Optical fibres are either made as a single fibre or a flexible bundle of cable. A bundle is a **number of fibres in a single jacket.**

Basic propose of cladding is to confine the light to the core as the light falling on core and striking core cladding interface at angle greater than the *critical angle* will be reflected back to the core.

8.29. PROPAGATION OF LIGHT THROUGH FIBRE

Main function of the optical fibre is to accept maximum light and transmit the same with minimum **attenuation.**

Light gathering ability of a fibre depends on two factors:

(*i*) Core size

(*ii*) Numerical aperture

Numerical aperture of fibre is determined by **acceptance angle and fractional refraction index change.**

8.30. ACCEPTANCE ANGLE AND ACCEPTANCE CONE

Consider an optical fibre through which light is being sent. The end at which light enters is called **launching end.** Let the refractive indices of the core and cladding be n_1 and n_2 respectively; $n_2 < n_1$. Let the refractive index of the medium k through which light is launched be n_0.

Let the light beam enter at an angle i to the axis of the fibre. The ray gets refracted at an angle r and strikes the core cladding interface at an angle ϕ. For angle ϕ more than the critical angle C, } light will undergo **total internal reflection**. The ray will also undergo total internal reflection at interface as $n_1 > n_2$. It means that so long as ϕ is greater than critical angle C, light will stay within the fibre.

Let us now compute the incident angle i for which $\phi \leq C$ such that light rebounds within the fibre.

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

$$\frac{\sin i}{\sin r} = \frac{n_1}{n_0} \qquad ...(1)$$

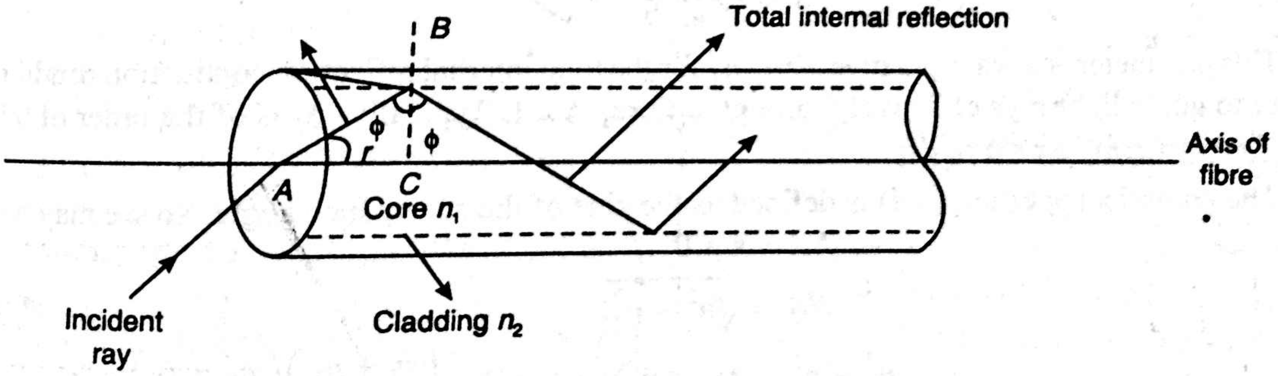


Fig. 8.24

If i is increased beyond a light, ϕ will drop below the critical value C and the ray escapes from the side walls of the fibre. The largest value of i occurs when $\phi = C$.

For the ΔABC, we have

$$\sin r = \sin(90° - \phi) = \cos\phi \qquad ...(2)$$

Putting sin i from Equation (1) into Equation (2), we get

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

When

$$\phi = C$$

$$\sin i\ (\text{max}) = \frac{n_1}{n_0}\cos C \qquad ...(3)$$

But

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

$$\therefore \qquad \cos C = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \qquad \text{...(4)}$$

Putting the expression (4) into (3), we get

$$\sin i\,(\max) = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \qquad \text{...(5)}$$

When incident ray is launched from air medium, we have $n_0 = 1$.
Designing i (max) = θ_0, Equation (5) may be simplified to

$$\sin \theta_0 = \sqrt{n_1^2 - n_2^2} \qquad \text{...(6)}$$

$$\therefore \qquad \theta_0 = \sin^{-1}[\sqrt{n_1^2 - n_2^2}] \qquad \text{...(7)}$$

The angle θ_0 is called the acceptance angle of the fibre. Acceptance angle may be *defined as the maximum angle that a light ray can have relative to the axis of the fibre and propagate down the fibre.*

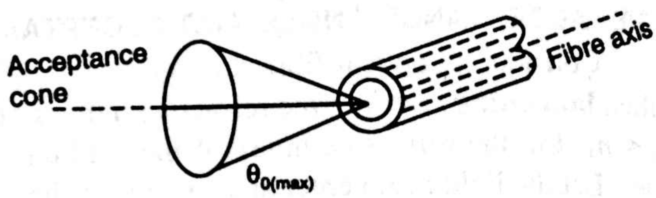


Fig. 8.25

The light rays contained within the cone having a full angle $2\theta_0$ are accepted and transmitted along the fibre. The cone is called the acceptance cone (Fig. 8.25).

Light incident at an angle beyond θ_0 refracts through the cladding and the corresponding optical energy is lost. *It is clear that the greater the diameter of the core, the larger the acceptance angle.*

8.31. FRACTIONAL REFRACTIVE INDEX CHANGE

The fractional difference Δ between the refractive indices of the core and the cladding is called *fractional refractive index change.* It may be expressed as

$$\Delta = \frac{n_1 - n_2}{n_1} \qquad \text{...(8)}$$

This parameter is always positive as n_1 n_2 for the total internal reflection conduction condition. In order to guide light rays effectively through a fibre, $\Delta < 1$. Typically, Δ is of the order of 0.01.

8.32. NUMERICAL APERTURE

The numerical aperture (NA) is defined as the sine of the acceptance angle. So we may write

$$NA = \sin \theta_0$$

$$\therefore \qquad NA = \sqrt{n_1^2 - n_2^2} \qquad \text{...(9)}$$

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

Approximating $\frac{n_1 + n_2}{2} \approx n_1$, we can express the above may be written as

$$(n_1^2 - n_2^2) = 2n_1^2\,\Delta$$

$$\therefore \qquad NA = n_1\sqrt{2\,\Delta} \qquad \text{...(10)}$$

Numerical aperture accounts for the light gathering ability of the fibre and it measures the amount of light accepted by the fibre. As is clear from Equation (9) numerical aperture depends only on the refractive indices of the core and cladding materials.

Numerical aperture ranges between 0.13 to 0.50 and a larger value of numerical aperture will mean that the fibre can accept more light from the source.

Example 1. *Calculate the refractive indices of the core and cladding material of a fibre from following data: $NA = 0.22$ and $\Delta = 0.012$.*

Solution: Given, $\Delta = \dfrac{n_1 - n_2}{n_1} = 0.012$ ...(1)

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

$\therefore$ $n_1 = \dfrac{NA}{\sqrt{2\Delta}} = \dfrac{0.22}{\sqrt{2\times .012}} = \mathbf{1.42}$

Putting in Equation (1), we get

$$\frac{1.42 - n_2}{1.42} = 0012$$

$\therefore$ $n_2 = 1.40.$

Example 2. *Calculate the numerical aperture, acceptance angle and the critical angle of a fibre having core refractive index = 1.50 and the cladding refractive index = 1.45.*

Solution: We have the relation, $\Delta = \dfrac{n_1 - n_2}{n_1} = \dfrac{1.5 - 1.45}{1.5} = 0.033$

Numerical aperture $(NA) = n_1\sqrt{2\Delta} = 1.5\times\sqrt{2\times 0.033} = 0.387$

Acceptance angle $\theta_0 = \sin^{-1} NA = 22.78°$

and critical angle $C = \sin^{-1}\dfrac{n_2}{n_1} = \sin^{-1}\dfrac{1.45}{1.50} = \mathbf{75.2°}.$

Example 3. *An optical fibre has a NA of 0.20 and a cladding refractive index of 1.59. Determine the acceptance angle for the fibre in water which has a refractive index of 1.33.*

Solution: $NA = \dfrac{\sqrt{n_1^2 - n_2^2}}{n_0}$

When the fibre is in air $n_0 = 1$ and $NA = \sqrt{n_1^2 - n_2^2} = 0.20$

$\therefore$ $n_1 = \sqrt{(NA)^2 + n_2^2} = \sqrt{(0.20)^2 + (1.59)^2} = \mathbf{1.6025}$

When the fibre is in water $n_0 = 1.33.$

$\therefore$ $NA = \dfrac{\sqrt{n_1^2 - n_2^2}}{n_0} = \dfrac{\sqrt{(1.6025)^2 - (1.59)^2}}{1.33} = \mathbf{0.15}$

$\therefore$ $\theta_0\,(\max) = \sin^{-1}(NA) = \sin^{-1}(0.15) = 8.6°.$

Example 4. *A glass clad fibre is made with the core glass of refractive index 1.5 and the cladding is doped to give a fractional index difference of 0.0005. Determine (i) the cladding index, (ii) the critical internal reflection index, (iii) the external critical acceptance angle, (iv) the numerical aperture.*

Solution: Given, $n_1 = 1.5, \Delta = 0.0005$

(*i*) Let the refractive index of cladding be n_2. So we have

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

$\therefore$ $0.0005 = \dfrac{1.5 - n_2}{1.5}$

or $n_2 = 1.5 - 1.5 \times 0.005 = \mathbf{1.4925}$

(*ii*) Let the critical internal reflection angle be C

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

$\therefore$ $C = \sin^{-1}\left[\dfrac{n_2}{n_1}\right] = \sin^{-1}\left[\dfrac{1.4925}{1.5}\right] = \sin^{-1}(0.9995)$

$= 88.2°$

(*iii*) Let the external critical acceptance angle be θ_0, so we have,

$$\sin C = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}; \text{ where } n_0 = 1$$

$$\therefore \quad \theta_0 = \sin^{-1}[\sqrt{n_1^2 - n_2^2}]$$
$$= \sin^{-1}(1.5^2 - 1.4925^2)^{1/2}$$
$$= \sin^{-1}(2.25 - 22.2764625)^{1/2}$$
$$= \sin^{-1}(0224) = 112°$$

(*iv*) Numerical aperture $\quad NA = n_1\sqrt{2\Delta}$

$\therefore \quad NA = 1.5\sqrt{2 \times 0.005} = 1.5\ (0.03162) = \mathbf{0.0474}.$

8.33. MODES OF PROPAGATION

In an optical fibre light travels as an e.m. wave and all the waves moving in directions above the critical angle will be trapped in the fibre due to total internal reflections. However, all such waves do not propagate through the fibre, and only certain ray directions are allowed for propagations. These allowed directions corresponds to **modes of the fibre.**

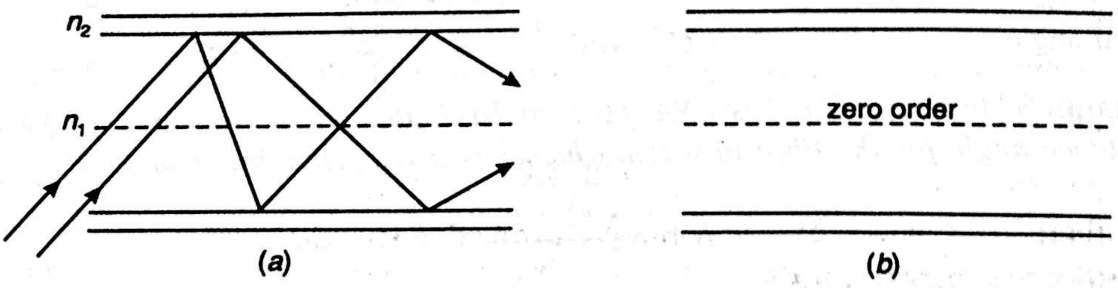


Fig. 8.26

In simple form, we can understand the modes as the **number of paths of light** in an optical fibre. The paths are all **zig-zag** with the exception of light moving along axial directions. So the light rays moving through a fibre may be classified as (*i*) axial rays (*ii*) zig-zag rays.

Since the rays get repeatedly reflected at the walls of the fibre, there occurs a phase shift. So wave along certain zig-zag path be in phase and get intensified while some other waves moving in other paths will be out of phase and may fade out due to **destructive interference.**

The light ray paths along which the waves are in phase inside the fibre are called modes.

Number of modes, a fibre can support depends on the ratio $\frac{d}{\lambda}$ where **d is the diameter of the core and λ is the wavelength of the wave transmitted.**

In general, modes are represented by an order number m. In a fibre of fixed thickness, the higher order propagates at smaller angles than the lower order modes.

Axial ray that travels along the axis of the fibre is called **zero order ray.**

8.34. TYPES OF OPTICAL FIBRE

Optical fibres are in general of two types:

(*i*) Single Mode fibre (SMF) (*ii*) Multimode Fibre (MMF)

A single fibre has a smaller core diameter and can support only one mode of propagation while a **multimode fibre** has a large core diameter and can support a large number of modes.

Multimode fibres are further classified on the basis of index profile. **An index profile is graph** of refractive index (along X-axis) and distance from the core (along Y-axis). Index profit of a MMF can be either step index (SI) type or graded index (GRIN) type. Index profile of SMF is usually a step index (SI) type.

SINGLE MODE STEP INDEX FIBRE

A single mode step index fibre consists of a very fine thin core of uniform refractive index surrounded by a cladding of refractive index lower than that of the core. Since the refractive index abruptly changes at the core cladding boundary, it is known as step index fibre. A typical SMF has a core diameters of 4μm which corresponds to some of the wavelengths of light waves. Light travels along a single path, *i.e.*, along the axis only and so zero order mode is supported by SMF. Usually SMF is characterised by a very small value of Δ (~0.002).

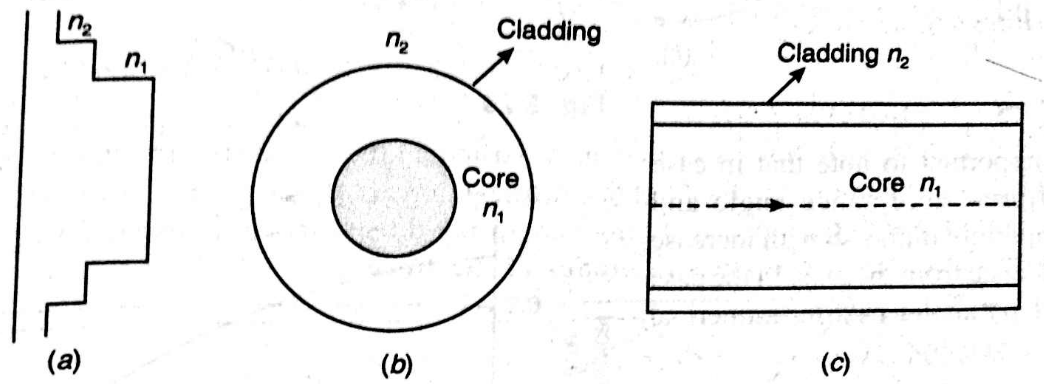


Fig. 8.27

The fibre is surrounded by some **opaque protective sheath.**

MULTIMODE STEP INDEX FIBRE

It is similar to the single mode step index fibre with the exception that it has a large diameter (~100 *mm*). Core diameter is very large as compared to the wavelength of transmitted light. Light moves along zig-zag paths along MMF. A typical structure along with profile of step index MMF are shown in Fig. 8.28.

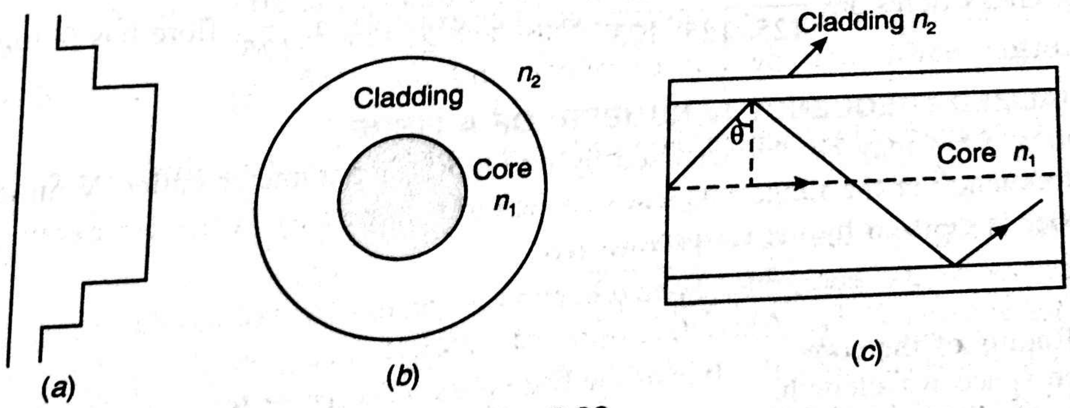


Fig. 8.28

NA in case of a MMF is quite large as core diameter is larger and is ~ 0.3.

GRAIN INDEX FIBRE (GRIN)

A GRIN is a multimode fibre which has concentric layers of refractive indices which means that the refractive index of the core varies with distance from the fibres axis, *i.e.*, it has high value at the centre and falls of rapidly as the radial distance increases from the axis.

As is shown in profile (Fig. 8.29) such a profile causes typical periodic focussing of the light moving through the fibre.

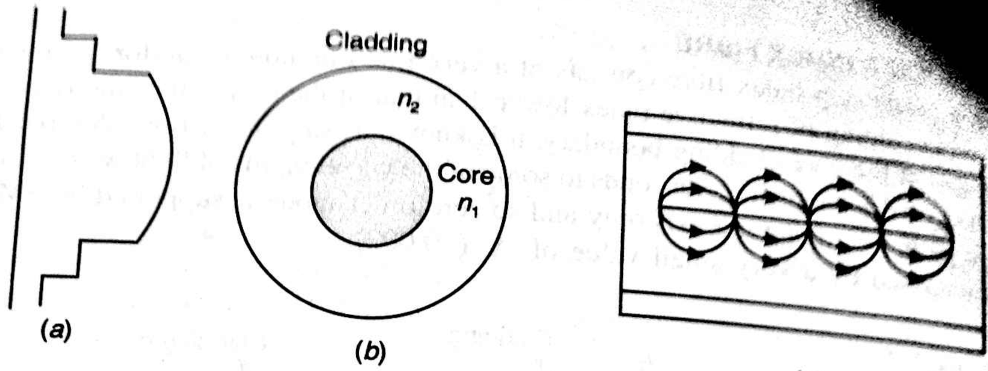


Fig. 8.29

It is important to note that in case of GRIN fibres, acceptance angle and numerical aperture diminish with increase of radial distance from the axis. In the case of fibres of parabolic profile, numerical aperture is given by:

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

The convention of writing the size of optical fibre is to given the core/cladding diameter.

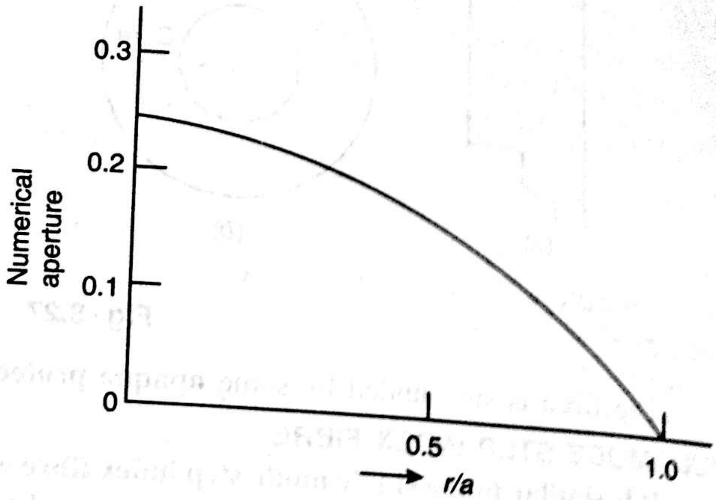


Fig. 8.30

Sizes of SI fibre are $\frac{50}{125}, \frac{10}{140}, \frac{200}{230}$ etc.

Size of GRIN fibres are $\frac{50}{125}, \frac{62.5}{125}, \frac{85}{125}$, etc. For example, a $\frac{50}{125}$ fibre has $50\mu m$ core and $125\mu m$ cladding.

8.35. NORMALIZED FREQUENCY (V-NUMBER) OF A FIBRE

An optical fibre may be characterised by one more or parameter called V-number or the normalized frequency of the fibre.

V-number is denoted by the relation

$$V = \frac{2\pi a}{\lambda}\cdot\sqrt{n_1^2 - n_2^2} \qquad ...(1)$$

where $a \rightarrow$ Radius of the core
and $\lambda \rightarrow$ Free space wavelength.

Also we have Numerical Aperture given as:

$$NA = \sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta} \qquad ...(2)$$

$$V = \frac{2\pi a}{\lambda}(NA) = \frac{2\pi a}{\lambda} n_1\sqrt{2\Delta} \qquad ...(3)$$

Maximum number of modes N_m supported by an SI fibre may be got using the relation

$$N_m = \frac{1}{2}V^2$$

e.g., for $V = 10,\ N_m = 50.$

In case $V < 2.405$, fibre can support only one mode and is called SMF.

For $V > 2.405$, it is classified as MMF and it can support number of modes simultaneously.

Wavelengths corresponding to value of $V = 2.405$ is called the *cut off wavelength* of the fibre and is given as

Cut off wavelength $\lambda_C = \dfrac{\lambda V}{2.405}$ ...(4)

In the case of GRIN fibres, for large values of V, we have

$$N_m = \frac{V^2}{4} \quad \text{...(5)}$$

Example 5. *A step index fibre in air has a NA of 0.16, a core refractive index of 1.45 and a core diameter of 60 cm. Determine the normalized frequency for the fibre when light at a wavelength of 0.9µm is transmitted.*

Solution: Given, $NA = 0.16$

$$n_1 = 1.45$$

$$d = 60 \text{ cm} = 0.6 \text{ m}$$

$$\lambda_0 = 0.9\mu m = 9 \times 10^{-7} \text{ m}$$

The normalized frequency (V-number) is given by

$$V = \frac{\pi d}{\lambda_0}\sqrt{n_1^2 - n_2^2} = \frac{3.143 \times 0.60 \text{ m}}{9 \times 10^{-7} \text{ m}}$$

$$\therefore \quad V = 335103.22 = 3.35 \times 10^5.$$

Example 6. *Find the core diameter necessary for single mode operation at 850µm in S.I. fibre with $n_1 = 1.480$ and $n_2 = 1.47$. What is the numerical aperture and maximum acceptance angle of this fibre?*

Solution: (*i*) For single mode propagation, V-number is 2.405, so we have,

$$V = \frac{\pi d}{\lambda_0}\sqrt{n_1^2 - n_2^2}$$

$$\therefore \quad 2.405 = \frac{\pi d}{450 \times 10^{-9} \text{m}} \times 0.1717$$

$$d = \frac{2.405 \times 850 \times 10^{-9}}{3.143 \times 0.1717} \text{ m} = 3.79\mu m$$

(*ii*) $\quad NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.48^2 - 1.47^2} = 0.1717$

(*iii*) $\quad \sin\theta_0 = NA$

$$\theta_0 = \sin^{-1}(NA) = \sin^{-1}[n_1^2 - n_2^2]^{1/2}$$

$$= \sin^{-1}(0.1717) = 953'12''.$$

Example 7. *A step index fibre is made with a core of index 1.52, a diameter of 29µm and fractional difference index of 0.007. It is operated at a wavelength of 1.3µm· find (i) the fibre V-number, and (ii) the number of modes the fibre will support.*

Solution: Core refractive index $n = 1.52$

$$d = 29\ \mu m = 29 \times 10^{-6}$$

$$\Delta = 0.007$$

$$\lambda_0 = 1.3\mu m = 1.3 \times 10^{-6}$$

Using the relation, $\Delta = \dfrac{n_1 - n_2}{n_1}$

We get, $\quad 0.007 = \dfrac{1.52 - n_2}{n_1}$

$$\therefore \quad n_2 = 1.52 - 1.52 \times 0.007 = 1.5189$$

(*i*) $\quad V = \dfrac{\pi d}{\lambda_0}\sqrt{n_1^2 - n_2^2}$

$$\therefore \quad V = \frac{3.143 \times 29 \times 10^{-6}}{1.3 \times 10^{-6}}[1.52^2 - 1.5189^2]^{1/2} = \mathbf{4.049}$$

(*ii*) Number of modes $N = \frac{1}{2}V^2 = \frac{1}{2}(4.049)^2 = 8.19 = \mathbf{8}$ **modes.**

Example 8. *Calculate the maximum radius allowed for a fibre having core refractive index = 1.47 and cladding refractive index = 1.46. Fibre has a support of only one mode at a wavelength of 1300 nm.*

Solution: Condition for single mode is $V < 2.405$

or
$$\frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2} < 2.405$$

or
$$d < \frac{2.405\lambda}{\pi\sqrt{n_1^2 - n_2^2}} < \frac{2.405 \times 1300 \times 10^{-9}}{3.142 \times \sqrt{(1.47)^2 - (1.46)^2}} < \mathbf{5.82\mu m}$$

∴ Maximum diameter = $\mathbf{5.82\mu m}$.

Example 9. *Calculate the maximum value of Δ in the case of a single mode fibre core of diameter 10μm and core refractive index 1.5. Fibre is coupled to a light source of wavelength 1.3μm. Also calculate the cladding refractive index and the acceptance angle. Given V cut off for a single mode propagation = 2.405.*

Solution: We have the relations,

$$V_{\text{cut-off}} = \frac{\pi d}{\lambda} NA \text{ (cut off)}$$

∴
$$NA \text{ (cut off)} = \frac{V \times \lambda}{\pi d} = \frac{2.405 \times 1.3 \times 10^{-6}}{3.142 \times 10} = 0.09957$$

∴ Acceptance angle $= \sin^{-1}(0.09957) = 5.71°$

Also numerical aperture, $NA = n_1\sqrt{2\Delta}$

∴
$$\Delta = \frac{NA^2}{n_1^2} \times \frac{1}{2} = \frac{(0.09957)^2}{(1.5)^2} \times \frac{1}{2} = 2.2 \times 10^{-3}$$

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

∴
$$n_2 = n_1 - \Delta n_1 = n_1(1 - \Delta) = 1.5\,(1 - 2.2 \times 10^{-3}) = 1.496.$$

8.36. FABRICATION OF OPTICAL FIBRES

Materials which are used for optical fibres are transparent to optical frequencies. Normally, step index fibres are produced in the following three forms:

(*i*) Glass core cladded with glass which has lower refractive index than the glass-core.

(*ii*) Silica glass core cladded with plastic.

(*iii*) Plastic core cladded with another plastic.

In case of all glass fibres, **refractive step index** is smallest, slightly more for plastic cladded silica (PCS) and largest for plastic core and plastic cladded fibre.

(*i*) **Glass Fibre**

Most abundant and inexpensive optical fibres are made from silica (SiO_2) which has refractive index = 1.458 for λ = 8500Å.

We get material for different refractive index by dropping the basic material. If basic material is doped with Germenia (GeO_2) or Phosphorus pentoxide (P_2O_5), value of refractive index increases and **such materials can be used as core while pure silica is used as cladding.**

If pure silica is doped with B_2O_3 or fluorine, its refractive index reduces and so **it can be used as cladding while pure silica is used as core material.**

Glass optical fibres exhibit very low losses and are used for long distance communication.

(*ii*) **PCS Fibres**

Core is normally of pure quartz while cladding and sheath are of some transparent polymer such as silicon resin of low refractive index. These fibres are less expensive but transmission losses are very high. So these are used for short distances.

(*iii*) **Plastic Fibres**

In this case both core and cladding are of plastics. Using approximate polymers, a high refractive index difference can be achieved between core and cladding. So this type of fibre will have large **Numerical Aperture.** The main advantage of all plastic fibres is low cost and high mechanical flexibility. However, since those fibres are temperature sensitive. So they are limited in application between 80°C to 100°C temperatures. Also they have high transmission losses and so have limited use because of this limitation.

8.37. ATTENUATION

An optical signal passing through a fibre will get progressively reduced. This reduction or attenuation of signal may be defined as the **ratio of the optical output power from a fibre of length L to the input optical power.** It is expressed in terms of decibel/km (dB/km)

$$\alpha = \frac{10 \log P_1/P_2}{L}$$

where $P_1 \rightarrow$ Power of optical signal at launching end

$P_2 \rightarrow$ Power of optical signal at the receiving end.

In an ideal fibre $P_1 = P_2$ and attenuation will be 0 dB/km. However an attenuation upto 3 dB is within permissible limit. It is important to note that attenuation is wavelength dependent and so the wavelength must also be specified.

8.38. FIBRE LOSSES

The following three losses may occur in optical fibres:

(*i*) Absorption

(*ii*) Geometric effects

(*iii*) Rayleigh scattering

(*i*) **Absorption**

Even very pure glass absorbs light of a specific wavelength. Strong **electronic absorption** occurs in UV region and **vibrational absorption** occurs in IR region of wavelength 7μm to 12μm. These losses are attributed due to inherent property of the glass and is called **intrinsic absorption.** However, this loss is insignificant.

Impurities are major extrinsic source of losses in fibre. Hydroxyl radical ions (OH) and transition metals like Nickel, Chromium, Copper, Manganese etc. have electronic losses in **near visible range of spectrum.** These impurities should be kept away as far as possible from the fibre. Intrinsic as well as extrinsic losses are found to be minimum at about 1.3μm.

(*ii*) **Geometric Effects**

These may occur due to manufacturing defects like irregularities in fibre dimensions during drawing process or during coating, cabling or insulation processes.

(*iii*) **Rayleigh Scattering**

As glass has disordered structure having local microscopic variation in density which may also cause variation in refractive indices. So light travelling through these structures may suffer scattering losses due to Rayleigh, *i.e.*, scattering $\propto \frac{1}{\lambda^4}$. It means Rayleigh scattering sets a lower limit on wavelength that can be transmitted by a glass fibre at 0.8μm below which scattering loss is appreciably high.

8.39. TIME DELAY BETWEEN HIGHEST AND LOWEST ORDER MODE

Two rays of different modes are given in the Fig. 8.31.

If $AD = x$, then from Fig. 8.31.

$$AB = \frac{x}{\sin \phi_2}$$

So the total zig-zag path for L km fibre may be written as

$$L = \frac{L}{\sin \phi_2} \quad ...(i)$$

In general, we may write, Length $= \dfrac{L}{\sin\phi}$

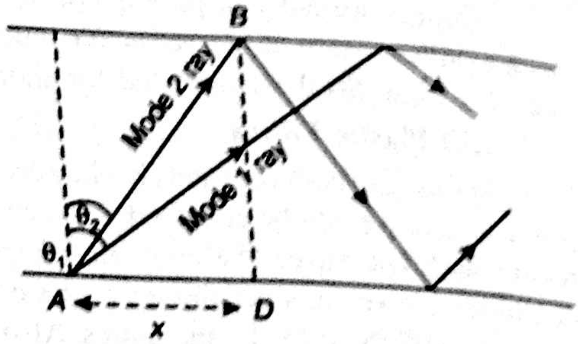


Fig. 8.31

where ϕ corresponds to the angle of incidence in the mode in question, with the normal to the wall of the fibre. In the highest order mode, the angle of incidence has minimum value and so is given by the critical angle C.

$$\phi_{min} = C = \sin^{-1} \frac{n_1}{n_2} \quad ...(2)$$

where n_2 is the refractive index of cladding material and n_1 is the refractive index of core material. In the lowest order mode, path length is given by

$$L_{min} = \frac{L}{\sin 90°} = L \quad [\because = \phi_{max} = 90°]$$

So the highest mode path length

$$L_{max} = \frac{L}{\sin \phi_{min}} \quad ...(3)$$

$$L_{max} = \frac{L}{\sin C} = L \cdot \frac{n_1}{n_2} \quad \left[\because \sin C = \frac{n_1}{n_2}\right] \quad ...(4)$$

Let Δx be the path-difference between the two rays,

$$\therefore \quad \Delta x = L_{max} - L_{min} = L\left[\frac{n_1}{n_2} - 1\right]$$

also

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

$$\therefore \quad \Delta x = L \cdot \left(\frac{\Delta}{1-\Delta}\right) \quad ...(5)$$

As the fibre acts like a dielectric medium of relative dielectric constant ε_r (say) which is normally more than one, so the rays move with a speed less than that in free spaces.

Also phase velocity V_p is given by

$$V_p = \frac{1}{\sqrt{\mu_r \mu_0 \varepsilon_r \varepsilon_0}} \quad ...(6)$$

where μ_0 and ε_0 are free space permeability and permittivity respectively.

Velocity of light is given by

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

$$\therefore \quad V_p = \frac{c}{\sqrt{\varepsilon_r \mu_r}}$$

Also since $\mu_r = 1$

$$\therefore \quad V_p = \frac{c}{\sqrt{\varepsilon_r}}$$

This phase velocity is the same as that of transmission line. Also we have the relation for refractive index and dielectric constant as

$$n^2 = \varepsilon r$$

$$\therefore \quad V_p \text{ (glass)} = \frac{c}{n_1}$$

So we may represent the time delay between highest and lowest order mode as

$$\Delta t = \frac{\Delta x}{V_p \text{ (glass)}} = L \cdot \frac{\Delta}{1-\Delta} / V_p$$

$$= L \cdot \frac{\frac{\Delta}{1-\Delta}}{c/n_1} = \frac{L \Delta n_1}{c\,(1-\Delta)} \quad \text{...(9)}$$

$$= \frac{L}{c} \cdot \frac{\Delta}{1-\Delta} \cdot n_1$$

This time delay is the characteristic of the fibre and **independent of the wavelength of light and is of the order of neno second per kilometer.**

It may be noted that this type of delay is absent in single mode fibre as it has only **one mode of propagation.**

In the case of GRIN fibre, the time delay due to intermodal dispersion is given by,

$$\Delta t = \frac{n_1 L \Delta^2}{8c} \quad \text{...(10)}$$

In this case n_1 in the refractive index of glass at the core centre and Δ is the fractional refraction index change from *core centre to cladding.*

It is observed that the graded index fibres (GRIN fibre) have much lower intermodal dispersion than that of S.I. fibre, as in the case of GRIN fibre, the ray on its passage from centre of fibre core to outer edge in zig-zag path moves through regions of decreasing refractive index. As phase velocity is given by

$$V_p = \frac{c}{n}$$

So the phase velocity increases with distance, measured from fibre core. So the group velocity is also faster at the outer edge.

Reverse phenomenan occurs when the ray is refracted back to the axis of fibre core. But again it will increase on the other side of the core axis. So we will get alternatively rising and falling group velocity with an average higher than that in the lower modes which propagate straight down the fibre, with the result that a much lower intermodal dispersion is left out in the graded index.

Time delay in this type of fibre is much less than 1 ns/km.

Example 10. *A certain optical fibre has an attenuation of 3.5 dB/km at 850 nm. If 0.5 mw of optical power is initially launched with fibre, calculate the power level after 4 km.*

Solution: In this case

Attenuation $\alpha = 3.5$ dB/km

Initial power level $P_1 = 0.5$ mW

Final power level $P_2 = ?$

length of cable = 4 km

We have the relation $\alpha = \frac{10}{L} \log \frac{P_1}{P_2}$

$$\therefore \quad 10 \log_{10} \frac{P_1}{P_2} = \alpha . L = 3.5 \times 4 = 14 \text{ dB}$$

$$\log_{10} \frac{P_1}{P_2} = \frac{14}{10} = 1.4 \text{ or } \log_{10} \frac{0.5}{P_2} = 1.4$$

Taking antilog on both sides

$$\therefore \quad \frac{0.5}{P_2} = 25.11 \text{ or } P_2 = \frac{0.5}{25.11} \text{ mw} = 19.9 \mu\text{W}.$$

Example 11. *A 15 km optical fibre link uses fibre with a loss of 1.5 dB/km. The fibre is joined every km with connectors, which give attenuation of 0.80 dB each. Find the minimum mean optical power which must be launched with the fibre to maintain a mean optical power level of 0.3 μω at the detector.*

Solution: (*i*) Connector loss = 0.8 dB/km

∴ Connector loss for 15 km length = 0.8 × 15 = 12 dB.

(*ii*) Fibre loss = 1.5 dB/km

∴ Fibre loss for 15 km = 1.5 × 15 = 22.5 dB

Total loss = 12 dB + 22.5 dB = 34.5 dB

Optical power level at detector $P_2 = 0.3\,\mu W$

Optical power at launch position $= P_1$

Now we have the relation $\alpha = 10 \log \frac{P_1}{P_2}$

$$34.5 = 10 \log \frac{P_1}{0.3\mu W} \text{ or } \log \frac{P_1}{0.3\mu W} = 3.45$$

Taking antilogs on both sides

$$\frac{P_1}{0.3\mu W} = 2818.3$$

$$\therefore \quad P_1 = 8.455 \times 10^{-4} \text{ W}$$

$$= \mathbf{0.846 \text{ mW}}.$$

8.40. OPTICAL WINDOWS

A typical curve of fibre attenuation v/s wave length for a silica based optical fibre is given in Fig. 8.32.

As may be observed from the above curve, there are minima at a particular optical wave-lengths. The band of wavelengths, at which the attenuation is minimum, is called an optical window or transmission window. Optical signals, having wave-lengths in this region travel through the fibre with least attenuation. Because of the said property, such windows are quite suitable for transmission of information.

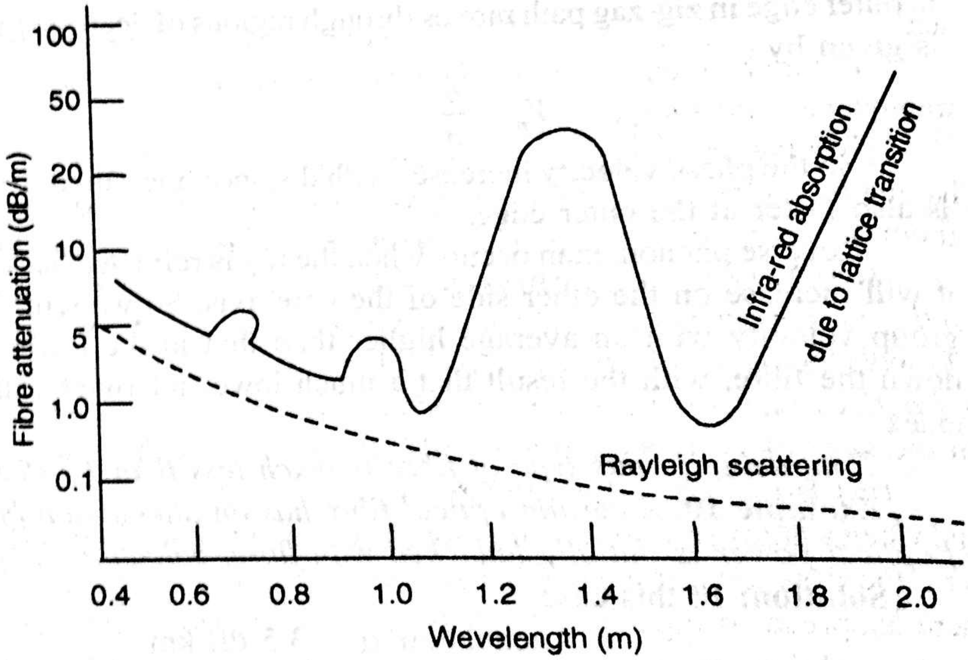


Fig. 8.32

In fibre optical communi-cation, two such windows are chosen:

(*i*) First window lies between 0.8μ*m* to 0.9μ*m*.

(*ii*) Second window lies between 1.3μ*m* to 1.6μ*m*.

8.41. DISPERSION

As stated earlier a pulse launched with a fibre gets attenuated due to losses in fibre. Moreover the incoming pulse also spreads during the transit through the fibre. So a pulse at the output is wider than the pulse at the in put *i.e.*, the pulse gets distorted as it moves through the fibre (Fig. 8.33). This distortion of pulse is due to dispersion effects which is measured in terms of nanoseconds per km (ns/km).

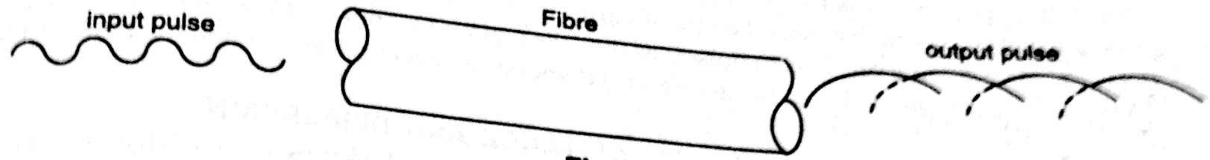


Fig. 8.33

There are three phenomenan that may contribute towards the distortion effect:

(i) Material dispersion

(ii) Wave guide dispersion.

(iii) Intermodal dispersion.

(i) Material Dispersion: Light waves having different wavelengths will travel with different speeds through a medium. Light waves having *shorter wavelengths* will move slower than those of longer wavelengths. So narrow pulses of light tend to broaden as they move through an optical fibre. This process is called material dispersion. As may be evident, the spectral width of the source will determine the extent of dispersion and the material dispersion is given by the equation

$$D_m = \frac{\lambda\,(\Delta\lambda)}{C} \cdot L \frac{d^2 n}{d\lambda^2} \qquad ...(1)$$

where

λ = corresponds to peak wavelength

$\Delta\lambda$ = is the spectral width

L = is the angle; of the fibre

and n = corresponds to core refractive index

It may be mentioned that the material dispersion can be very much reduced by a using a pure monochromatic source.

To give an example of material dispersion we observe that a LED operating at 820 nm and having a spectral spread of 38 nm gives dispersion of 3 ns/km. This dispersion can be reduced of to about 0.3 ns/km with the help of a laser diode that operates at 1140 nm with a spectral width 3 nm.

(ii) Wave-Guide Dispersion: Wave guided dispersion arises due to the *guiding properties of the fibre*. Amount of wave guide dispersion may also be expressed in a way similar to the Equation (1) with the *material refractive index* being replaced by effective refractive index as the *effective refractive index* for any mode of propagation varies with wavelength that may cause pulse spreading in the same way as the variation of refractive index does, in case of material dispersion.

(iii) Intermodal Dispersion: A ray of light passing through a fibre follows a zig-zag path and when a number of modes are moving through a fibre, they will move with different net velocities w.r.t. the fibre axis. It means that some modes will arrive at the out put earlier than the others *i.e.*, there is spread of input pulse. This process is called intermodal dispersion. It may be noted that this type of dispersion does not depend on the *spectral width of the source i.e.*, a light pulse from a pure monochromatic source $(\Delta\gamma = 0)$ will still be giving *intermodal dispersion.*

In the case of MMF, all the three spreading mechanisms are observed simultaneously while in case of SMF, *only material and wave guide* dispersion are observable.

In the case of fibres with low numerical aperture (NA), smaller dispersion is observed while for fibre with high NA, large dispersion in observed. Dispersion may be restricted by the use of a *low NA fibre and a narrow spectral width source.*

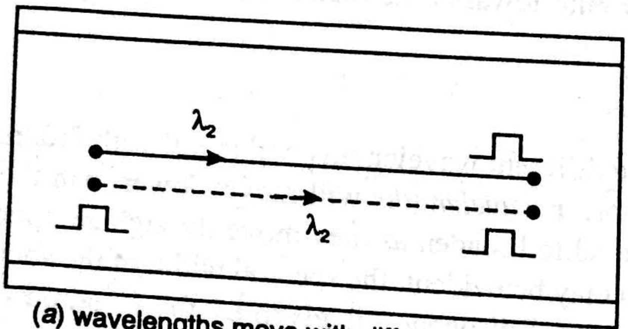
A solution to the above problem may be got by the use of GRIN fibres which produce less distortion than the SI fibres and they have pulse spread of only few ns/km, which is guide small as compared to the spread in case of SI fibres. However, GRIN fibres are more expensive. Also in the case of a short length of fibre, dispersion is proportional to the length of the fibre and so may not pose any problem but in case of large lengths, dispersion is proportional to the square root of fibre length and so may limit the use of *rate of data transmission.*

Another important aspect to be kept in mind is that the *dispersion limits the bandwidth of fibre*. Information flow, which means the rate of varies pulses must be quite slow so that the dispersion may not cause over-lapping of adjacent pulses, as then the signals can not be got separated at the output.

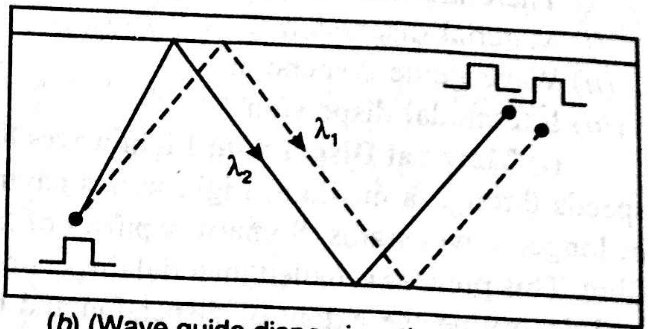
A typical signal spread due to the above said dispersion processes is given in the Fig. 8.30 (*a*), (*b*), (*c*).

8.42. RELATION BETWEEN BAND WIDTH, DISTANCE AND DISPERSION

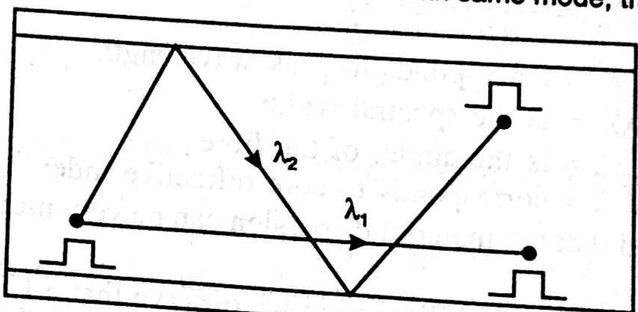
Band width in the case of optical fibres can be known from the knowledge of dispersion using the relation



(*a*) wavelengths move with different speeds



(*b*) (Wave guide dispersion, though propagating with same mode, travel at different angles.)



(*c*) Mode-Dispersion. A pulse at a single wavelength divides itself into modes that wave at different axial velocities.

Fig. 8.34

$$\text{Bandwidth (MHZ.km)} = \frac{310}{(\text{Dispersion ns/km})} \quad \text{...(2}$$

Bandwidth is a very important property of fibre cable and as is evident, cables with low valu of NA will have the widest band width.

Band width-distance product will specify the information capacity of the optical fibre.

Another important characteristic of the cable is the attenuation/km. Bandwidth-kilometer produc and attenuation/km may be used to find the *bit rate for transmission of information*.

Maximum bit rate B_{max} may be calculated from the relation

$$B_{max} = \frac{1}{5\ (\text{Dispersion})} \quad \text{...(3}$$

Example 12. *A step index multimode fibre has core index of 1.5 and cladding index of 1.498 Calculate (i) intermodal factor for the cable; (ii) Total dispersion in a 18 km length and (iii) Maximur bitrate allowed.*

Solution: In this case,

$$n_1 = 1.5;\ n_2 = 1.498;\ l = 18 \text{ km}$$

$$\therefore \quad \Delta = \frac{n_1 - n_2}{n_1} = \frac{1.5 - 1.498}{1.5} = 0.00133$$

(*i*) For 1 km length fibre

$$\Delta t = \frac{n_1 . L}{c}\left(\frac{\Delta}{1-\Delta}\right) = \frac{1.5 \times 1000m}{3 \times 10^8 \text{ ms}^{-1}} \times \frac{0.00133}{1 - 0.00133}$$

$$= 0.6659 \times 10^{-8} \text{ sec} = \mathbf{6.66\ ns/km.}$$

(*ii*) Total dispersion for 18 km length

$$\Delta t\,(\text{total}) = (\Delta t)1\,\text{km} \times 10\,\text{km}$$
$$= 6.66 \text{ ns/km} \times 18 \text{ km} = 119.9 \text{ ns}$$

(*iii*)
$$B_{max} = \frac{1}{5\Delta_t\,(\text{total})} = \frac{1}{5 \times 119.9ns} = 0.00166 \times 10^9 \text{ bits/sec}$$
$$= 1.66 \times 10^6 \text{ bits/sec} = \mathbf{1.66\ M\ bits/sec.}$$

Example 13. *Compute the dispersion/km of length and total dispersion in a 10 km length of SI fibre from the following data:*

Refractive index of core = 1.558 and Δ = 0.026.

Solution: Maximum dispersion $= \frac{n_1}{c} \cdot \frac{\Delta}{1-\Delta}$

∴ Max. dispersion/km $= \frac{1.558}{3 \times 10^8} \times \frac{.026}{1-0.026} \times 1000 \text{ m} \quad [\because L = 1\,\text{km} = 10^3\,m]$

13.8×10^{-9} sec = 13.8 *n* sec.

∴ Dispersion in 10 km = 13.8 × 10 = **138*n* sec.**

Example 14. *Compute the maximum dispersion for an optically graded fibre from the following data refractive index at the centre of core = 1.5, Δ = 0.0260 and length of fibre = 1 km.*

Solution: In case of GRIN fibre,

We have the relation,
$$\Delta t = \frac{n_1 . L . \Delta^2}{8c} = \frac{1.5 \times 1000m \times (0.026)^2}{8 \times 3 \times 10^8 \text{ ms}^{-1}} = \mathbf{0.42\ ns/km.}$$

8.43. COUPLING COMPONENTS OF AN OPTICAL FIBRE (SPLICES, CONNECTORS AND COUPLERS)

1. Fibre Splices: *Fibre splices are permanent joints in fibres and are analogous to soldered joints in electrical system.* A splice in a fibre which produces a localised optical distortion that may increase the signal attenuation and some of the signal may get scattered at splices. *Mode conversion* generally from low to high order modes may occur thereby increasing the attenuation beyond splices. Combination of all these effects may *attenuate* a signal significantly.

So, for less distortion and attenuation of the signal, proper matching of the front ends of the fibres to be joined is required. These losses may be due to the *misalignment* of core and cladding of the fibres to be joined. The joining process generally introduces a loss of 0.2 to 0.3 db for a 50 micron *core index fibre*. Fibre mismatches of core diameter, cladding diameter, index profile and numerical aperture between the adjoining fibres increase this loss to about 0.5 db.

In view of the above discussion, it is important that the fibre splices must have low *insertion loss* and sufficient mechanical strength. A number of techniques have been developed, *e.g.*, *V*-groove splices, fusion splices and sleeve splices etc. It should be noted that in designing a splice system, simplicity of the operation must have high priority because of the following reasons.

1. Working conditions in the fields do not allow complicated splicing procedures.
2. Operating companies do not want to increase cost factor by employing more persons to maintain the fibres.

8.44. V-GROOVE TECHNIQUE

This technique is usually employed during testing of optical fibres in the laboratory or in field or for quick restoration of fibre fault in the communication link. The V-grooved system or *Jig* consists of a central pillar and two side alignment blocks called magnetic clamps.

On the central pillar V-grooves impressed by mandrel into copper substrate measuring about 6 × 2 mm are mounted. Figure 8.31 shows the V-groove arrangement in which the fibres to be joined are held in alignment blocks by magnetic clamps. Central pillar is raised so that the fibres are forced down into V-grooves under there own spring force. Some of epoxy resin or glue is applied over the fibre ends which are brought near by moving the right hand fibre clamp towards *V-groove jig*.