5

FIBRE OPTICS

INTRODUCTION TO FIBRE OPTICS

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

With the development of lasers, reliable and powerful coherent radiation became available. So, it was natural to use this light for communication purposes. There are two reasons for this, *i.e.,* (i) higher frequency and (ii) more information carrying capacity compared to conventional radio and micro-wave carriers. We also know that light waves cannot travel far in open atmosphere as the energy gets very rapidly dissipated. Hence, some kind of guiding channel is needed just like for guiding electric current a conducting path, like a metal wire, is needed. Optical fibre provides the necessary wave guide for light.

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

5.1 PRINCIPLE OF OPTICAL FIBRE (Propagation Mechanism)

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. This is shown in Fig. (1).

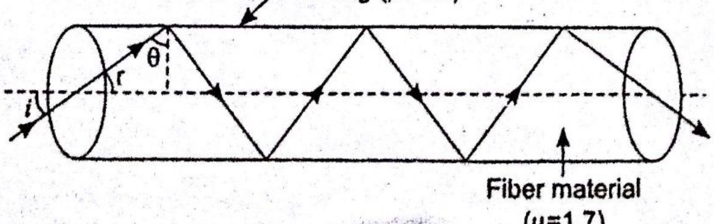

Fig. (1)

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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* $\theta_C = \sin^{-1}(1/n_1)$ *then the ray is totally internally reflected.*

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

The bundle of optical fibres are found of immense use. It can be used for *optical signal transmission.* They can also be used for *transmission and receiving electrical signals* (which are converted to light by suitable devices).

In case of optical fibres, it is essential that there must be very little absorption of light as it travels through a long distance inside optical fibre. This is achieved by purification and special preparation of the material used.

5.2 STRUCTURE OF OPTICAL FIBRES

The fibres which are used for optical communication are wave guides made of transparent dielectrics. 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 *core.* The core carriers light. The core is surrounded by another cylindrical shell of lower refractive index called the *cladding.* The cladding helps to keep the light within the core through the phenomenon of total internal reflection. The core and cladding are shown in Fig. (2).

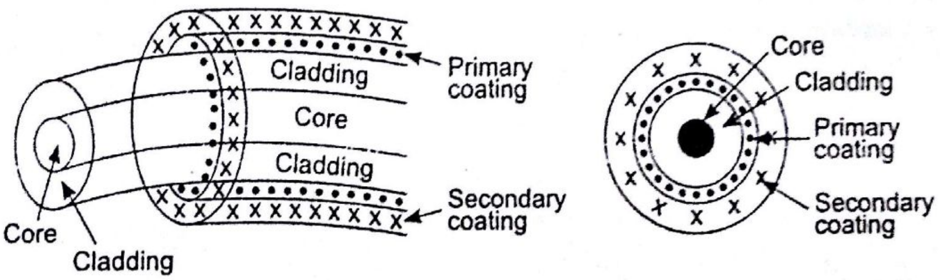

Fig. (2)

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.*

5.3 TYPES OF OPTICAL FIBRES

The optical fibres are classified into two categories based on:

1. The number of modes, and
2. The refractive index.

1. 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: (i) Single mode fibre (SMF), and (ii) Multi-mode fibre (MMF).

(i) Single mode fibre (SMF)

The single mode fibre is shown in Fig. (3). 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. In single mode fibre only one mode can propagate through the fibre. There is no dispersion, *i.e.*, no degradation of signal during travelling through the fibre. We know that information transmission capacity in optical fibre is inversely proportional to dispersion and hence the single mode fibres are more suitable for long distance communications such as telephone lines. The light is passed into single-mode fibre through laser diodes. The fabrication of such fibres is very difficult and so they are costly.

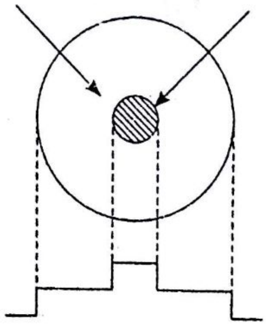

Fig. (3)

(ii) Multi-mode fibre (MMF)

The multi-mode fibre is shown in Fig. (4). 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. There is signal degradation (more dispersion) due to multimode dispersion. They are not suitable for long distance communication due to large dispersion and attenuation of the signal. As the diameter of the core is high, the propagation of light in the fibre is easy. The light ray is entered into the fibre using a LED source. The fabrication of multi-mode fibre is less difficult and so the fibre is not costly.

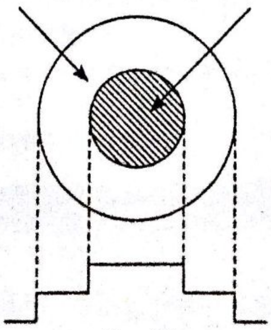

Fig. (4)

Classification of Fibre Based on Refractive Index

There are two types of optical fibres, viz.

(i) Step-index optical fibre, and (ii) Graded-index optical fibre.

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(i) Step-index optical fibre

In step-index optical fibre, the core has a uniform refractive index (say n_1), and the cladding has also a uniform refractive index (say n_2), of course, $n_1 > n_2$. Let a and b the radii of core and cladding respectively. The refractive index profile and radius of core and cladding of a step-index fibre are shown in Fig. (5).

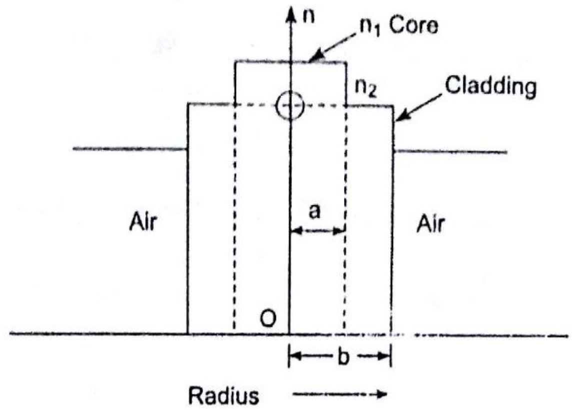

Fig. (5)

These fibres have greatest range of core sizes (50–200 μm). As the diameter of the core is high, therefore, more number of modes of propagation of light can be possible. So, the fibre is also called as multi-mode step index fibre. The diameter of cladding is 110 μm. The diameter of the core (in case of single mode fibre) is approximately 10 μm.

The light rays propagate through it are in the form of meridional rays which cross the fibre axis during every reflection at the core-cladding boundary. Figure (6) shows the paths of rays in step-index fibre. We have shown two tays entering at different angles of incidence with the axis. The two rays travel different path lengths and emerge out at different times. It is obvious from the figure that an input pulse gets widened as it travels along the fibre.

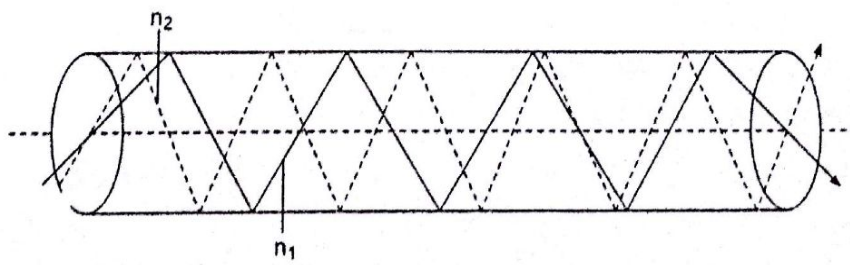

Fig. (6)

Signal distortion is more in multi-mode step index fibre. This is due to the fact that the rays reflected at high angles travel a greater distance than the rays reflected at low angles to reach the exit end of the fibre. The distortion does not take place in single mode step index fibre.

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.

They have the following disadvantages:
(i) lower bandwidth,
(ii) high dispersion, and
(iii) smearing of signal pulse.

(ii) 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 refractive index profile of graded-index fibre is shown in Fig. (7).

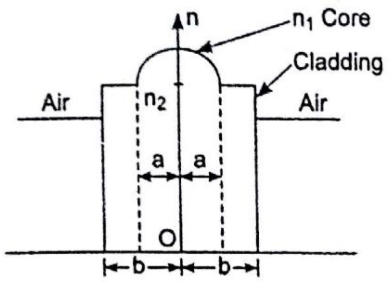

Fig.(7)

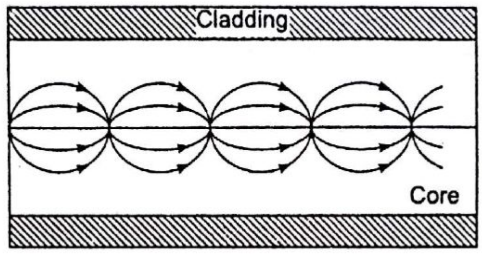

Fig. (8)

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 paths of the rays in multimode graded index fibre are shown in Fig. (8).

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.

Here, the signal distortion is very low because of self focussing effect. In this case, the light rays travel at different speeds in different paths of the fibre because the refractive index varies throughout the fibre. As a result, light rays near the edge travel faster than the light rays near the centre of the core.

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.

Following are the disadvantages of graded-index multimode-fibre:
(i) expensive and
(ii) very difficult to manufacture.

5.4 ACCEPTANCE ANGLE AND NUMERICAL APERTURE

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. (9). 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.

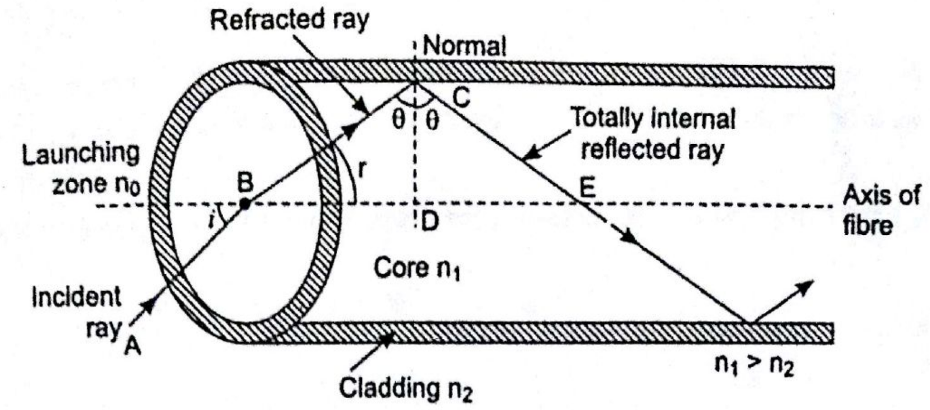

Fig. (9)

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

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

From triangle BCD, it is seen that

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

$$\therefore \qquad \sin r = \cos \theta \qquad \text{...(2)}$$

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

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

or

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

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

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

We know that,

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

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

From eq. (4), we have

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

Quite often the incident ray is launched from air medium, *i.e.*, $n_0 = 1$. Designating i_{max} as i_0, eq. (5) can be written as

$$\boxed{\sin i_0 = \sqrt{(n_1^2 - n_2^2)}} \qquad \text{...(6)}$$

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

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

$$\boxed{i_0 = \sin^{-1}\sqrt{(n_1^2 - n_2^2)}} \quad \ldots(7)$$

So, the acceptance angle is defined as the maximum angle that a light ray can have relative to the axis of the fibre so that it may propagate down the fibre. It may also be 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.

If the ray AB is rotated around the fibre axis keeping i_0 same, then it describes a conical surface as shown in Fig. (10). 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*. The light incident at an angle beyond i_0 will be refracted through the cladding and the corresponding optical energy is lost.

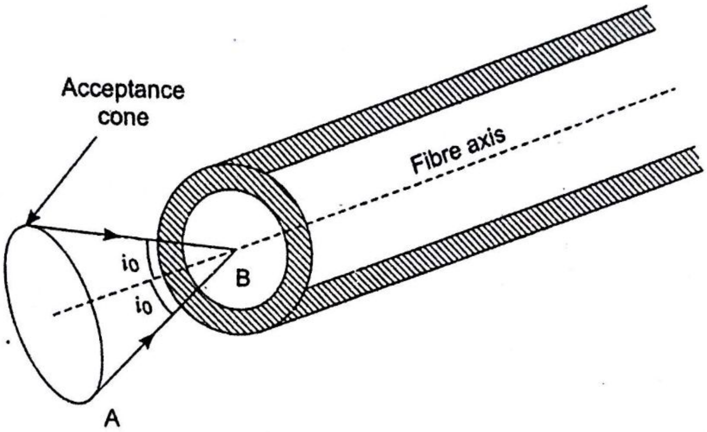

Fig. (10)

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.*

$$\text{NA} = \sin i_0$$

or

$$\boxed{\text{NA} = \sqrt{(n_1^2 - n_2^2)}} \quad \ldots(8)$$

Figure (11) shows the variation of NA with acceptance angle.

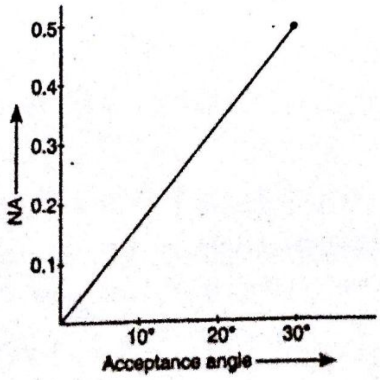

Fig. (11)

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

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

$$\therefore \quad \frac{n_2}{n_1} = (1 - \Delta) \qquad \ldots(9)$$

$$\text{From eq. (8), NA} = \sqrt{(n_1^{\,2} - n_2^{\,2})} = n_1 \sqrt{\left[1 - \left(\frac{n_2}{n_1}\right)^2\right]} \qquad \ldots(10)$$

Substituting the value of (n_2 / n_1) from eq. (9) in eq. (10), we get

$$\text{NA} = n_1 \sqrt{[1 - (1 - \Delta)^2]} = n_1 \sqrt{(2\Delta - \Delta^2)} \qquad \ldots(11)$$

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,

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

Figure (12) 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.

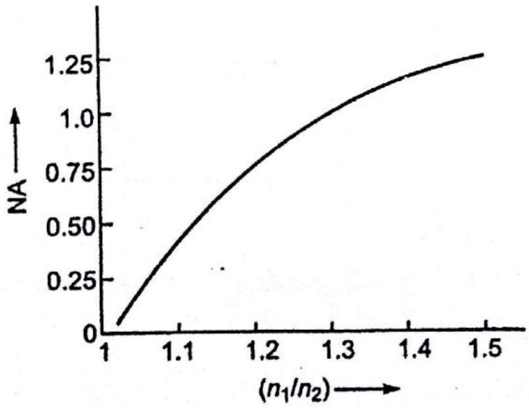

Fig. (12) Showing the plot of NA as a function of (n_1/n_2)

Condition for propagation

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

$$i < i_0$$

or $$\sin i < \sin i_0$$

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

or $$\sin i < \text{NA} \qquad \ldots(9)$$

This is condition for propagation of light within the fibre.

...OLVED EXAMPLES

...AMPLE 1 *Determine the numerical aperture of a step index fibre when the core refractive ...ex $n_1 = 1.5$ and the cladding refractive index $n_2 = 1.48$. Find the maximum angle for ...ance of light if the fibre is placed in air.*

...tion: The numerical aperture NA is given by

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

$$= \sqrt{[(1.5)^2 - (1.48)^2]}$$

$$= \sqrt{(2.98 \times 0.02)}$$

$$= 0.24413$$

...i) The maximum entrance angle i_0 is given by

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

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

...XAMPLE 2 *An optical fibre has* NA *of* 0.20 *and a cladding refractive index of* 1.59. *...etermine the acceptance angle for the fibre in water which has refractive index of* 1.33.

...ution

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

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

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

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

$$= \sqrt{[(0.20)^2 + (1.59)^2]}$$

$$= 1.6025$$

...hen the fibre is in water, $n_0 = 1.33$

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

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

$$= 0.15$$

$$i_0 = \sin^{-1}(\text{NA})$$

$$= \sin^{-1}(0.15) = \mathbf{8.6°}$$

...XAMPLE 3 *An optical fibre has the following characteristics : Fibre index* 1.36 *and relative ...ifference in index* $\Delta = 0.025$. *Find the numerical aperture and the acceptance angle.*

...ution The numerical aperture in terms of Δ is given by

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

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EXAMPLE 2 *A step index fibre has refractive index 1.466, cladding refractive index 1. Compute the maximum radius allowed for a fibre, if it supported only one mode at a waveleng* 1300 nm.

Solution A fibre will support only one mode if its cut-off parameter V is less than 2.405, *i.e* $V < 2.405$

$$\therefore \quad \frac{2\pi r}{\lambda}\sqrt{(n_1^2 - n_2^2)} < 2.405$$

or
$$r < \frac{2.405\,\lambda}{2\pi\sqrt{(n_1^2 - n_2^2)}}$$

$$< \frac{2.405 \times (1300 \times 10^{-3})}{2 \times 3.14\sqrt{[(1.466)^2 - (1.46)^2]}}$$

Here, $\lambda = 1300\text{ nm} = 1300 \times 10^{-3}\ \mu\text{m}$

$$< \frac{3.1265}{6.28\sqrt{(2.149 - 2.131)}} < \frac{3.1265}{6.28 \times 0.1341}$$

$$< 3.71\,\mu\text{m}$$

The maximum radius for the fibre = **3.71** μm

EXAMPLE 3 *A multimode step index fibre having core refractive index of 1.5 and a relative refractive index difference of 1%. If the number of modes propagating at a wavelength of 1.3 μm is 1100, find the diameter of the fibre core.*

Solution V-number is given by

$$V = \frac{2\pi r}{\lambda} n_1 \sqrt{(2\Delta)}$$

$$\sqrt{2N_m} = \frac{2\pi r}{\lambda} n_1 \sqrt{(2\Delta)} \qquad (\because N_m = V^2/2)$$

or
$$d = 2r = \frac{\lambda\sqrt{2N_m}}{\pi n_1\sqrt{2\Delta}} = \frac{\lambda}{\pi n_1}\sqrt{\left(\frac{N_m}{\Delta}\right)}$$

$$= \frac{1.3 \times 10^{-6}}{\pi \times 1.5}\sqrt{\left(\frac{1100}{0.01}\right)} = 91.5 \times 10^{-6}\text{ m}$$

Hence, the diameter of the fibre core is **91.5** μm.

EXAMPLE 4 *A multimode graded index fibre has a core with a parabolic refractive index profile which has a diameter of 60 μm and numerical aperture of 0.25. If the fibre is operating at a wavelength of 1.1 μm, then determine the total number of guided modes that the fibre will support.*

Solution We know that

$$V = \frac{2\pi r}{\lambda}(\text{NA})$$

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$$V = \frac{2 \times 3.14 \times \left(\frac{60}{2} \times 10^{-6}\right)}{1.1 \times 10^{-6}} = 42.84$$

The number of guided modes in multimode graded index fibre is

$$N_m = \frac{V^2}{4} = \frac{(42.84)^2}{4} = 459$$

5.6 FIBRE MATERIALS

In selecting a material for optical fibre, the following requirements must be satisfied:

1. It must be possible to make a long, thin and flexible fibres from the material.
2. For the fibre to guide light efficiently, its material must be transparent at a particular optical wavelength.
3. Materials having slightly different refractive indices for the core and cladding must be available.

Glasses and plastics satisfy the above requirements. Therefore, the following combinations of materials are used to construct optical fibres:

(i) Glass core and glass cladding,
(ii) Glass core and plastic cladding,
(iii) Plastic core and plastic cladding.

The majority of fibres are made of glass consisting either of silica or a silicate. To produce two similar materials having slightly different indices of refraction for the core and cladding, either fluorine or various oxides such as B_2O_3, GeO_2 or P_2O_5 are added to silica. It is important to mention here that addition of GeO_2 or P_2O_5 increases the refractive index whereas the doping of silica with fluorine or B_2O_3 decrease the refractive index.

The examples of glass fibres combinations are:

	Core	Cladding
1.	$GeO_2 - SiO_2$	SiO_2
2.	$P_2O_5 - SiO_2$	SiO_2
3.	SiO_2	$B_2O_3 - SiO_2$
4.	$GeO_2 - B_2O_3 - SiO_2$	$B_2O_3 - SiO_2$

Here, $GeO_2 - SiO_2$ denotes a GeO_2 depoed silica glass.

Plastic optical fibre (POF) is a low cost and easy to use fibre for short distance applications like local area network. The fibres have a diameter of around one millimetre while the glass fibres have diameter about (50 μm – 62 μm). Thus, the diameter of plastic fibre is far larger than those of glass fibre. Therefore, it is easier to connect critical alignments with plastic fibres. The base material in POF are polymethyl-methacrylate (PMMA), teflon, polysterene, silicon resins and fluoropolymers. These makes POF durable and flexible than glass fibre. The drawback is that they limits its use to about 100 metre. The reason is substantially higher attenuation.

5.7 FIBRE OPTICS COMMUNICATION SYSTEM

The most important application of optical fibres occurs in the field of communication. A basic optical fibre communication system consists of a *transmitter* which transforms an electric signal (information signal) to be transmitted into an optical system, a *receiver* which converts the optical signal back to the original electric form and an *information channel* (Fibre transmission line) which conducts the optical signal from transmitter to receiver. These parts are shown in Fig. (14).

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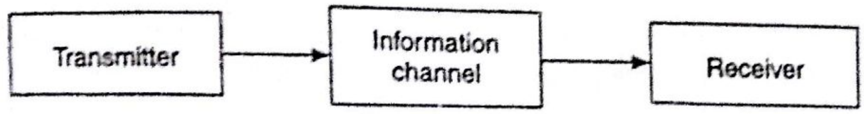


Fig. (14)

A more general block diagram is shown in Fig. (15).

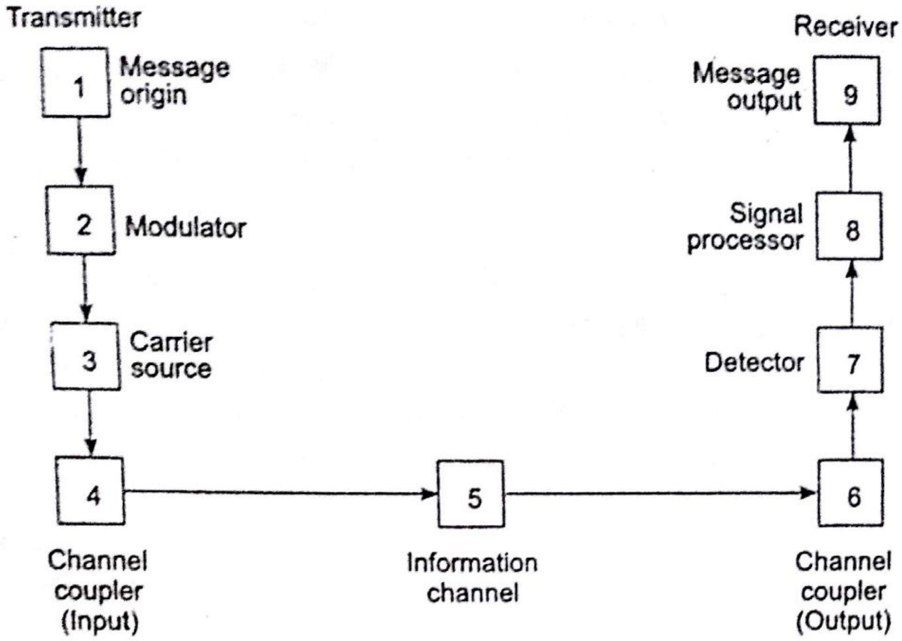


Fig. (15)

The functions of different parts are discussed below:

(1) Message Origin: It converts a nonelectrical message into an electrical signal. For example, microphone is used for converting sound waves into current and Video (TV) camera for converting images into currents.

(2) Modulator: It performs two main functions. Firstly, it converts the electrical message into proper format and secondly it impresses this signal onto the wave generated by the carrier source.

There are two types of modulation format *analog* and *digital*. An analog signal is continuous and reproduces the form of original message. For example, a microphone when picks up a sound wave, it produces the same shape as the wave itself as shown in Fig. 16 (a). Thus, the modulator need not change the format of the signal. On the other hand, digital modulation involves transmitting information in discrete form. The signal is either ON or OFF as shown in Fig. 16 (b). Here, ON state represents a digital 1 and OFF state represents a digital 0. These states are the *binary digits* of the digital system. The data rate is the number of bits per second transmitted.

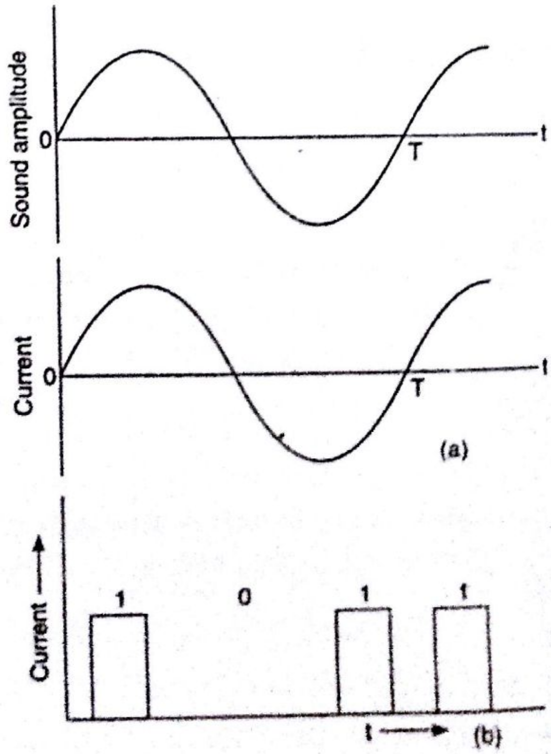


Fig. (16)

(3) **Carrier source:** The function of carrier source is to generate the wave on which the information is transmitted. The wave is known as carrier wave. We know that in radio-frequency communication, the carrier wave is produced by electronic oscillator. In fibre optic system, a laser diode (LD) or a light-emitting diode (LED) is used. Here, these are called as optical oscillators. These devices produce stable, single frequency waves with sufficient power for long distance propagation.

Here, it should be emphasized that the information being transmitted its contained in the variation of optic power. This is called as *intensity modulation* (IM).

(4) **Channel Coupler (Input):** The function of channel power is to feed power into the information channel. For example, the channel coupler in radio or television broadcasting system is an antenna. The antenna transfers the signals from transmitter onto information channel (atmosphere). In fibre system, the coupler transfers the modulated light beam from the source to the optic fibre.

(5) **Information channel:** The information channel provides a path between transmitter and receiver. In fibre optic communication, a glass (or plastic) fibre is the channel. It should be remembered that the information channels are of two types : unguided and guided channels. The atmosphere is an example of unguided channel. Guided channels include a variety of conducting transmission structures as two-wire line, coaxial cable and rectangular wave guide.

(6) **Channel Coupler (Output):** In radio communications system, an antenna is a channel coupler which collects the signal from information channel and routes it to the receiver. In fibre system, the output coupler directs the light emerging from the fibre onto the light detector. For this purpose, a simple butt connection is used.

(7) **Detector :** The function of detector is to separate the information from the carrier wave. In electronic system, the process is known as *demodulation*. In fibre system, the optic wave is converted into an electronic current by photodetector. The current developed by the photo-detector is proportional to the power in the incident optic wave. As the information is contained in the optical power variation, the detector output current contains this information.

(8) **Signal Processor:** Signal processing includes amplification and filtering of undesired frequencies in analog transmission. In digital system, the processor may include decision circuit in addition to amplifiers and filters.

(9) **Message output:** Here, the message is presented to a person. The person may either hear or view the information. For hearing, the electrical signal is transformed into sound waves and for visual image, cathode ray tube is used. So, suitable transducers are used for specfic purpose.

5.8 ADVANTAGES OF COMMUNICATION WITH OPTICAL FIBRE

(i) The optical fibre communication has far more information carrying capacity.

(ii) Smaller size and weight of the systems make fibre optics more suitable in space and aeronautical applications.

(iii) Since, fibre is made up of glass hence the raw material of the glass (silica) is available in plenty on the earth.

(iv) It has lower cost of cables per unit length compared to that of metal counter part.

interference and coupling with other communication channels.

(vii) Fibres will not pick up or propagate electromagnetic pulses caused by nuclear explosions.

(viii) When high voltage lines are present, a wire communication link could short circuit the lines by falling across them, causing considerable damage. This problem disappears with fibres.

(ix) As the fibres do not radiate energy within them and hence it is difficult for an intruder to detect the signal being transmitted. So, they offer high degree of security and privacy.

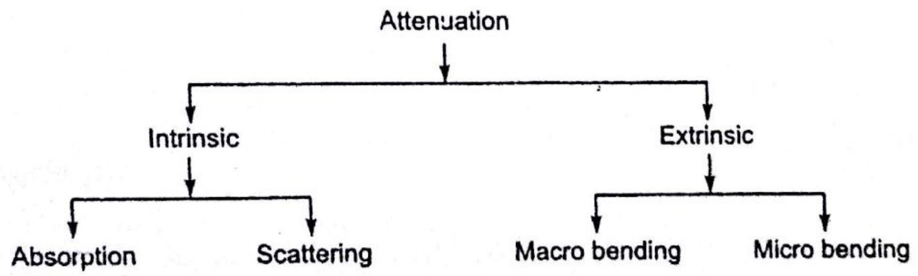
(x) They can withstand extreme temperature before deteriorating. Temperature approaching 800°C leave glass fibre unaffected.

(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.

5.9 ATTENUATION

Attenuation is the loss of the input optical power applied to the optical fibre. 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. Following are the various factors responsible for attenuation :



We shall discuss these losses in the next article.

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

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

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

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

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

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.

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.

Solution The loss per km is dB is given by

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

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

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

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

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

5.10 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 prominant factor causing the attenuation in optical fibre. The absorption of light may be ***intrinsic*** (caused by interaction of light with one or more major components of glass) or ***extrinsic*** (caused by impurities within the glass).

Following are the three main sources of absorption of light:

(i) ***The absorption of light by the material of the core itself.*** The intrinsic absorption is a natural property of glass itself. When the frequency of the propagating light is in resonance with the natural frequency of the material of core, the light is absorbed by the material. This absorbed light appears in the form of heat. A pure silicate glass has a very small intrinsic absorption due to its basic structure in near infrared region. However, it has major absorption in ultraviolet region (ultraviolet-absorption) and infrared region (infrared absorption).

(ii) ***The presence of impurities in the fibre material is a major source of loss in practical fibres.*** The impurities of metal ions and hydroxyl ions (OH^- ions) absorb light at a specific wavelength when light-signal passes through the fibre. Actually, transition metals used in fabricating glasses are usually Chromium, Nickel, Copper, Manganese, etc. These metals in the form of their oxides are sensitive towards electromagnetic spectrum. They cause heavy losses by changing their oxidation states after absorbing energy in the form of photons.

(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, Y-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.* According to Rayleigh scattering, the loss is found to be inversely proportional to the fourth power of the wavelength of light used.

3. Bending Losses

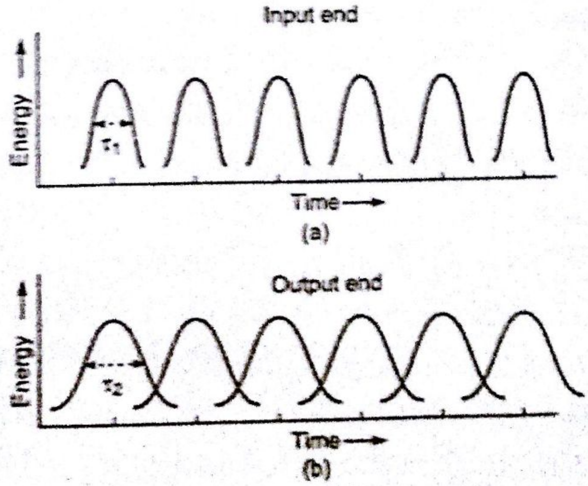
The bending losses occur due to imperfections and deformations present in the fibre structure. These are of two types.

(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 cladding rather than to reflect or scatter into the core.

(ii) ***Macrobending losses.*** Excessive bending of the fibre results the loss light energy known as macrobending loss. The marcobending losses depend on the core radius and the bend radius.

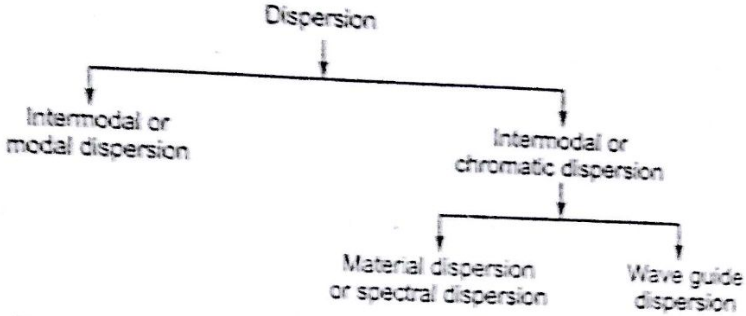
5.11 DISPERSION

The dispersion is defined as the distortion or spreading of light pluse 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. In a digital communication system, the information to be transmitted through fibre is first coded in the form of pulses. After this, these pulses are transmitted through the optical fibre. Finally, these pulses are received at the receiver end and decoded. 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. 17 (a) and Fig. 17 (b), respectively. If the broading is large, it



(a)
(b)
Fig. (17)

becomes very difficult to decode the information. The deformation in the pulse is called as *pulse dispersion*. Therefore, smaller is the pulse dispersion, greater is the information carrying capacity of the fibre. The pulse distortion is of the following types:



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. The mechanism of intermodal dispersion is that light inside the fibre propagates in different modes. The higher order modes travel a longer distance and arrive at the receiver end later than the lower order modes. In this way one modes travel more slowly than other. This shows that different modes have different group velocities.

2. Material dispersion or spectral dispersion

This is a wavelength based effect. 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 velocities inside the fibre, the pulse broadens. This is known as material dispersion.

3. Wave guide dispersion

Due to wave guide structure, the light rays in the fibre follow different paths. So, they take different times during travel of these paths. This dispersion is called as waveguide dispersion.

5.12 CALCULATION OF DISPERSION

1. Step Index Fibres

Consider a ray of light OA be incident at an angle θ_i on the entrance aperture of the fibre as shown in Fig. (18).

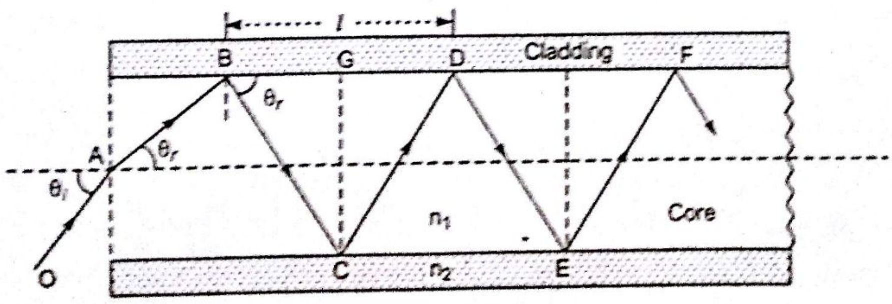


Fig. (18)

The ray is refracted into the core along AB and makes an angle θ_r with the axis of the core. Now, the ray strikes at the upper-core cladding at B. After this the ray is totally internally reflected back inside the core. Further it strikes at point C of lower cladding and after reflection it again strikes the upper interface at D. Let t be the time taken by the light ray to cover the distance B to C and then from C to D with velocity v.

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Then,
$$t = \frac{BC + CD}{v} \quad \ldots(1)$$

If n_1 be the refractive index of core and c is the speed of light in vacuum, then
$$v = c/n_1 \quad \ldots(2)$$

From figure, $BC = \frac{BG}{\cos\theta_r}$ and $CD = \frac{GD}{\cos\theta_r}$

$$\therefore \quad BC + CD = \frac{BG + GD}{\cos\theta_r} = \frac{l}{\cos\theta_r} \quad \ldots(3)$$

Substituting the values from eqs. (2) and (3) in eq. (1), we get
$$t = \frac{l}{\cos\theta_r} \times \frac{n_1}{c} = \frac{n_1\, l}{c\cos\theta_r} \quad \ldots(4)$$

As the ray in the fibre propagates by a series of total internal reflections at the interface, the time taken by the ray in traversing an axial length l of the fibre will be
$$\tau = \frac{n_1\, l}{c\cos\theta_r} \quad \ldots(5)$$

Now, we consider that all the light rays lying between angle 0 and critical angle θ_C are present. The time taken by rays making zero angle with fibre axis will be minimum. This is given by putting $\theta_r = 0$ in eq. (5), *i.e.*,
$$\tau_{\min} = \frac{n_1\, l}{c} \quad \ldots(6)$$

The maximum time is given by
$$\tau_{\max} = \frac{n_1\, l}{c\cos\theta_C} \qquad \text{(where } \cos\theta_C = n_2/n_1\text{)}$$

$\cos\theta_{r_{max}} = \cos(90° - \theta_c) = \sin\theta_c$

or
$$\tau_{\max} = \frac{(n_1)^2\, l}{c\,(n_2)} \quad \ldots(7)$$

The time interval $\Delta\tau$ at the output is given by
$$\Delta\tau = \tau_{\max} - \tau_{\min} = \frac{(n_1)^2 l}{c\, n_2} - \frac{n_1\, l}{c}$$

$\tau_{max} = \frac{n_1 l}{c \sin\theta_c}$

or
$$\Delta\tau = \frac{n_1\, l}{c}\left[\frac{n_1}{n_2} - 1\right] = \frac{n_1\, l}{c}\Delta \quad \ldots(8)$$

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

where $\Delta = \left(\frac{n_1 - n_2}{n_2}\right)$

$\tau = \frac{n_1 l}{c \times \frac{n_2}{n_1}}$

We know that, numerical aperture NA $= n_1\sqrt{(2\Delta)}$

So, in terms of numerical aperture, delay difference $\Delta\tau$ is given by
$$\Delta\tau = \frac{l\,(\text{NA})^2}{2\, n_1\, c} \quad \ldots(9)$$

Expressions (8) and (9) are employed to estimate the maximum pulse broadening.

2. Material dispersion

Material dispersion arises due to the variation of refractive index of the core material as a function of wavelength. Therefore, various wavelengths in light pulse (every laser source has a range of optical wavelengths) travel with different velocities in optical fibre ($v = c/n$). So, different spectral components of an optical pulse have different speeds and as a result the pulses get spread out in time after travelling some distance in the fibre. The longer wavelengths travel faster, *i.e.*, the light components of a pulse with shorter wavelengths will experience more delay than components having longer wavelengths.

To calculate the material dispersion, consider a plane electromagnetic wave of spectral width $\Delta\lambda_0$, centred about wavelength λ_0 is travelling through the fibre. The wave is expressed as

$$\psi = E_0\, e^{i(kx - \omega t)} \qquad \text{...(1)}$$

where k is propagation constant. Now

$$k = \frac{\omega}{v} = \frac{\omega}{(c/n)} = \frac{n\omega}{c} \qquad \text{...(2)}$$

where n is the refractive index, ω is angular frequency and c is the speed of light in free space.

The group velocity v_g of the wave is expressed as

$$v_g = \frac{d\omega}{dk} \qquad \text{...(3)}$$

Differentiating eq. (2) with respect to ω, we get

$$\frac{dk}{d\omega} = \frac{n}{c} + \frac{\omega}{c}\frac{dn}{d\omega} \qquad \text{...(4)}$$

Substituting this value in eq. (3), we get

$$v_g = \frac{1}{\left(\frac{n}{c} + \frac{\omega}{c}\frac{dn}{d\omega}\right)} = \frac{c}{\left(n + \omega\frac{dn}{d\omega}\right)} \qquad \text{...(5)}$$

In order to express group velocity v_g, in terms of free space wavelength λ_0, consider the relation

$$\omega = \frac{2\pi c}{\lambda_0} \quad \text{or} \quad \lambda_0 = \frac{2\pi c}{\omega}, \; i.e., \; \frac{d\lambda_0}{d\omega} = -\frac{2\pi c}{\omega^2}$$

Now,

$$\frac{dn}{d\omega} = \frac{dn}{d\lambda_0} \times \frac{d\lambda_0}{d\omega} = \frac{dn}{d\lambda_0} \times \left(-\frac{2\pi c}{\omega^2}\right)$$

$$\frac{dn}{d\omega} = \frac{dn}{d\lambda_0} \times \left(-\frac{2\pi c}{(2\pi c/\lambda_0)^2}\right) \qquad \left(\because \omega = 2\pi \nu_0 = \frac{2\pi c}{\lambda_0}\right)$$

$$\frac{dn}{d\omega} = \frac{dn}{d\lambda_0} \times \left(-\frac{\lambda_0^2}{2\pi c}\right) = -\frac{\lambda_0^2}{2\pi c}\frac{dn}{d\lambda_0} \qquad \text{...(6)}$$

Substituting the value of $(dn/d\omega)$ from eq. (6) in eq. (5), we get

$$v_g = \frac{c}{n + \omega\left(-\frac{\lambda_0^2}{2\pi c}\frac{dn}{d\lambda_0}\right)} = \frac{c}{\left(n - \omega\frac{\lambda_0^2}{2\pi c}\frac{dn}{d\lambda_0}\right)} \qquad \text{...(7)}$$