1 Introduction

After reading this chapter you will be able to appreciate the following:

- The subject of fiber optics and optoelectronics
- Historical developments in the field
- The configuration of a fiber-optic communication system
- Advantages of fiber-optic systems
- Emergence of fiber optics as a key technology
- Role of fiber optics technology

1.1 FIBER OPTICS AND OPTOELECTRONICS

Fiber optics is a branch of optics that deals with the study of propagation of light (rays or modes) through transparent dielectric waveguides, e.g., optical fibers. Optoelectronics is the science of devices that are based on processes leading to the generation of photons by electrons (e.g., laser diodes) or electrons by photons (e.g., photodiodes). The large-scale use of optoelectronic devices in fiber-optic systems has led to the integration of these two branches of science, and they are now synonymous with each other.

Prior to delving into the subject and its applications, a curious reader would like to know the following:

(i) the emergence of fiber optics as a dominant technology
(ii) the basic configuration of a fiber-optic system
(iii) the merits of such a system
(iv) the role of this technology in sociological evolution

This chapter aims at exploring these and other related issues.

1.2 HISTORICAL DEVELOPMENTS

The term 'fiber optics' was first coined by N.S. Kapany in 1956 when he along with his colleagues at Imperial College of Science and Technology, London, developed an image-transmitting device called the ‘flexible fiberscope’. This device soon found application in inspecting inaccessible points inside reactor vessels and jet aircraft engines. The flexible endoscope became quite popular in the medical field. Improved versions of these devices are now increasingly being used in medical diagnosis and surgery.

The next important development in this area was the demonstration of the first pulsed ruby laser in 1960 by T. Maiman at the Hughes Research Laboratory and the realization of the first semiconductor laser in 1962 by researchers working almost independently at various research laboratories. However, it took another eight years before laser diodes for application in communications could be produced.

Almost around the same period, another interesting development took place when Charles Kao and Charles Hockham, working at the Standard Telecommunication Laboratory in England, proposed in 1966 that an optical fiber might be used as a means of communication, provided the signal loss could be made less than 20 decibels per kilometer (dB/km). (The definition of a decibel is given in Appendix A1.1.) At that time optical fibers exhibited losses of the order of 1000 dB/km.

At this point, it is important to know why the need for optical fibers as a transmission medium was felt. In fact, the transfer of information from one point to another, i.e., communication, is achieved by superimposing (or modulating) the information onto an electromagnetic wave, which acts as a carrier for the information signal. The modulated carrier is then transmitted through the information channel (open or guided) to the receiver, where it is demodulated and the original information sent to the destination. Now the carrier frequencies present certain limitations in handling the volume and speed of information transfer. These limitations generated the need for increased carrier frequency. In fiber-optic systems, the carrier frequencies are selected from the optical range (particularly the infrared part) of the electromagnetic spectrum shown in Fig. 1.1.

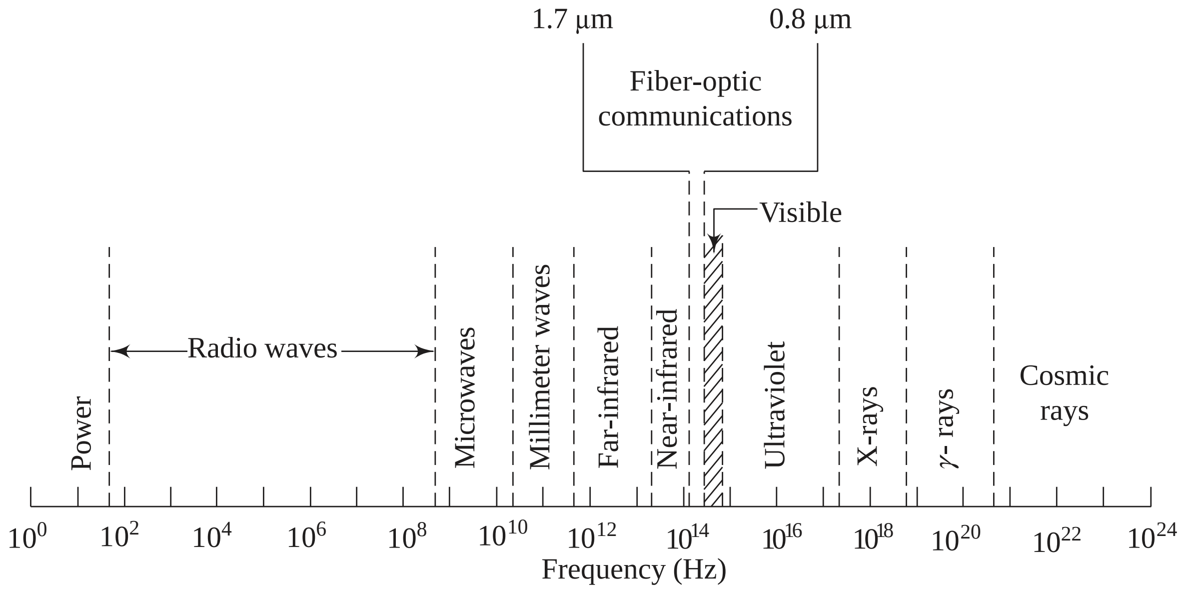

Fig. 1.1 Electromagnetic spectrum

The typical frequencies are of the order of 10^{14} Hz, which is 10,000 times greater than that of microwaves. Optical fibers are the most suitable medium for transmitting these frequencies, and hence they present theoretically unlimited possibilities.

Coming back to Kao and Hockham's proposal, the production of a low-loss optical fiber was required. The breakthrough came in 1970, when Dr Robert Maurer, Dr Donald Keck, and Dr Peter Schultz of Corning Glass Corporation of USA succeeded in producing a pure glass fiber which exhibited an attenuation of less than 20 dB/km. Concurrent developments in optoelectronic devices ushered in the era of fiber-optic communications technology.

1.3 A FIBER-OPTIC COMMUNICATION SYSTEM

Before proceeding further, let us have a look at the generalized configuration of a fiber-optic communication system, shown in Fig. 1.2. A brief description of each block in this figure will give us an idea of the prime components employed in this system.

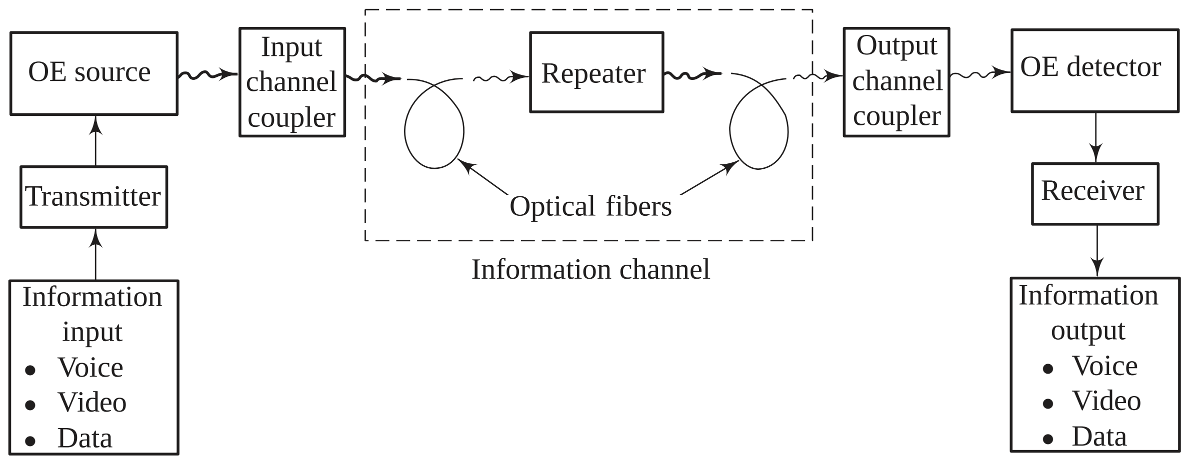

Fig. 1.2 Generalized configuration of a fiber-optic communication system

1.3.1 Information Input

The information input may be in any of the several physical forms, e.g., voice, video, or data. Therefore an input transducer is required for converting the non-electrical input into an electrical input. For example, a microphone converts a sound signal into an electrical current, a video camera converts an image into an electric current or voltage, and so on. In situations where the fiber-optic link forms a part of a larger system, the information input is normally in electrical form. Examples of this type include data transfer between different computers or that between different parts of the same computer. In either case, the information input must be in the electrical form for onward transmission through the fiber-optic link.

1.3.2 Transmitter

The transmitter (or the modulator, as it is often called) comprises an electronic stage which (i) converts the electric signal into the proper form and (ii) impresses this signal onto the electromagnetic wave (carrier) generated by the optoelectronic source.

The modulation of an optical carrier may be achieved by employing either an analog or a digital signal. An analog signal varies continuously and reproduces the form of the original information input, whereas digital modulation involves obtaining information in the discrete form. In the latter, the signal is either on or off, with the *on* state representing a digital 1 and the *off* state representing a digital 0. These are called *binary digits* (or bits) of the digital system. The number of bits per second (bps) transmitted is called the *data rate*. If the information input is in the analog form, it may be obtained in the digital form by employing an analog-to-digital converter.

Analog modulation is much simpler to implement but requires higher signal-to-noise ratio at the receiver end as compared to digital modulation. Further, the linearity needed for analog modulation is not always provided by the optical source, particularly at high modulation frequencies. Therefore, analog fiber-optic systems are limited to shorter distances and lower bandwidths.

1.3.3 Optoelectronic Source

An optoelectronic (OE) source generates an electromagnetic wave in the optical range (particularly the near-infrared part of the spectrum), which serves as an information carrier. Common sources for fiber-optic communication are the light-emitting diode (LED) and the injection laser diode (ILD). Ideally, an optoelectronic source should generate a stable single-frequency electromagnetic wave with enough power for long-haul transmission. However, in practice, LEDs and even laser diodes emit a range of frequencies and limited power. The favourable properties of these sources are that they are compact, lightweight, consume moderate amounts of power, and are relatively easy to modulate. Furthermore, LEDs and laser diodes which emit frequencies that are less attenuated while propagating through optical fibers are available.

1.3.4 Channel Couplers

In the case of open channel transmission, for example, the radio or television broadcasting system, the channel coupler is an antenna. It collects the signal from the transmitter and directs this to the atmospheric channel. At the receiver end again the antenna collects the signal and routes it to the receiver. In the case of guided channel transmission, e.g., a telephone link, the coupler is simply a connector for attaching the transmitter to the cable.

In fiber-optic systems, the function of a coupler is to collect the light signal from the optoelectronic source and send it efficiently to the optical fiber cable. Several designs are possible. However, the coupling losses are large owing to Fresnel reflection and limited light-gathering capacity of such couplers. At the end of the link again a coupler is required to collect the signal and direct it onto the photodetector.

1.3.5 Fiber-optic Information Channel

In communication systems, the term 'information channel' refers to the path between the transmitter and the receiver. In fiber-optic systems, the optical signal traverses along the cable consisting of a single fiber or a bundle of optical fibers. An optical fiber is an extremely thin strand of ultra-pure glass designed to transmit optical signals from the optoelectronic source to the optoelectronic detector. In its simplest form, it consists of two main regions: (i) a solid cylindrical region of diameter 8–100 μm called the core and (ii) a coaxial cylindrical region of diameter normally 125 μm called the cladding. The refractive index of the core is kept greater than that of the cladding. This feature makes light travel through this structure by the phenomenon of total internal reflection. In order to give strength to the optical fiber, it is given a primary or buffer coating of plastic, and then a cable is made of several such fibers. This optical fiber cable serves as an information channel.

For clarity of the transmitted information, it is required that the information channel should have low attenuation for the frequencies being transmitted through it and a large light-gathering capacity. Furthermore, the cable should have low dispersion in both the time and frequency domains, because high dispersion results in the distortion of the propagating signal.

1.3.6 Repeater

As the optical signals propagate along the length of the fiber, they get attenuated due to absorption, scattering, etc., and broadened due to dispersion. After a certain length, the cumulative effect of attenuation and dispersion causes the signals to become weak and indistinguishable. Therefore, before this happens, the strength and shape of the signal must be restored. This can be done by using either a regenerator or an optical amplifier, e.g., an erbium-doped fiber amplifier (EDFA), at an appropriate point along the length of the fiber.

1.3.7 Optoelectronic Detector

The reconversion of an optical signal into an electrical signal takes place at the OE detector. Semiconductor *p-i-n* or avalanche photodiodes are employed for this purpose. The photocurrent developed by these detectors is normally proportional to the incident optical power and hence to the information input. The desirable characteristics of a detector include small size, low power consumption, linearity, flat spectral response, fast response to optical signals, and long operating life.

1.3.8 Receiver

For analog transmission, the output photocurrent of the detector is filtered to remove the dc bias that is normally applied to the signal in the modulator module, and also to block any other undesired frequencies accompanying the signal. After filtering, the photocurrent is amplified if needed. These two functions are performed by the receiver module.

For digital transmission, in addition to the filter and amplifier, the receiver may include decision circuits. If the original information is in analog form, a digital-to-analog converter may also be required.

The design of the receiver is aimed at achieving high sensitivity and low distortion. The signal-to-noise ratio (SNR) and bit-error rate (BER) for digital transmission are important factors for quality communication.

1.3.9 Information Output

Finally, the information must be presented in a form that can be interpreted by a human observer. For example, it may be required to transform the electrical output into a sound wave or a visual image. Suitable output transducers are required for achieving this transformation. In some cases, the electrical output of the receiver is directly usable. This situation arises when a fiber-optic system forms the link between different computers or other machines.

1.4 ADVANTAGES OF FIBER-OPTIC SYSTEMS

Fiber-optic systems have several advantages, some of which were apparent when the idea of optical fibers as a means of communication was originally conceived.

For communication purposes, the transmission bandwidth and hence the information-carrying capacity of a fiber-optic system is much greater than that of coaxial copper cables, wide-band radio, or microwave systems. (The concepts of bandwidth and channel capacity are explained in Appendix A1.2.) Small size and light weight of optical fibers coupled with low transmission loss (typically around 0.2 dB/km) reduces the system cost as well as the need for numerous repeaters in long-haul telecommunication applications.

Optical fibers are insulators, as they are made up of glass or plastic. This property is useful for many applications. Particularly, it makes the optical signal traversing through the fiber free from any radio-frequency interference (RFI) and electromagnetic interference (EMI). RFI is caused by radio or television broadcasting stations, radars, and other signals originating in electronic equipment. EMI may be caused by these sources of radiation as well as from industrial machinery, or from naturally occurring phenomena such as lightning or unintentional sparking. Optical fibers do not pick up or propagate electromagnetic pulses (EMPs). Thus, fiber-optic systems may be employed for reliable monitoring and telemetry in industrial environments, where EMI and EMPs cause problems for metallic cables. In fact, in recent years, a variety of fiber-optic sensor systems have been developed for accurate measurement of parameters such as position, displacement, liquid level, temperature, pressure, refractive index, and so on.

In contrast to copper cables, the signal being transmitted through an optical fiber cannot be obtained from it without physically intruding the fiber. Further, the optical signal propagating along the fiber is well protected from interference and coupling with other communication channels (electrical or optical). Thus, optical fibers offer a high degree of signal security. This feature is particularly suitable for military and banking applications and also for computer networks.

For large-scale exploitation, the system's cost and the availability of raw material are two important considerations. The starting material for the production of glass fibers is silica, which is easily available. Regarding the cost, it has been shown that for long-distance communication, fiber cables are cheaper to transport and easier to install than metallic cables. Despite the fragile nature of glass fiber, these cables are surprisingly strong and flexible.

1.5 EMERGENCE OF FIBER OPTICS AS A KEY TECHNOLOGY

Fiber optics technology has been developed over the past three decades in a series of generations mainly identified by the operating wavelengths they employed. The first-generation fiber-optic systems employed a wavelength of 0.85 μm. This wavelength corresponds to the 'first (low-loss) window' in a silica-based optical fiber. This is shown in Fig. 1.3, where attenuation (dB/km) has been plotted as a function of wavelength for a typical silica-based optical fiber. The region around 0.85 μm was attractive for two reasons, namely, (i) the technology for LEDs that could be coupled to optical fibers had already been perfected and (ii) silicon-based photodiodes could be used for detecting a wavelength of 0.85 μm. This window exhibited a relatively high loss of the order of 3 dB/km. Therefore, as technology progressed, the first window become less attractive.

In fact from the point of view of long-haul communication applications, it is not only the attenuation but also the dispersion of pulses by a fiber that plays a key role in selecting the wavelength and the type of fiber. Therefore second-generation systems used a 'second window' at 1.3 μm with theoretically zero dispersion for silica fibers and also lesser attenuation around 0.5 dB/km.

In 1977, Nippon Telegraph and Telephone (NTT) succeeded in developing a 'third window' at 1.55 μm that offered theoretically minimum attenuation (but non-zero dispersion) for silica fibers. The corresponding loss was about 0.2 dB/km. The same year witnessed the successful commercial deployment of fiber-optic systems by AT&T Corp. (formerly, American Telephone and Telegraph Corporation) and GTE Corp.

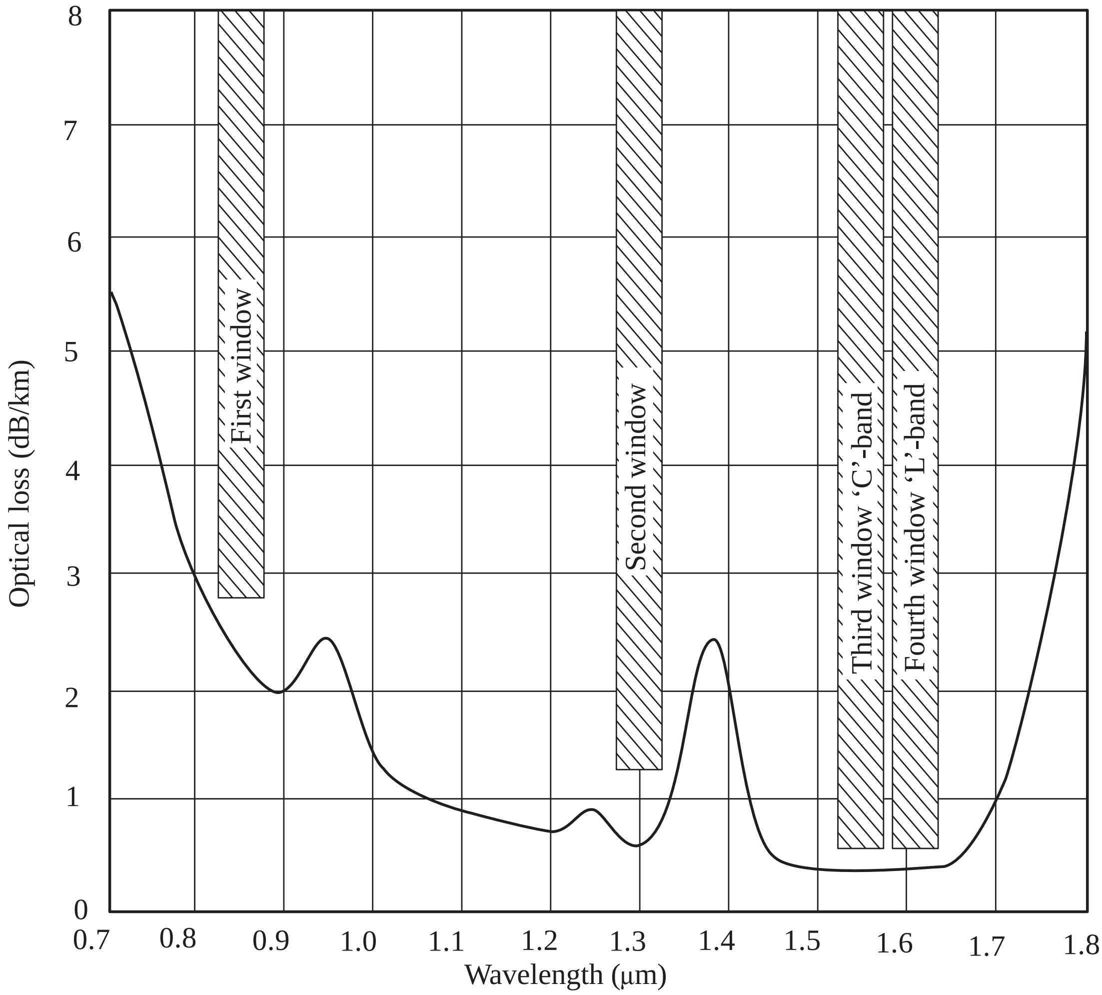

Fig. 1.3 Attenuation versus wavelength for a typical silica-based fiber. Low-loss windows (i.e., wavelength ranges) have been shown by hatched areas.

(formerly, General Telephone and Electronics Corporation). Since then there has been tremendous progress in this technology.

Originally, short-haul fiber-optic links were designed around multimode graded-index fibers; but in the 1980s fiber-optic networks first used single-mode fibers (SMF) operating at 1.31 μm. Later on, use of the dispersion-shifted fiber (DSF) with low dispersion and low attenuation (at 1.55 μm) became the standard practice in long-haul communication links.

In 1990, Bell Laboratories demonstrated the transmission of 2.5 Gbits (10^9 bits) per second over 7500 km without regeneration. This system employed a soliton laser and an EDFA.

In 1998 Bell Laboratories achieved another milestone of transmitting 100 simultaneous optical signals, each at a data rate of 10 Gbits per second, for a distance of nearly 400 km. In this experiment, the concept of dense wavelength-division multiplexing (DWDM), which allows multiple wavelengths to be transmitted as a single optical signal, was employed to increase the total data rate on one fiber to 1 Tbit (10^{12} bits) per second. Since then this technology has been growing fast.

In fact, researches in dispersion management technologies have played a key role in the explosive progress in optical-fiber communications in the past decade. As the demand for more capacity, more speed and more clarity increases, driven mainly by the phenomenal growth of the Internet, the move to optical networking is the focus of new technologies. Therefore the next-generation fiber-optic systems will involve a revamping of existing network architectures and developing all-optical networks. Tunable lasers offer the possibility of connecting any WDM node with a single transmitter, thus enhancing network flexibility and also enabling smooth upgrading of networks. In order to get maximum benefit from a reconfigurable network, one would need not only tunable transmitters but also tunable wavelength add-drop multiplexers (WADM) and tunable receivers. Such configurations are called tunable-transmitter–tunable-receiver (TTTR) networks.

As an optical fiber has immense potential bandwidth (more than 50 THz), there are extraordinary possibilities for future fiber-optic systems and their applications.

1.6 THE ROLE OF FIBER OPTICS TECHNOLOGY

We are living in an 'information society', where the efficient transfer of information is highly relevant to our well-being. Fiber-optic systems are going to form the very means of such information transfer and hence they are destined to have a very important role, directly or indirectly, in the development of almost every sphere of life. Table 1.1 gives just a glance at the areas in which fiber optics technology is going to have a major impact.

Table 1.1 Role of fiber optics technology

Direct	Indirect
Voice Communication • Inter-office • Intercity • Intercontinental links	Entertainment • High-definition television (HDTV) • Video on demand • Video games
Video communication • TV broadcast • Cable television (CATV) • Remote monitoring • Wired city • Videophones	Power systems • Monitoring of power-generating stations • Monitoring of transformers Transportation • Traffic control in high-speed electrified railways • Traffic control in metropolitan cities • Monitoring of aircraft
Data transfer • Inter-office data link • Local area networks • Computers • Satellite ground stations	Health care • Minimal invasive diagnosis, surgery, and therapy

(*contd*)

Table 1.1 (*contd*)

Direct	Indirect
Internet • Email • Access to remote information (e.g., web pages) • Videoconferencing Sensor systems for industrial applications • Point sensors for measurement of position, flow rate, temperature, pressure, etc. • Distributed sensors • Smart structures • Robotics	• Endoscopes • Biomedical sensors • Remote monitoring of patients Military defence • Strategic base communication • Guided missiles • Sensors • Virtual wars Business development • Videoconferencing • Industrial CAD/CAM • Monitoring of manufacturing plants Education • Closed-circuit television (CCTV) • Distance learning • Access to remote libraries

1.7 OVERVIEW OF THE TEXT

An optical fiber is the heart of any fiber-optic system. We, therefore, begin with an easy-to-understand ray model of the propagation of light through optical fibers. The effect of multipath and material dispersion is discussed to assess the limitation of optical fibers. This is presented in Chapter 2.

In fact, light is an electromagnetic wave. Its propagation through optical fibers cannot be properly analysed using a ray model. Therefore, in Chapter 3, we start with Maxwell's equations governing the propagation of electromagnetic waves through any medium and apply them with appropriate boundary conditions to the simplest kind of planar waveguide. This treatment provides the much needed understanding of the concept of modes. Wave propagation in cylindrical dielectric waveguides is treated in Chapter 4. The modal analysis of step-index fibers is given in detail. The relevant parameters of graded-index fibers are also discussed in this chapter.

Modern fiber-optic communication systems use SMFs. Therefore, Chapter 5 is fully devoted to the discussion of such fibers. Thus key parameters of SMF—dispersion, attenuation, and types—have been explained here in detail.

Chapter 6 deals with the manufacturing methods of optical fibers, the optical fiber cable design, and the losses associated with fiber-to-fiber connections. Several methods of characterization of optical fibers have also been given in this chapter.

Any fiber-optic system would require an appropriate source of light at the transmitter end and a corresponding detector at the receiver end. The treatment of optoelectronic sources is given in Chapter 7. Starting with basic semiconductor physics, this chapter explains the theory behind LEDs, their design, and limitations, and then focuses on ILDs, which are commonly used in fiber-optic communication systems. Chapter 8 explains the basic principles of optoelectronic detection. Different types of photodiodes have also been described briefly.

A newer trend in fiber-optic communications is to use optoelectronic modulation rather than electronic modulation. Thus, Chapter 9 includes different types of optoelectronic modulators based on the electro-optic and the acousto-optic effect.

The in-line repeaters, power boosters, or pre-amplifiers of present-day communication systems are all optical amplifiers. Therefore, Chapter 10 is fully devoted to the discussion of different types of optical amplifiers, e.g., semiconductor optical amplifier, EDFA, etc.

Chapters 11 and 12 together present a discussion of the relevant concepts and related components of modern fiber-optic communication systems. Thus, the latest concepts of WDM and DWDM and related components have been described in Chapter 11. System design considerations for digital and analog systems, different types of system architectures, effects of non-linear phenomena, dispersion management, and solitons have been described in Chapter 12.

Optical fibers have not only revolutionized communication systems but also, owing to their small size, immunity from EMI and RFI, compatibility with fully distributed sensing, etc., they have, along with lasers, invaded the field of industrial instrumentation. Thus, Chapter 13 describes various types of point and distributed fiber-optic sensors and their applications in industrial measurements. Chapter 14 focuses mainly on laser-based systems and their applications in various fields.

Finally, in order to obtain hands-on experience and a deeper understanding of the basic principles and also a feel of their applications, some laboratory-oriented projects in this area have been described in Chapter 15. Industrious students can use the material presented in this chapter for making their own kit with the help of their professors for performing various measurements.

APPENDIX A1.1: RELATIVE AND ABSOLUTE UNITS OF POWER

The relative power level between two points along a fiber-optic communication link is measured in decibels (dB). For a particular wavelength λ, if P_0 is the power launched at one end of the link and P is the power received at the other end, the efficiency of transmission of the link is P/P_0. When P and P_0 are both measured in the same units, their ratio in decibels is expressed as follows:

$$\text{dB} = 10\log_{10}(P/P_0)$$

There is always some loss in the communication link. Hence the ratio P/P_0 is always less than 1 and the logarithm of this ratio is negative.

In order to make absolute measurements, P_0 is given a reference value, normally 1 mW. The value of power (say, P) relative to P_0 (= 1 mW) is denoted by dBm. Thus

$$\text{dBm} = 10\log_{10}\frac{P\ (\text{mW})}{P_0\ (1\,\text{mW})} = 10\log_{10} P$$

APPENDIX A1.2: BANDWIDTH AND CHANNEL CAPACITY

The optical bandwidth of a fiber-optic system is the range of frequencies (transmitted by the system) between two points (f_1 and f_2 on a frequency scale) where the output optical power drops to 50% of its maximum value (see Fig. A1.2). This corresponds to a loss of –3 dB. Normally f_1 is taken to be zero.

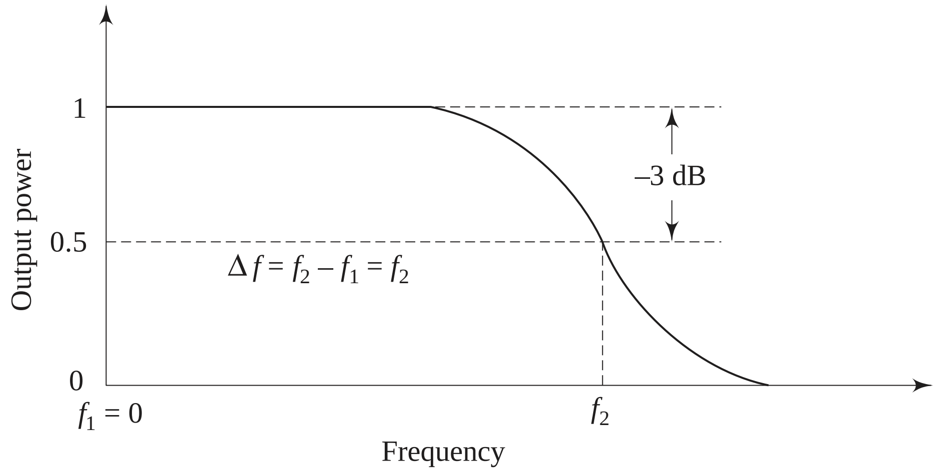

Fig. A1.2

It is important to note that in an all-electrical system, the power is proportional to the square of the root-mean-square value of the current. Thus the 0.5 (or –3 dB) point on a power scale corresponds to 0.707 on a current scale. The electrical bandwidth for such systems (with $f_1 = 0$) is defined as the frequency for which the output current amplitude drops to 0.70 of its maximum value. In a fiber-optic system, the power supplied by the optical source is normally proportional to the current supplied to it (and not to the square of the current as in an all-electrical system). In this case, therefore, the half-power point is equivalent to half-current point. Thus the electrical bandwidth $(\Delta f)_{el}$ of a fiber-optic system is less than its optical bandwidth $(\Delta f)_{opt}$. Actually,

$$(\Delta f)_{el} = (\Delta f)_{opt}(1/2)^{1/2}$$

or

$$(\Delta f)_{el} = 0.707(\Delta f)_{opt}$$

The term ‘channel capacity’ is used in connection with a digital system or a link. It is the highest data rate (in bps) a system can handle. It is related to the bandwidth Δf and is limited by the S/N ratio of the received signal. Employing information theory, it can be shown that the channel capacity or the maximum bit rate B of a communication channel which is able to carry analog signals covering a bandwidth Δf (in Hz) is given by Shannon’s formula:

$$B \text{ (bps)} = \Delta f \log_2 [1 + (S/N)^2]$$

where S is the average signal power and N is the average noise power. If $S/N \gg 1$,

$$B \approx 2\Delta f \log_2(S/N) \approx 6.64\Delta f \log_{10}(S/N)$$

Note In practice, when analog signals are to be transmitted digitally, the bit rate will depend on the sampling rate of the analog signal and the coding scheme. The Nyquist criterion suggests that an analog signal can be transmitted accurately if it is sampled at a rate of at least twice the highest frequency contained in the signal, i.e., if the sampling frequency $f_s \gg 2f_2$. Thus a voice channel of 4 kHz bandwidth would require $f_s = 8$ kHz. A standard coding procedure requires 8 bits to describe the amplitude of each sample, so that the data rate required to transmit a single voice message would be 8×8000 bps = 64 kbps.

Part I: Fiber Optics

2 Ray Propagation in Optical Fibers

After reading this chapter you will be able to understand the following:

- Ray propagation in step-index fibers
- Ray propagation in graded-index fibers
- Effect of multipath time dispersion
- Effect of material dispersion
- Calculation of rms pulse width

2.1 INTRODUCTION

Fiber optics technology uses light as a carrier for communicating signals. Classical wave theory treats light as electromagnetic waves, whereas the quantum theory treats it as photons, i.e., quanta of electromagnetic energy. In fact, this is what is known as the wave-particle duality in modern physics.

Both points of view are valid and valuable in their respective domains. However, it will be easier to understand the propagation of light signals through optical fibers if we think of light as rays that follow a straight-line path in going from one point to another. *Ray optics* employs the geometry of a straight line to explain the phenomena of reflection, refraction, etc. Hence, it is also called *geometrical optics*. Let us review, in brief, certain laws of geometrical optics, which aid the understanding of ray propagation in optical fibers.

2.2 REVIEW OF FUNDAMENTAL LAWS OF OPTICS

The most important optical parameter of any transparent medium is its refractive index n. It is defined as the ratio of the speed of light in vacuum (c) to the speed of light in the medium (v). That is,

$$n = \frac{c}{v} \tag{2.1}$$

As v is always less than c, n is always greater than 1. For air, $n = n_a \approx 1$.

The phenomenon of refraction of light at the interface between two transparent media of uniform indices of refraction is governed by Snell's law. Consider a ray of light passing from a medium of refractive index n_1 into a medium of refractive index n_2 [see Fig. 2.1(a)]. Assume that $n_1 > n_2$ and that the angles of incidence and refraction with respect to the normal to the interface are, respectively, ϕ_1 and ϕ_2. Then, according to Snell's law,

$$n_1 \sin\phi_1 = n_2 \sin\phi_2 \tag{2.2}$$

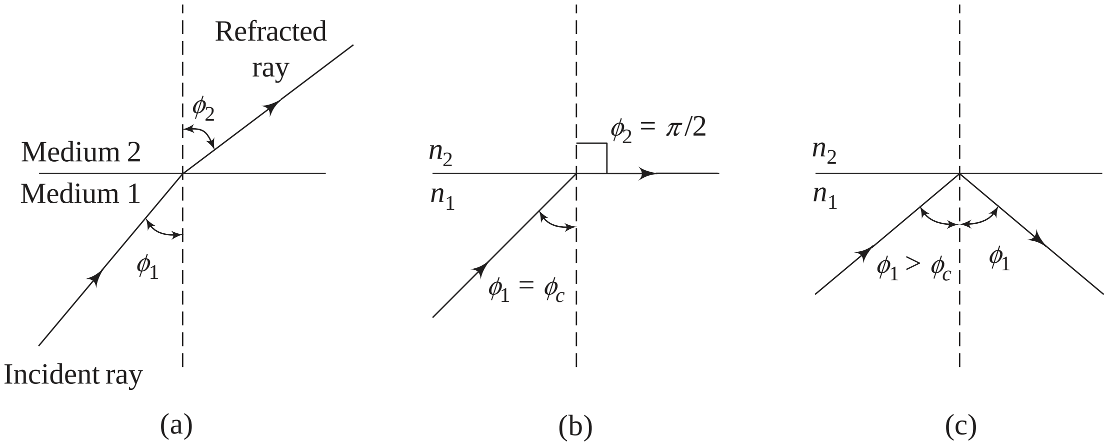

Fig. 2.1 (a) Refraction of a ray of light. (b) Critical ray incident at $\phi_1 = \phi_c$ and refracted at $\phi_2 = \pi/2$. (c) Total internal reflection ($\phi_1 > \phi_c$).

As $n_1 > n_2$, if we increase the angle of incidence ϕ_1, the angle of refraction ϕ_2 will go on increasing until a critical situation is reached, when for a certain value of $\phi_1 = \phi_c$, ϕ_2 becomes $\pi/2$, and the refracted ray passes along the interface. This angle $\phi_1 = \phi_c$ is called the critical angle. If we substitute the values of $\phi_1 = \phi_c$ and $\phi_2 = \pi/2$ in Eq. (2.2), we see that $n_1 \sin\phi_c = n_2 \sin(\pi/2) = n_2$. Thus

$$\sin\phi_c = n_2/n_1 \tag{2.3}$$

If the angle of incidence ϕ_1 is further increased beyond ϕ_c, the ray is no longer refracted but is reflected back into the same medium [see Fig. 2.1(c)]. (This is ideally expected. In practice, however, there is always some tunnelling of optical energy through this interface. The wave carrying away this energy is called the *evanescent wave*. This can be explained in terms of electromagnetic theory, discussed in Chapters 3 and 4.) This is called total internal reflection. It is this phenomenon that is responsible for the propagation of light through optical fibers.

There are several types of optical fibers designed for different applications. We will discuss these in Chapter 4. For the present discussion, we will begin with ray propagation in the simplest kind of optical fiber.

2.3 RAY PROPAGATION IN STEP-INDEX FIBERS

A step-index optical fiber is a thin dielectric waveguide consisting of a solid cylindrical core (diameter, $2a$ = 50–100 μm) of refractive index n_1, surrounded by a coaxial cylindrical cladding (diameter, $2b$ = 120–140 μm) of refractive index n_2 ($n_1 > n_2$), as shown in Fig. 2.2. The refractive index n is a step function of the radial distance r, as shown in Fig. 2.2(a). Hence it is called a *step-index* (SI) fiber.

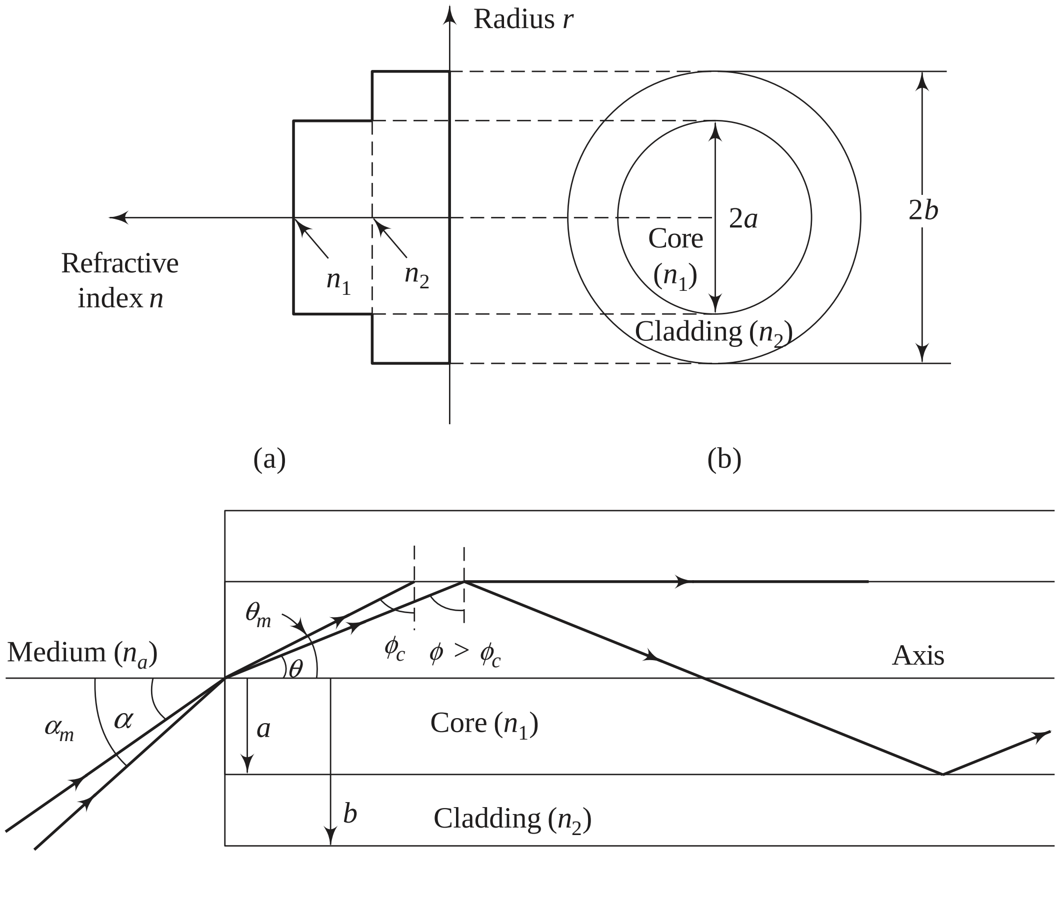

Fig. 2.2 Basic structure of a step-index fiber: (a) refractive index profile, (b) cross section (front view), (c) ray propagation (side view)

The material used for the production of an optical fiber is either silica (glass) or plastic. Assume that such a fiber is placed in a medium (normally air) of refractive index n_a ($n_1 > n_2 > n_a$). If a ray of light enters from the flat end of the fiber at some angle α, from the medium into the core, it will bend towards the normal, making an angle of refraction, θ. This ray then strikes the core–cladding interface at an angle of incidence ϕ. If $\phi > \phi_c$, the ray will undergo total internal reflection. It will suffer multiple reflections at the core–cladding interface and emerge out of the fiber at the other end.

What is the allowed range of α? The propagation of rays by total internal reflection requires ϕ to be greater than ϕ_c and hence θ to be less than $\theta_m = \pi/2 - \phi_c$. Thus, the angle of incidence α should be less than a certain angle α_m. This maximum value of α_m will correspond to the limiting value of $\theta_m = \pi/2 - \phi_c$.

Applying Snell's law at the core–medium (air) interface, we get for $\alpha = \alpha_m$ and corresponding $\theta = \theta_m$,

$$n_a \sin\alpha_m = n_1 \sin\theta_m = n_1 \cos\phi_c$$

for the incident ray at the core–cladding interface. From Eq. (2.3), we know that $\sin\phi_c = n_2/n_1$. Therefore,

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

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

Thus $$n_a \sin\alpha_m = n_1 \frac{(n_1^2 - n_2^2)^{1/2}}{n_1} = (n_1^2 - n_2^2)^{1/2}$$

The light collected and propagated by the fiber will thus depend on the value of α_m, which is fixed for a given optical fiber (n_1 and n_2 being constants). This limiting angle α_m is called the *angle of acceptance* of the fiber. This means that all the rays incident within a cone of half-angle α_m will be collected and propagated by the fiber. The term $n_a \sin\alpha_m$ is called the *numerical aperture* (NA) of the fiber; it determines the light-gathering capacity of the fiber. Thus

$$\text{NA} = n_a \sin\alpha_m = (n_1^2 - n_2^2)^{1/2} \tag{2.4}$$

NA can also be expressed in terms of the relative refractive index difference Δ, of the fiber, which is defined as follows:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{2.5}$$

Hence $$\text{NA} = (n_1^2 - n_2^2)^{1/2} = n_1\sqrt{2\Delta} \tag{2.6}$$

So far, we have considered the propagation of a single ray of light. However, a pulse of light consists of several rays, which may propagate at all values of α, varying from 0 to α_m. The paths traversed by the two extreme rays, one corresponding to $\alpha = 0$ and the other corresponding to α very nearly equal to (but less than) α_m, are shown in Fig. 2.3.

An axial ray travels a distance L inside the core of index n_1 with velocity v in time

$$t_1 = \frac{L}{v} = \frac{Ln_1}{c}$$

since, by definition, $n_1 = c/v$.

The most oblique ray corresponding to $\alpha \approx \alpha_m$ will cover the same length of fiber

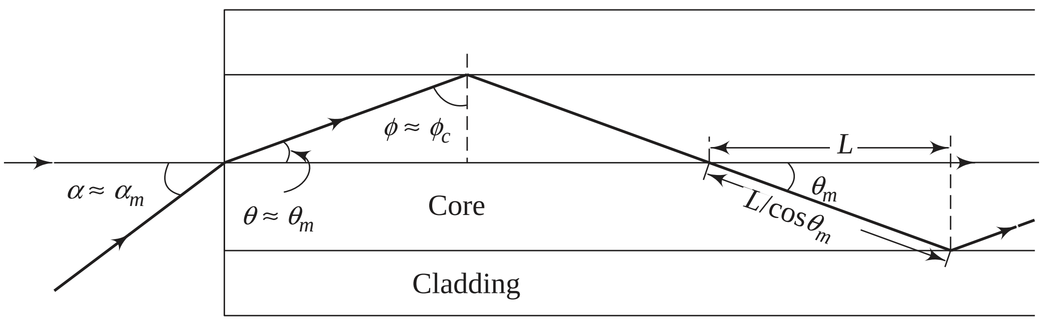

Fig. 2.3 Trajectories of two extreme rays inside the core of a step-index fiber

(axial length L, but actual distance $L/\cos\theta_m$) in time t_2 given by

$$t_2 = \frac{L/\cos\theta_m}{v} = \frac{Ln_1}{c\cos\theta_m} = \frac{Ln_1}{c\sin\phi_c} = \frac{Ln_1}{c(n_2/n_1)} = \frac{Ln_1^2}{cn_2}$$

The two rays are launched at the same time, but will be separated by a time interval ΔT after travelling the length L of the fiber, given by

$$\Delta T = t_2 - t_1 = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c} = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right)$$

Thus a light pulse consisting of rays spread over $\alpha = 0$ to $\alpha = \alpha_m$ will be broadened as it propagates through the fiber, and the pulse broadening per unit length of traversal will be given by

$$\frac{\Delta T}{L} = \frac{n_1}{n_2}\left(\frac{n_1 - n_2}{c}\right) \tag{2.7}$$

This is referred to as *multipath time dispersion* of the fiber.

Example 2.1 If the step-index fiber of Fig. 2.3 has a core of refractive index 1.5, a cladding of refractive index 1.48, and a core diameter of 100 µm, calculate, assuming that the fiber is kept in air, the (a) NA of the fiber; (b) angles α_m, θ_m, and ϕ_c; and (c) pulse broadening per unit length ($\Delta T/L$) due to multipath dispersion.

Solution

$n_1 = 1.5$, $n_2 = 1.48$, $2a = 100$ µm, and $n_a = 1$.

(a) $\text{NA} = \sqrt{n_1^2 - n_2^2} = \sqrt{2.25 - 2.19} = 0.244$

(b) $\text{NA} = n_a \sin\alpha_m = 1 \times \sin\alpha_m = 0.244$

Therefore, $\alpha_m = 14.13°$

Also $n_a \sin\alpha_m = n_1 \sin\theta_m$

or $0.244 = 1.5 \sin\theta_m$

Therefore, $\theta_m = \sin^{-1}\left(\dfrac{0.244}{1.5}\right) = 9.36°$

Further, $\phi_c = \sin^{-1}\left(\dfrac{n_2}{n_1}\right) = 80.63°$

(c) $$\frac{\Delta T}{L} = \frac{n_1}{n_2}\left(\frac{n_1 - n_2}{c}\right) = \frac{1.5}{1.48}\left(\frac{1.5 - 1.48}{3 \times 10^8 \text{ m s}^{-1}}\right) = 6.75 \times 10^{-11} \text{ s m}^{-1}$$

Example 2.2 For the optical fiber of Example 2.1, what are the minimum and maximum number of reflections per metre for the rays guided by it?

Solution

The ray that passes along the axis of the fiber, that is, the one for which $\alpha = 0$, will not be reflected, but the ray that follows the most oblique path, that is, is incident at an angle α very nearly equal to (but less than) α_m, will suffer maximum number of reflections. These can be calculated using the geometry of Fig. 2.3.

$$\tan\theta_m = \frac{a}{L}$$

Hence $$L = \frac{a}{\tan\theta_m} = \frac{50 \times 10^{-6} \text{ m}}{\tan(9.36°)} = 3.03 \times 10^{-4} \text{ m}$$

Therefore, the maximum number of reflections per metre would be

$$\frac{1}{2L} = 1648 \text{ m}^{-1}$$

All other rays will suffer reflections between these two extremes of 0 and 1648 m^{-1}.

2.4 RAY PROPAGATION IN GRADED-INDEX FIBERS

In a step-index fiber, the refractive index of the core is constant, n_1, and that of the cladding is also constant, n_2; n_1 being greater than n_2. The refractive index n is a step function of the radial distance. A pulse of light launched in such a fiber will get broadened as it propagates through it due to multipath time dispersion. Therefore, such fibers cannot be used for long-haul applications. In order to overcome this problem, another class of fibers is made, in which the core index is not constant but varies with radius r according to the following relation:

$$n(r) = \begin{cases} n_1 = n_0\left[1 - 2\Delta\left(\dfrac{r}{a}\right)^{\alpha}\right]^{1/2} & \text{for } r \le a \\ n_2 = n_0\,[1 - 2\Delta]^{1/2} = n_c & \text{for } b \ge r \ge a \end{cases} \tag{2.8}$$

where $n(r)$ is the refractive index at radius r, a is the core radius, b is the radius of the cladding, n_0 is the maximum value of the refractive index along the axis of the core, Δ is the relative refractive index difference, and α is called the *profile parameter*. Such a fiber is called a *graded-index* (GI) fiber. For $\alpha = 1$, the index profile is triangular; for $\alpha = 2$, the profile is parabolic; and for $\alpha = \infty$, the profile is that of a SI fiber, as shown in Fig. 2.4.

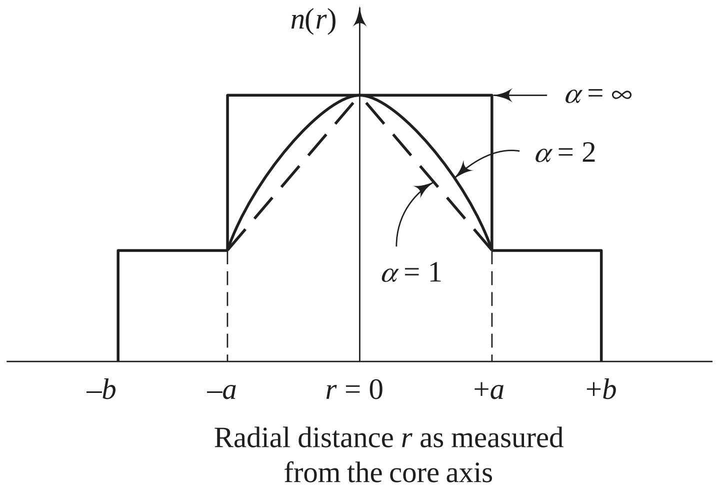

Fig. 2.4 Variation of $n(r)$ with r for different refractive index profiles

For a parabolic profile, which reduces the modal dispersion considerably, as we will see later, the expression for NA can be derived as follows:

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

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

$$= n_0 \left[2\Delta \left(1 - \frac{r^2}{a^2} \right) \right]^{1/2} \tag{2.9}$$

Therefore axial NA $= n_0 \sqrt{2\Delta}$; the NA decreases with increasing r and becomes zero at $r = a$.

In order to appreciate ray propagation through a GI fiber, let us first visualize the core of this fiber as having been made up of several coaxial cylindrical layers, as shown in Fig. 2.5.

The refractive index of the central cylinder is the highest, and it goes on decreasing in the successive cylindrical layers. Thus, the meridional ray shown takes on a curved path, as it suffers multiple refractions at the successive interfaces of high to low refractive indices. The angle of incidence for this ray goes on increasing until the condition for total internal reflection is met; the ray then travels back towards the core axis. On the other hand, the axial ray travels uninterrupted.

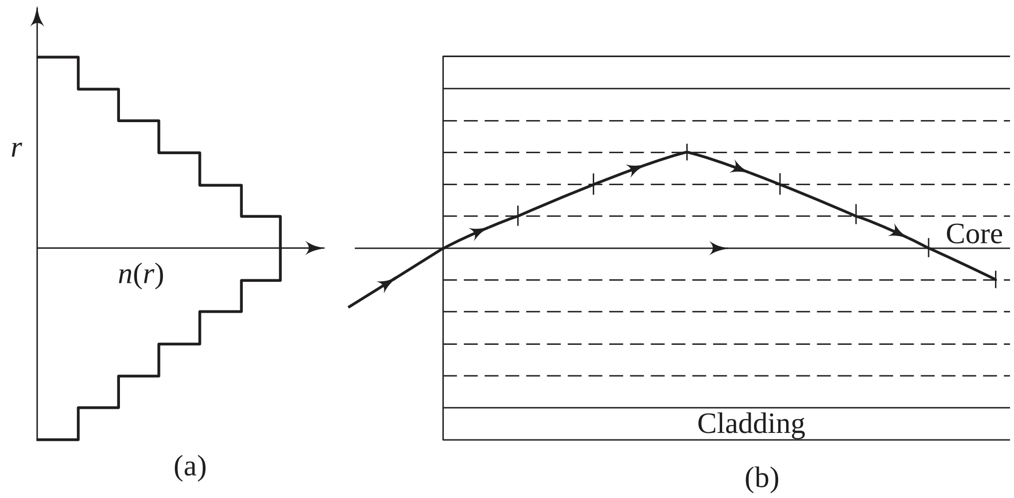

Fig. 2.5 (a) Variation of n with r, (b) ray traversal through different layers of the core

In this configuration, the multipath time dispersion will be less than that in SI fibers. This is because the rays near the core axis have to travel shorter paths compared to those near the core–cladding interface. However, the velocity of the rays near the axis will be less than that of the meridional rays because the former have to travel through a region of high refractive index ($v = c/n$). Thus, both the rays will reach the other end of the fiber almost simultaneously, thereby reducing the multipath dispersion. If the refractive index profile is such that the time taken for the axial and the most oblique ray is same, the multipath dispersion will be zero. In practice, a parabolic profile ($\alpha = 2$), shown in Fig. 2.6, reduces this type of dispersion considerably.

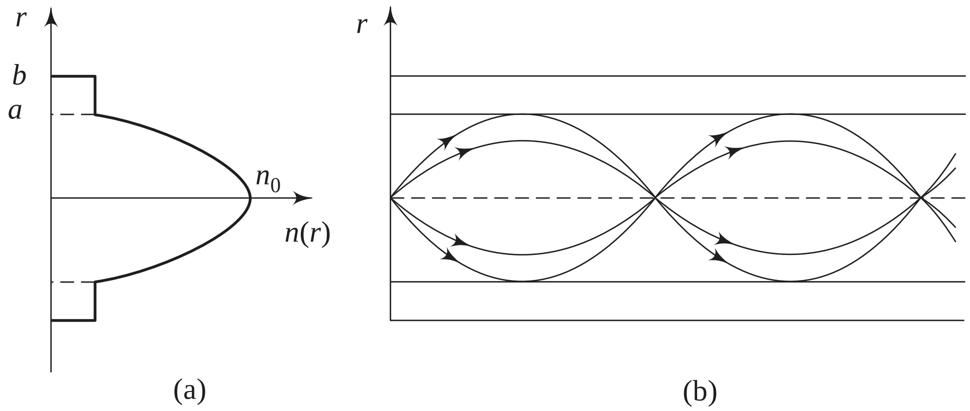

Fig. 2.6 (a) The parabolic profile of a GI fiber, (b) ray path in such a fiber

2.5 EFFECT OF MATERIAL DISPERSION

We know from our earlier discussion that the refractive index n of any transparent medium is given by $n = c/v$, where c is the velocity of light in vacuum and v is its velocity in the medium. In terms of wave theory, v is called the *phase velocity* v_p of the wave in the medium. Thus,

$$v = v_p = c/n \tag{2.10}$$