10

FIBRE OPTICS AND HOLOGRAPHY

[A] FIBRE OPTICS

FUNDAMENTAL IDEAS ABOUT OPTICAL FIBRES

❑ From time to time scientists have tried to design and improve communication ...em by which messages are sent over long distances. The communication ...em consists of three parts viz. (i) transmitter, (ii) transmission channel (may ...either a ***guided transmission line*** such a wire or ***waveguide***) and (iii) receiver. ...ing a transmission line, the signal gets progressively attenuated and distorted. So ...e improvement in the communication process would mean motivation to ...prove the transmission fidelity and at the same time to improve the data rate of ...ansmission.

With the development of lasers, reliable and powerful coherent radiation became ...ailable. So it was natural to use this light for communication purposes. We also know ...at light waves cannot travel far in open atmosphere as the energy gets very rapidly ...ssipated. Hence, some kind of guiding channel is needed. Optical fibre provides the ...ecessary wave guide for light.

The guiding medium to light is called ***optical fibre.*** The communication through ...ical fibre is called as ***light-wave communication*** or ***optical communication.***

Fibre optics is a technology related to transportation of optical energy (light ...ergy) in guiding media specifically glass fibres.

Now-a-days most part of the world, fibre optics is used to transmit, video and ...ital data signals using light wave from one place to another place.

...1-1 STRUCTURE OF OPTICAL FIBRES

The optical fibre is a wave guide. It is made of thin transparent dielectrics (like ...ass). Its function is to guide visible and infrared light over long distances.

An optical fibre consists of an inner cylinder which is made of glass, called the ...re. The core carries light. The core is surrounded by another cylindrical shell of lower ...fractive index called the ***cladding.*** The cladding helps to keep the light within the core ...rough the phenomenon of ***total internal reflection.*** The core and cladding are shown ...fig. (1).

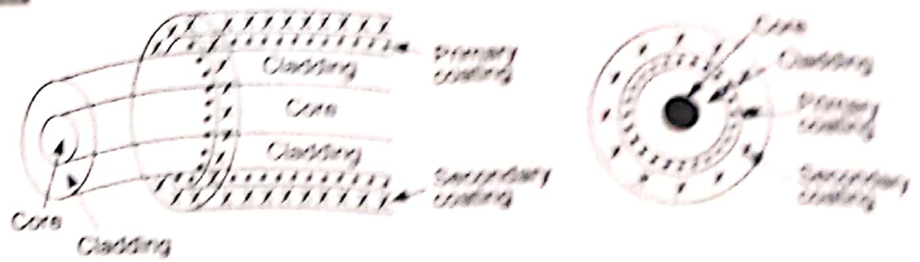


Fig. (1)

The core diameter can vary from about 5 μm to about 100 μm. The cladding diameter is usually 125 μm. For greater strength and protection of the fibre, a soft plastic coating (***primary coating***) is done whose diameter is about 250 μm. This is often followed by another layer of coating known as ***secondary coating***.

10.2 PROPAGATION MECHANISM (Principle of Optical Fibre)

The optical fibres are based on the principle of ***total internal reflection***. An optical fibre is a hair-thin cylindrical fibre of glass or any transparent dielectric medium. In practical applications, they consist of many thousands of very long fine quality glass/quartz fibres. The fibres are coated with a layer of lower refractive index.

Total internal reflection at the fibre will occur only if the following two conditions are satisfied :

1. The refractive index of the core material (n_1) must be slightly higher than that of cladding (n_2) surrounding it.
2. At the core-cladding interface the angle of incidence θ (between the ray and normal to the surface) must be greater than critical angle (θ_c). This is defined as

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

This is shown in fig. (2)

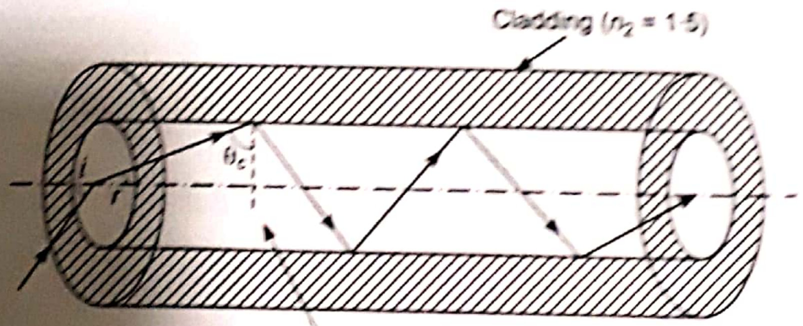


Fig. (2)

When light is incident on one end of the fibre at small angle, it passes through the fibre as explained below. Let *i* be the angle of incidence of the light ray with the axis and *r*, the angle of refraction. If θ be the angle at which the ray is incident on the fibre boundary, then $\theta = (90 - r)$. *Suppose* n_1, *be the refractive index of fibre. If* $\theta \geq \theta_c$ *critical angle where* $\theta_c = \sin^{-1}(n_2/n_1)$ *then the ray is totally internally reflected*

...this way the ray undergoes repeated total internal reflections until it emerges ...f the other end of the fibre, even if the fibre is bent. Thus, the light ray is guided ...gh the fibre from one end to other end without any energy lost due to reflection.

...l internal reflection.

...otal internal phenomenon is shown in fig. (3).

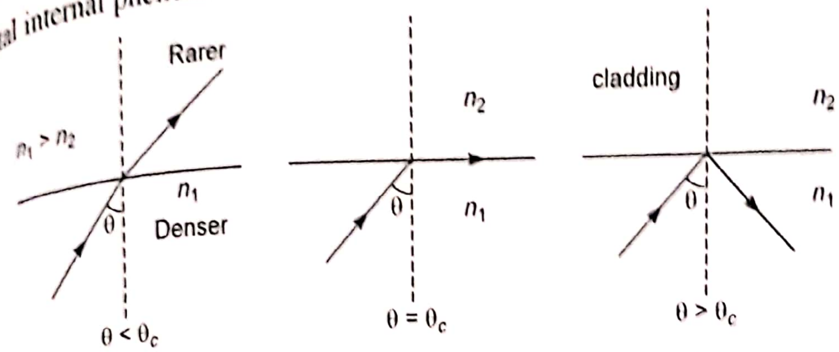


Fig. (3) Total internal reflection.

We consider the following points :

(i) When the angle of incidence (say θ) is less than critical angle θ_c, then the ray is ***refracted*** in rarer medium as shown in fig. (3a).

(ii) For a particular angle of incidence, the refracted ray just ***grazes*** the interface between the two media as shown in fig. (3b). This angle of incidence is known as ***critical angle.***

(iii) When the angle of incidence is further increased ($\theta > \theta_c$), the ray is reflected back in the same medium. This phenomenon is called as ***total internal reflection.***

.3 TYPES OF OPTICAL FIBRES

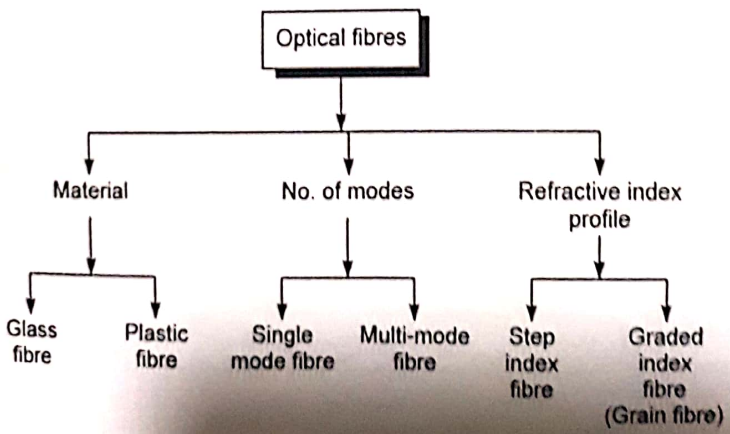
The optical fibres are classified into three major types based on

(a) ***Material***

(b) ***Number of modes***

(c) ***Refractive index profile***

A general classification is given below :



10.3-1 CLASSIFICATION BASED ON MATERIAL USED

On the basis of materials, the optical fibres are classified as follows :

(1) Glass fibre

When the optical fibre is made up of mixture of metal oxides and silica glasses, then it is called as glass fibre.

The glass fibres can be made by one of the following combinations of core and cladding

(i) ***Core :*** SiO_2, ***Cladding :*** $P_2O_5 - SiO_2$

(ii) ***Core :*** $GeO_2 - SiO_2$, ***cladding :*** SiO_2

(2) Plastic fibre

When the fibres are made up of plastics, then it is called as plastic fibre.

The plastic fibres can be made by one of the following combinations of core and cladding

(i) ***Core :*** Polystyrene, ***Cladding :*** Methyl methacrylate

(ii) ***Core :*** Polymethyl methacrylate, ***Cladding :*** Co-polymer

10.3-2 CLASSIFICATION OF FIBRE BASED ON NUMBER OF MODES

On the basis of number of modes of propagation, the optical fibres are classified into two types:

(1) Single mode fibre (SMF), and **(2)** Multi-mode fibre (MMF).

(1) Single mode fibre (SMF)

The single mode fibre is shown in fig. (4). It has smaller core diameter (5 μm) and high cladding diameter (70 μm). The difference between the refractive indices of the core and the cladding is very small.

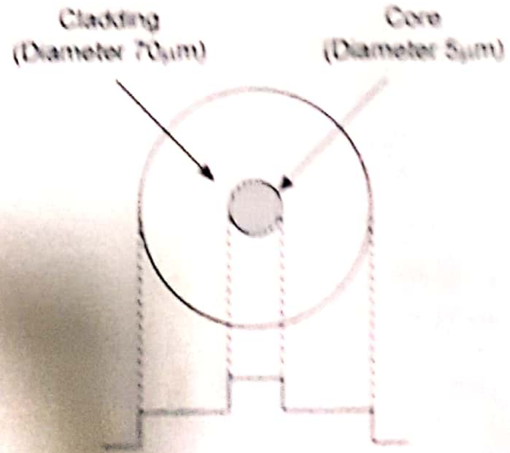


Fig. (4)

When only a single mode is transmitted through an optical fibre, then it is known as single-mode fibre. This is shown in fig. (5).

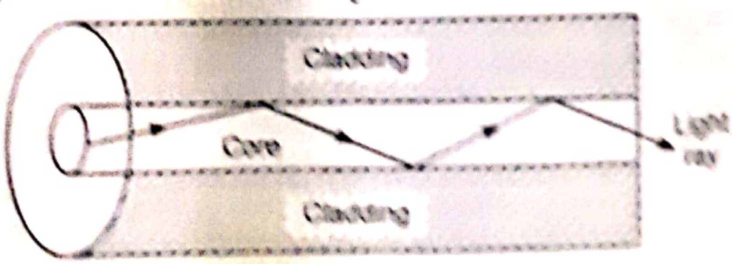


Fig. (5) Light way propagation

It is clear from the fig. (5) that the light rays can travel only at one discrete path through the core. It can enter and leave the fibre at one angle.

Characteristics :

- The single mode fibre can support only one mode of propagation.
- Suitable for long distance communication such as telephone lines.
- The light is passed through laser diodes
- Fabrication is very difficult and costly.

2) Multi-mode fibre (MMF)

The multi-mode fibre is shown in fig. (6). It has larger core diameter than single mode fibre. The core diameter is (40 μm) and that of cladding is (70 μm). The relative refractive index difference is also larger than single mode fibre. Multi-mode fibre allows a large number of modes for the light rays travelling through it.

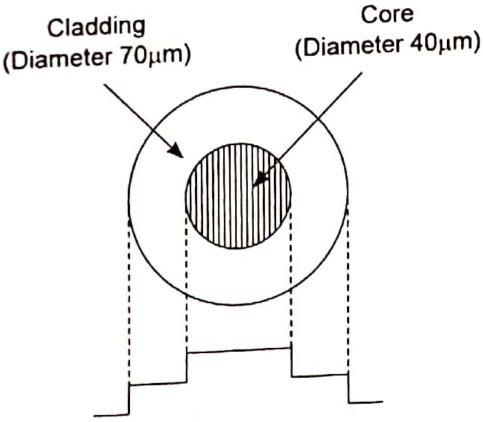


Fig. (6)

When one than one mode is transmitted through an optical fibre, then it is known as multimode fibre. This is shown in fig. (7).

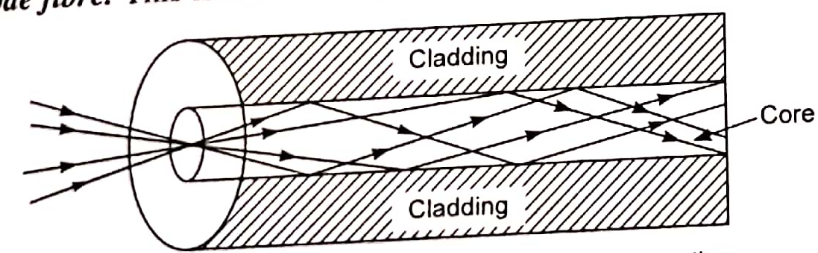


Fig. (7) Multimode fibre showing light wave propagation.

Therefore, in multiomode fibre, the light can travel through the core through many different paths. The light can enter and leave the fibre at various angles.

Characteristics :

- The multimode can support a number of modes
- Propagation of light is easy
- The light ray enters into the fibre using LED (Light Emitting Diode) source
- The fabrication is less difficult than single mode fibre
- The fibre is not costly
- Not suitable for long distances communication.

10.3-3 CLASSIFICATION OF FIBRE BASED ON REFRACTIVE INDEX

There are two types of optical fibres, *viz.*

(1) Step-index optical fibre, and **(2)** Graded-index optical fibre.

1. Step-index optical fibre.

When the refractive indices of core, cladding and air in optical fibre vary step by step, then the fibre is known as step index fibre.

It is important to mention here that the core has a uniform refractive index (say n_1), and the cladding has also a uniform refractive index (say n_2), of course $n_1 > n_2$.

Based on refractive index and number of modes, the step index fibres can further be classified into following two types :

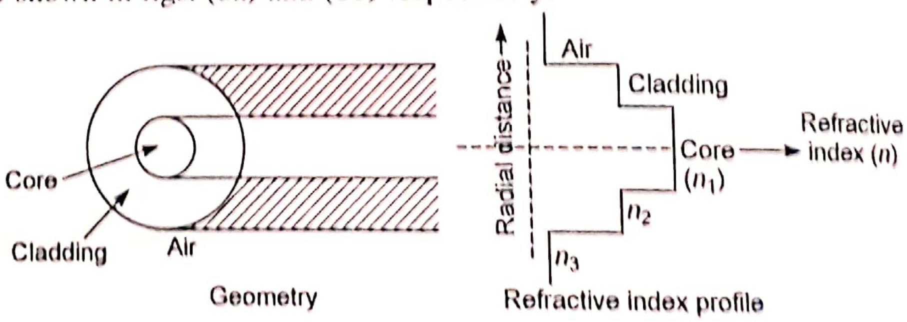
(i) Step index-single mode fibre

(ii) Step index-multi-mode fibre.

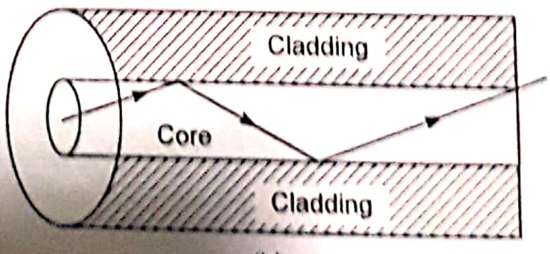
(i) *Step index-single mode fibre.*

A typical step-index single mode fibre has a core diameter of 5 to 10 μm and an external diameter of cladding of 50 to 125 μm. The core has a uniform refractive index of higher value than the uniform refractive index of cladding.

The refractive index profile and light ray propagation in step index-single mode fibre are shown in figs. (8a) and (8b) respectively.



(a)



(b)

Fig. (8) Light propagation.

(ii) *Step index-multi mode fibre*

In step index-multimode fibre, the core has a much larger diameter, therefore more number of modes of propagation of light can be possible.

A typical step-index multimode fibre has a core diameter of 50 to 200 μm and an external diameter of cladding 125 to 300 μm. It has a core material with uniform refractive index and a cladding material of lesser refractive index than that of core.

The refractive index profile and light ray propagation in step-index multimode fibre are shown in figs. (9a) and (9b) respectively.

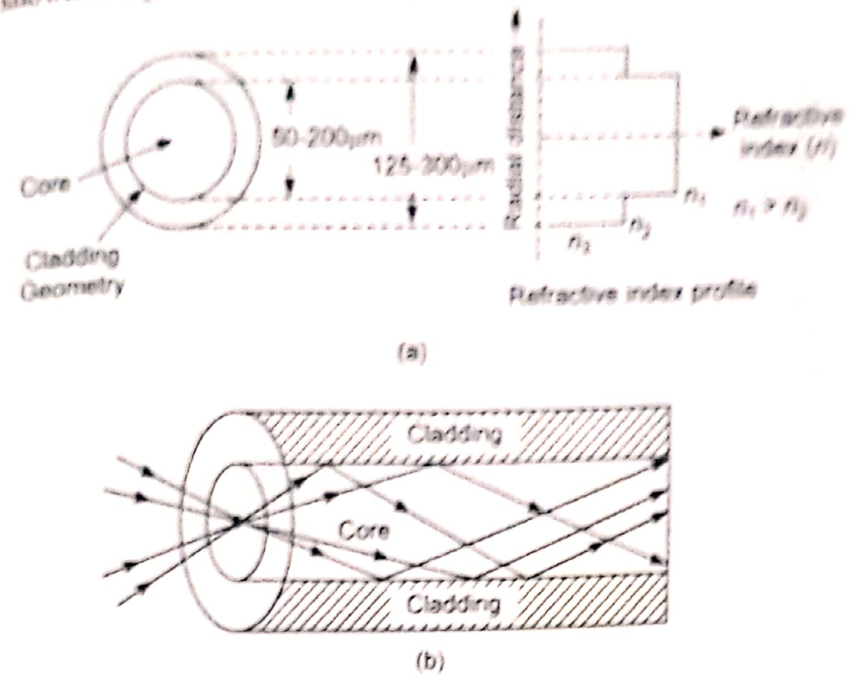


Fig. (9) Step-index multimode fibre

Advantages

Following are the advantages of step-index multimode fibre:

(i) relatively easy to manufacture,

(ii) cheaper than other types,

(iii) larger layer NA,

(iv) they have longer life times than laser diodes.

Disadvantages

They have the following disadvantages:

(i) lower bandwidth,

(ii) high dispersion, and

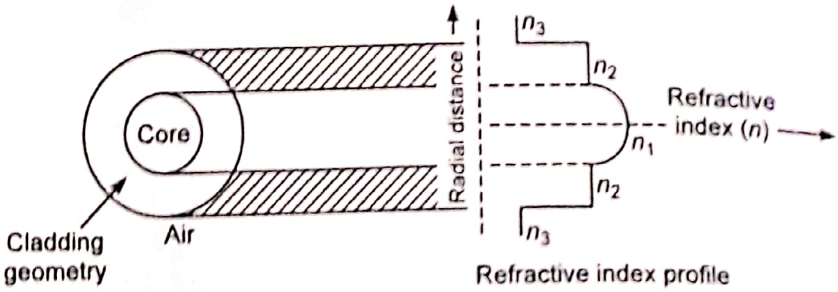
(iii) smearing of signal pulse.

2. Graded-index optical fibre

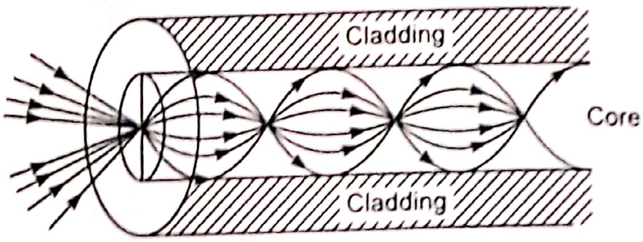
If the core has a non-uniform refractive index that gradually decreases from the centre towards the core-cladding interface, the fibre is called a graded-index fibre. The cladding has a uniform refractive index.

The core and cladding diameters are about 50 μm and 70 μm respectively in case of multimode fibre. The light rays propagate through it in the form of skew rays or helical rays. They do not cross the fibre axis at any time and are propagating around the fibre axis in helical or spiral manner.

The refractive index profile and light ray propagation in graded index fibre (GRIN fibre) are shown in figs. (10a) and (10b) respectively.



(a)



(b)

Fig. (10) Multimode step index fibre

It is obvious from the figure that a ray is continuously bent and travels a periodic path along the axis. The rays entering at different angles follow different paths with the same period, both in space and time. Thus, there is a periodic self focussing of the rays.

Advantages.

Following are the advantages of graded-index multimode fibre :

(i) dispersion is low,

(ii) bandwidth is greater than step-index multimode fibre, and

(iii) easy to couple with optical source.

Disadvantages.

Following are the disadvantages of graded-index multimode-fibre :

(i) expensive and

(ii) very difficult to manufacture.

Table 1 **Difference between single mode fibre and multi-mode fibre**

S. No.	Single mode fibre	Multimode fibre
1.	Only one mode can propagate through the fibre.	A large number of modes or paths for the light rays may pass through the fibre.
2.	The core has smaller diameter and difference in refractive index of core and cladding is very small.	The core diameter is large and the refractive index difference between core and cladding is larger than single mode fibre.

3.	There is no dispersion, *i.e.*, degradation of signal during travel in fibre.	There is more dispersion, *i.e.*, degradation of signal due to multimode.
4.	Fabrication is difficult and costly.	Fabrication is less difficult and not costly.
5.	The fibre can carry information to longer distances.	Information can be carried to shorter distances only.

Table 2 **Difference between step index and graded index fibre**

S. No.	Single index fibre	Graded index fibre
1.	The refractive index of the core is uniform throughout and undergoes an abrupt step change at cladding boundary.	The refractive index of the core is made to vary gradually such that it is maximum at the centre.
2.	The path of light propagation is in zig zag manner.	The path of light propagation is helical, *i.e.*, spiral manner.
3.	Distortion is more in multimode step-index fibre.	Distortion is less.
5.	Numerical aperature is more for multimode step index fibre.	Numerical aperture in less.

10.4 ACCEPTANCE ANGLE AND CONE

10.4-1 ACCEPTANCE ANGLE

Consider a cylindrical fibre wire which consists of an inner core of refractive index n_1 and an outer cladding of refractive index n_2 where $n_1 > n_2$. Let n_0 be the refractive index of the medium from which the light ray enters the fibre. This end of the fibre is known as ***launching end.***

Let a ray of light enter the fibre at an angle i to the axis of fibre as shown in fig. (11).

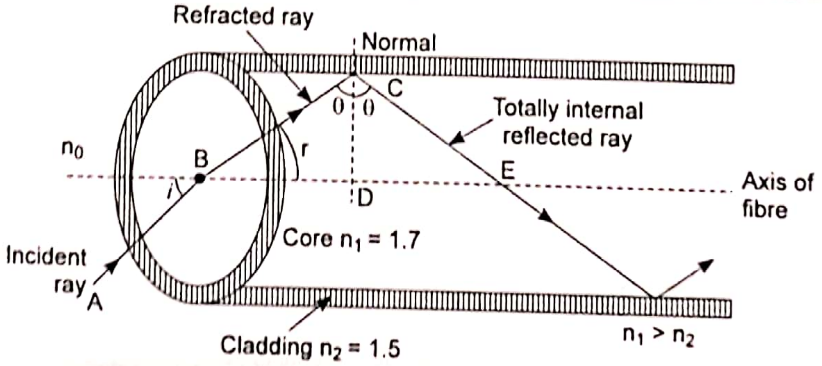


Fig. (11)

The ray refracts at an angle r and strikes the core-cladding interface at an angle θ. Let θ is greater than critical angle θ_C. As long as the angle θ is greater than θ_C, the light will stay within the fibre.

Mathematical analysis

Now we shall calculate the angle of incidence i for which $\theta \geq \theta_C$ (critical angle) so that the light rebounds within the fibre.

Applying Snell's law of refraction at the point of entry of the ray AB into the core, we have

$$n_0 \sin i = n_1 \sin r \quad ...(1)$$

From triangle BCD, it is seen that

$$r = (90 - \theta) \quad \text{or} \quad \sin r = \sin(90 - \theta)$$

$$\therefore \quad \sin r = \cos\theta \quad ...(2)$$

Substituting, the value of $\sin r$ from eq. (2) in eq. (1), we get

$$n_0 \sin i = n_1 \cos\theta$$

or
$$\sin i = \left(\frac{n_1}{n_0}\right)\cos\theta \quad ...(3)$$

If i is increased beyond a limit, θ will drop below the critical value θ_C and the ray will escape from the side walls of the fibre. The largest value of i, *i.e.*, i_{max} occurs when $\theta = \theta_C$. Applying this condition in eq. (3), we get

$$\sin(i_{max}) = \left(\frac{n_1}{n_0}\right)\cos\theta_C \quad ...(4)$$

We know that,

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

$$\therefore \quad \cos\theta_C = \sqrt{1-\sin^2\theta_C} = \sqrt{\left(1-\frac{n_2^2}{n_1^2}\right)}$$

or
$$\cos\theta_C = \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \quad ...(5)$$

From eq. (4), we have

$$\sin(i_{max}) = \frac{n_1}{n_0} \times \frac{\sqrt{(n_1^2 - n_2^2)}}{n_1} = \frac{\sqrt{(n_1^2 - n_2^2)}}{n_0} \quad ...(6)$$

Quite often the incident ray is launched from air medium, *i.e.*, $n_0 = 1$. Designating i_{max} as i_0, eq. (6) can be written as

$$\sin i_0 = \sqrt{(n_1^2 - n_2^2)} \quad ...(7)$$

Here, i_0 is called the acceptance angle of the fibre.

$$\therefore \quad i_0 = \sin^{-1}\sqrt{(n_1^2 - n_2^2)} \quad ...(8)$$

Acceptance angle is defined as the maximum angle from the fibre axis at which light may enter the fibre so that it will propagate in the core by total internal reflection.

0.4-2 ACCEPTANCE CONE

If the ray *AB* is rotated around the fibre axis keeping i_0 same, then it describes a conical surface as shown in fig. (12). Now only those rays which are funnelled into the fibre within this cone having a full angle $2\,i_0$ will only be totally internally reflected and thus confined within the fibre for propagation, *i.e.*, only the rays within the cone are accepted. Therefore, the cone is called as ***acceptance cone.***

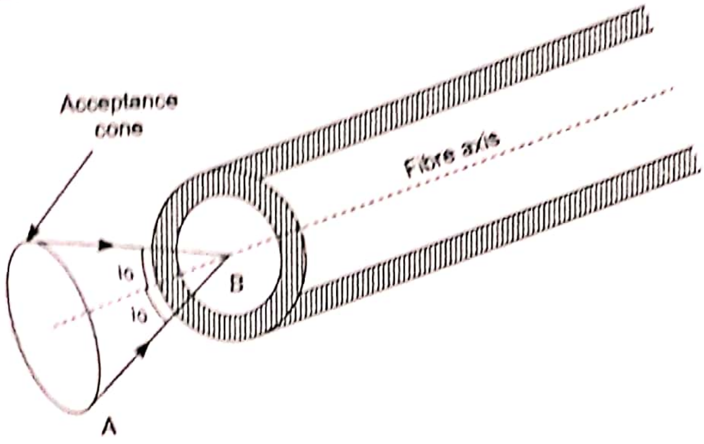


Fig. (12)

A cone within which all the rays incident will be collected and propagated through the fibre is known as acceptance cone.

The light incident at an angle beyond i_0 will be refracted through the cladding and the corresponding optical energy is lost.

0.5 NUMERICAL APERTURE

Sometimes, it is also called as ***figure of merit*** for optical fibre. ***Numerical aperture determines the light gathering ability of the fibre.*** So, it is a measure of the amount of light that can be accepted by the fibre. ***This is also defined as the sine of acceptance angle.***

$$NA = \sin i_0$$

or

$$NA = \sqrt{(n_1^2 - n_2^2)} \qquad \ldots(1)$$

Fig. (13) shows the variation of NA with acceptance angle.

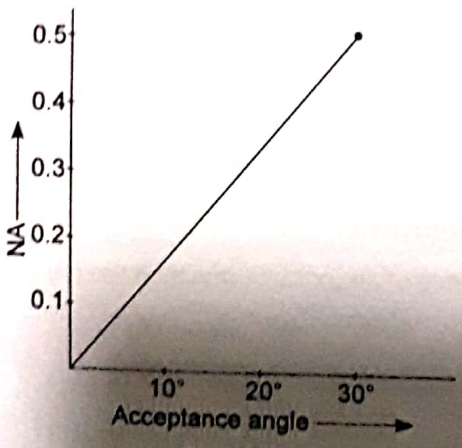


Fig. (13)

It is obvious from the figure that for the fibres used in short distance communication, the numerical apertures range from 0.4 to 0.5 whereas for long distance communications numerical aperture range from 0.1 to 0.3.

The numerical aperture may also be evaluated in terms of ***relative refractive index*** difference Δ defined as

$$\Delta = \frac{\text{Refractive difference between core and cladding}}{\text{Refractive index of core of optical fibre}}$$

or $$\Delta = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$$

$\therefore$ $$\frac{n_2}{n_1} = (1 - \Delta) \quad ...(2)$$

From eq. (1), $$\text{NA} = \sqrt{(n_1^2 - n_2^2)} = n_1 \sqrt{\left[1 - \left(\frac{n_2}{n_1}\right)^2\right]} \quad ...(3)$$

Substituting the value of (n_2/n_1) from eq. (2) in eq. (3), we get

$$\text{NA} = n_1 \sqrt{[1 - (1 - \Delta)^2]} = n_1 \sqrt{(2\,\Delta - \Delta^2)} \quad ...(4)$$

As the difference between the refractive indices of the core and cladding is very small, the term Δ^2 is very small and hence, it can be neglected. Therefore,

$$\text{NA} = n_1 \sqrt{(2\,\Delta)}$$

Fig. (14) shows the plot of NA as a function of ratio n_1/n_2. It is obvious from the figure that as the ratio n_1/n_2 increases, NA also increases.

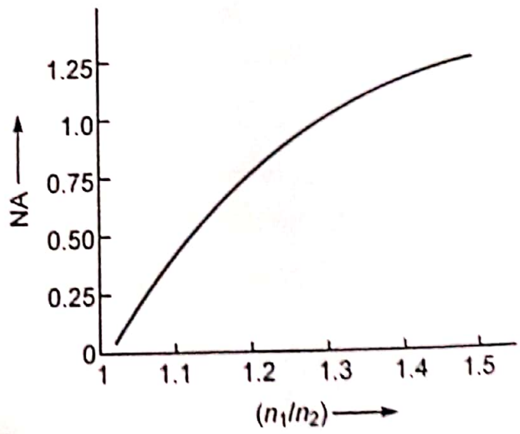


Fig. (14) Showing the plot of NA as a function of (n_1/n_2)

1. Condition for propagation

If i is the angle of incidence of an incident ray, then the ray will be able to propagate, if

$$i < i_0 \quad \text{or} \quad \sin i < \sin i_0$$

or $$\sin i < \sqrt{(n_1)^2 - (n_2)^2} \quad ...(5)$$

or $$\sin i < \text{NA}$$

This is condition for propagation of light within the fibre.

V-number (Cut-off parameter) and Number of modes of fibres.

The number of modes supported by a fibre is determined by an important parameter called cut-off parameter. This is referred to V parameter or V-number.

Mathematically, V-number is expressed as

$$V = \frac{2\pi a}{\lambda_0}\sqrt{(n_1^2 - n_2^2)} \qquad \ldots(1)$$

where a = radius of the core

λ_0 = free space wavelength

$$\therefore \quad V = \frac{2\pi a}{\lambda_0}\,\mathrm{NA} = \frac{2\pi a}{\lambda_0}\, n_1\sqrt{2\Delta} \qquad \ldots(2)$$

where NA = numerical aperture

For single mode fibre V-number is 2.405

The number of modes (N) supported by fibre is

$$N = \frac{V^2}{2} \quad \text{S.I.} \qquad N = \frac{V^2}{4} \text{ GRIN} \qquad \ldots(3)$$

(provided V-number is considerably larger than unity).

Solved Examples

EXAMPLE 1 *Calculate the angle of acceptance of a given optical fibre, if the refractive indices of the core and cladding are 1.563 and 1.498 respectively.*

Solution We know that $\sin i_0 = \sqrt{(n_1^2 - n_2^2)}$

$\therefore \quad \sin i_0 = \sqrt{[(1.563)^2 - (1.498)^2]} = 0.4461$

or $\quad i_0 = \sin^{-1}(0.4461) = \mathbf{26.49°}$

EXAMPLE 2 *In an optical fibre, the core material has refractive index 1.6 and the refractive index of clad material is 1.3. What is the value of critical angle? Also calculate the value of acceptance cone.*

Solution The critical angle θ_c is given by

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

$\therefore \quad \theta_c = \sin^{-1}(0.8125) = \mathbf{54.3°}$

Acceptance angle $\quad i_0 = \sin^{-1}[\sqrt{n_1^2 - n_2^2}] = \sin^{-1}[(1.6)^2 - (1.3)^2]^{1/2}$

or $\quad i_0 = \sin^{-1}(0.87) = \mathbf{60.5°}$

EXAMPLE 3 *A fibre cable has acceptance angle of 30° and a core index of refraction of 1.4. Calculate the refractive index of the cladding.*

Solution We know that $\sin i_0 = \sqrt{(n_1^2 - n_2^2)}$

$$\sin^2 i_0 = (n_1^2 - n_2^2) \quad \text{or} \quad n_2^2 = n_1^2 - \sin^2 i_0$$

$$n_2^2 = (1.4)^2 - \sin^2 30° = 1.96 - 0.25 = 1.71$$

or $$n_2 = \sqrt{(1.71)} = \mathbf{1.308.}$$

EXAMPLE 4 *A silica optical fibre has a core refractive index of 1.50 and a cladding refractive index 1.47. Determine*

(i) Critical angle at core-cladding interface

(ii) NA for fibre

(iii) The acceptance angle in air for the fibre.

Solution (i) The critical angle θ_c is given by

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.47}{1.50}\right) = \mathbf{78.5°}$$

(ii) $NA = \sqrt{(n_1^2 - n_2^2)} = [(1.50)^2 - (1.47)^2]^{1/2} = \mathbf{0.30}$

(iii) Acceptance angle $i_o = \sin^{-1}(\text{NA}) = \sin^{-1}(0.30) = \mathbf{17°28'}$

EXAMPLE 5 *Calculate the fractional index change for a given optical fibre of the refractive indices of the core and cladding are 1.563 and 1.498 respectively.*

Solution Fractional index change Δ is given by

$$\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.563 - 1.498}{1.563} = \frac{0.065}{1.563} = \mathbf{0.0415.}$$

EXAMPLE 6 *Determine the numerical aperture of a step index fibre when the core refractive index $n_1 = 1.5$ and the cladding refractive index $n_2 = 1.48$. Find the maximum angle for entrance of light if the fibre is placed in air.* **(UPTU 2009)**

Solution The numerical aperture NA is given by

(i) $$\text{NA} = \sqrt{(n_1)^2 - (n_2)^2}$$

$$= \sqrt{[(1.5)^2 - (1.48)^2]} = \sqrt{(2.98 \times 0.02)} = 0.24413$$

(ii) The maximum entrance angle i_0 is given by

$$i_0 = \sin^{-1}\left[\frac{\text{NA}}{n}\right]$$

$$= \sin^{-1}\left(\frac{0.24413}{1}\right) = \mathbf{14.13°}$$

EXAMPLE 7 *An optical fibre has NA of 0.20 and a cladding refractive index of 1.59. Determine the acceptance angle for the fibre in water which has refractive index of 1.33.*

Solution

$$\text{NA} = \sqrt{(n_1)^2 - (n_2)^2}\,/n_0$$

When the fibre is in air, $n_0 = 1$. Then

$$\text{NA} = \sqrt{(n_1)^2 - (n_2)^2} = 0.20$$

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

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

$\therefore$ $$\text{NA} = \sqrt{(n_1)^2 - (n_2)^2}\,/n_0$$

$$= \frac{\sqrt{[(1.6025)^2 - (1.59)^2]}}{1.33} = 0.15$$

Now, $$i_0 = \sin^{-1}(\text{NA}) = \sin^{-1}(0.15) = \mathbf{8.6°}$$

EXAMPLE 8 *An optical fibre has the following characteristics : Fibre index 1.36 and relative difference in index $\Delta = 0.025$. Find the numerical aperture and the acceptance angle.*

Solution The numerical aperture in terms of Δ is given by

$$\text{NA} = n_1\sqrt{(2\,\Delta)}$$

$\therefore$ $$\text{NA} = 1.36 \times \sqrt{(2 \times 0.025)} = 1.36 \times 0.2236 = 0.304$$

Acceptance angle, $i_0 = \sin^{-1}(\text{NA}) = \sin^{-1}(0.304) = \mathbf{17.7°}$

EXAMPLE 9 *Calculate the numerical aperture, acceptance angle and critical angle of the fibre from the following data : $n_1 = 1.50$ and $n_2 = 1.45$.*

(UPTU 2009; MTU 2012)

Solution $$\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.50 - 1.45}{1.50} = 0.033$$

Numerical aperture, $\text{NA} = n_1\sqrt{(2\,\Delta)}$

$\therefore$ $$\text{NA} = 1.50\sqrt{(2 \times 0.33)} = \mathbf{0.385}$$

Acceptance angle, $i_0 = \sin^{-1}(\text{NA}) = \sin^{-1}(0.385) = \mathbf{22.63°}$

Using Snell's law, the critical angle θ_c can be calculated as follows :

$$\sin\theta_c = \frac{n_2}{n_1} = \left(\frac{1.45}{1.50}\right)$$

$\therefore$ $$\theta_c = \sin^{-1}\left(\frac{1.45}{1.50}\right) = \sin^{-1}(0.967) = \mathbf{75.3°}$$

EXAMPLE 10 *Calculate the refractive indices of the core (n_1) and cladding (n_2) material of a fibre from the following data :*

$$\text{NA} = 0.22, \quad \Delta = \frac{n_1 - n_2}{n_1} = 0.012$$

Solution

$$\text{NA} = \sqrt{(n_1^2 - n_2^2)} = 0.22$$

$$n_1^2 - n_2^2 = (0.22)^2 = 0.0484 \qquad \text{...(1)}$$

$$\Delta = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1} = 0.012$$

or $$\frac{n_2}{n_1} = 1 - 0.012 = 0.988$$

or $$n_2 = 0.988\, n_1 \qquad \text{...(2)}$$

Substituting the value of n_2 from eq. (2), in eq. (1), we get

$$n_1^2 - (0.988\, n_1)^2 = 0.0484$$

$$n_1^2 (1 - 0.976) = 0.0484$$

$$n_1^2 = \frac{0.0484}{0.024} = 2.0167$$

$$n_1 = \mathbf{1.42}$$

From eq. (2), $$n_2 = 0.988 \times 1.42 = \mathbf{1.40}$$

EXAMPLE 11 *A silica optical fibre has numerical aperture of 0.40 and core refractive index of 1.50. If the relative refractive index difference for the fibre is 1%, determine :*

(a) the acceptance angle for the fibre if the launching takes place from air

(b) the critical angle at the core-cladding interface.

Solution (a) $i_0 = \sin^{-1}(\text{NA}) = \sin^{-1}(0.40)$ or $i_0 = \mathbf{23.6°}$

(b) $$\frac{n_2}{n_1} = 1 - \Delta \quad \text{or} \quad \frac{n_2}{n_1} = 1 - 0.01 = 0.99$$

Therefore, the critical angle θ_C is given by

$$\sin \theta_C = \frac{n_2}{n_1} = 0.99$$

$$\theta_C = \sin^{-1}(0.99) = \mathbf{81.9°}$$

EXAMPLE 12 *If the fractional difference between the core and clading refractive indices of a fibre is 0.0135 and numerical aperture NA is 0.2425, calculate the refractive indicesof the core and clading materials.*

Solution Given NA = 0.2425 and Δ = 0.0135

We know that $\Delta = \dfrac{n_1 - n_2}{n_1}$

$$n_1 = \frac{\text{NA}}{\sqrt{2\Delta}} = \frac{0.2425}{\sqrt{(2 \times 0.0135)}} = \frac{0.2425}{0.1643} \quad \text{or} \quad n_1 = \mathbf{1.476}$$

Now $$\Delta = 0.0135 = \frac{n_1 - n_2}{n_1} = \frac{1.476 - n_2}{1.476}$$

or $$1.476 - n_2 = 1.476 \times 0.0135 = 0.02$$

or $$n_2 = 1.476 - 0.02 = \mathbf{1.456}$$

EXAMPLE 13 *A step index fibre has core refractive index 1.466, clading refractive index 1.46. If the operating wavelength of the ray is 0.85 μm, calculate the cut-off parameter and the number of modes which the fibre will support. The diameter of core = 50 μm.* **(UPTU 2011)**

Solution The cut-off parameter or cut-off number or normalized frequency of cut-off

$$V = \frac{2\pi a}{\lambda_0} \sqrt{(n_1^2 - n_2^2)}$$

where a is the radius of the core and λ_0 is operating wavelength

$$\therefore \quad V = \frac{2 \times 3.14 \times 25}{0.85} \sqrt{[(1.466)^2 - (1.46)^2]}$$

($\because$ $a = 50/2 = 25$ μm and $\lambda_0 = 0.85$ μm)

or $$V = 184.70 \sqrt{[2.149 - 2.131]} = 184.70 \times 0.134 = \mathbf{24.75}$$

We know that number of modes

$$N = \frac{V^2}{2} = \frac{(24.75)^2}{2} \approx \mathbf{306}$$

EXAMPLE 14 *Calculate the maximum radius allowable for $n_1 = 1.53$, $n_2 = 1.5$ operating at wavelength 1300 nm.* **(UPTU 2015)**

Solution We know that $V = \dfrac{2\pi a}{\lambda_0} \sqrt{(n_1^2 - n_2^2)}$

For single mode fibre V-numbers is 2.405

$$\therefore \quad 2.405 = \frac{2 \times 3.14 \times a}{1300 \times 10^{-9}} \sqrt{[(1.53)^2 - (1.5)^2]}$$

or $$a = \frac{2.405 \times (1300 \times 10^{-9})}{2 \times 3.14 \times \sqrt{[(1.53)^2 - (1.5)^2]}}$$

Solving we get $\quad a = 1.65 \times 10^{-6}$ m $= \mathbf{1.65\ μm}$

EXAMPLE 15 *Compute the cut-off parameter and number of modes supported by a fibre n_1 (core) = 1.54 and n_2 (clading) = 1.5; core radius 25 μm and operating wavelength is 1300 nm.*

(X) They can withstand extreme temperature before deteriorating. Temperature approaching 800°C leave glass fibre unaffected.

(XI) Corrosion due to water or chemicals is less severe for glass than for copper.

(XII) There is no need for additional equipment to protect against grounding and voltage problems.

10.7 ATTENUATION

Let us consider that light propagates through an optical fibre. It is observed that power of light at output end is always less than the power launched at the input end. Therefore, a small percentage of light is lost due to ***fibre material, wavelength of light and length of fibre***. The loss of optical power is known as ***attenuation***.

The attenuation is defined as the reduction in amplitude (or power) and intensity of a signal as it is guided through optical fibre. A fibre with lower attenuation will allow more power to reach a receiver than with a higher attenuation.

The attenuation losses in optical fibres are generally expressed in terms of decibel (dB). The decibel is expressed as the base 10 logarithm of the ratio of the power at output to the power at input. If P_i is input (transmitted) power and P_o output (received) optical power, then the number of decibels is given by

$$\text{dB} = 10 \log_{10}\left(\frac{P_o}{P_i}\right)$$

In optical fibre communication, the attenuation is usually expressed in decibels per unit length *i.e.*, dB/km. If α is signal attenuation per unit length in decibel and L is the length of optical fibre, then dB $= \alpha L$. Therefore,

or
$$\alpha L = 10 \log_{10}\left(\frac{P_o}{P_i}\right) \frac{\text{dB}}{\text{km}}$$

or
$$\alpha = \frac{10}{L} \log_{10}\left(\frac{P_o}{P_i}\right) \frac{\text{dB}}{\text{km}}$$

To indicate the loss, we put a negative sign in the above expression. Therefore,

$$\alpha = -\frac{10}{L} \log_{10}\left(\frac{P_o}{P_i}\right) \frac{\text{dB}}{\text{km}}$$

Solved Examples

EXAMPLE 1 *The optical power, after propagating through a fibre that is 500 m long is reduced to 25% of its original value. Calculate the fibre loss in dB/km.*

(UPTU 2010)

Solution The loss per km is given by

$$\text{dB} = -\frac{10}{L} \log_{10}\left(\frac{P_o}{P_i}\right)$$

$$\text{Loss} = -\frac{10}{(1/2)}\log_{10}\left(\frac{25}{100}\right) \qquad [L = 500 \text{ m} = (1/2) \text{ km}]$$

$$= -20(\log 25 - \log 100) = -20(1.3979 - 2)$$

$$= \mathbf{12.042} \text{ dB/km}$$

EXAMPLE 2 *A communication system uses* 10 km *fibre having a loss of* 2.3 dB/km. *Compute the output power if the input power is* 400 μw. **(MTU 2012)**

Solution The loss per km in dB is given by

$$\text{dB} = -\frac{10}{L}\log_{10}\left(\frac{P_o}{P_i}\right)$$

Loss per km = 2.3 dB/km and total length si 10 km

$$2.3 = -\frac{10}{10}\log_{10}\left(\frac{P_o}{P_i}\right)$$

or
$$\log_{10}\left(\frac{P_o}{P_i}\right) = -2.3$$

∴
$$\frac{P_o}{P_i} = \text{Antilog of } (-2.3) = 0.00199$$

or
$$P_o = 0.00199 \times P_i = 0.00199 \times 400 = \mathbf{0.795}\ \mu\text{w}$$

10.8 SIGNAL LOSSES IN OPTICAL FIBRES

The signal losses in optical fibres are basically of three types :

1. ***Absorption losses***
2. ***Scattering losses***
3. ***Geometry losses or Bending Losses***

1. Absorption losses

Absorption is the most prominent factor causing the attenuation in optical fibre. The absorption of light is caused by the following three different mechanisms :

(i) ***Intrinsic absorption***

(ii) ***Extrinsic absorption***

(iii) ***Absorption by atomic defect.***

(i) *Intrinsic absorption is the absorption of light by the material of the core itself.* The intrinsic absorption is a natural property of glass itself. There is a tendency of the fibre material to absorb a small amount of light energy.

(ii) *The presence of impurities in the fibre material is a major source of loss in practical fibres.* This is known as ***extrinsic absorption.*** The impurities of metal ions and hydroxyl ions (OH^- ions) absorb light at a specific wavelength when light-signal passes through the fibre. So, when light signal propagates through the fibre, the photons interact with the present impurities. The electrons of impurity absorb these photons. As a result, there is a loss of light.

(iii) ***Atomic defects in the fibre material are also responsible for the loss of light energy.*** The atomic defects are created in the manufacture of the fibre. These defects are also created when the fibre is exposed to X-rays, γ-rays, neutrons and electron beams.

2. Scattering Losses

Scattering is the loss of optical energy due to imperfections in the fibre. During the formation of fibre, submicroscopic variation in the density and doping impurities are frozen into the glass. These becomes a source of reflection, refraction and scattering the light passing through the glass. So, the light is scattered in all directions and causes the loss of optical power in the forward direction. The loss is known as ***Rayleigh scattering loss.***

3. Bending Losses or *radiative losses*

The bending losses occur due to bends present in the fibre structure. These are of two types :

(i) ***Microbending losses.*** Microbending losses occur due to manufacturing. In the manufacturing process, the core surface has small variations in shape (microbends) which are not visible with the nacked eye. These microbends act as a scattering faces within the fibre. They cause some of the light to refract or scatter into clading rather than to reflect or scatter into the core. This is shown in fig. (18).

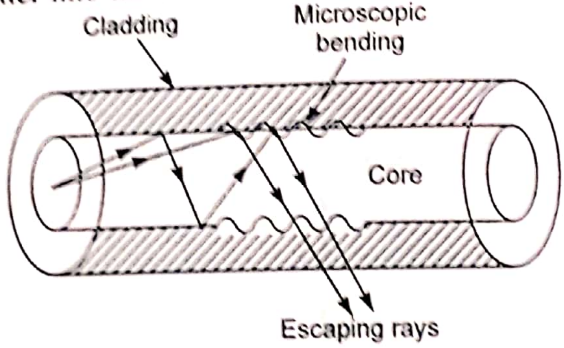


Fig. (18) Microscopic bending

(ii) ***Macrobending losses.*** Excessive bending of the fibre results the loss light energy known as macrobending loss. These losses occur when the radius of curvature of bend is greater than fibre diameter. This situation arises when a fibre cable turns in a corner.

At the corner, the light will not satisfy the condition of total internal reflection. Therefore, the light escapes from the fibre as shown in fig. (19).

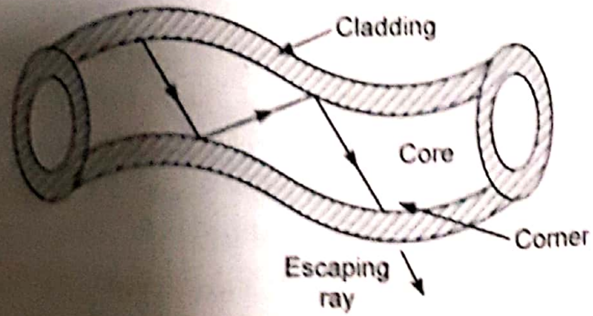
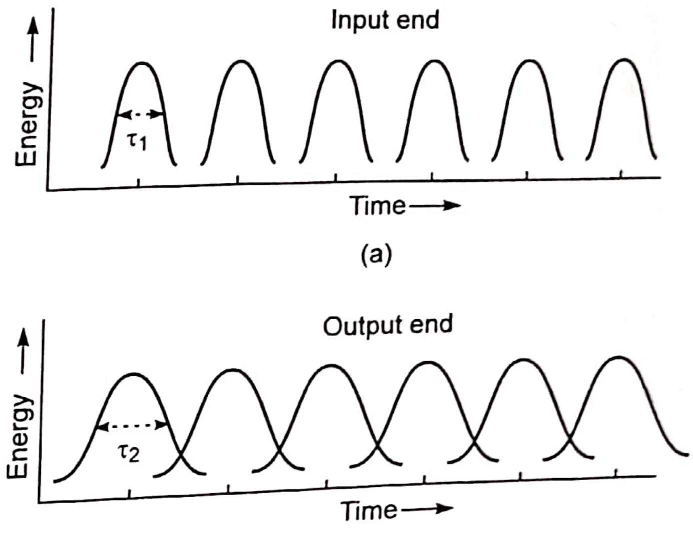


Fig. (19) Macrobending losses

10.9 DISPERSION

The dispersion is defined as the distortion or spreading of light pulse as it travels from one end of the fibre to the other end of fibre.

A pulse of a light with a given width and shape when transmitted at one end of the fibre should reach the other end of fibre with shape and width unchanged. The light pulses, entering at different angles at input of fibre take different times to reach at the output end. Consequently, the pulses are broaden at the output end. The pulses at input and output ends are shown in fig. (20a) and fig. (20b), respectively.



(b)

Fig. (20)

Therefore, ***when a optical signal or pulse is sent into the fibre, the pulse spreads or broaden as it propagates through the fibre. This phenomenon is known as dispersion.*** This is shown in fig. (21).

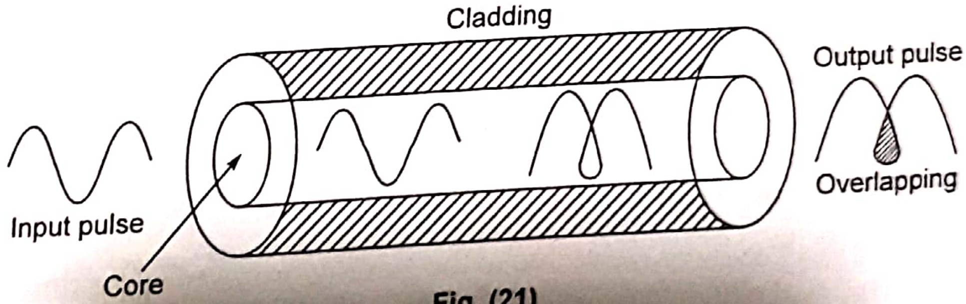
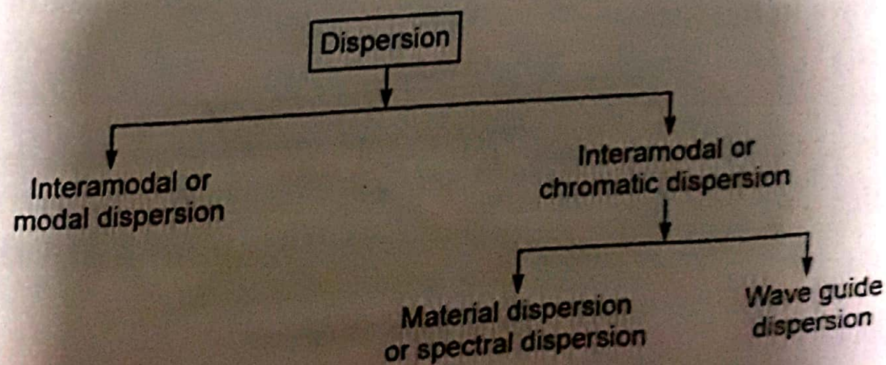


Fig. (21)



1. Intermodal dispersion or modal dispersion

Modal dispersion does not exist in a single mode fibres but it is a dominant source in multimode fibres. When more than one mode propagate through a fibre, then intermodal dispersion occur. ***Since many modes are propagating, they will have different wavelengths and will take different time to propagate through the fibre.*** This leads to inter-modal dispersion.

The internal dispersion is shown in fig. (22).

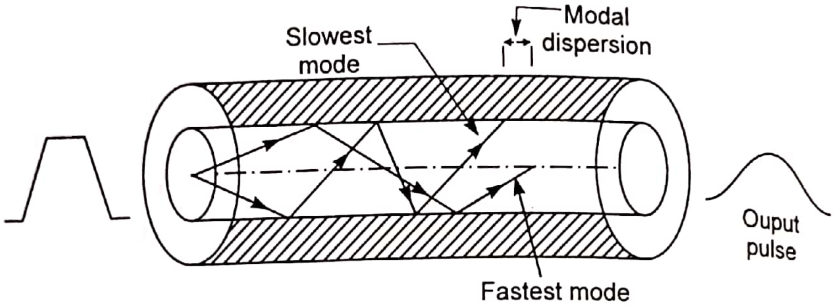


Fig. (22) Internal dispersion.

It is clear from the fig. (22) that the modes in a given optical pulse arrive at the fibre end at slightly different times. This causes the pulse to spread in time as it travels along the fibre. This is known as ***intermodel dispersion.***

2. Material dispersion or spectral dispersion

We have studied that the refractive index of fibre core depends on wavelength or frequency of light. When different components of input pulse travel with different wavelengths they travel with different velocities inside the fibre, the pulse broadens. This is known as ***material dispersion.***

The material dispersion is shown in fig. (23).

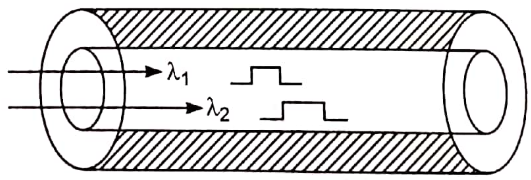


Fig. (23) Material dispersion.

3. Wave guide dispersion

The wave guide dispersion arises due to the guiding property of the fibre and due to their different angles at which they incident at the core-cladding interface of the fibre.

This is shown in fig. (24).

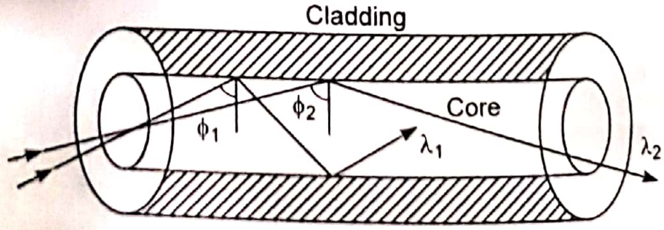


Fig. (24) Wave guide dispersion.