5 CHAPTER

Optical Fibre Systems

Learning Objectives

After studying this chapter, students will be able to

- understand the propagation of light in optical fibres
- comprehend the basic principle of operation of optical fibres
- realize step-index optical fibres
- explain the concept of numerical aperture
- elucidate the meaning of multipath time dispersion
- explain graded-index optical fibres
- describe fabrication of optical fibres (double-crucible technique of fibre drawing)
- demonstrate some important applications of optical fibres

List of Symbols

i = Angle of incidence
r = Angle of refraction
n = Refractive index
i_c = Critical angle of incidence
θ_c = Critical angle
α_m = Angle of acceptance
NA = Numerical aperture
Δn_r = Relative refractive index difference
ν = Velocity
t = Time
L = Distance
c = Velocity of light in vacuum
P_{in} = Input power
P_{out} = Output power
A = Attenuation loss
λ = Wavelength
h = Planck's constant
E_g = Energy bandgap
I_L = Photocurrent
μ_P = Mobility of holes
μ_n = Mobility of electrons
G_L = Photogeneration rate
τ_p = Excess minority carrier hole lifetime
e = Electronic charge
L_n = Diffusion length for electrons
L_p = Diffusion length for holes
Φ_i = Incident flux
α = Absorption coefficient

5.1 INTRODUCTION

Communication is an important driver of technology. Transfer of information in any communication system uses a carrier wave that is modulated by the information signal. This modulated carrier wave is then demodulated at the receiver end to extract the necessary information. The volume and speed of information transfer are dependent on the frequency of the carrier wave. It is advantageous to use higher frequencies for the carrier wave in order to increase the volume and speed of information that is transferred. Fibre-optic communication utilizes carrier frequency spectra corresponding to frequencies of the order of 10^{14} Hz, which is 10,000 times higher than microwave frequencies. Optical fibres constitute the medium that is used for transmitting such high frequencies. The first low-attenuation optical fibre was developed by Robert Maurer, Donald Keck, and Peter Schultz of Corning Glass Corporation of USA in the year 1970. We will study some important aspects of fibre optics in this chapter, such as characteristics of optical fibres, their fabrication process, and, finally, their applications.

5.2 PROPAGATION OF LIGHT IN OPTICAL FIBRES

We will present the basic operating principle along with the underlying physics of optical fibres in this section.

5.2.1 Total Internal Reflection

A ray of light travelling from a medium of refractive index n_1 to another medium of refractive index n_2 undergoes refraction at the interface. This refraction is governed by Snell's law, given as follows:

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1} \tag{5.1}$$

where i and r represent the angle of incidence and the angle of refraction, respectively. If a ray of light travels from a denser to a rarer medium, it bends away from the normal. In such a scenario, three different possibilities can result, depending on the incidence angle, as shown in Fig. 5.1.

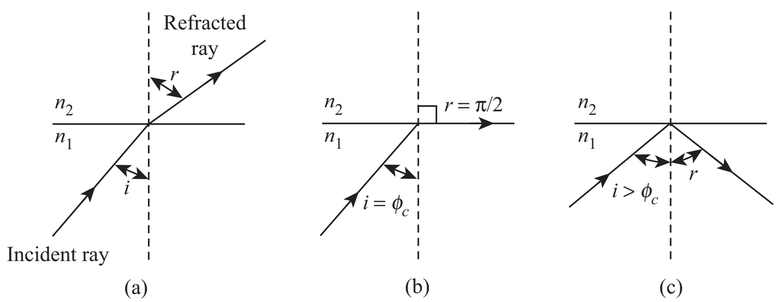

Fig. 5.1 Refraction of light travelling from denser to rarer medium (a) $i < \phi_c$, (b) $i = \phi_c$, (c) $i > \phi_c$

Figure 5.1(a) shows the refracted ray bending away from the normal in a general case. As the incidence angle increases, the refracted ray bends more and more towards the interface between the two media. When i reaches a certain critical value (the critical angle), the angle of refraction becomes equal to 90° and the refracted ray travels horizontally, along the interface. Any further increase in the angle of incidence results in the refracted ray being reflected back into the medium of refractive index n_1. This phenomenon of re-entering of the refracted ray into the medium from which the ray incident on the interface originated is called *total internal reflection*. From Eq. (5.1) we can write the following expression: $\frac{\sin i_c}{\sin 90°} = \frac{n_2}{n_1}$

resulting in the following relation:

$$\sin i_c = \frac{n_2}{n_1} \tag{5.2}$$

5.2.2 Principle of Optical Fibres

An optical fibre consists of a cylindrical glass core surrounded by a cladding layer of a slightly lower refractive index. Figure 5.2 shows a schematic diagram of an optical fibre along with the path traversed by a ray of light incident on one end of the optical fibre.

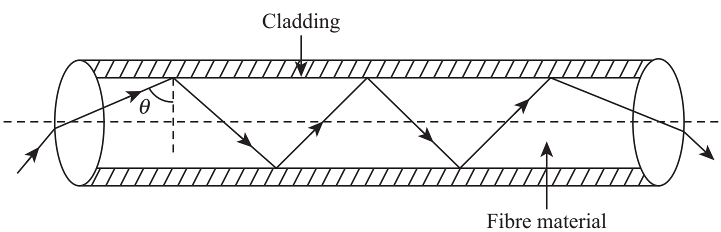

Fig. 5.2 Schematic of ray travelling in optical fibre

The ray of light is incident on the interface between the fibre material and the cladding at an angle of θ. If $\theta \geq \theta_c$, then the incident ray is totally internally reflected. From Snell's law, this implies that

$$\sin\theta_c = \frac{n_2}{n_1} \tag{5.3}$$

The incident ray suffers multiple total internal reflections and can travel long distances before emerging out of the optical fibre. Thus, optical fibres have been proved to be extremely useful for long-distance transmission. It is, however, necessary to first convert the original electrical signals to optical signals using suitable devices. In addition, for transmission to be efficient, signal attenuation due to absorption should be minimized. In practice, this can be achieved by special preparations and the use of purification techniques.

5.2.3 Fractional Refractive Index

Let us assume that the refractive index of the core material is n_1 and that of the cladding material is n_2. A quantity Δn_r is then defined by the following term:

$$\Delta n_r = (n_1 - n_2)/n_1$$

The quantity Δn_r is called the relative refractive index difference or the fractional refractive index.

5.3 NUMERICAL APERTURE AND ACCEPTANCE ANGLE

A ray of light entering the flat end of an optical fibre at an angle α with respect to the axis gets bent towards the normal, as shown in Fig. 5.3. The ray entering the solid core makes an angle ϕ with the axis. The ray travels through the core and is incident at an angle θ on the core–cladding interface. Note that

$$\phi = \frac{\pi}{2} - \theta$$

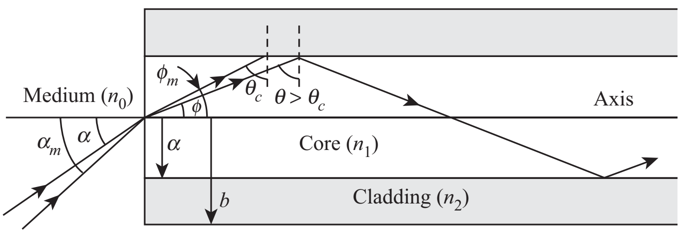

Fig. 5.3 Propagation of light in optical fibre

If $\theta > \theta_c$, the ray undergoes total internal reflection at the core–cladding interface. Multiple total internal reflections ensure that the ray travels a long distance before emerging out of the fibre. Since $\theta > \theta_c$ for total internal reflection to take place, ϕ needs to be less than a limiting value ϕ_m, given as follows: $\phi_m = \frac{\pi}{2} - \theta_c$

In other words, the angle α that the incident ray makes with the axis of the optical fibre should be less than a maximum value α_m for total internal reflection to take place. The angle α_m is called the *angle of acceptance* of the fibre. All the incoming rays that are incident within a cone of half-angle α_m are collected and propagated by the optical fibre.

Application of Snell's law at the core–air interface gives the following equation:

$$n_0 \sin \alpha = n_1 \sin \phi \tag{5.4}$$

Using the limiting values in Eq. (5.4), the following relation is obtained:

$$n_0 \sin \alpha_m = n_1 \sin \phi_m \tag{5.5}$$

We also have the following relation:

$$\phi_m = \frac{\pi}{2} - \theta_c \tag{5.6}$$

The use of Eq. (5.6) in Eq. (5.5) yields the following expression:

$$n_0 \sin \alpha_m = n_1 \cos \theta_c \tag{5.7}$$

We can write that

$$\cos \theta_c = [1 - \sin^2 \theta_c]^{1/2} \tag{5.8}$$

The use of Eq. (5.3) in Eq. (5.8) leads to the following expression:

$$\cos \theta_c = \left[1 - \frac{n_2^2}{n_1^2}\right]^{1/2}$$

which gives the following relation:

$$\cos \theta_c = \frac{\left(n_1^2 - n_2^2\right)^{1/2}}{n_1} \tag{5.9}$$

Substitution of Eq. (5.9) into Eq. (5.7) results in the following expression:

$$n_0 \sin \alpha_m = n_1 \frac{\left(n_1^2 - n_2^2\right)^{1/2}}{n_1}$$

which implies that

$$n_0 \sin \alpha_m = (n_1^2 - n_2^2)^{1/2} \tag{5.10}$$

The term $n_0 \sin \alpha_m$ is called the *numerical aperture* (NA) for an optical fibre. The numerical aperture decides the light-gathering capacity of a fibre. Thus, we can write the following expression:

$$\boxed{\mathrm{NA} = (n_1^2 - n_2^2)^{1/2}} \tag{5.11}$$

Let us define a quantity called relative refractive index difference Δ by the following expression:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{5.12}$$

The use of Eq. (5.12) in Eq. (5.11) leads to the following relation:

$$\mathrm{NA} = n_1\sqrt{2\Delta} \tag{5.13}$$

Numerical aperture is a measure of the quantity of light that can be collected by an optical fibre. The light-gathering capability of an optical fibre increases with an increase in its numerical aperture. From Eqs (5.10) and (5.11), it is clear that NA = $\sin \alpha_m$ for $n_0 = 1$. Since the maximum value of $\sin \alpha_m$ can be 1, NA cannot exceed 1. For $\alpha_m = 90$, NA = 0; that is, the fibre completely reflects the incident light. Numerical apertures of practical optical fibres generally fall in the range of 0.2–1.

5.4 TYPES OF OPTICAL FIBRES

Optical fibres are classified into three major categories based on the following parameters:

1. Raw material of the fibre
2. Number of modes of propagation
3. Refractive index profile

We will discuss the various types of optical fibres in this section.

5.4.1 Classification Based on Raw Material of Fibre

Optical fibres are generally made from two basic materials:
1. Glass
2. Plastic

5.4.1.1 Glass Optical Fibres

If an optical fibre is made by fusing mixtures of metal oxides and silica glasses, it is known as a glass fibre. Examples include GeO_2–SiO_2 core and SiO_2 clad; SiO_2 core and P_2O_3–SiO_2 clad.

5.4.1.2 Plastic Optical Fibres

Polystyrene and acrylate compounds are used to fabricate plastic optical fibres. In general, plastic optical fibres are inexpensive and highly flexible. They are extremely tough and have a long life. However, on the negative side, they exhibit greater attenuation compared to glass fibres. Examples are polystyrene core and methylmethacrylate clad; polymethyl-methacrylate core and copolymer clad.

5.4.1.3 Types of Rays

As light propagates through an optical fibre, two possibilities exist (Fig. 5.4):
1. The light ray can be launched in such a manner that it is in a plane that contains the axis of the optical fibre. Even after total internal reflection, the light ray continues to remain in the same plane. The ray thus always crosses the axis of the optical fibre. Such rays are called *meridional rays*.
2. The light ray can also be launched in a manner such that it belongs to a plane that does not contain the fibre axis. This can happen, for example, in a situation where the ray is launched at an angle such that it does not intersect the axis of the fibre. Even after total internal reflection, the light ray would never intersect the axis of the optical fibre. Such rays are called *skew rays*.

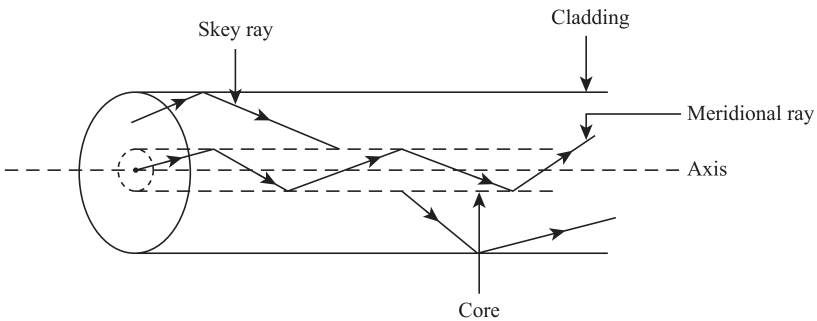

Fig. 5.4 Schematic representation of meridional and skew rays

5.4.2 Classification Based on Number of Modes of Propagation

Depending on the number of modes of propagation of the signal, optical fibres can be divided into two types:

1. Single-mode optical fibres
2. Multimode optical fibres

5.4.2.1 Single-mode Optical Fibres

A single-mode optical fibre is designed to carry only one signal of light (mode). This signal or ray of light often contains a range of different wavelengths. A typical single-mode optical fibre has a core diameter of 8–10 μm and a cladding diameter of 125 μm. It is designed such that only a small refractive index difference exists between the core and the cladding. Some special types of single-mode optical fibres exist that have been chemically or physically altered to give special properties, such as dispersion-shifted fibre and non-zero dispersion-shifted fibre. Only laser light can be used for the signals propagating through single-mode fibres.

5.4.2.2 Multimode Optical Fibres

In a multimode optical fibre, more than one signal can be propagated. Multimode fibres have several advantages over single-mode fibres (Table 5.1). Larger core diameter of a multimode fibre is an added advantage for end-to-end connection of similar fibres. Multimode optical fibres are mostly used for communication over shorter distances, such as within a building or inside a campus. Typical multimode links have data rates of 10 Mbit/s to 10 Gbit/s over link lengths of up to 600 m—more than sufficient for the majority of applications within the premises.

Table 5.1 Differences between single-mode and multimode fibres

Single-mode fibres	Multimode fibres
Only one mode can be propagated.	A large number of modes can be propagated.
Core diameter is small.	Core diameter is large.

5.4.3 Classification Based on Refractive Index Profile

Optical fibres can be divided into two more types based on the refractive index difference between the core and the cladding, which are as follows:

1. Step-index optical fibres
2. Graded-index optical fibres

5.4.3.1 Step-index Optical Fibres

A step-index optical fibre consists of a solid cylindrical core of diameter $2a$ and refractive index n_1, surrounded by a coaxial cylindrical cladding of outer

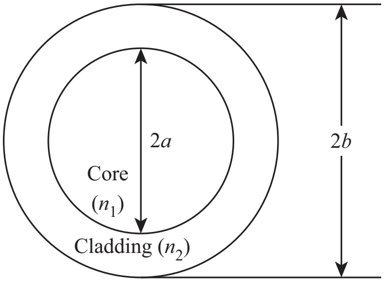

Fig. 5.5 Schematic diagram of step-index fibre

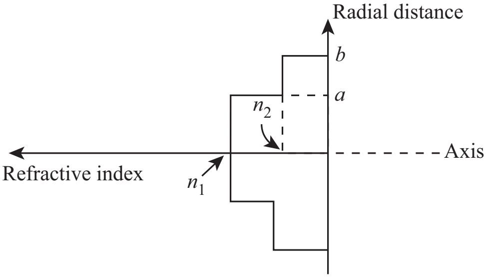

Fig. 5.6 Step function dependence of refractive index

diameter $2b$ and refractive index n_2. A schematic diagram of a step-index fibre is shown in Fig. 5.5.

Typical solid cylindrical core diameters are in the range of 50–100 μm, and cylindrical cladding diameters are in the range of 118–140 μm. Such an optical fibre is called a *step-index fibre* due to the step function dependence of the refractive index on radial distance, as shown in Fig. 5.6.

As mentioned earlier, for light to propagate through a fibre, the incoming rays must be incident within a cone of half-angle α_m around the axis of the optical fibre limit of $\alpha = 0$ to $\alpha = \alpha_m$. Figure 5.7 is a schematic diagram showing the path travelled by (a) a ray incident at one end of the fibre at an angle $\alpha = 0°$ and (b) a ray incident at an angle $\alpha = \alpha_m$.

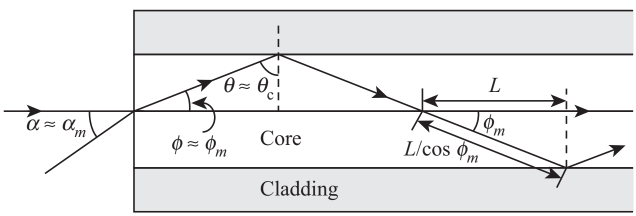

Fig. 5.7 Paths of rays travelling through step-index fibre

The ray incident along the axis of the core traverses a distance L with a velocity v in time t_1, which can be expressed as follows:

$$t_1 = \frac{L}{v} \tag{5.14}$$

However, by definition,

$$n_1 = \frac{c}{v} \tag{5.15}$$

where c is the velocity of light.

Using Eq. (5.15) in Eq. (5.14), we get the following relation:

$$t_1 = \frac{Ln_1}{c} \tag{5.16}$$

Since the ray with $\alpha = \alpha_m$ covers the same distance L, the actual distance traversed is given by $L/\cos\phi_m$, as shown in Fig. 5.7. The time t_2 taken for this travel is given as follows:

$$t_2 = \frac{Ln_1}{c(n_2/n_1)} = \frac{Ln_1}{c\cos\phi_m} \tag{5.17}$$

Using Eq. (5.6) in Eq. (5.17), we get the following relation:

$$t_2 = \frac{Ln_1}{c\sin\theta_c} \tag{5.18}$$

Using Eq. (5.3), Eq. (5.18) can be rewritten in the following form:

$$t_2 = \frac{Ln_1}{c(n_2/n_1)} = \frac{Ln_1^2}{cn_2} \tag{5.19}$$

The rays entering the optical fibre at $\alpha = 0°$ and $\alpha = \alpha_m$ are launched at the same time but are separated by a time interval Δt after traversing a length L within the optical fibre. This time interval Δt is given by the following relation:

$$\Delta t = t_2 - t_1$$

which, on using Eqs (5.19) and (5.16), yields the following equation:

$$\Delta t = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c} = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right) \tag{5.20}$$

Pulse broadening per unit length can be expressed in the following form:

$$\frac{\Delta t}{L} = \frac{n_1}{n_2}\left(\frac{n_1 - n_2}{c}\right) \tag{5.21}$$

The term $\Delta t/L$ is also referred to as *multipath time dispersion* of an optical fibre.

5.4.3.2 Graded-index Fibres

Multipath time dispersion is one serious disadvantage of step-index fibres, which limits their use in long-distance applications. A fibre in which the refractive index of the core varies with radius helps minimize or even eliminate this disadvantage. Such an optical fibre is called a *graded-index fibre*. The variation of the refractive index with radial distance r from the axis for a graded-index fibre is described by the following equation:

$$n(r) = \begin{cases} n_1 = n_0\left[1 - 2\Delta\left(\dfrac{r}{a}\right)^{\alpha}\right]^{1/2}, \text{ for } r \le a \\[2ex] n_2 = n_0\left[1 - 2\Delta\right]^{1/2}, \text{ for } b \ge r \ge a \end{cases} \tag{5.22}$$

where $n(r)$ represents the refractive index at a radial distance r and n_0 its maximum value along the axis of the optical fibre (i.e., at $r = 0$), a is the core radius, b is the radius of the cladding, and α is the profile parameter. The value of the profile parameter decides the exact variation of the refractive index within the

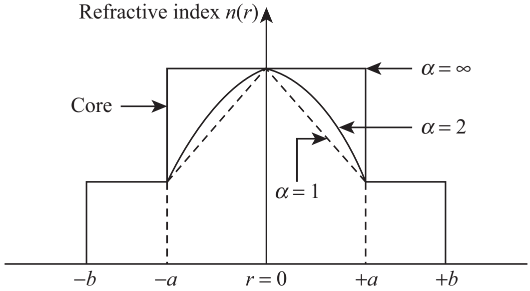

Fig. 5.8 Refractive index variation for graded-index fibre

core of the fibre. Figure 5.8 shows the variation of the refractive index within the core for some specific values of the profile parameter.

The refractive index variation with radial distance is triangular for $\alpha = 1$, parabolic for $\alpha = 2$, and equivalent to that of a step-index fibre for $\alpha = \infty$.

The numerical aperture NA for a parabolic profile of refractive index is expressed as follows:

$$\mathrm{NA} = \left(n_1^2 - n_2^2\right)^{1/2} \tag{5.23}$$

Using Eq. (5.22) in Eq. (5.23), we get the following expression:

$$\mathrm{NA} = \left[n_0^2\left\{1 - 2\Delta\left(\frac{r}{a}\right)^2\right\} - n_0^2\left(1 - 2\Delta\right)\right]^{1/2}$$

or $$\mathrm{NA} = n_0\left[2\Delta\left(\left(1 - \frac{r^2}{a^2}\right)1 - \frac{r^2}{a^2}\right)\right]^{1/2} \tag{5.24}$$

At $r = 0$, that is, along the axis of the optical fibre,

$$(\mathrm{NA})_{\mathrm{axis}} = n_0\sqrt{2\Delta} \tag{5.25}$$

At $r = a$, that is, at the core–cladding interface,

$$(\mathrm{NA})_{r=a} = 0 \tag{5.26}$$

Propagation of the ray through a graded-index optical fibre can be visualized by assuming the fibre to be made up of several coaxial cylindrical layers with progressively decreasing refractive index as one goes away from the axis of the fibre. A schematic representation of this visualization is given in Fig. 5.9.

The changing refractive index of successive coaxial cylindrical layers continues to bend the incident ray till the condition for total internal reflection is met, after which the ray travels back towards the axis of the core. The ray travelling along the axis is not affected during its journey through the optical fibre. The rays near the axis of the core travel shorter paths in comparison with those near the core–cladding interface. Velocity of the rays near the axis of the core is, however, lower than that of the rays near the core–cladding interface. These two opposing conditions help in reducing the multipath time dispersion. The reduction of multipath dispersion to

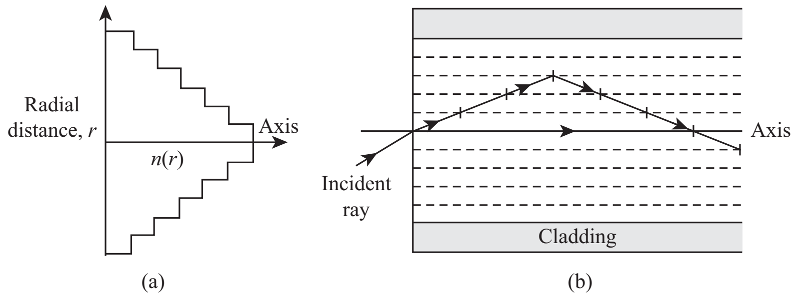

Fig. 5.9 Ray propagation through graded-index optical fibre (a) Refractive index dependence (b) Ray propagation

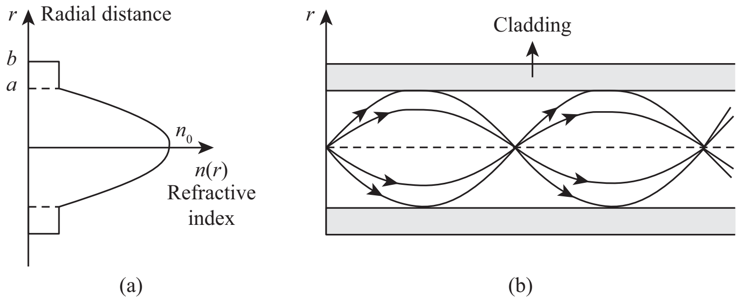

Fig. 5.10 Reduction of multipath dispersion (a) Refractive index profile (b) Ray propagation

Table 5.2 Differences between step-index and graded-index fibres

Step-index fibre	Graded-index fibre
The refractive index at the core–cladding interface changes suddenly.	The refractive index at the core–cladding interface changes gradually.
Light rays pass through the fibre axis.	Light rays propagate in the form of skew rays.
Light rays follow a zigzag path.	Light rays follow a helical path.
This fibre has a low bandwidth.	This fibre has a high bandwidth.
Distortion is high in multimode type.	Distortion is low.

nearly zero for a parabolic refractive index profile is shown schematically in Fig. 5.10 (Table 5.2).

5.4.4 Classification Based on Refractive Index Profile and Number of Modes

Optical fibres can be divided into three more categories based on the refractive index profile and modes of propagation of signals, which are as follows:

1. Step-index single-mode (SISM) optical fibre
2. Step-index multimode (SIMM) optical fibre
3. Graded-index multimode (GIMM) optical fibre

5.4.4.1 Step-index Single-mode Optical Fibre

A typical SISM optical fibre has a core diameter of 10 μm and a cladding diameter of around 120 μm. Due to the small core diameter, only one signal can be transmitted through this fibre. SISM fibres have small numerical apertures, negligible dispersion, and high bandwidths. For transmission of signals, laser diodes (LDs) can be used. The main disadvantage of SISM fibres is their high cost. These fibres are used in laying undersea cable and submarine cable systems and in long-distance communications.

5.4.4.2 Step-index Multimode Optical Fibre

A typical SIMM optical fibre has a core diameter of 200 μm and a cladding diameter of around 300 μm. Due to the larger core diameter, many signals can be transmitted simultaneously through this fibre. Light-emitting diodes (LEDs) can be used to send signals through these fibres. These fibres have low bandwidth, high attenuation, and high numerical aperture. They are of very low cost, but suffer from intermodal dispersion loss.

5.4.4.3 Graded-index Multimode Optical Fibre

A typical GIMM optical fibre has a core diameter of 200 μm and a cladding diameter of around 250 μm. As the refractive index of the core decreases gradually from the core axis to the cladding, the intermodal loss is reduced to a great extent. This is the main advantage of a GIMM fibre, compared to an SIMM fibre. These fibres have low signal attenuation, intermediate bandwidth, and small numerical aperture. The cost of GIMM fibres is, however, high. They are used in intercity trunks between telephone offices.

5.5 DOUBLE-CRUCIBLE TECHNIQUE OF FIBRE DRAWING

The conventional glass-refining techniques are used for producing high-purity powders of raw materials such as SiO_2, GeO_2, B_2O_3, and Al_2O_3. An appropriate mixture of these materials is then melted in platinum or silica crucibles at temperatures in the range 1000–1300°C. After suitable processing, the melt is cooled and drawn into rods or tubes. The double-crucible technique is suitable for continuous manufacture of optical fibres. Figure 5.11 shows a schematic diagram of the set-up for the double-crucible method.

The set-up consists of two concentric platinum crucibles mounted within a vertical cylindrical muffle furnace. The temperature within the furnace can be varied and set extremely accurately within the range 800–1200°C. Raw materials for the core and the cladding are fed into the two crucibles in powder form or as preformed rods. The crucibles have nozzles at the base that allow the clad fibre to be drawn from the melt. Refractive index grading is achieved by diffusion of dopant ions across the core–cladding interface. The technique can be used to

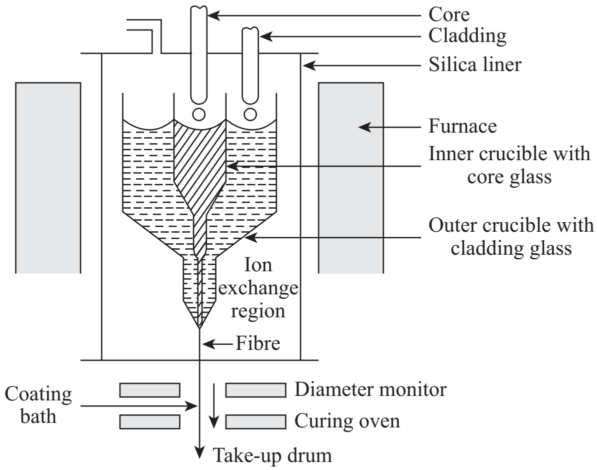

Fig. 5.11 Schematic diagram of the set-up for double-crucible method

produce relatively inexpensive fibres with large core diameters. These in turn result in large numerical apertures. An attenuation level of 3 dB/km has been achieved for sodium borosilicate glass fibres fabricated using this technique.

5.6 SPLICING

The process of forming a permanent joint between two optical fibres is called *splicing*. Splicing is resorted to under two circumstances: (a) to increase the length of the optical fibre and (b) to repair a broken fibre cable. There are two ways in which splicing can be achieved: (a) fusion splicing and (b) mechanical splicing.

5.6.1 Fusion Splicing

Figure 5.12 shows a schematic diagram of a fusion splicing set-up. The set-up uses an electric arc as a heating source. The ends of the prepared fibres requiring splicing are placed in precise alignment.

This is performed using an inspection microscope. A short arc discharge is then used to polish the fibre ends. This fire polishing removes defects due to

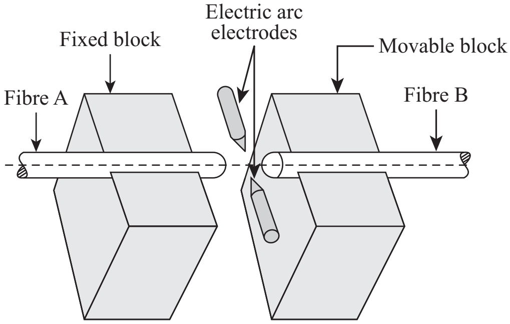

Fig. 5.12 Schematic diagram of fusion splicing set-up

imperfect cleaving. The two ends are then pressed together and fused with a stronger arc. The heat produced during the fusion splicing process can weaken the optical fibre in the vicinity of the splice.

5.6.2 Mechanical Splicing

Several mechanical techniques are available for splicing of optical fibres. Of these, the snug tube splicing technique is the most popular. In this technique, a glass or ceramic capillary with an inner diameter just sufficient to accommodate the optical fibres is used, as shown in Fig. 5.13. After inserting the fibre ends into the capillary, a transparent adhesive (e.g., epoxy resin) is injected through a transverse hole onto the ends requiring splicing. The adhesive produces mechanical bonding as well as index matching. This stable low-loss splicing method places stringent limits on the usable capillary diameters.

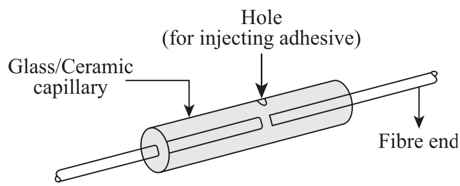

Fig. 5.13 Mechanical splicing technique

5.7 POWER LOSSES IN OPTICAL FIBRES

As an optical signal propagates through an optical fibre, it undergoes a loss in signal strength due to different causes. We will discuss the concept of signal loss in this section.

5.7.1 Losses Due to Attenuation

If P_{in} represents the input power and P_{out} the output power at the receiving end of the optical fibre, the attenuation loss in dB/km is given by the following expression:

$$A = \frac{10}{L}\log_{10}\frac{P_{in}}{P_{out}} \tag{5.27}$$

where L represents the fibre length in km.

Power loss is given by the following expression:

$$\text{Power loss}(\text{dB}) = -10\log\left(\frac{P_{out}}{P_{in}}\right) \tag{5.28}$$

Thus, $$\text{Attenuation} = \frac{\text{Power loss}}{\text{Fibre length}} \tag{5.29}$$

Using Eq. (5.28) in Eq. (5.29), we get the following expression:

$$\log\left(\frac{P_{out}}{P_{in}}\right) = \frac{[-A\times L]}{10}$$

or $$P_{out} = P_{in}\times 10^{-\left(\frac{A\times L}{10}\right)} \tag{5.30}$$

where P_{in} and P_{out} are expressed in W and L is expressed in km.

Conversely, using Eq. (5.30), the length of the optical fibre in km is given by the following expression:

$$L = \frac{10}{A}\log_{10}\left(\frac{P_{in}}{P_{out}}\right) \tag{5.31}$$

5.7.2 Losses Due to Dispersion

For a step-index optical fibre, pulse broadening per unit length given in Eq. (5.21) is as follows:

$$\frac{\Delta t}{L} = \frac{n_1}{n_2}\left(\frac{n_1 - n_2}{c}\right) \tag{5.32}$$

As mentioned earlier, the term $\Delta t/L$ is referred to as *solidus multipath time dispersion* of the optical fibre. Multipath time dispersion can be minimized or even eliminated using a graded-index optical fibre. Figure 5.9 shows how multipath dispersion can be reduced to a negligible level using a parabolic refractive index profile.

5.7.3 Losses Due to Bending of Optical Fibre

Optical fibres radiate the propagating power if they are bent. Generally, two types of bends are encountered: bends with radii much larger than the fibre diameter, called *macrobends*, and smaller bends, called *microbends*. Random microbends of the fibre axis can arise due to faulty cabling.

Electric field distribution for any guided core has a tail extending into the cladding. This tail is called the *evanescent field* and decays exponentially with distance from the core. Thus, a portion of the net energy contained in the wave travels in the cladding. At the macrobend, the tail on the far side of the centre of curvature has to move faster to keep pace with the field within the core. At a certain distance r_c, called the *critical distance*, the field tail needs to move faster than the speed of light in the cladding material, in order to keep pace with the core field. Since this is not possible, the optical energy contained in the tail beyond the critical distance is lost in the form of radiation. This effect is demonstrated schematically in Fig. 5.14.

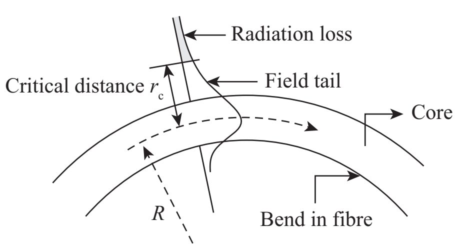

Fig. 5.14 Radiation loss at bends

5.7.4 Attenuation Curve

Light attenuates as it passes through an optical fibre. Two primary factors are responsible for this attenuation, namely, absorption and scattering. Light is absorbed by molecules in the glass and gets converted to heat. One of the

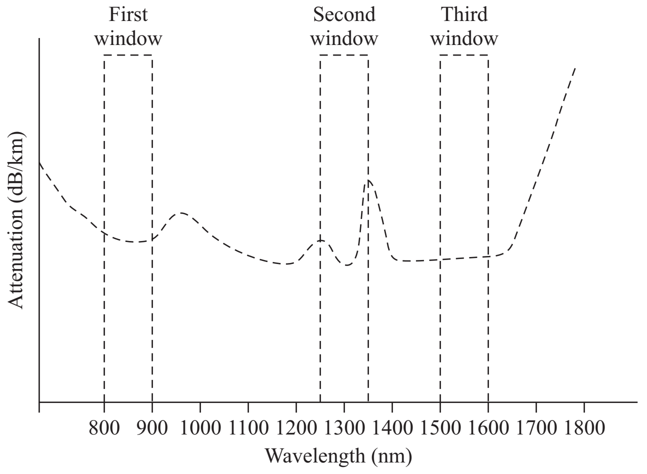

Fig. 5.15 Attenuation curve

primary absorbers is residual OH^+. Absorption of light is wavelength-dependent. Light also undergoes scattering as it collides with individual atoms in the glass. Scattering is wavelength-dependent and is inversely proportional to the fourth power of wavelength. Thus, if the wavelength of light is doubled, scattering losses are reduced by a factor of 16. On the other hand, absorption occurs strongly at select bands. For example, absorption due to residual OH^+ peaks around 1000, 1400, and above 1600 nm. A typical attenuation curve is shown in Fig. 5.15.

The attenuation curve clearly shows three transmission windows, at 800–900, 1260–1360, and 1500–1600 nm. The corresponding operating wavelengths are 850, 1310, and 1550 nm, respectively. Commonly used sources are LEDs and LDs operating at these infrared wavelengths.

5.7.5 Illumination and Image Transfer

Optical fibres are also used for illumination and image transfer. For transferring images, fibres are wrapped in bundles; these are useful in viewing images of confined spaces. Applications of fibre optic-based illuminations are prevalent in the field of dentistry, internal examination, and photography. In applications that need bright illumination but lack a clear line-of-sight path, fibres can be very useful and effective. An important device that uses fibres is endoscope. An endoscope is a long, thin imaging device used to view objects through a small hole. It uses a coherent bundle of fibres sometimes with a lens. Medical endoscopes assist during surgical procedures and diagnostics. Industrial endoscopes are used to inspect complex objects like jet engine interiors. Optical fibres also find use in spectroscopy. Sometimes, substances need to be analysed for their composition, even if they cannot be placed inside a spectrometer. In such situations, optical fibres carry light to and from the object under analysis.

Example 5.1 A step-index fibre has a core of refractive index 1.5 and a cladding of refractive index 1.47. The diameter of the core of the fibre is 100 μm, and the medium surrounding the fibre is air. Determine (a) NA of the fibre, and (b) angles α_m, ϕ_m, and θ_c.

Solution The calculations are as follows:

(a) $$\text{NA} = (n_1^2 - n_2^2)^{1/2} \tag{5.33}$$

Substitution of the given values of n_1 and n_2 in Eq. (5.33) leads to the following relation: $\text{NA} = \sqrt{(1.5)^2 - (1.47)^2}$

(b) or $$\text{NA} = \sqrt{2.25 - 2.16} = 0.3 \tag{5.34}$$

(i) We have

$$\text{NA} = n_0 \sin \alpha_m \tag{5.35}$$

Using Eq. (5.34) and the refractive index value for air in Eq. (5.35), we get the following relation: $0.3 = 1 \times \sin \alpha_m$

or $$\alpha_m = 17.46° \tag{5.36}$$

(ii) From Eq. (5.5),

$$n_0 \sin \alpha_m = n_1 \sin \phi_m \tag{5.37}$$

The use of Eq. (5.36) and known values of n_0 and n_1 in Eq. (5.37) yields the following relation: $0.3 = 1.5 \sin \phi_m$

or $$\phi_m = \sin^{-1}\left(\frac{0.3}{1.5}\right) = 11.54°$$

(iii) The critical angle θ_c is given by the following relation:

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \tag{5.38}$$

Substitution of the given values of n_1 and n_2 in Eq. (5.38) yields the following result:

$$\theta_c = \sin^{-1}\left(\frac{1.47}{1.5}\right) = 78.52°$$

Example 5.2 For the optical fibre of Example 5.1, calculate the pulse broadening per unit length due to multipath dispersion.

Solution From Eq. (5.21), we get the following relation:

$$\frac{\Delta t}{L} = \frac{n_1}{n_2}\left(\frac{n_1 - n_2}{c}\right) \tag{5.39}$$

Using the given values of n_1 and n_2 and the known value of c in Eq. (5.39), the following result can be obtained:

$$\frac{\Delta t}{L} = \frac{1.5}{1.47}\left(\frac{1.5 - 1.47}{3 \times 10^8}\right)$$

or $$\frac{\Delta t}{L} = \frac{1.5 \times 0.03}{1.47 \times 3 \times 10^8} = 10.2 \times 10^{-11} \text{ s/m}$$

Example 5.3 Use the details of the optical fibre described in Example 5.1, and calculate the minimum and maximum number of total internal reflections per metre for the rays travelling through the optical fibre.

Solution From Fig. 5.7, we can write the following relation:

$$\tan\phi_m = \frac{a}{L} \tag{5.40}$$

Using the value of ϕ_m from Example 5.1, we get the following expression:

$$\tan(11.54°) = \frac{a}{L}$$

or
$$L = \frac{a}{\tan(11.54°)} \tag{5.41}$$

The use of the values of a and tan (11.54°) in Eq. (5.41) leads to the following result:

$$L = \frac{0.5}{0.2042} \times 10^{-4}\,\text{m}$$
$$= 2.45 \times 10^{-4}\,\text{m} \tag{5.42}$$

The rays travelling with $\alpha = 0$ suffer no internal reflection; therefore, the minimum number of reflections per metre is zero. For rays travelling with $\alpha \approx \alpha_m$, one internal reflection takes place for a transverse distance of $2L$. Thus, the total number of internal reflections for 1 m is as follows: $\frac{1}{2L} = \frac{1}{2\times 2.45\times 10^{-4}} = 2040/\text{m}$

5.8 FIBRE-OPTIC COMMUNICATION SYSTEMS

A simplified block diagram of a fibre-optic communication system is shown in Fig. 5.16.

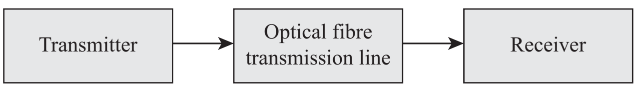

Fig. 5.16 Simplified block diagram of fibre-optic communication system

The communication system consists of a transmitter that converts the information to be transmitted, which is in the form of an electrical signal, into an optical signal. The optical signal then travels through the optical fibre transmission line to a receiver, which converts the optical signal back to the original electrical form. A more detailed block diagram is shown in Fig. 5.17.

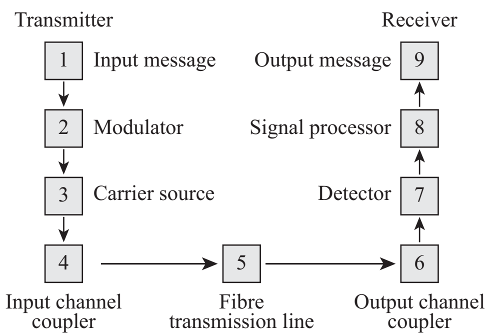

Fig. 5.17 Detailed block diagram of optical fibre-based communication system

5.9 ADVANTAGES OF FIBRE-OPTIC COMMUNICATION SYSTEM

Fibre-optic communication systems are becoming popular due to the several advantages these offer. The following are some of the more important advantages.

Immunity to electromagnetic interference Flow of electrons through a conductor generates a magnetic field. Any change in the pattern of flow of electrons leads to a change in the generated magnetic field. This, in turn, leads to the generation of an electrical current. This phenomenon of the generation of an electrical current from a changing magnetic field is called electromagnetic interference or EMI. EMI is a common form of noise in communication systems involving coaxial cables. Fibre optic-based systems are, however, immune to EMI, since in these systems signals are transmitted as light instead of current.

Data security Current-carrying conductors have magnetic fields associated with these currents. In spite of the most effective shielding, signal leakage can always take place. These leakages can result in tapping and therefore affect data security. In case of optical fibres, electromagnetic fields are confined within the fibre. Therefore, transmitted signals cannot be tapped. This leads to a high degree of data security.

Non-conductive cables Electromagnetic design requires a uniform ground potential. The nominal ground potential can, however, differ by several volts if signal-carrying cables are spread over large distances. In circuits involving semiconductor devices, any difference in the ground potential leads to problems such as ground loop and noise. In extreme cases, these effects can also damage sensitive components of the circuit. Fibre-optic cables are fabricated using non-conducting materials such as *glass* and *plastic*, and are, therefore, much more immune to ground loop and noise-related problems associated with conducting materials.

Elimination of spark hazards Signals being carried by an electric current can result in small sparks. These sparks can be hazardous, causing accidental fire in environments such as chemical plants or oil refineries. The risk associated with sparks is not present in fibre optic-based systems, since no current flow is involved in such systems.

Ease of installation As the transmission capacity increases, coaxial cables can become extremely thick and rigid. Installation of such thick cables within a complex structure of a building is a big problem. Fibre cables are, however, leaner and more flexible, leading to a considerable ease of installation.

Higher bandwidth and distances The information-carrying capacity of fibre-optic cables is much more than that of coaxial cables, that is, the bandwidth parameter of a fibre-optic cable is higher than that of a coaxial cable. Coaxial cables have a typical bandwidth parameter of a few MHz/km, whereas fibre-optic cables have a bandwidth in the region of 400 MHz/km.

Thus, systems based on fibre-optic cables can carry high-speed signals over longer distances without the need of repeaters. The information-carrying capacity of fibre-optic cables increases with frequency.

5.10 LIGHT SOURCES

Fibre-optic systems require a light source at the transmitter end. This light source converts electrical signals into optical signals. Generally, two types of sources are used: (a) incoherent optoelectronic sources like LEDs and (b) coherent optoelectronic sources like injection laser diodes (ILDs).

5.10.1 Light-emitting Diodes

When a p–n junction is forward biased, injection of carriers takes place across the junction. As the injected carriers travel, they undergo recombination in the space-charge region and in the neutral regions close to the junction. Figure 5.18 shows a schematic diagram of a p–n junction with no applied bias and with an applied forward bias. The corresponding band diagram showing injection of carriers across the junction is also shown in Fig. 5.18.

In the case of indirect-gap semiconductors such as Si and Ge, this recombination releases heat to the lattice. In direct-bandgap materials, on the other hand, the released energy can be given off as light emitted from the junction. This process is called *injection electroluminescence* and is the fundamental principle underlying the working of LEDs. LEDs find applications in digital

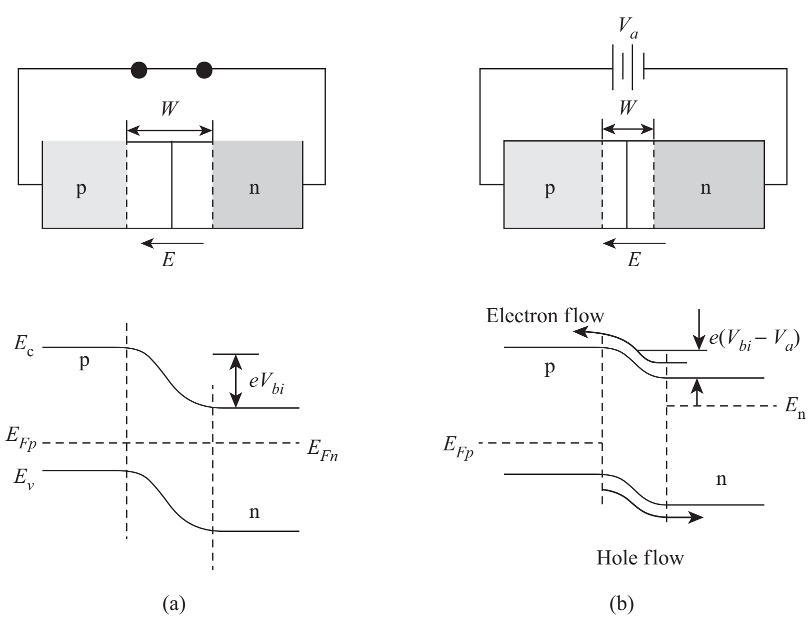

Fig. 5.18 Schematic diagram of p–n junction with its energy band (a) Zero bias (b) Forward bias

displays and communication systems. The wavelength of the emitted light is governed by the following equation:

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g}\,\mu\text{m} \tag{5.43}$$

where E_g is the bandgap in eV.

5.10.2 Laser Diodes

The photons produced in an LED are the result of transitions of electrons from the conduction band to the valence band. Light emission is spontaneous because each band-to-band transition is, in itself, an independent event. The spectral output of the LED, however, has a fairly wide bandwidth. With suitable modifications in the structure and operating conditions of the LED, it is possible to operate the device in a mode that produces a coherent output with a wavelength bandwidth of < 0.1 nm. This special-mode-operated device is then called a *laser diode*.

5.11 DETECTORS

Photodetectors are devices that convert optical signals into electrical signals. Photons give their energies to valence-band electrons and excite them to the conduction band. The resultant electron–hole pairs increase the conductivity of the material. All photodetectors use these excess carriers in some way or the other to detect the incident radiation. Photoconductors, photodiodes, and phototransistors are some examples of such devices.

5.11.1 Photoconductors

A photoconductor consists of a bar of semiconductor material with ohmic contacts at the two ends. Figure 5.19 shows a semiconductor bar (n-type) of length L and cross-sectional area A, with illumination on the face having a larger area.

The photocurrent I_L generated by length L of the bar can be shown to be as follows:

$$I_L = eG_L\left(\frac{\tau_\text{p}}{t_\text{n}}\right)\left(1+\frac{\mu_\text{p}}{\mu_\text{n}}\right)AL \tag{5.44}$$

Where G_L is the photogeneration rate of excess carriers, τ_p the excess minority carrier lifetime, μ_p the mobility of the holes, and μ_n the mobility of the electrons.

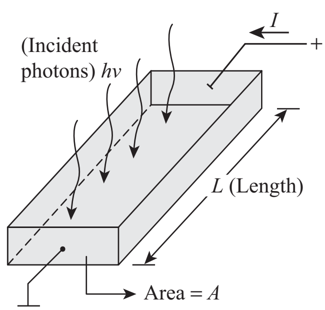

Fig. 5.19 Semiconductor bar under illumination

5.11.2 Photodiodes

A p–n junction can be used to separate the photogenerated excess carriers. A photodiode uses a reverse-biased p–n junction diode to detect photons.

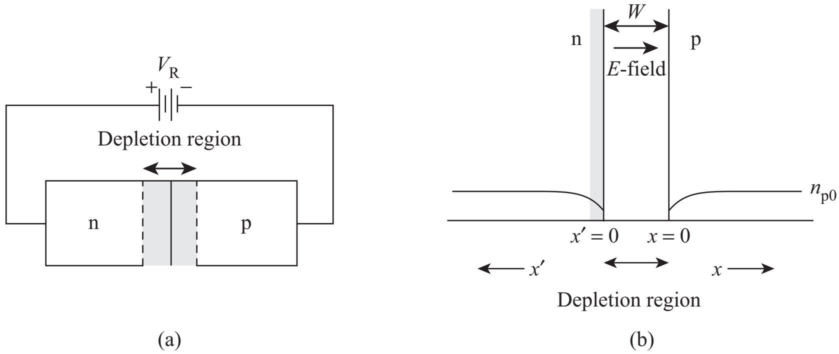

Fig. 5.20 Biasing and carrier profile of a long diode (a) Schematic diagram of reverse-biased long diode (b) Minority carrier concentration profile

Figure 5.20 shows a schematic diagram of a long reverse-biased diode along with the associated minority carrier concentration profile. Photocurrent is generated from three different sources. There are excess carriers in the space-charge region, neutral p-region, and neutral n-region. The total photocurrent density for a long diode is written as follows:

$$J_L = eG_L(W + L_n + L_p) \tag{5.45}$$

Here, G_L represents the photogenerated excess carrier generation rate, L_n is the diffusion length of the electrons, L_p is the diffusion length of holes, and W is the space-charge width.

5.11.3 PIN Photodiode

The photodiode discussed in the previous section is inherently slow due to the dominance of diffusion-based currents. In many photodetector applications such low speeds are not acceptable. Light-based communication systems are examples of such an application. Photogenerated carriers in the space-charge region can, however, be collected very fast due to the built-in electric field. Fast photodiodes must, therefore, use large depletion widths to enhance the speed of response. PIN photodiodes use this concept to achieve fast responses. A PIN diode consists of an intrinsic semiconductor region sandwiched between two heavily doped semiconductor regions of opposite type. Under an applied reverse bias, the complete intrinsic region can be swept off and the entire intrinsic region constitutes the space charge region. A schematic representation of a typical PIN photodiode with a suitable biasing arrangement is shown in Fig. 5.21.

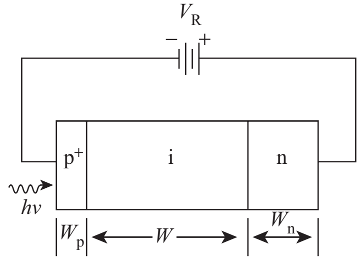

Fig. 5.21 Schematic representation of PIN photodiode along with its biasing arrangement

The photocurrent density J_L is as follows:

$$J_L = e\phi_i(1 - e^{-\alpha W}) \tag{5.46}$$

where ϕ_i represents the incident flux, α is the absorption coefficient, and W is the width of the ith layer.

5.11.4 Avalanche Photodiode

Under certain conditions, the reverse bias applied across a photodiode reaches the value that is sufficient to create electron–hole pairs by impact ionization. Excess carriers initially generated due to the absorption of photons create additional electron–hole pairs through the process of impact ionization. This avalanche process leads to huge current gains in photodiodes.

5.11.5 Phototransistors

A schematic representation of an n–p–n bipolar transistor is shown in Fig. 5.22.

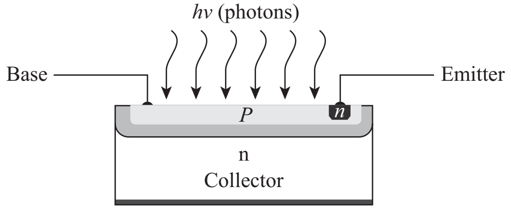

Fig. 5.22 Schematic representation of n–p–n phototransistor

The base terminal is generally kept open when a bipolar junction transistor is operated as a phototransistor. The incident photons create electron–hole pairs in the large-area base–collector junction. The built-in electric field in the space-charge region sweeps out these charge carriers to produce a photocurrent. The holes created are swept away into the p-type base to make the base positive with respect to the emitter. This results in forward biasing of the base–emitter junction, which causes the electrons to get emitted from the emitter region towards the base region, which leads to the usual transistor action.

5.11.6 Fibre-optic Sensors—Temperature and Displacement

A device that uses light guided within an optical fibre for detection of an external physical, chemical, or biomedical parameter is called a *fibre-optic sensor* (FOS). Figure 5.23 is a schematic diagram showing the general configuration of an FOS.

The sensor consists of a source, the output of which is fed into the modulating element using optical fibres. The measured parameter, which could be displacement or temperature, modulates the intensity of the light propagating through the optical fibre. The modulated light is fed through an optical fibre to a detector system. The signal processor then processes and calibrates the modulated light before it is displayed in the readout.

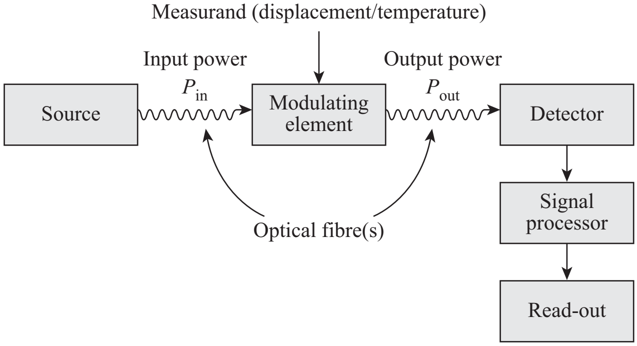

Fig. 5.23 Schematic diagram of FOS

A temperature sensor can also be designed based on the phenomenon of fluorescence. In this phenomenon, a material emits light after absorption of a suitable electromagnetic radiation. This material is called a *phosphor*. The intensity of fluorescence for most phosphors is temperature-dependent. A temperature sensor for the requisite temperature range can be designed by choosing an appropriate fluorescent material.

5.12 ENDOSCOPE

An endoscope is used by physicians to view the internal parts of the human body. This imaging can help surgeons decide on the proper procedures to be followed for treating patients. A typical endoscopy system is shown schematically in Fig. 5.24.

The endoscopy tube consists of two optical fibres. The outer fibre carries light from the source and projects it on the viewed object. The inner fibre is used to pick up the light reflected from the object surface and feeds it into a suitable imaging system.

Note: LEDs used in fibre-optic communication are generally fabricated using gallium arsenide (GaAs) or gallium arsenide phosphide (GaAsP). GaAsP LEDs operate at 1.3 μm, whereas those fabricated using GaAs operate at 0.81–0.87 μm. The output spectrum of GaAsP LED is wider than that of GaAs LED by a factor of around 1.7. This leads to higher fibre dispersion in case of GaAsP LEDs. LEDs are increasingly being replaced by vertical cavity surface emitting laser (VCSEL) devices. These devices offer better speed, power,

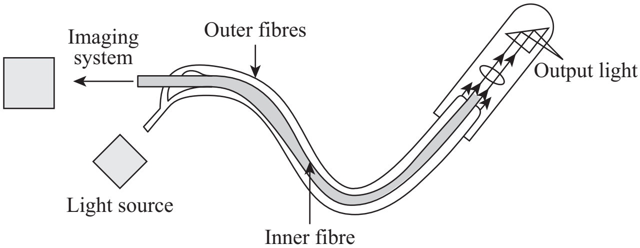

Fig. 5.24 Schematic representation of endoscope

and spectral properties in comparison to LEDs. VCSEL are semiconductor LDs that emit beams perpendicular to the top surface instead of the more conventional edge-emitting semiconducting lasers.

Example 5.4 A step-index fibre has a core of refractive index 1.5. If the NA of the fibre is 0.26, calculate the refractive index of the cladding material.

Solution For a step-index fibre,

$$\text{NA} = (n_1^2 - n_2^2)^{1/2} \tag{5.47}$$

Substituting the given value of NA in Eq. (5.47), we get the following relation:

$$0.26 = (n_1^2 - n_2^2)^{1/2}$$

yielding, $n_1^2 - n_2^2 = (0.26)^2 \cong 0.068$

resulting in $n_2^2 = n_1^2 - 0.068$

The use of the given value of n_1 yields the following result:

$$\begin{aligned} n_2^2 &= (1.5)^2 - 0.068 \\ &= 2.25 - 0.068 = 2.182 \end{aligned}$$

giving $n_2 = \sqrt{2.182} = 1.48$

Example 5.5 Calculate α_m and ϕ_m for the fibre indicated in Example 5.4 if the medium surrounding the fibre is air.

Solution We have

$$\text{NA} = n_0 \sin\alpha_m \tag{5.48}$$

For a fibre surrounded by air, using the calculated value of NA in Eq. (5.48), we get the following relation: $0.26 = \sin\alpha_m$

resulting in $\alpha_m = \sin^{-1} 0.26 = 15.07°$

In addition, we have

$$n_0 \sin\alpha_m = n_1 \sin\phi_m \tag{5.49}$$

Substitution of the given values in Eq. (5.49) results in the following expression:

$$0.26 = 1.5 \sin\phi_m$$

giving $\sin\phi_m = \dfrac{0.26}{1.5} \cong 0.17$

resulting in $\phi_m \cong \sin^{-1}(0.17) \cong 9.79°$

Example 5.6 The cladding of a step-index fibre has a refractive index of 1.40. If NA of the fibre is 0.25, calculate the refractive index of the core material.

Solution We have

$$\text{NA} = (n_1{}^2 - n_2{}^2)^{1/2} \tag{5.50}$$

Using the given value of NA in Eq. (5.50), we get the following expression:

$$0.25 = (n_1{}^2 - n_2{}^2)^{1/2}$$

which, after solving, results in $n_1^2 - n_2^2 = (0.25)^2 = 0.0625$

yielding $n_1^2 = n_2^2 + 0.0625$ (5.51)

Substitution of the given value of n_2 in Eq (5.51) gives the following equation:

$$n_1^2 = (1.40)^2 + 0.0625$$

yielding $n_1^2 = 1.96 + 0.0625 = 2.0225$

resulting in $n_1 = \sqrt{2.0225} = 1.42$

Example 5.7 The pulse broadening per unit length for an optical fibre is 12×10^{-11} s/m. If the refractive index of the core is 1.5, calculate the refractive index of the cladding material.

Solution Using Eq. (5.21), we can write, for pulse broadening per unit length, that

$$\frac{\Delta t}{L} = \frac{n_1}{n_2}\left(\frac{n_1 - n_2}{C}\right) \tag{5.52}$$

Substituting the given values in Eq. (5.52), we get the following relation:

$$12 \times 10^{-11} = \frac{1.5}{n_2}\left(\frac{1.5 - n_2}{C}\right)$$

which results in $12 \times 10^{-11} \times 3 \times 10^8 = \frac{1.5}{n_2}(1.5 - n_2)$

giving $36 \times 10^{-3} = \frac{(1.5)^2}{n_2} - 1.5$

yielding $\frac{(1.5)^2}{n_2} = 36 \times 10^{-3} + 1.5 = 1.536$

giving us the following result: $n_2 = \frac{(1.5)^2}{1.536} \cong 1.46$

Example 5.8 The cladding material for the fibre indicated in Example 5.7 is changed keeping the core material unchanged. The pulse broadening per unit length changes to 20×10^{-11} s/m. Calculate the change in the refractive index of the cladding material.

Solution From Eq. (5.21), pulse broadening per unit length is expressed as follows:

$$\frac{\Delta t}{L} = \frac{n_1}{n_2}\left(\frac{n_1 - n_2}{C}\right)$$

Substituting these values and simplifying, we get the following relation:

$$20 \times 10^{-11} \times 3 \times 10^8 = \frac{(1.5)^2}{n_2} - 1.5$$

yielding $n_2 = \frac{(1.5)^2}{(0.06 + 1.5)} = 1.44$

Thus, $\Delta n_2 = 1.46 - 1.44 = 0.02$.

IMPORTANT CONCEPTS

1. A ray of light travelling from a medium of refractive index n_1 to a medium of refractive index n_2 undergoes refraction at the interface.

2. Optical fibres are classified into three categories based on the following criteria: (a) raw material of the fibre, (b) number of modes of propagation, and (c) refractive index profile.
3. A fibre in which the refractive index of the core varies with the radius helps minimize multipath time dispersion.
4. As the optical signal propagates through an optical fibre, it undergoes loss in signal strength.
5. LEDs utilize the process of injection electroluminescence.
6. PIN photodiodes have extremely high speed of response.

APPLICATIONS

1. An optical fibre consists of a cylindrical glass core surrounded by a cladding layer of a slightly lower refractive index.
2. Optical fibres are generally made from glass or plastic.
3. Optical fibres are of two types: single-mode and multimode.
4. Based on the refractive index profile, optical fibres can be classified into two types: step-index optical fibres and graded-index optical fibres.
5. Optical fibres are drawn using the double-crucible technique.
6. The process of forming a permanent joint between two optical fibres is called splicing.
7. Power loss in optical fibres can take place due to attenuation, dispersion, and bending.
8. Fibre optic-based communication systems are immune to EMI and are secure.
9. LEDs and LDs are two commonly used light sources.
10. Photoconductors, photodiodes, and phototransistors are commonly used photodetectors.
11. Fibre optic sensors can be used to monitor temperature and displacement.
12. An endoscope uses optical fibres to view the internal parts of the human body.

IMPORTANT FORMULAE

1. $\sin i/\sin r = n_2/n_1$
2. $\sin \theta_C = n_2/n_1$
3. $\mathrm{NA} = (n_1^2 - n_2^2)^{1/2}$
4. $\Delta t/L = n_1/n_2(n_1 - n_2)/c$
5. $L = 10/A \log_{10}(P_{in}/P_{out})$
6. $\lambda = hc/E_g = 1.24/E_g$ (μm)
7. $I_L = eG_L(\tau_p/t_n)\,(1 + \mu_p/\mu_n)AL$
8. $I_L = eG_L(W + L_n + L_p)$
9. $J_L = e\Phi_i(1 - \exp(-\alpha W)$
10. $\mathrm{NA} = \left(n_1^2 - n_2^2\right)^{1/2}$
11. $$\frac{\Delta t}{L} = \frac{n_1}{n_2}\left(\frac{n_1 - n_2}{c}\right)$$
12. $$A = \frac{10}{L}\log_{10}\frac{P_{in}}{P_{out}}$$
13. $$I_n = eG_n\left(\frac{\tau_p}{t_n}\right)\left(1 + \frac{\mu_p}{\mu_n}\right)^{AL}$$

SELF-ASSESSMENT

Multiple-choice Questions

5.1 The correct form of Snell's law is
(a) $\sin i/\sin r = n_2/n_1$
(b) $\sin r/\sin i = n_2/ n_1$
(c) $\sin i \sin r = n_2/\mathrm{n}_1$
(d) $\sin i = n_2/n_1$

5.2 NA is given by
(a) $\mathrm{NA} = (n_1^2 - n_2^2)$
(b) $\mathrm{NA} = (n_1^2 - n_2^2)^{1/2}$
(c) $(n_1^2 - n_2^2)^3$
(d) $1/(n_1^2 - n_2^2)$

5.3 Typical multimode links have data rates of
(a) 10–20 Mbit/s
(b) 10–100 Mbit/s
(c) 10 Mbit/s–10 Gbit/s
(d) (1 − 100) Mbit/s

5.4 Multiple time dispersion of optical fibre is expressed as
(a) $\Delta t/L = n_1 n_2 (n_1 - n_2)/c$
(b) $\Delta t/L = n_1/n_2[c/(n_1 - n_2)$
(c) $\Delta t/L = n_1 c/[n_2(n_1 - n_2)]$
(d) $\Delta t/L = n_1/n_2[(n_1 - n_2)/c]$

5.5 Light travelling in a graded-index fibre follows a
(a) helical path
(b) zigzag path
(c) circular path
(d) straight-line path

5.6 Attenuation loss, A, is given by the relation
(a) $A = 10L \log_{l0} (P_{\text{in}}/P_{\text{out}})$
(b) $A = (10/L) \log_{l0} (P_{\text{in}}/P_{\text{out}})$
(c) $A = (L/10) \log_{10} (P_{\text{in}}/P_{\text{out}})$
(d) $A = \log_{10} (P_{\text{in}}/P_{\text{out}})$

5.7 Solidus multipath time dispersion of optical fibre refers to
(a) $(\Delta t)L$ (b) $L/\Delta t$ (c) $\Delta t/L$ (d) $(\Delta t L)^2$

5.8 Fibre-optic communication is immune to EMI since it uses
(a) plastic (b) LEDs (c) photodiodes (d) light

5.9 Bandwidth parameter has the units
(a) MHz/km (b) MHz-km (c) (MHz)^2 km (d) dB/km

5.10 Wavelength of light emitted by an LED is governed by the equation
(a) h/cE_g (b) hc/E_g (c) E_g/hc (d) $E_g h/c$

5.11 LEDS use
(a) indirect-gap semiconductors
(b) direct-gap semiconductors
(c) both indirect- and direct-gap semiconductors
(d) none of these

5.12 The correct choice for fabricating an LED is
(a) Si (b) Ge (c) GaAs (d) carbon

5.13 Spectral output of an LED is
(a) narrow (b) wide (c) sharp (d) negligible

5.14 Wavelength bandwidth of an LD is typically
(a) >1 nm (b) >10 nm (c) = 1 nm (d) < 0.1 nm

5.15 Choose the one that is not a photodetector:
(a) Solar cell
(b) Photoconductor
(d) Photodiode
(d) Phototransistor

5.16 Photocurrent generated in a photoconductor is proportional to
(a) τ_p^2 (b) τ_p (c) $\dfrac{1}{\tau_p^2}$ (d) $\dfrac{1}{\tau_p}$

5.17 A photodiode uses a p–n junction that is
(a) forward biased
(b) not biased
(c) reverse biased
(d) none of these

Review Questions

5.1 Explain the phenomenon of total internal reflection.
5.2 What is an optical fibre?
5.3 Express Snell's law mathematically.
5.4 How many types of optical fibres are commonly used in fibre-optic communication?
5.5 Draw a schematic layout of a step-index optical fibre.
5.6 What are graded-index optical fibres?
5.7 Demonstrate, with a schematic diagram, refractive index dependence on radial distance for a graded-index optical fibre.
5.8 Write an expression for the numerical aperture of a graded-index fibre for $r = a$.
5.9 Provide a detailed description of an optical fibre-based communication system using a block diagram.
5.10 Explain the principle of operation of optical fibres.
5.11 What is the angle of acceptance for an optical fibre?
5.12 Define and explain numerical aperture for an optical fibre.
5.13 Derive the expression for NA.
5.14 Write an expression for $n(r)$ for a graded-index fibre.
5.15 Write expressions for the following parameters, for a graded-index fibre: (a) $(\mathrm{NA})_{axis}$ and (b) $(\mathrm{NA})_{r=a}$
5.16 What is demodulation?
5.17 What are the advantages of using optical fibres in communication systems?
5.18 Give some medical applications of optical fibres.
5.19 State and explain Snell's law.
5.20 Show the process of total internal reflection using a suitable diagram.
5.21 What is a cladding layer?
5.22 What is the role of the core in an optical fibre?
5.23 What is fractional refractive index?
5.24 Can we have a negative fractional refractive index?
5.25 What is the significance of angle of acceptance of an optical fibre?
5.26 What is the relationship between the angle ϕ_m and the critical angle θ_c?
5.27 What is the significance of numerical aperture of an optical fibre?
5.28 What is the maximum possible value of numerical aperture?
5.29 What are the two materials generally used for fabricating optical fibres?
5.30 Give one disadvantage of plastic optical fibres.
5.31 What are meridional rays?
5.32 What are skew rays?
5.33 Give the typical cladding diameter of a single-mode optical fibre.
5.34 Describe step function dependence of refractive index with a suitable sketch.
5.35 Draw a typical attenuation curve for an optical fibre.

Numerical Problems

5.1 A step-index fibre has a core of refractive index 1.5 and a cladding of refractive index 1.48. Calculate the numerical aperture of the fibre.

$$\left[\mathit{Hint}\text{: NA} = (n_1^2 - n_2^2)^{1/2}\right]$$

5.2 Determine the angles α_m and ϕ_m for the optical fibre indicated in Problem 5.1.
[*Hint*: NA = $n_0 \sin \alpha_m$ and $n_0 \sin \alpha_m = n_1 \sin \phi_m$]

5.3 Determine the pulse broadening per unit length due to multipath dispersion for the optical fibre mentioned in Problem 5.1. $\left[Hint\text{: } \dfrac{\Delta t}{L} = \dfrac{n_1}{n_2}\left(\dfrac{n_1 - n_2}{c}\right)\right]$

5.4 The core of the optical fibre mentioned in Problem 5.1 is replaced with a material of refractive index 1.52. Calculate the percentage change in pulse broadening per unit length. $\left[Hint\text{: } \dfrac{\Delta t}{L} = \dfrac{n_1}{n_2}\left(\dfrac{n_1 - n_2}{c}\right)\right]$

5.5 Calculate the critical angle for the optical fibre indicated in Problem 5.1. $\left[Hint\text{: } \theta_c = \sin^{-1}\left(\dfrac{n_2}{n_1}\right)\right]$

5.6 The optical fibre indicated in Problem 5.1 has a core diameter of 100 μm. Calculate the maximum number of total internal reflections per metre for the rays travelling through the optical fibre. $\left[Hint\text{: } \tan\phi_m = \dfrac{a}{L}\right]$