C\,(1-\Delta)} \quad ...(23)$$

This time delay (also called dispersion delay) is characteristic of the fibre and is independent of wavelength of light. It is of the order of nanosecond per kilometer. This delay is absent in single mode fibre.

In case of graded index fibre, theoretical minimum value of time delay between lowest and highest order mode is given as'

$$\tau_{int} = \frac{n_1 L \Delta^2}{8C}$$

Where n_1 is the refractive index of the core at the centre. The intermodal dispersion is much lower in graded index fibre.

2. Intramodal Dispersion : The pulse spreading that occurs within a single mode is called Intramodal Dispersion. This dispersion is wavelength dependent because group velocity of a guided mode is a function of wavelength. This dispersion is also called Chromatic Aberration. It is also of two types :

(*a*) **Material Dispersion :** The refractive index of a material is different for different wavelengths. Any light source emits light waves over a wide range of wavelengths. Thus different wavelength components of an optical pulse have different transit times. Hence the spectral components of pulse combine to produce a broadened pulse with reduced value of peak amplitude at the receiving end of the fibre. This broadening is expressed as

$$\tau_{mat} = N(\lambda)\, \Delta\lambda\, L \qquad ...(24)$$

Where $N(\lambda)$ = Material dispersion and is expressed in the unit $ps\,(nm)^{-1}\,(km)^{-1}$

$\Delta\lambda$ is spectral width and L is length of fibre.

(*b*) **Wave guide Dispersion :** This kind of dispersion arises because of the geometry of the waveguide (optical fibre). We know that there are two layers of different ref. index in optical fibre. If a is radius of core and t is thickness of clad layer then effective refractive index of the fibre is given by

$$n_{effective} = \frac{a+t}{\left(\frac{a}{n_1}\right)+\left(\frac{t}{n_2}\right)} \qquad ...(25)$$

Due to minute geometrical changes, the values of a & t are not constant in the optical fibre. Hence effective refractive index will change. This results in the dispersion of signal and is called waveguide dispersion. This dispersion is present even in the single mode fibre. Remember this dispersion arises due to guiding properties (geometry) of fibre only. Hence it will be present even when intermodal and material dispersion are absent.

The total dispersion delay due to combined effect of all kinds of dispersions is given as

$$\tau = \sqrt{\tau_{int}^2 + \tau_{mat}^2 + \tau_{waveguide}^2}$$

(13) PLASTIC FIBRES

So far we have described only glass cored fibres. But fibres of other compositions are now available. Plastic fibres (Plastic core) have been manufactured from a polymer perform drawn into a fibre. These fibres have inherent potential for many present and future applications. These fibres are ideal medium for optical sensors, process control and short distance communications. A fibre having plastic clad and glass core are called Plastic Cladded Silica (PCS) fibre. The cladding layer in PCS fibres is of a soft plastic polymer. When hard plastic polymer is used in cladding, the resulting fibre is called Hard Clad Silica (HCS) fibre. There are all plastic fibres also, in which core as well as clad is of plastic. Core is made from polymethyl methacrylate and cladding material is a fluoropolymer.

The losses associated with plastic fibres are usually in hundreds of decibels per kilometer. These operate at low temperature *e.g.* plastic fibres can be used to maximum temperature of

125°C while glass fibres can be used upto a maximum temperature of 1000°C. The wavelength of operation of these fibres is 1.3 μm to 1.4 μm. Plastic fibres are not available for use at longer wavelengths, because fibres of that kind are difficult to fabricate and also very expensive. Instead of all these limitations, they have a few advantages also *e.g.* these fibres have high light gathering capacity, large core area, low cost components like fibres, cables, data links & LEDS. These fibres are easy to connectorize.

(14) EXPRESSION FOR TOTAL NUMBER OF REFLECTIONS

Fig. (13) shows propagation of a ray of light through a step index fibre. Let θ is angle of launching of ray of light into the fibre, r is angle of refraction. The ray strikes at point B on core clad interface at angle of incidence i, which is greater than the critical angle. Thus ray will suffer total internal reflections successively at points C, D, E, F, G, H and so on and will travel along the length of fibre.

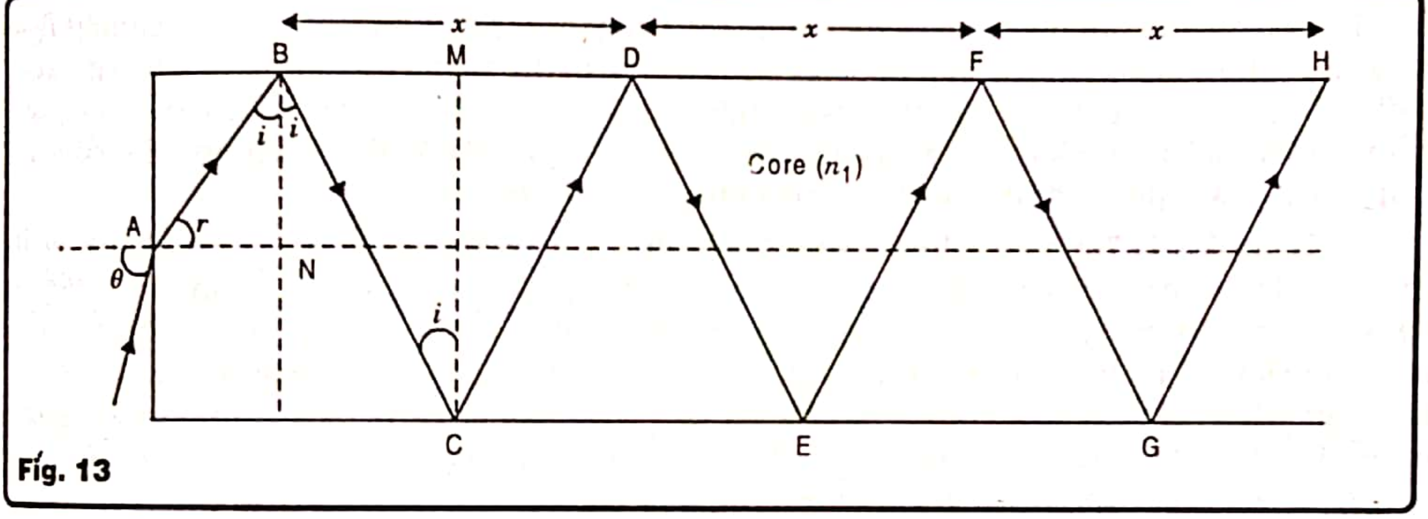


Fig. 13

Let d = diameter of core

In ΔBCM we have

$$\tan i = \frac{BM}{MC} = \frac{x/2}{d} \qquad \text{...(26)}$$

But $\qquad i + r = 90°$ (see Δ ABN)

$$\therefore \qquad \tan i = \tan(90 - r) = \cot r = \frac{1}{\tan r}$$

Put in (26), we get

$$\frac{1}{\tan r} = \frac{x}{2d}$$

$$\Rightarrow \qquad x = \frac{2d}{\tan r} \qquad \text{... (27)}$$

If we carefully analyze fig. (13) we see that in a distance of $3x$, the number of reflections suffered are seven (one each at B, C, D, E, F, G, H). In general if length of fibre is mx then number of reflections will be equal to $2m + 1$.

Now we suppose that length of fibre is L then

Let $\qquad L = mx$

$$\therefore \qquad m = \frac{L}{x} = \frac{L \tan r}{2d} \qquad \text{(using (27))}$$

Let N is total number of reflections suffered in the fibre.

Then $$N = 2m + 1$$

$$= \frac{2L\tan r}{2d} + 1$$

$$\therefore \quad \boxed{N = \left(\frac{L\tan r}{d}\right) + 1} \qquad ...(28)$$

(15) OPTICAL COUPLERS

The distribution of electrical signal passing through a conventional cable into two or more cables/wires is an easy task. However this job is very difficult in case of optical fibres. "The devices, which are used for distributing optical signal from one to many or many to one fibre are called Fibre Optic Couplers". Functionally couplers are of two types, namely (*i*) Directional Couplers (*ii*) Wavelength dependent couplers or Distributive Couplers.

In case of directional couplers, the signal coupling takes place because of the geometry or material of the coupler, independent of the wavelength of the signal transmitted. While in case of distributive couplers, the signal division takes place because of dependence of refractive index of material of coupler on the wavelength of optical signal. We shall discuss only directional couplers. A few types of directional couplers are explained below :

(*i*) **Biconically Tapered Directional Couplers :** A brief diagram of biconically tapered directional coupler is shown in fig. (14). In this type of coupler, two multimode fibres are firstly made bare by removing the sheath. Then these are twisted together around each other and put under tension. Then the twisted portion of fibres is heated gently. Then the twisted & softened fibre is gently stretched, which gives biconical taper at each of the four parts. Suppose a higher mode (1) travels through the core of first fibre. As it enters in the tapered region, the angle of incidence starts decreasing at every reflection, due to tapering (see points A, B). Hence by chance the angle of incidence may become less than critical angle (this chance actually depends on extent of tapering and we can achieve this by putting optical detectors at both fibre ends and, we continue to stretch the twisted portion untill coupling takes place so that some optical

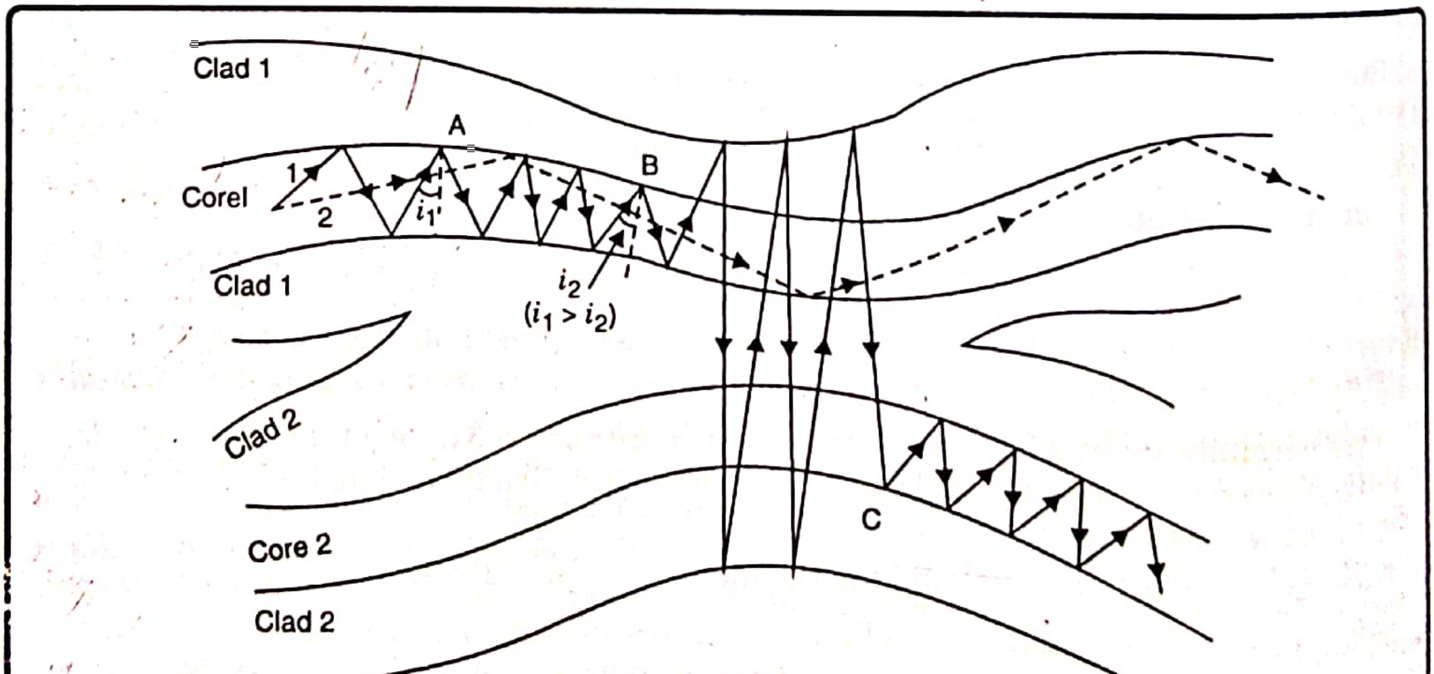


Fig. 14

power enters into core of 2nd fibre) and the ray of light will refract into the clad of fibre 1. Then it suffers total internal reflection at outer boundary of clad of fibre 1 and starts travelling as a clad mode (instead of core mode) through the total internal reflections suffered at boundaries of clad of both fibres. However as it progresses through the two clad layers, the curvature of tapering starts reversing. Hence now angle of incidence starts increasing in the core of fibre 2 and at point C (say) this angle becomes more than critical angle. Hence the ray is now trapped in the core of fibre number 2. This is how coupling of signal takes place. It is worth noting that lower modes like ray 1, make large angles of incidence at core clad interface. Hence even after tapering, these modes continue to travel in the first fibre. Thus we shall get optical power in both fibres.

(*ii*) **Offset Butt Joint Couplers :** It is a four port directional coupler. Input signal is provided through port 1. This signal is divided into ports and 3 at the offset. The strength of power received by port 2 & 3 depends on the extent of the offset. This is shown in fig. (15).

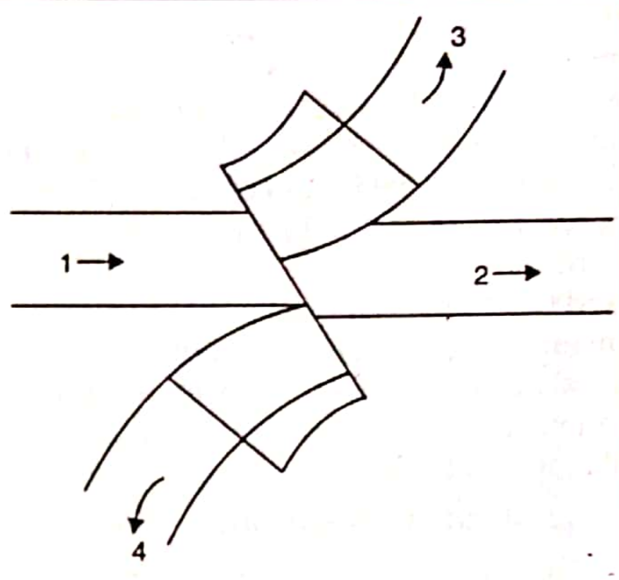


Fig. 15

(*iii*) **Beam splitting coupler :** Fig. (16) (*a*, *b*) represent a plate type and a cube type beam splitter coupler respectively. In plate type beam splitter, a thin partially reflecting coating is placed on transparent slab. This layer reflects some fraction of the light beam along direction 2 and rest portion of beam is transmitted along direction 3. The fraction of the power transmitted and reflected depends on the thickness and nature of the coating. The working of cube type beam splitter is same as that of plate type beam splitter.

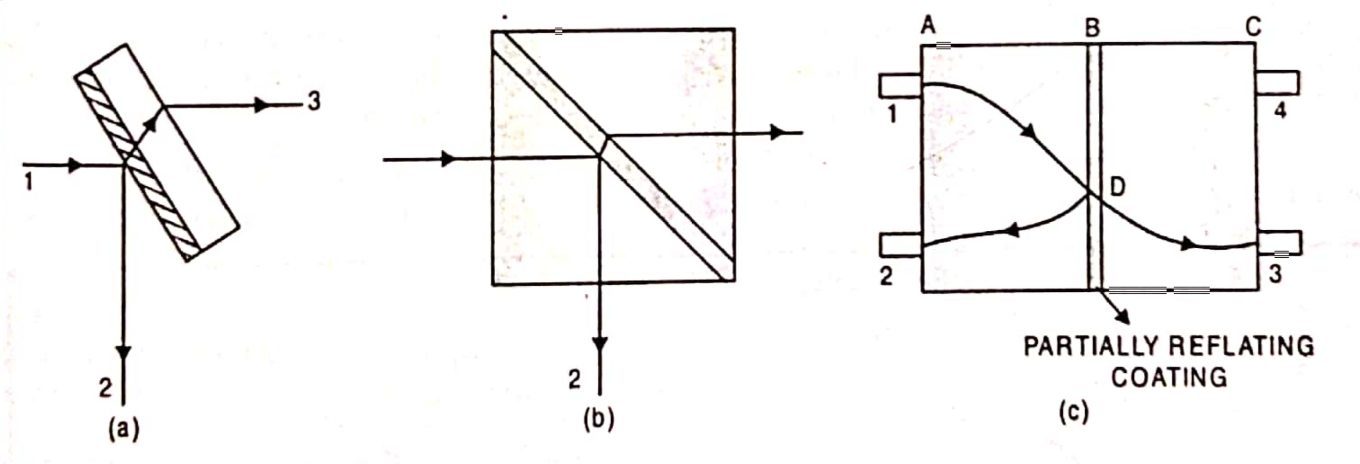


Fig. 16

In fig. (16 (c)), we have shown GRIN beam splitter coupler. This coupler is made from two GRIN (Graded Index) lenses separated by a partially reflecting coating. The refractive index of first lens is maximum at A and as one moves along B, its value decreases gradually and is minimum at partially reflecting coating. While in the second GRIN lens the refractive index increases in going from B to C. When light signal enters from port 1 into first GRIN lens, the ray of light starts bending away from normal due to gradual decrease in refractive index. It strikes the coating layer at point D and is partially reflected back into same lens and partially transmitted into 2nd lens. Both reflected and transmitted rays now bend towards normal as these are travelling along the direction of increasing refractive index. Thus the signal is coupled into ports 2 & 3. If on the other hand input signal comes from port 4, then it will be coupled into ports 2 & 3.

(16) OPTICAL SPLICERS

Splices are permanent fibre joints. These are used in the fields to extend the length of fibre or to repair the damaged fibre. A few splicing techniques are discussed below :

1. Fusion splicing : In this case, the fibres to be spliced are made bare by removing sheath layer using special cutter. Then the end faces are cut normally to the length of fibre. The ends are then well polished so as to remove any inhomogeneity or dust particles. The fibre ends are then placed on adjustable vernier screws. The fibre ends are then alinged using these screws to high degree of accuracy. The alignment can be seen by a microscope. The fibre ends are then brought closer and fused together using an electric arc. During fusion, surface tension tends to align the fibre axes, thus minimizing lateral off set. The loss of power per splice in this case is less than 0.245 dB. The spliced area is then protected by covering with materials like RTV, epoxy and heat shrikable tubing. Fusion splicing can be used for all glass fibres (single as well as multimode).

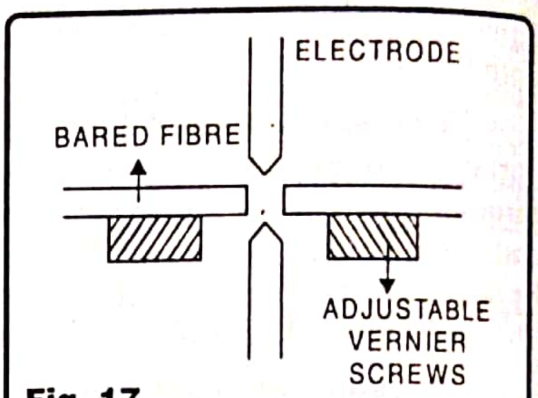


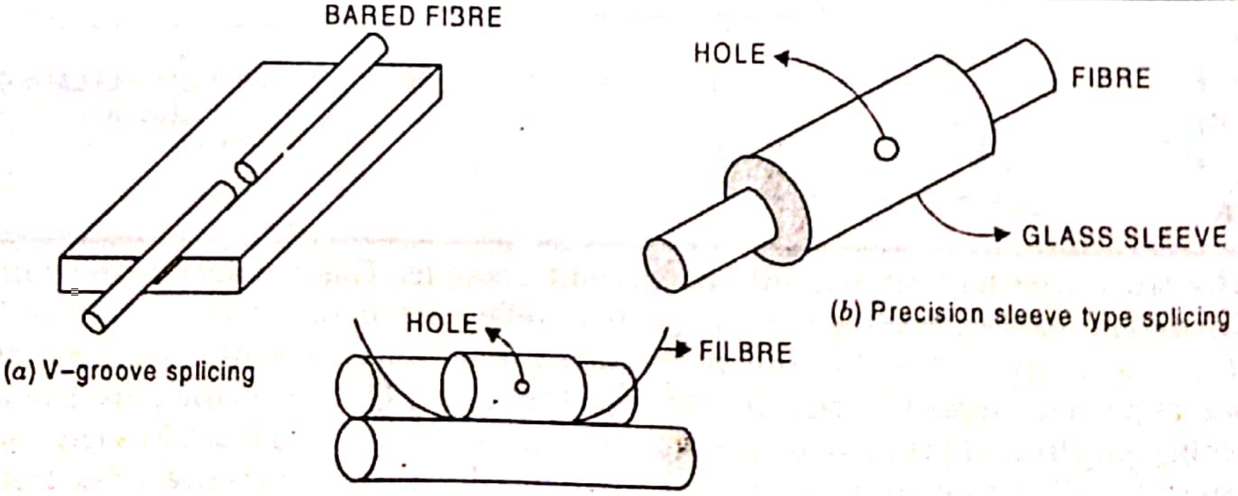
Fig. 17

2. Mechanical Splicing : A few mechanical splicing techniques are shown in fig. (18)

In V-groove splicing, the bared fibres are placed in V-groove. The two fibres can slide in the groove untill they touch and a but joint is formed. Then the joint is made permanent by putting epoxy. If the refractive index of epoxy is matched with that of core then signal loss is minimum.

In the precision sleeve type splice, the bared fibres are displaced into glass sleeve whose inner diameter is slightly loose than diameter of bared fibres. The fibre ends are then joined permanently by putting epoxy through a hole in the middle of the fibre.

In the three rod splicing technique, three identical rods are joined to each other so that a triangular void is formed in the space between the rods. The diameters of glass rods are so



(a) V-groove splicing

(b) Precision sleeve type splicing

(c) 3 Rod splicing

Fig. 18

chosen that hole formed at the junction is just large enough to accept the fibres. Then an index matching epoxy is inserted into the hole made in one of the rod. As a result of permanent joint is formed. Then slight amount of heat is applied, which secures the rods & sqeezes them against the fibre.

(17) OPTICAL CONNECTORS

Connectors are the devices, which are used to join two optical fibres or a fibre end with the device temporarily. These can be mounted and dismounted as and when required. A few different types of connectors are discussed below :

1. **Tapered Sleeve Ferrule Connector :** Figure (19) shows a biconical tapered sleeve connector. A tapered sleeve accepts and guides only tapered ferrules. The fibre ends are prepared and slid into left and right end of the ferrule. Then these ferrules are slid into the tapered sleeve and a butt joint is formed between fibre ends. The joint can be fixed at its position by locking the ferrule arrangement. When required, the fibres can be again separated by unlocking the ferrule.

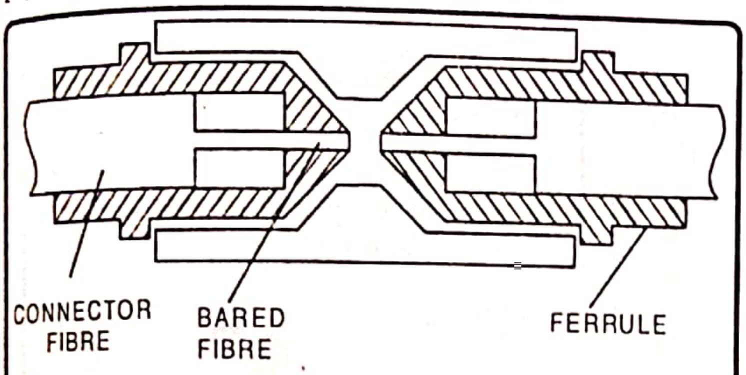


Fig. 19

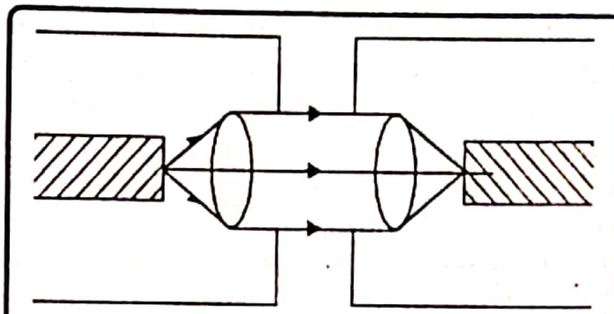


Fig. 20

2. **Expanded beam connector :** Fig. (20) shows an expanded beam connector. It employs lenses on the ends of the fibre. These lenses either collimate the light emerging from the light emitting fibre or focus the expanded beam onto the core of the receiving fibre. The fibre to lens distance is equal to the focal length of the lens. The advantage this scheme is that since the beam is collimated, the separation of the fibre ends may take place with in the connector. The configuration of lenses is an imaging system with unity magnification, regardless the spacing between the lenses.

(18) FIBRE FABRICATION

Optical fibres are manufactured by various techniques. These are described briefly below:

(*a*) **Double Crucible Method.** This is the oldest method of fibre fabrication. In this method two very high purity glass rods are taken. Refractive indices of there two rods are different. These rods contain boro-silicate (Na_2O — B_2O_3 — SiO_2) with different compositions so as to

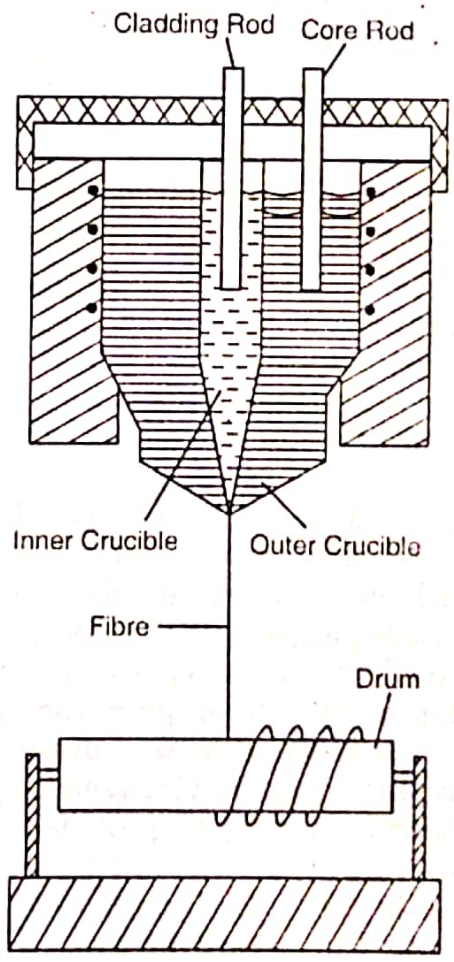


Fig. 21

have different refractive indices. There are two concentric crucibles in the set up shown in the figure (21). These can be heated externally using induction coils around them. These taper to a sharp point at the ends. The glass rod of large refractive index is dipped in inner crucible and that of smaller refractive index in outer crucible. Now furnace coils are switched on and temperature of crucibles rise to 850°-1100°C so that molten glass is obtained in two crucibles. There molten materials come out of nozzle of crucible and two layered glass fibre is obtained. This fibre is cooled and wound on a rotating drum. In order to ensure uniformity in the fibre formed, the height of molten glass must remain constant with time. For that rods are dragged down continuously into the crucibles. Further the pulling speed is given by rotating drum to which fibre is wound.

Double crucible method is a low cost method and can be used to manufacture graded index fibre also.

(*b*) **External Chemical Vapour Deposition method.** This process is used to produce high purity core as well as clad material. In this process ultra pure vapours of $SiCl_4$ and $GeCl_4$ are burnt in a flame producing a fine root of SiO_2 and GeO_2. The refractive index can be changed by doping with germanium oxide, boron oxide phosphorus pentoxide etc. Finally this soot is deposited on a rotating glass rod or mandrel. In the first phase core glass is deposited on the rod. Then doping material is changed so as to lower the refractive index and hence second layer deposited on the rod will be of cladding material. At last the rod is removed and we get a hollow cylindrical shape having core and clad layers. Now this hollow cylinder is heated and allowed to collapse so that inner hollow part is filled by core material and fibre is formed. Since all substances are deposited in vapour phase, thus extremely pure preform is formed.

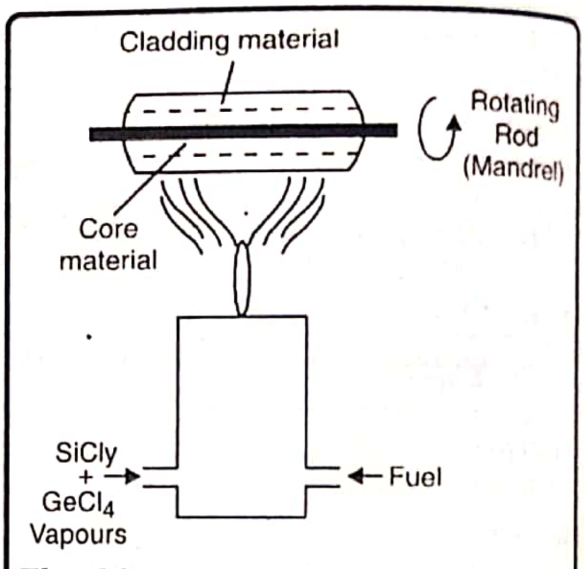


Fig. 22

(*c*) **Internal or Modified chemical vapour deposition method.** This method is a slight improvement of external vapour deposition method. Glass of desired composition is deposited on the inner side of a rotating glass tube (called glass lathe). The deposited material is no fused by travelling oxyhydrogen burner which moves along the tube and a transparent glassy film is formed. When the desired thickness of glass is deposited, then supply of vapour is stopped. Now dopant concentration is changed and vapour supply is again provided so that new layer has different refractive index. In this way, we can get 30-100 layers of different refractive index. Thus this method can be used to fabricate step index

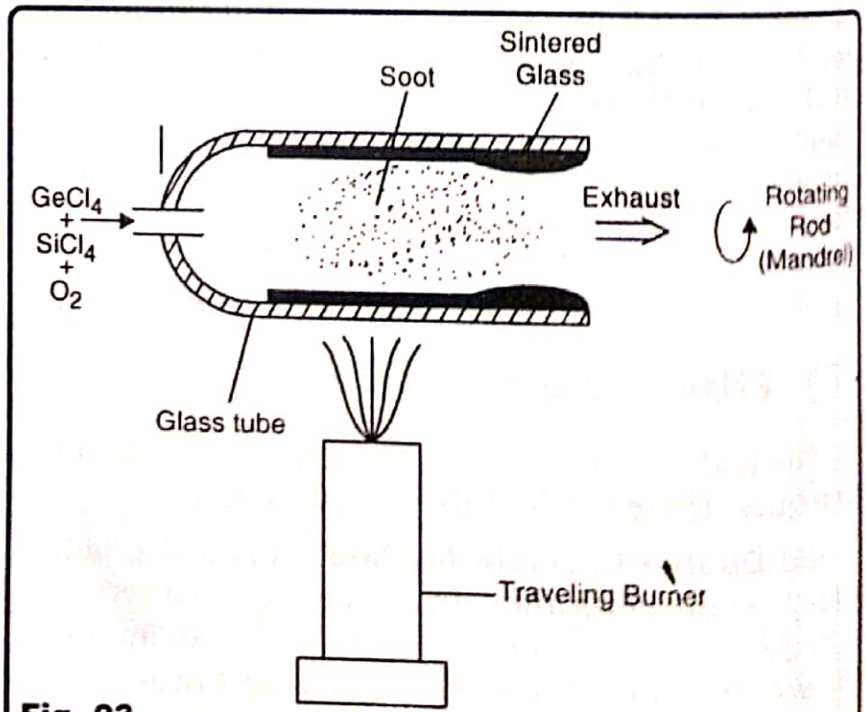


Fig. 23

as well as graded index fibres. After the vapour deposition is over, the tube is thermally collapsed into a solid perform.

(19) LIGHT SOURCES

Light sources for optical fibres are the devices which can generate optical pulses carrying desired information and send these into the optical fibres. Basic requirements for a suitable light source for optical fibre are given below :

(*i*) Since size of core of optical fibre is very large, so the optical source must emitt light beam in the form of a narrow beam so that it is easy to launch light into its core.

(*ii*) Light launched into optical fibre always carry some information *i.e.* it is modulated. Thus it must be an easy task to modulate the light output of source according to desired signal.

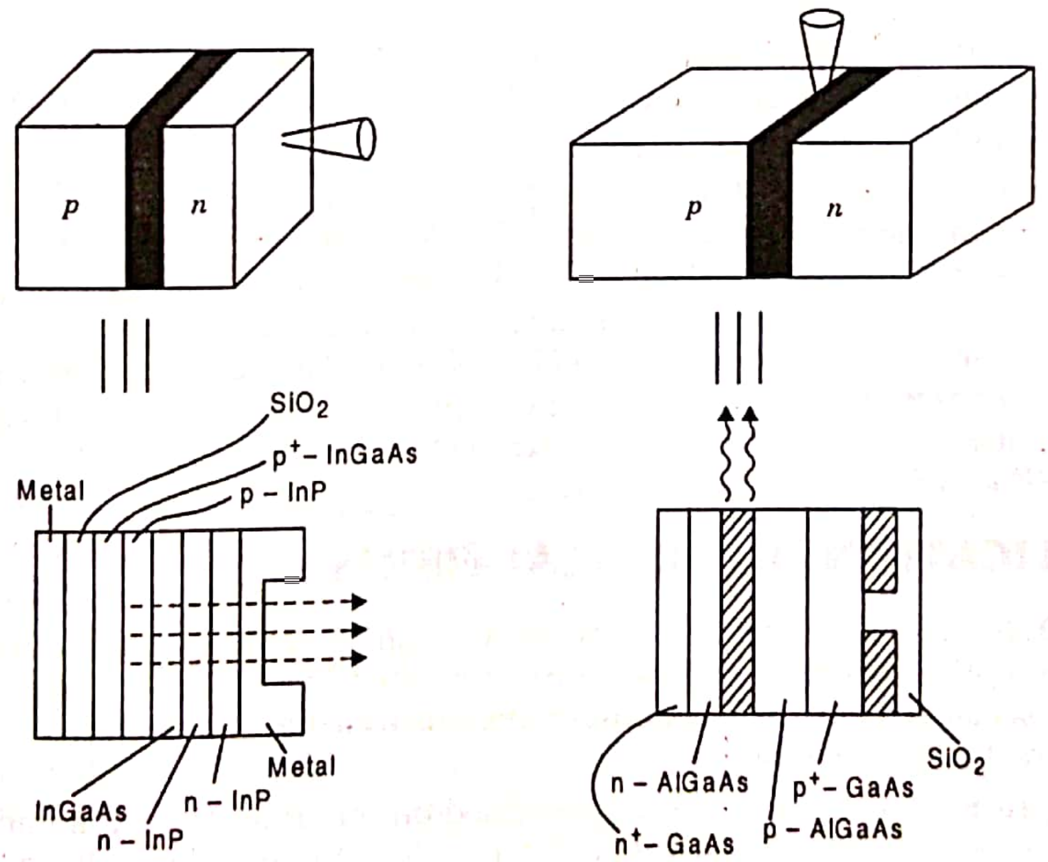
(*iii*) In order to minimise the effect of pulse dispersion the light emitted by source must be monochromatic.

(*iv*) As light travels through optical fibre various energy losses like bending loss, material loss etc. take place along the length of fibre. Thus it is advantageous if the intensity of light emitted from the source is large. So that information can travels upto long distance without any requirement of repeaters.

(*v*) Life of light source should be large and it must be cost effective.

(*vi*) The source must be free from random fluctuations (noise). These requirements are not satisfied by ordinary light sources. Thus special light sources are required for opticl fibres. The commonly used light sources are LED and LASER Diode.

(*a*) Light Emitting Diode (LED). It is a *pn* junction operated in the forward bias. On providing forward bias electrons from *n* type material diffuse into *p* type material and recombine



(a) (S-LED)

(b) (E-LED)

Fig. 24

with holes and release energy in the form of photons of electromagnetic radiation. The energy of emitted photon is equal to or more than the band gap energy between valence and conduction band. For silicon and Germanium diodes this energy is very small and hence lies in IR region. However for GaAs the energy gap is large and lies in the visible region. The semiconductor used for optical source must have a direct gap. In case of indirect gap material, part of combination energy released is wasted as heat. On the other hand for a direct gap semiconductor whole of recombination energy is released as light/optical energy.

Light from LED can be emitted along an edge or perpendicular to the surface. The first kind of LED is called edge or E-LED and second kind of LED is called surface or S-LED. These LEDs are heterojunction devices and contain three or more layers.

Typical structures of S-LED & E-LED are shown in figure (24). The upper and lower layers have lower refractive index compared with central layer. This helps in confining the emitted light to active region. Note that light emitted from LED is incoherent and large spectral width.

(*b*) **Laser Diode.** A laser diode is also a *p-n* junction semiconductor diode but it produces coherent light unlike LED. Light is emitted by spontaneous emission in LED but by stimulated emision in laser diode. A laser diode works at high current compared with LED. Further more the laser action is enhanced by polished surfaces, which act as mirrors of optical resonator just like in lasers. Laser diodes have narrow line width.

(20) OPTICAL RECEIVERS OR PHOTODETECTORS

An optical receiver converts optical signal into electrical signal. Optical detectors are usually photodiodes. These are *pn* junction made from indirect band gap semiconductors made from Ge and Si. A good photodetector should have following characteristics :

1. It should be highly sensitive so as to detect even weak signals.
2. It must respond uniformly to all wavelengths.
3. Their size must be compatible with optical fibre.
4. These should not produce additional noise

The commonly used optical detectors are P-I-N photodiode and avalanche photodiode (APD). The former has lightly doped *n* type intrinsic layers sandwiched between *p* and *n* type regions. With the addition of intrinsic layer, the active region of the diode is increased. In case of later a high electric field intensity region is added between *p* & *n* type regions. In this region primary electron hole pairs are generated by incident photons and high electric field accelerates these electrons. These electrons collide with the atoms present in this region and thus generating more electron hole pairs. This process is called Avalanche effect. Due to avalanche the current generated in APD is much large than PIN device.

(21) APPLICATIONS OF OPTICAL FIBRES

1. Fibre Optic Sensors : These are the devices, which are used to convert a physical quantity into an optical signal and thereby measuring the value of physical quantity. These sensors are not sensitive to external conditions and are available easily to suit any design. A few examples are discussed below :

(*a*) **Pressure Sensor :** These sensors are based on the principle that a microbend in optical fibre results in the loss of optical power. The loss of power depends on the size of microbend. To measure pressure, a light signal is passed through optical fibre and output intensity is noted using a photometer. Now known pressure is applied at a point on the fibre, which creates a microbend. Then the power loss at microbend takes place, due to which the intensity level at output decreases. The decreased value of intensity is noted. The experiment is repeated for a number of known values of pressure. Then graph is plotted between pressure applied and intensity level. Now unknown pressure is applied across the fibre and value of intensity is noted. Corresponding to this value of intensity the value of unknown pressure can be found from graph.

(*b*) **Liquid Level Sensor.** Figure (25) shows a liquid level sensor. Here a fibre is cut into two parts and placed above the liquid at danger mark. The ends of two fibres are tapered by angle θ such that θ is greater than critical angle i_c for core - air interface. When initially liquid level is below the danger mark, then there will be air in the gap. Hence when an axial ray of light reaches at point A, it makes angle of incidence θ, which is more than critical angle. Hence ray of light is reflected back into same part of fibre. Thus if a detector is connected to second part, it will record no light. However when liquid level rises to danger mark, it fills up the air gap between the two faces of tapered fibres. Since refractive index of liquid is more than that of air, thus value of critical angle increases. Hence θ now becomes less than new value of critical angle. Due to this refraction of light takes place at point A. Hence light ray enters in the second fibre and is detected by the detector. This detector then switches on an automated alarm or indicator. In this way liquid level can be monitored.

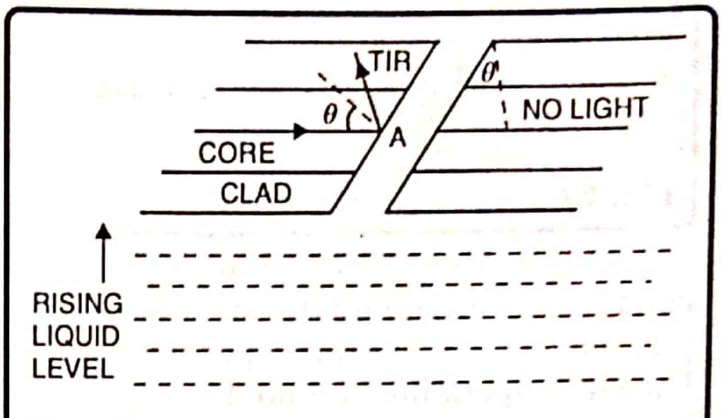


Fig. 25

(*c*) **Displacement Sensor.** Figure 26(*a*) shows the diagram of displacement sensor using optical fibre bundles. Light from a suitable source travels along a fibre bundle and strikes a surface whose displacement is to be monitored. The reflected light from the surface is gathered from other set of fibre bundle where it is detected by a suitable optical detector and thus intensity of light received after reflecting from surface is measured. Now surface is given a known displacement x and corresponding value of intensity of received light (I) is noted. The process is repeated many times and a graph is plotted between I and x as shown in the figure (26) (*b*). The variation of I w.r.t. x is linear in certain region and sensor can be used to measure displacement of reflecting surface in this region.

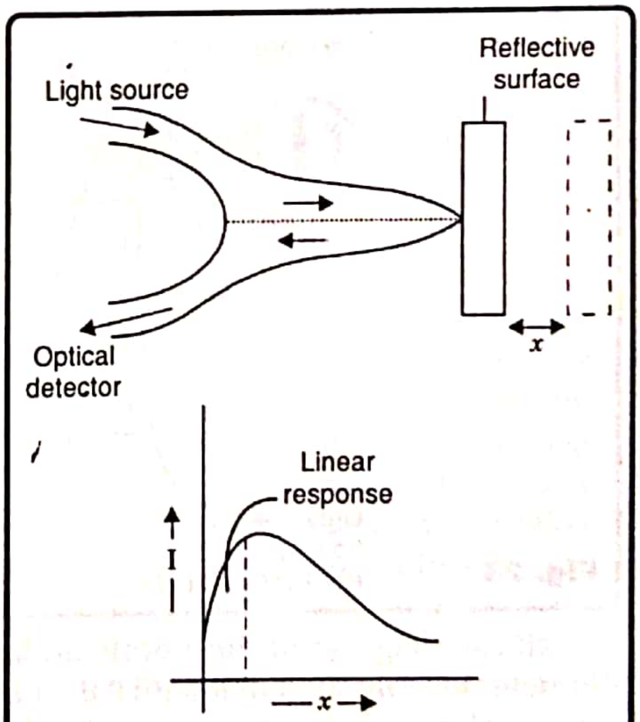


Fig. 26

(*d*) **Temperature Sensor.** When temperature of fibre material changes then refractive index of core and clad also changes slightly. This effect is used to design a temperature sensor. Basic diagram of an optical thermometer (pressure sensor is shown in figure (27).

It consists of a sensing probe made from a single crystal aluminium oxide (called saphire) optical fibre of diameter 0.25 mm–2mm and length $\approx 5 - 100$ cm. A cup shaped blackbody cavity is formed at the sensing tip coated with platinum or irridium. For measuring the

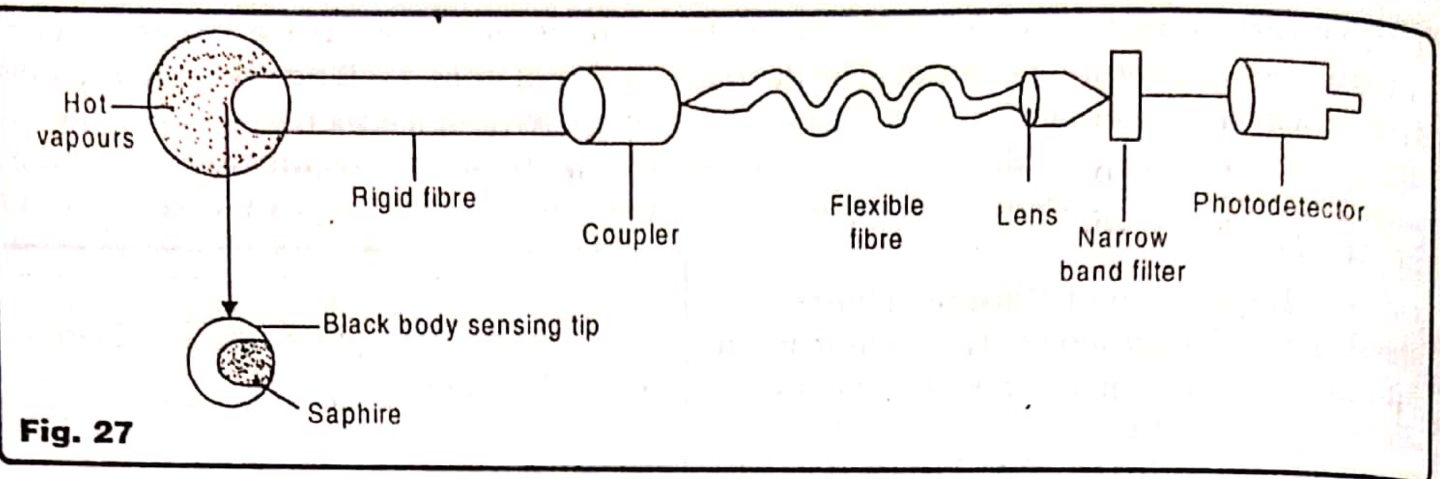


Fig. 27

temperature the sensing probe is kept in contact with the hot object. Due to low thermal conductivity of saphire the radiation travels only along the fibre and is then received by the photodetector. Initially the thermometer is calibrated by touching the sensor with objects of known temperature and noting corresponding valves of intensity. Then a calibration curve between intensity and temperature is plotted. Now body of unknown temperatre is brought in contact with the sensor and intencity of light received by detector is noted. Then from calibration graph temperature of body can be obtained.

2. Endoscope. Endoscopy means looking inside and typically refers to look inside the body for medical reasons. An endoscope is a device used to examine interior organs of body. Unlike most other medical imaging devices, endoscopes are inserted directly into the organ.

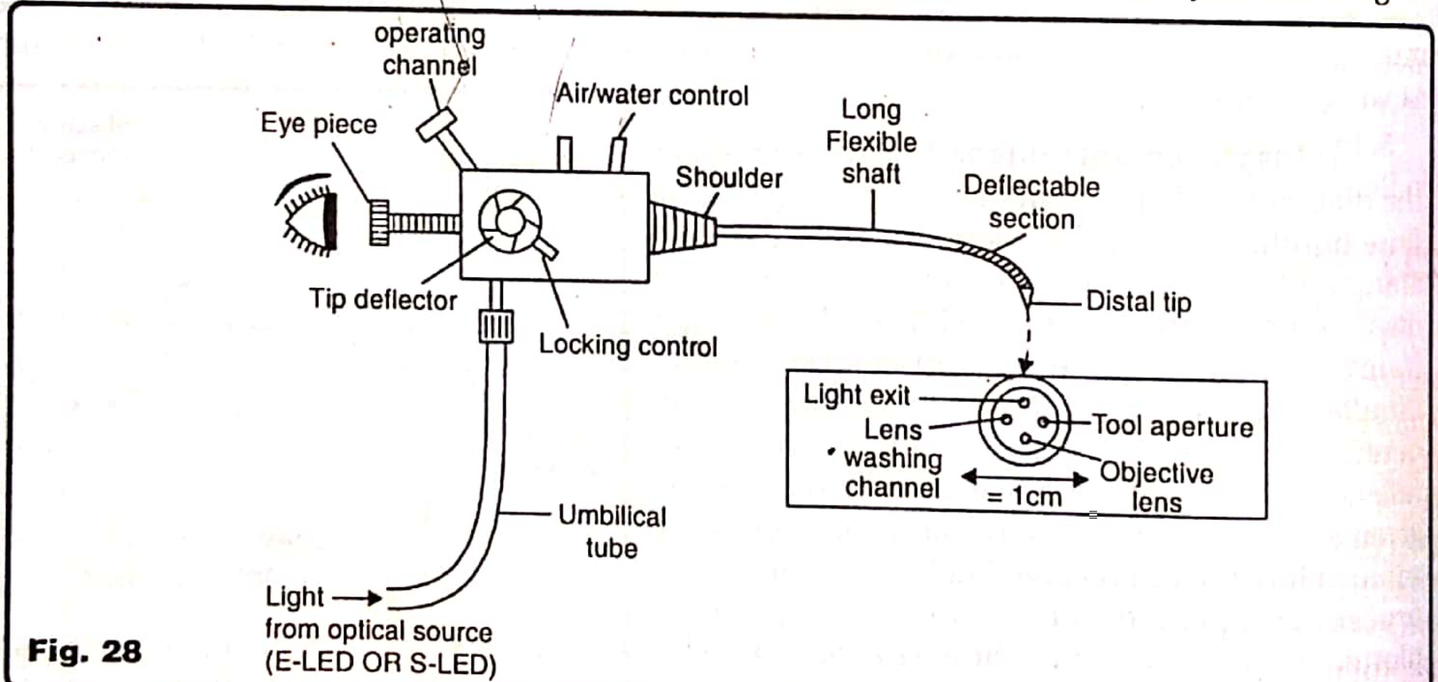


Fig. 28

Basic diagram of fibre optic endoscope is shown in figure (28). It consists of a 1 cm diameter flexible shaft of length 0.6 – 1.8 m. The bottom portron of the shaft has a deflectable return of length 5 cm – 9 cm and a distal tip at the end which is shown separately in dotted box. It consists of (*i*) an irrigation channel to wash the objective lens by pumping water (*ii*) a coherent bundle of optical fibres to transmit the light from outside to interior parts of body (*iii*) Another bundle of fibres to transmit the reflected right from interior parts of body (*iv*) An operation channel to perform the desired task.

The viewing end of endoscope consists of following arrangements :

(*i*) an eyepiece with camera attachment and focus control (*ii*) Distal tip control capable of rofating it through 200°

(*iii*) operation channel valve that controls the entry of catheters, electrode, biopsy foreceps and other flexible devices.

(*iv*) Valve control for aplication of water or air through irrigation channel

(*v*) A connection with umbilical tube for control of light transmission from source.

Working. The flexible shaft is inserted into the body and distal tep is positioned correctly so as to face the organ which is to be examined. Light is transmitted through one optical fibre coharent bundle which falls on the organ and reflected light is received from second coherent bundle, which is connected to camera. Hence organ is seen on a screen attached with camera. Then through the operating channel desired treatment can be given to affected part.

Uses of Endorscopy. The main application of endoscopy are the following :

1. For examination of gastrointestinal trait.
2. For study and treatment of ulcers, cancers, bleeding sites etc.
3. To measure proportion of haemoglobin in blood.

3. Military and Aerospace Applications : In military, optical fibres find their use in guided weapons and submarine warfare nets, nuclear testing and fixed plant installations etc. In aerospace, optical fibres are widely used because of their low weight and small size. Further these fibres provide full signal security.

4. Communication : These fibres were initially developed for communication purpose. The non conducting nature of the material used in their fabrication, light weight, small size, immunity to external electrical disturbances, enormous band width etc. make optical fibres most widely used communication medium.

5. In Medicine : Optical fibres are very useful in medical technology. These are used in bloodless surgery, clinical applications, Laser medicine etc.

(22) FIBRE OPTIC COMMUNICATION SYSTEM

The block diagrams of a fibre optic communication system is shown in figure (29). Essentially it contains three major parts (*i*) Transmitter (*ii*) Communication Medium or Channel (optical fibre) and (*iii*) Receiver. In a transmitter the input electrical signal is given to drive circuit, which in most of cases is a transistor amplifier. The output of transistor amplifier is connected to laser diode. The current through laser diode changes in accordance with the signal variations given to drive circuit. Hence light is modulated. The modulated light is launched into optical fibre, which distributes this optical power into various devices coupled to it. Each device which receives light from optical fibre works as receiver unit. This receiver unit contains a photodetector, which acts as transducer and generates electrical signal from optical signal. The electric signal is then amplified and then separated from carrier using signal restorer. Hence at the output end of transmitter, the original signal is obtained faithfully. Normally communication system can be of three types (*i*) Simplex (*ii*) Half Duplex (*iii*) Duplex. In simplex system data can flow only from transmitter to receiver and receiver cannot send any signal back to transmitter *e.g.* cable television. In case of Half Duplex communiçation system data can flow from transmitter to receiver and vice versa but only one direction of data flow is allowed at a time because same band of frequencies is used in both directions. *e.g.* wireless and telephone network of early nineties was half duplex. In case of Duplex (or Full Duplex) system data can flow in either direction simultaneously because different frequency bands are used for transmission and receiving. For example landline and mobile telephone network, internet network etc.

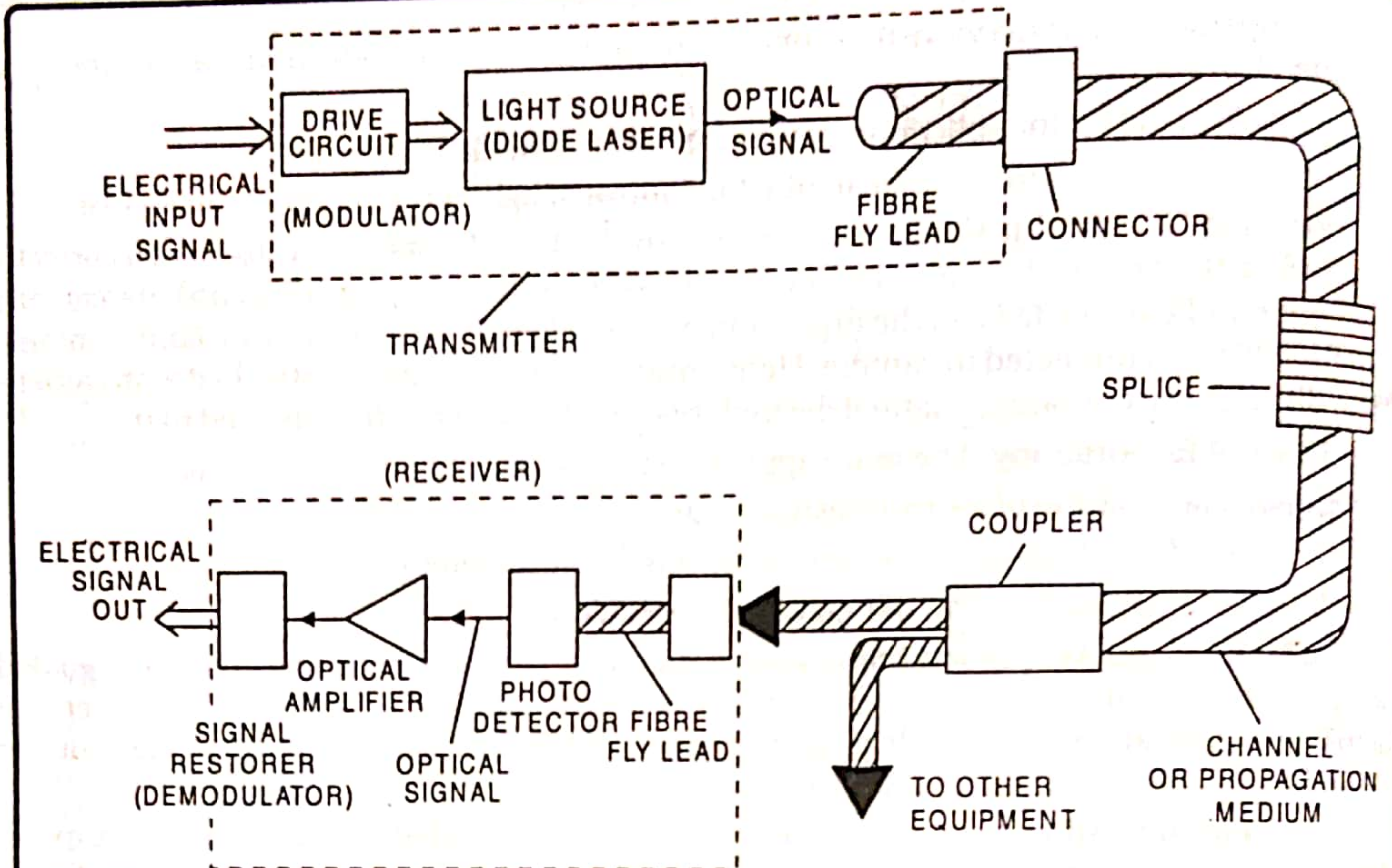


Fig. 29

(23) COHERENT BUNDLE

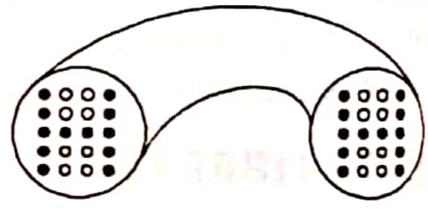


Fig. 30

If a large number of fibres are put together, this arrangement is called bundle. If the fibres are not arranged properly then bundle is called Incoherent Bundle. On the other hand if relative positions of optical fibres at input and output are identical, then bundle is called coherent bundle. A coherent bundle can transmit an image from one end to other end. This property makes coherent bundle an important device. It can be used as coder. At the transmitted end, image can be decoded by using a similar bundle in the reverse direction. Coherent bundle is used in Optic Endoscope. In this technique, a coherent bundle is slid into human body and light is sent inside the human body through sheath layer of optical fibres of coherent bundles. This light illuminates the interior of body and light reflected from interior parts of body comes out through core of optical fibres of coherent bundles and its image can be seen through the end outside human body. One example of transmission of image through coherent bundle is shown in fig. (30).

Example 1. *The core of a glass fibre has a refractive index of 1.5, while its cladding is doped to give a fractional change in refractive index of 0.005. Find (a) Refractive index of cladding (b) Critical internal reflecting angle (c) acceptance angle (d) Numerical Aperture.*

Solution. Given

$$n_1 = 1.5$$

$$\Delta = \frac{n_1 - n_2}{n_1} = 0.005$$

$$\therefore \quad n_1 \Delta = n_1 - n_2$$

$$\Rightarrow \quad n_2 = n_1(1-\Delta) = 1.5(1-0.005) = 1.4925$$

Also $$\sin i_c = \frac{n_2}{n_1} = \frac{1.4925}{1.5} = 0.995$$

$$\therefore \quad i_c = \sin^{-1}(0.995) = 84.26°$$

$$NA = \sqrt{n_1^2 - n_2^2} = 0.1498$$

$$\theta_0 = \text{Acceptance angle} = \sin^{-1}(NA) = 2.62°$$

Example 2. *Calculate the refractive index of the core and cladding material of fibre from the following data*

$$NA = 0.30\,,\ \Delta = 0.020$$

Solution. $$\Delta = \frac{n_1 - n_2}{n_1} \quad \text{...(1)}$$

$$\Rightarrow \quad n_2 = n_1(1-\Delta) \quad \text{...(2)}$$

Now $$NA \approx n_1\sqrt{2\Delta} \quad (n_0 = 1)$$

$$\Rightarrow \quad n_1 = \frac{NA}{\sqrt{2\Delta}}$$

$$= \frac{0.30}{\sqrt{2\times 0.020}} = 1.5$$

Now from (2) $$n_2 = 1.5(1-0.020) = 1.47$$

Example 3. *A step index fibre has core of refractive index 1.3725, cladding of refractive index 1.3275. The cut off parameter is 2.405. Calculate the core radius and NA.*

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

$$= \sqrt{(1.3725)^2 - (1.3275)^2} = 0.349$$

$$V = \frac{2\pi a}{\lambda} NA$$

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

$$= \frac{2.405\times 1300\times 10^{-9}}{2\times 3.142\times 0.349} = 1.43\,\mu m$$

Example 4. *Calculate the numerical aperture and hence the acceptance angle for an optical fibre given that refractive index of core and cladding are 1.45 & 1.40 respectively.*

Solution. $$n_1 = 1.45$$

$$n_2 = 1.40$$

$$NA = \sqrt{(1.43)^2 - (1.40)^2} = 0.377$$

$$\theta_0 = \text{Acceptance angle}$$

$$= \sin^{-1}(NA) = \sin^{-1}(0.377)$$

$$= 22.15°$$

Example 5. *Find the core radius necessary for single mode operation at 850 nm in a step index fibre, which has refractive indices of core and cladding equal to 1.48 and 1.47 respectively. What is the numerical aperture and acceptance angle of this fibre ?*

Solution. Given

$$n_1 = 1.48$$
$$n_2 = 1.47$$
$$\lambda = 850\ nm$$
$$V = 2.405 \text{ (for single mode operation)}$$
$$NA = \sqrt{n_1^2 - n_2^2}$$
$$= \sqrt{(1.48)^2 - (1.47)^2} = 0.17$$
$$\theta_0 = \sin^{-1}(0.17) = 9.89°$$

Now
$$V = \frac{2\pi a}{\lambda} NA \quad \text{(where } a = \text{core radius)}$$

∴
$$a = \frac{V\lambda}{2\pi(NA)}$$
$$= \frac{2.405 \times 850 \text{ mm}}{2 \times 3.142 \times 0.17} = 1.91\,\mu m$$

Example 6. *Consider a Gaussian beam, whose spot size is 1 mm when collimated. The operating wavelength is 0.82 μm. Compute the angle of divergence. Also calculate the spot size at 10 m.*

Solution. The angle of divergence is given as

$$\theta = \frac{2\lambda}{\pi W}$$

where W = spot size at output of optical fibre

∴
$$\theta = \frac{2 \times 0.82 \times 10^{-6}}{3.142 \times 10^{-3}} = 0.55 \times 10^{-3} \text{ radian}$$
$$= 0.032°$$

The spot size at 10m is given by

$$W' = \frac{\lambda \times \text{distance}}{\pi \times \text{spot size at output}} = \frac{0.82 \times 10^{-6} \times 10}{3.142 \times 10^{-3}}$$
$$= 2.6 \text{ mm.}$$

Example 7. *A step index fibre has $n_1 = 1.5$, $n_2 = 1.49$. The core diameters is 50 μm. Assume the guided ray travelling at steepest angle with respect to fibre axis. Calculate the number of reflections per metre.*

Solution. Given

$$n_1 = 1.5$$
$$n_2 = 1.49$$

Ray will travel steepest with respect to axis if it enters the fibre at angle of acceptance.

Now
$$\theta_0 = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$$
$$= \sin^{-1}\left(\sqrt{(1.5)^2 - (1.49)^2}\right) = 9.95°$$

Now r = angle of refraction into the fibre

∴ By Snell's law $\quad n_0 \sin\theta_0 = n_1 \sin r$

$$\Rightarrow \quad \sin r = \frac{n_0}{n_1}\sin\theta_0$$

$$= \frac{1\times 0.173}{1.5} = 0.115$$

$$\therefore \quad r = \sin^{-1}(0.115) = 6.61°$$

Total number of Reflections are given as

$$N = \frac{L\tan r}{d} + 1$$

$$= \frac{1\tan 6.61}{50\times 10^{-6}} + 1 = 2320$$

Example 8. *A step index single mode fibre has core radius 30 μm, $n_1 = 1.5, n_2 = 1.47$. The operating wavelength is 800 nm. Calculate the number of modes propagating through the fibre ?*

Solution.

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

$$\therefore \quad V = \frac{2\times 3.142\times 30\times 10^{-6}}{800\times 10^{-9}} \times \sqrt{(1.5)^2 - (1.47)^2}$$

$$= 70.34$$

Thus number of modes are given as

$$N \approx \frac{V^2}{2} = 2474$$

Example 9. *In above example what will be the number of modes propagating through fibre, if it is graded index with index parameter $\alpha = 3$.*

Solution.

$$N_{graded} = (N_{step\ index}) \times \left(\frac{\alpha}{\alpha+2}\right)$$

$$= \left(\frac{V^2}{2}\right)\left(\frac{3}{3+2}\right) = 2474 \times \frac{3}{5}$$

$$\approx 1484 \text{ modes}$$

Example 10. *A single mode step index fibre has a length of 5 km. Calculate the dispersion delay caused due to intermodal dispersion. If $n_1 = 1.5, n_2 = 1.48$.*

Solution.

$$n_1 = 1.5, n_2 = 1.48$$

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

$$= \frac{1.5 - 1.48}{1.5} = 0.0134$$

Now

$$\tau_{int} = \frac{n_1 L}{C}\left(\frac{\Delta}{1-\Delta}\right)$$

$$= \frac{5\times 10^3 \times 1.5}{3\times 10^8}\left(\frac{0.0134}{1-0.0134}\right)$$

$$= 33.95\,\mu s.$$

Example 11. *A step index single mode fibre has length of 5 km. The ratio of output to input power is 0.95. Calculate the fibre loss.*

Solution.
$$\alpha = \frac{10}{x}\log_{10}\left(\frac{P_0}{P}\right)$$
$$= \frac{10}{5\text{ km}}\log_{10}\left(\frac{1}{0.95}\right) = 0.045\ dB/\text{km}$$

Example 12. *Determine the cut of wavelength for single mode operation of an optical fibre of core diameter 12 μm and numerical aperture 0.35.*

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

$\therefore$ For single mode operation
$$\lambda = \frac{2\times 3.142\times 6\,(\mu m)\,(0.35)}{2.405} \qquad \left(\because\ a = \frac{12}{2} = 6\,\mu m\right)$$
$$= 5.49\,\mu\text{m}$$

Exercise 1. The loss of optical power in a fibre is 25 dB. Calculate the efficiency of fibre. [Ans. 0.316%]

Exercise 2. Compute the numerical aperture and acceptance angle for a fibre where $n_1 = 3.6$ and $n_2 = 3.5$. [Ans. 0.843, 57.42°]

Exercise 3. A step index fibre has core diameter 60 μm and NA = 0.3. Compute the number of propagating modes at an operating wavelength of 850 nm. [Ans. 2213]

Example 4. Calculate the refractive indices of core and clad from the following data. NA = 0.32, $\Delta = 0.005$. [Ans. 3.2, 3.184]

Exercise 5. Compute the maximum value of Δ and n_2 of a single mode fibre of core diameter 12 μm and core refractive index 1.54. The fibre is coupled to a source of wavelength 800 nm. Also find acceptance angle. [Ans. $\Delta = 1.373\times 10^{-4}$, $n_2 = 1.5398$, $\theta_0 = 1.243°$]

SHORT ANSWER TYPE QUESTIONS

Q. 1. Why there is need for clad ?

Ans. The cladding layer is helpful to reduce scattering loss resulting from discontinuities at the outer surface of core. Further it provides mechanical strength to the fibre and protects it from external contamination. Further by taking clad layer we can make $n_2 \approx n_1$. Due to this, value of Δ will deerease. Hence transit time dispersion will be come almost zero (see equation (23). Hence internmodal dispersion will decrease.

Q. 2. What are solitons ?

Ans. A soliton is a pulse, that travels along a fibre without changing shape. It is found that due to fibre non-linearity, the refractive index of fibre starts depending on intensity of light in addition to wave length. Thus intensity of beam itself can affect the velocity of pulse in fibre. Thus in solitons, the decrease in velocity due to decrease in wavelength can be compensated by increasing the intensity of low wavelength components in comparison to high wavelength components of the pulse. Thus all components of pulse travel with equal velocity in the fibre and pulse dispersion does not take place.

Q. 3. What is W-profile fibre ?

Ans. We know that certain modes are partially guided through the fibre core. A part of these leaky modes enter in the clad. These modes continue to travel inside clad upto long distances by suffering total internal reflections. However in clad, their velocity is different from that in core. Hence these modes if by chance re-enter back into core, will cause interference with other modes. To avoid this, a second layer of clad is provided. The refractive index n_3 of 2nd layer of clad is slightly more than that of first clad layer (n_2). Usually we take $n_3 = \frac{n_1 + n_2}{2}$. The second clad layer does not allow total internal reflection at boundary of first clad layer. Hence these modes will enter into 2nd clad layer so that they donot cause interference effects. If index profile of such a fibre (step index fibre) is plotted, its shape is similar to letter 'W'. Such a fibre is called W-profile fibre.

Q. 4. What are optical sources used for optical fibres ?

Ans. Laser diodes and Light Emitting Diodes are most common sources. Their small size is compatible with the small diameters of the fibres and these devices require very less power for operation.

Q. 5. What are optical detectors ?

Ans. These devices are used at output terminal of an optical fibre. These devices directly convert optical radiation into electrical signals and respond quickly to changes in the optic power level. Some examples are photodiode, photomultiplier tube, PIN Photodiode, Avalanche photodiode etc.

Q. 6. What are limitations of optical fibres?

Ans. (*i*) These are very difficult to couple.

(*ii*) These require sophisticated tools for cabling purposes.

(*iii*) Highly trained workforce is required for their installation.

(*iv*) Testing methods are much more complex.

(*v*) Ordinary light sources cannot be used for them.

Q. 7. Is the value of numerical aperture always constant?

Ans. NA = $\sqrt{n_1^2 - n_2^2}$ (assuming $n_0 = 1$). Clearly NA will be constant only if n_1, n_2 both are constant. This is true for step index fibre only. For graded index fibre n_1 is maximum at centre and decreases gradually in going towards clad. Hence numerical aperture of graded index goes on decreasing from centre of fibre towards clad. Thus average value of NA for graded index fibre is less than that of step Index fibre. Due to this reason, number of modes supported by graded index fibre are less than that of a corresponding step index fibre.

Q. 8. Enlist various techniques used for Fabrication of optical fibres.

Ans. (*i*) Outside Vapour Phase Oxidation Technique.

(*ii*) Vapour Phase Axial Deposition Method

(*iii*) Modified Chemical Vapour Deposition Method

(*iv*) Plasma Activated Chemical Vapour Deposition Method

(*v*) Double Crucible Method.

Q. 9. What are various reasons of power loss that occurs at the time of splicing or connectorizing two optical fibres?

Ans. These losses result because of any of following reasons :-

(*i*) **Core Size Mismatch.** When diameter of core of one fibre is more than second fibre then some light energy is lost, as it could not enter core of next fibre. This is shown in fig. (31).

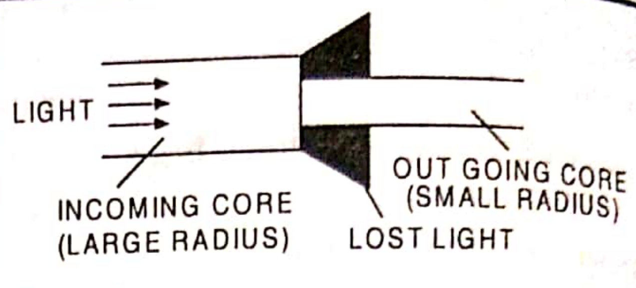


Fig. 31

(*ii*) **Longitudinal Gap Separation.** If the out going core is not properly butted against incoming core, then there will be small gap between two fibres. The refractive index of gap will be different from that of core. Due to this the light rays suffer lateral deviation on entering the gap. Hence some optical power is lost into the clad. See fig. (32).

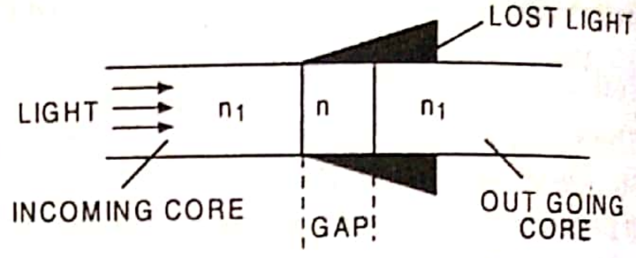


Fig. 32

(*iii*) **Lateral Core Misalignment.** Sometimes the two cores are of same size but they donot line up accurately w.r.t. each other. This results in power loss at the mismatch. This mismatch appears due to the fact that core and cladding may not be exactly concentric. See Fig. (33).

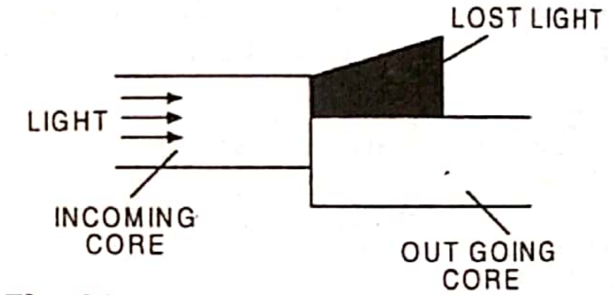


Fig. 33

(*iv*) **Angular Misalignment.** In this case the two cores are aligned at some angle w.r.t. to each other, which creates a gap of varying size on one side. Hence some optical power is lost in passing through this gap. See Fig. (34).

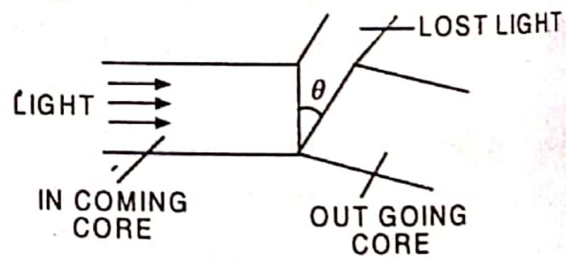


Fig. 34

(*v*) **Improper End Preparation.** Some times the two fibres to be joined may not be perfectly cleaved. Hence when butt joint is formed, then a gap remains between them, which results in power loss. See fig. (35) (*a*) & (*b*).

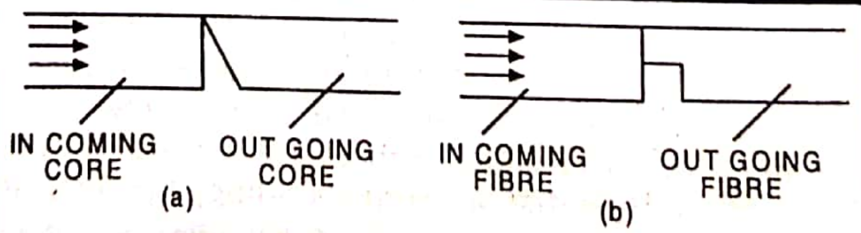


Fig. 35

Q. 10. Which optical fibre is used for long distance transmission?

Ans. Single mode fibre is preferred for use in long distance transmission, because this fibre is free from internodal dispersion effect. While intramodal dispersion is kept to a minimum using highly monochromatic laser light. On the other hand in multimode fibre, there will be large amount of dispersion due to internodal dispersion. Hence information loss is large over long distance transmission.

QUESTIONS

1. What is Numerical Aperture ?
2. What is total internal reflection ?
3. Write main Laser Sources for optical fibre systems.
4. What are the various modes of an optical fibre ? Give their importance.
5. How optical fibres and Lasers are useful in medical science ?
6. Distinguish between step index and graded index optical fibres.
7. Discuss the propagation of light through a step index multimode fibre. Explain the meaning of acceptance angle and numerical aperture. Also derive expressions for these.
8. Differentiate between step index and graded index fibre. Explain material dispersion in pulse dispersion in optical fibres.
9. Give some applications of optical fibres.
10. What do you understand by acceptance angle for an optical fibre ?
11. Describe briefly the construction and working of an optical fibre. What are various kinds of losses, a light suffers while propagating through a fibre ? Explain different mechanisms of dispersion.
12. What are the various optical fibre characteristics ? Derive expression for numerical aperture.
13. What is the principle of optical fibres ? Discuss various modes of an optical fibre.
14. Explain numerical aperture. Describe briefly the applications of optical fibres in communication.
15. What are various mechanisms, resulting in the loss of optical power through a fibre ? Hence define attenuation coefficient.