3

Basic characteristics of the optical fiber

3.1 Introduction

An optical waveguide is a structure that can guide a light beam from one place to another. The most extensively used optical waveguide is the step index optical fiber that consists of a cylindrical central dielectric core, clad by a dielectric material of a slightly lower refractive index (see Figure 3.1(a)). The corresponding refractive index distribution (in the transverse direction) is given by

$$\begin{aligned} n(r) &= n_1, \quad 0 < r < a \quad \text{core} \\ &= n_2, \quad r > a \quad \text{cladding} \end{aligned} \tag{3.1}$$

where r represents the cylindrical radial coordinate and a represents the radius of the core. Actually, the core extends only to a finite distance b (see Figure 3.1(b)); however, for all practical purposes, we will assume the cladding to extend to infinity. Typically, for a step index (multimode) silica fiber,

$$n_1 \simeq 1.48, \quad n_2 \simeq 1.46, \quad a \simeq 25\ \mu\text{m}, \quad b \simeq 62.5\ \mu\text{m} \tag{3.2}$$

In this chapter, we discuss the various characteristics of the optical fiber – namely, its light-gathering power and its loss- and pulse-broadening characteristics. Throughout the chapter we use ray optics, which is valid for highly multimoded waveguides.

To understand light guidance in an optical fiber, we consider a ray entering the fiber as shown in Figure 3.1(a). If the angle of incidence (at the core–cladding interface) ϕ is greater than the critical angle

$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \tag{3.3}$$

then the ray will undergo total internal reflection at that interface. Further, because of the cylindrical symmetry in the fiber structure, this ray will suffer total internal reflection at the lower interface also and therefore will get guided through the core by repeated total internal reflections. Even for a bent fiber, light guidance can take place through multiple total internal reflections (see Figure 3.2). Figure 3.3 shows the actual guidance of a light beam as it propagates through a long optical fiber.

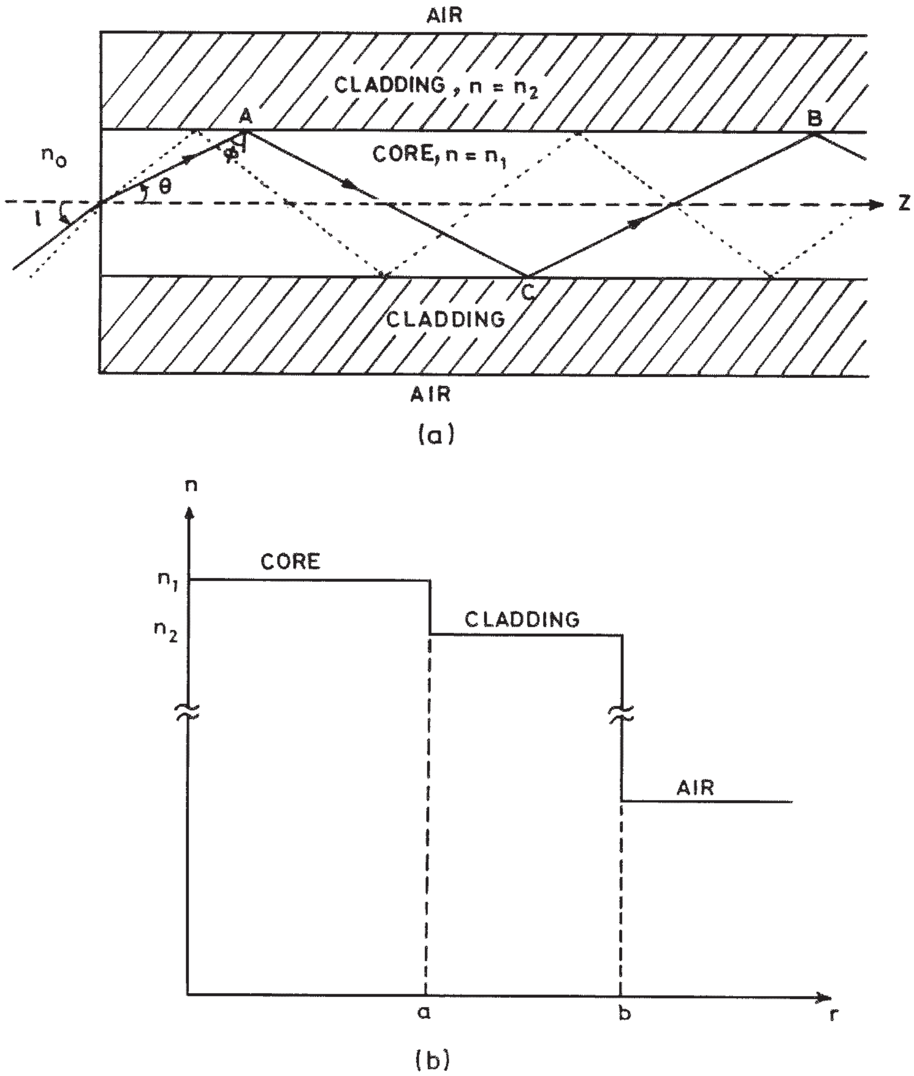


Fig. 3.1: (a) A glass fiber that consists of a cylindrical central core, clad by a material of slightly lower refractive index. Light rays impinging on the core–cladding interface at an angle greater than the critical angle are trapped inside the core of the waveguide. Rays making larger angles with the axis take a longer to traverse the length of the fiber. (b) Refractive index distribution of a cladded optical fiber that consists of a cylindrical glass structure surrounded by a material of slightly lower refractive index. In a typical (multimode) fiber, we may have the core refractive index $n_1 \simeq 1.5$, $\Delta = 0.01$, core radius $a = 25\,\mu$m, $2b = 125\,\mu$m.

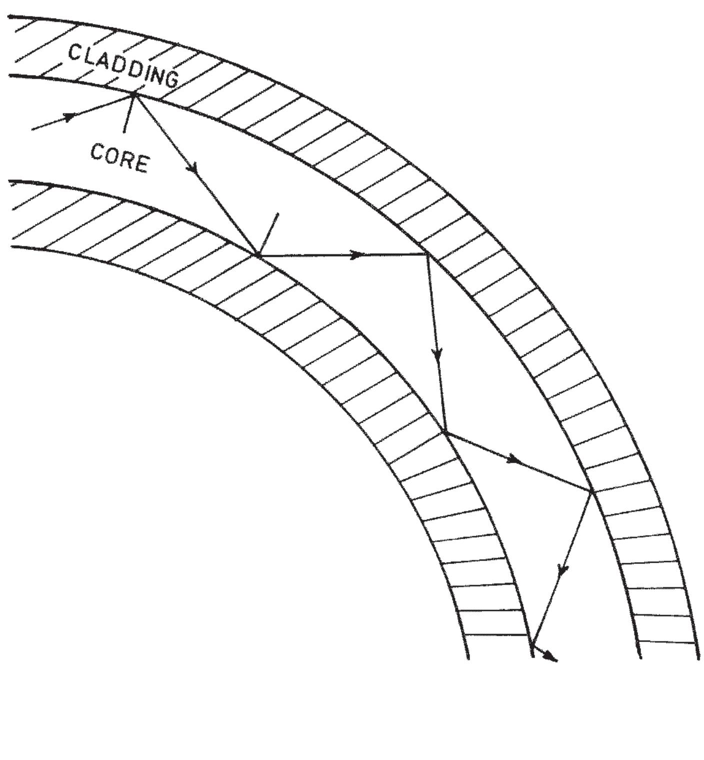


Fig. 3.2: Rays propagating through a bent fiber. Notice that whereas the angle of incidence (at the core–cladding interface) remains constant in a straight fiber [see Figure 3.1(a)], it changes in a bent fiber. Thus, a ray may eventually hit the core–cladding interface at an angle less than the critical angle and be refracted away.

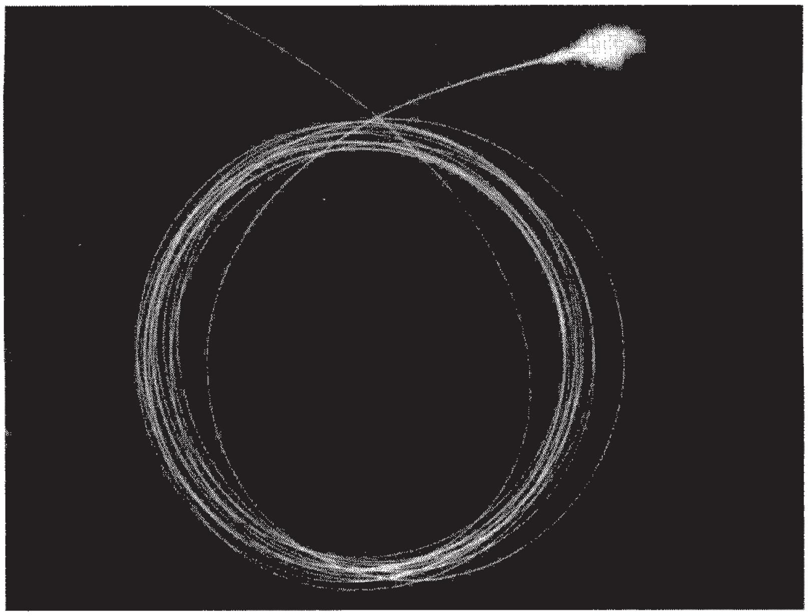


Fig. 3.3: A long optical fiber carrying a light beam.

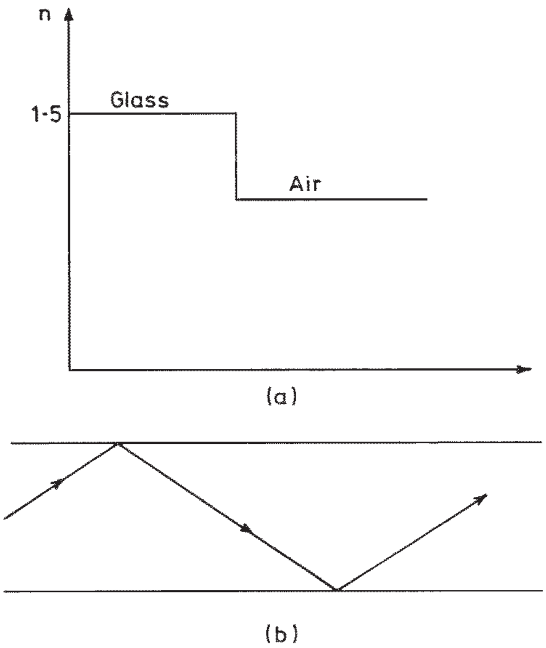


Fig. 3.4: (a) Refractive index distribution of an unclad fiber that consists of a cylindrical glass structure made of homogeneous material. (b) Light rays impinging on the glass–air interface at an angle greater than the critical angle are trapped inside the core of the waveguide through total internal reflections.

The phenomenon of guidance by multiple total internal reflections was in fact demonstrated by John Tyndall as early as 1854. In this demonstration, Tyndall showed that light travels along the curved path of water emanating from an illuminated vessel. However, fiber optics really developed in the 1950s with the works of Hopkins and Kapany in the United Kingdom and of Van Heel in Holland; these works led to use of the optical fiber in many optical devices.

The necessity of a cladded fiber (Figure 3.1) rather than a bare fiber (Figure 3.4) was felt because of the fact that, for transmission of light from one place to another, the fiber must be supported, and supporting structures may considerably distort the fiber, thereby affecting the guidance of the lightwave (see also Problems 3.1–3.3). This can be avoided by choosing a sufficiently thick cladding. Further, in a fiber bundle, in the absence of the cladding, light can leak through from one fiber to another.[1]

It is of interest to mention that the retina of the human eye consists of a large number of rods and cones that have the same kind of structure as the optical fiber – that is, they consist of dielectric cylindrical rods surrounded by another dielectric of slightly lower refractive index and the core diameters are in the range of a few microns. The light absorbed in these *light guides* generates electrical signals, which are then transmitted to the brain through various nerves.

3.2 The numerical aperture

We return to Figure 3.1(a) and consider a ray that is incident on the entrance aperture of the fiber making an angle i with the axis. Let the refracted ray make an angle θ with the fiber axis. Assuming the outside medium to have a refractive index n_0 (which for most practical cases is unity), we get

$$\frac{\sin i}{\sin\theta} = \frac{n_1}{n_0}$$

Obviously, if this ray has to suffer total internal reflection at the core–cladding interface,

$$\sin\phi(=\cos\theta) > n_2/n_1 \tag{3.4}$$

Thus

$$\sin\theta < \left[1 - \left(\frac{n_2}{n_1}\right)^2\right]^{1/2}$$

and we must have

$$\sin i < \frac{n_1}{n_0}\left[1 - \left(\frac{n_2}{n_1}\right)^2\right]^{1/2} = \left[\frac{n_1^2 - n_2^2}{n_0^2}\right]^{1/2} \tag{3.5}$$

If $(n_1^2 - n_2^2) \geq n_0^2$, then for all values of i total internal reflection will occur at the core–cladding interface. Assuming $n_0 = 1$, the maximum value of $\sin i$ for a ray to be guided is given by

$$\begin{aligned} \sin i_m &= \left(n_1^2 - n_2^2\right)^{1/2} && \text{when } n_1^2 < n_2^2 + 1 \\ &= 1 && \text{when } n_1^2 > n_2^2 + 1 \end{aligned} \tag{3.6}$$

Thus, if a cone of light is incident on one end of the fiber, it will be guided through the fiber provided the semiangle of the cone is less than i_m. This angle is a measure of the light-gathering power of the fiber and, as such, one defines

[1]This leakage is due to the fact that when a wave undergoes total internal reflection, it actually penetrates a small region of the rarer medium [see, e.g., Ghatak and Thyagarajan (1978) Chapter 11]. The wave in the rarer medium is known as the evanescent wave, which can couple light from one fiber to another. Thus, in the absence of the cladding, the light may leak away to an adjacent fiber (see Chapter 17).

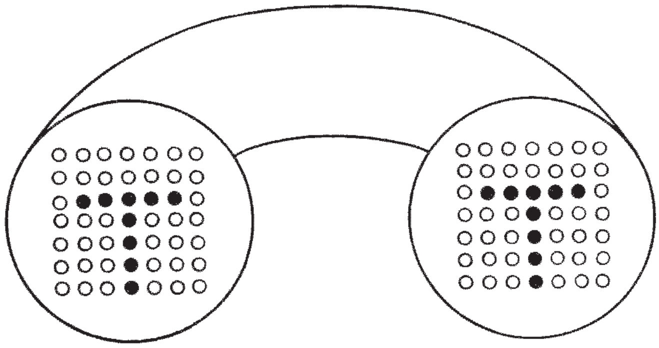


Fig. 3.5: A bundle of aligned fibers. A bright (or dark) spot at the input end of the fiber produces a bright (or dark) spot at the output end. Thus, an image will be transmitted (in the form of bright and dark spots) through a bundle of aligned fibers.

the numerical aperture (NA) of the fiber by the following equation

$$\mathrm{NA} = \left(n_1^2 - n_2^2\right)^{1/2} \tag{3.7}$$

where we have assumed that $n_1^2 < n_2^2 + 1$, which is true for all practical fibers. To get a numerical appreciation we note that for a typical fiber $n_1 = 1.48$, $n_2 = 1.46$ giving

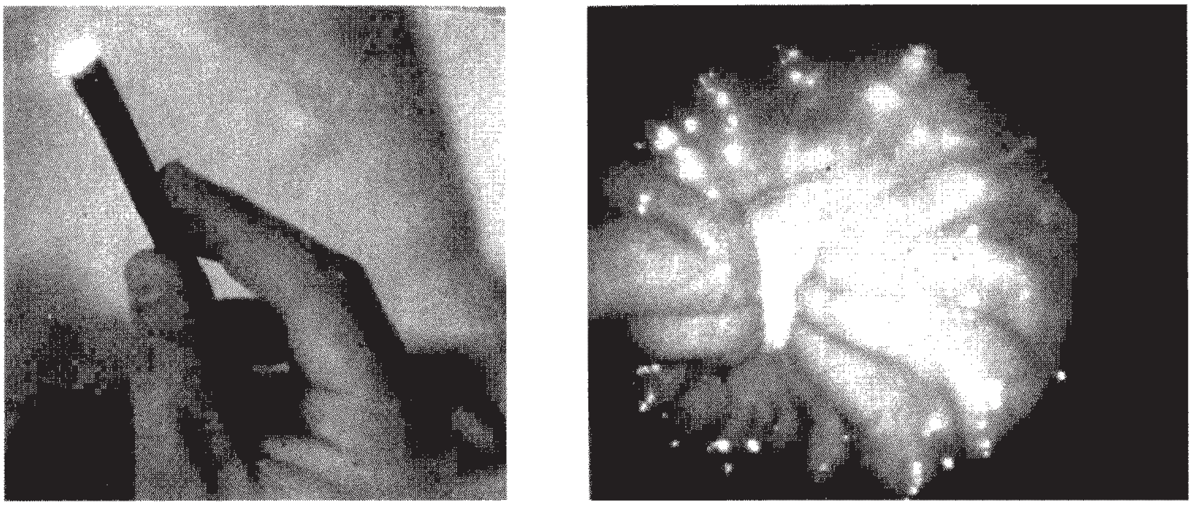
$$\mathrm{NA} = 0.242$$

which implies $i_m \simeq 14^\circ$. The NA of a fiber is a very important property and essentially determines the efficiency of coupling from a source to the fiber as well as losses across a misaligned joint in a splice. In Chapter 19 we discuss briefly an experimental procedure to measure NA of a fiber.

3.3 The coherent bundle

If a large number of fibers are put together, this forms what is known as a bundle. If the fibers are not aligned – that is, they are all jumbled up – the bundle is said to form an incoherent bundle. However, if the fibers are aligned properly – that is, if the relative positions of the fibers in the input and output ends are the same – the bundle is said to form a coherent bundle. Now, if a fiber is illuminated at one of its ends, then there will be a bright spot at the other end of the fiber; thus, a coherent bundle can transmit an image from one end to another (see Figure 3.5). On the other hand, in an incoherent bundle the output image will be scrambled. Because of this property, an incoherent bundle can be used as a coder; the transmitted image can be decoded by using a similar bundle in the reverse direction at the output end. In a bundle, because there can be hundreds of thousands of fibers, decoding without the original bundle configuration would be extremely difficult.

Perhaps the most important application of a coherent bundle is in a fiber optic endoscope, which can be put inside a human body and the interior of the body can be viewed from outside; for illuminating the portion that is to be seen, the bundle is enclosed in a sheath of fibers that carry light from outside to the interior of the body (see Figure 3.6). Each fiber transmits light from a small portion of the object and therefore the resolution is directly related to the packing density. A state-of-art fiberscope can have about 10,000 fibers, which would form a bundle of about 1 mm in diameter capable of resolving objects



(a) (b)

Fig. 3.6: (a) An optical fiber medical probe called an endoscope enables doctors to examine the inner parts of the human body; (b) a stomach ulcer as seen through an endoscope. [Photographs courtesy United States Information Service, New Delhi.]

70 μm across. Fiber optic bundles can also be used for viewing otherwise inaccessible parts of a machine.

3.4 Attenuation in optical fibers

Attenuation and dispersion represent the two most important characteristics of an optical fiber that determine repeater spacings in a fiber optic communication system (see Chapter 13). Obviously, the lower the attenuation (and similarly lower the dispersion) the greater will be the required repeater spacings and therefore the lower will be the cost of the communication system. Pulse dispersion will be discussed in the next section; in this section we briefly discuss the various attenuation mechanisms in an optical fiber.

The attenuation of an optical beam is usually measured in decibels (dB). If an input power P_1 results in an output power P_2, then the loss in decibels is given by

$$\alpha = 10 \log_{10} \frac{P_1}{P_2} \tag{3.8}$$

Thus, if the output power is only half the input power, then the loss is 10 log 2 $\simeq$ 3 dB. Similarly, a loss of 30 dB corresponds to

$$\log \frac{P_1}{P_2} = 3 \Rightarrow P_2 = \frac{1}{1000} P_1$$

Figure 3.7 shows the evolution of losses in glasses from ancient times. As can be seen until about mid-1960s, the losses in "pure" glass had been about over 1000 dB/km. These were primarily due to traces of impurities present in it. In 1966, Kao and Hockam suggested the use of optical fibers in communication systems and mentioned that for optical fiber communication to be a viable proposition, the losses should be less than 20 dB/km. Around 1966, the loss of the best available glass, which was about 1000 dB/km, implied a 50% loss in power after propagating through a 3-m length. Kao and Hockam's suggestion led to

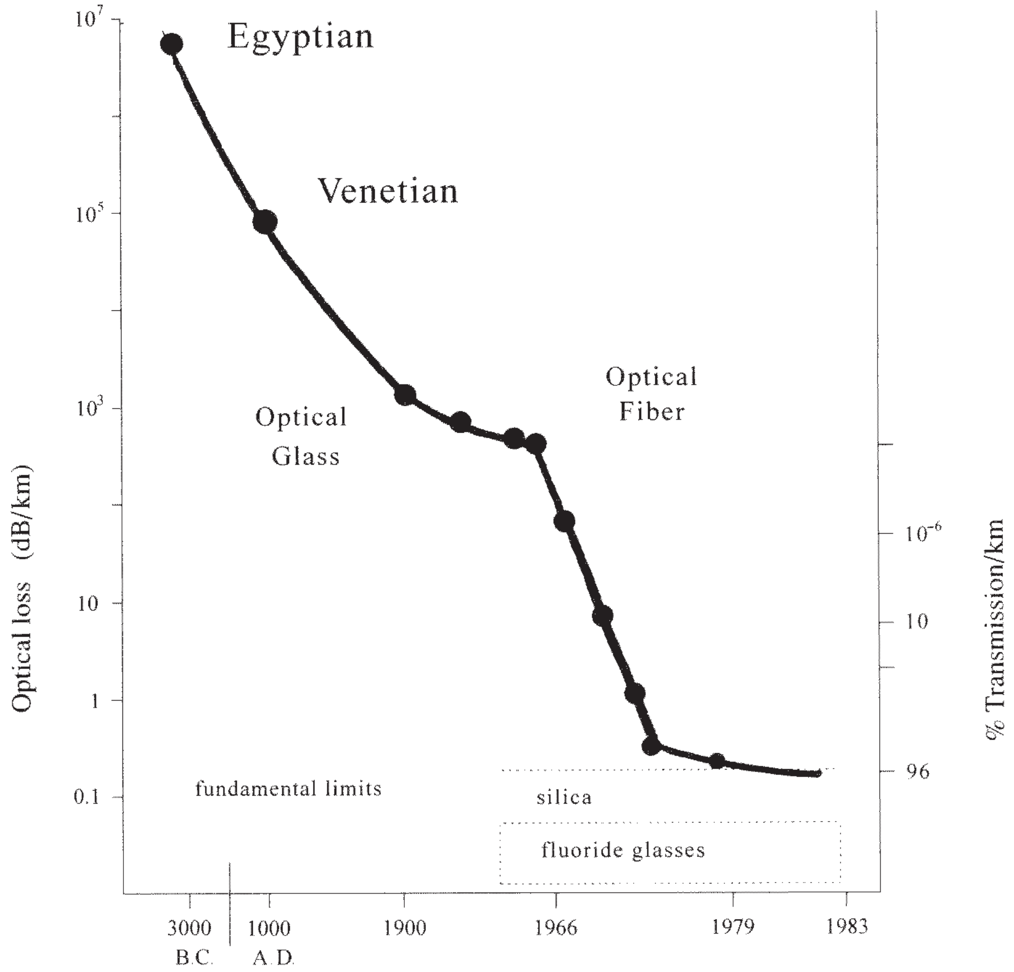


Fig. 3.7: Reduction of optical loss from the ancient times of Egyptian glasses to today's silica fibers. [After Nagel (1989).]

immense activity on the purification of fused silica, and in 1970 Corning Glass Works in the United States announced the fabrication of silica fibers having a loss of about 17 dB/km (at $\lambda_0 \simeq 0.6328\ \mu$m). Since then the technology has been continuously improving and the current state-of-art fabricated fibers have losses ≤ 0.2 dB/km at 1.55 μm (see Figure 3.8); a loss of 0.2 dB/km implies 95.5% transmission after propagating through a 1-km length of the fiber. In Figure 3.9, a comparison is made of typical attenuation curves for various guiding media along with the frequency range at which they operate. The loss curve for the optical fiber appears very sharp because of the logarithmic frequency scale.

3.5 Pulse dispersion in step index optical fibers

Pulse dispersion represents one of the most important characteristics of an optical fiber that determines the information-carrying capacity of a fiber optic communication system.

As shown in Figure 3.1, the simplest type of optical fiber consists of a thin cylindrical structure of transparent glassy material of uniform refractive index n_1 surrounded by a cladding of another material of uniform but slightly lower refractive index n_2. These fibers are referred to as step index fibers because of the step discontinuity of the index profile at the core–cladding interface.

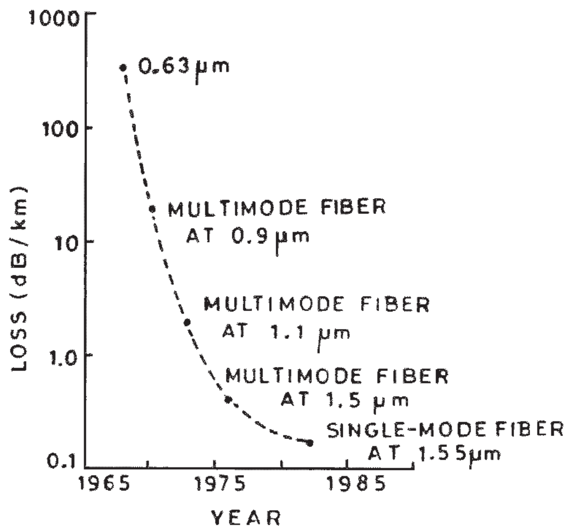


Fig. 3.8: The decrease in loss over the years of silica fibers [Adapted from Schwartz (1984).]

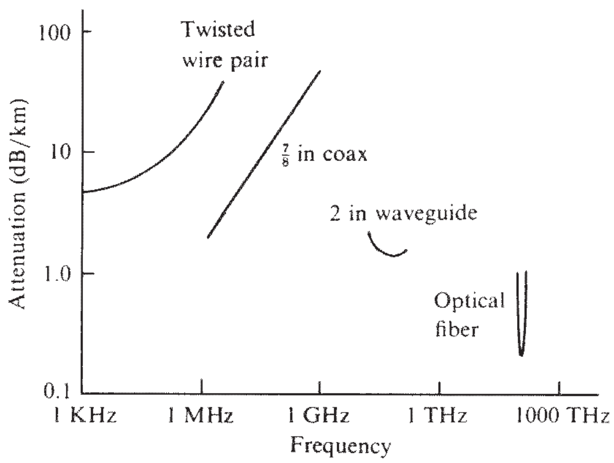


Fig. 3.9: Typical attenuation of various guiding media. The loss curve for the optical fiber appears very sharp because of the logarithmic frequency scale. [Adapted from Henry (1984).]

In digital communication systems, information to be sent is first coded in the form of pulses and then these pulses of light are transmitted from the transmitter to the receiver where the information is decoded (see Chapter 13). The larger the number of pulses that can be sent per unit time and still be resolvable at the receiver end, the larger will be the transmission capacity of the system. A pulse of light sent into a fiber broadens in time as it propagates through the fiber; this phenomenon is known as pulse dispersion and happens primarily for two reasons:

(1) Different rays take different times to propagate through a given length of the fiber (this is also known as intermodal dispersion) and
(2) Any given source emits over a range of wavelengths and, because of the intrinsic property of the material, different wavelengths take different amounts of time to propagate along the same path (also referred to as material dispersion)[2].

[2]There is also a third mechanism called waveguide dispersion that is important only in single-mode fibers (see Chapter 10). Both waveguide dispersion and material dispersion form part of what is known as intramodal dispersion.

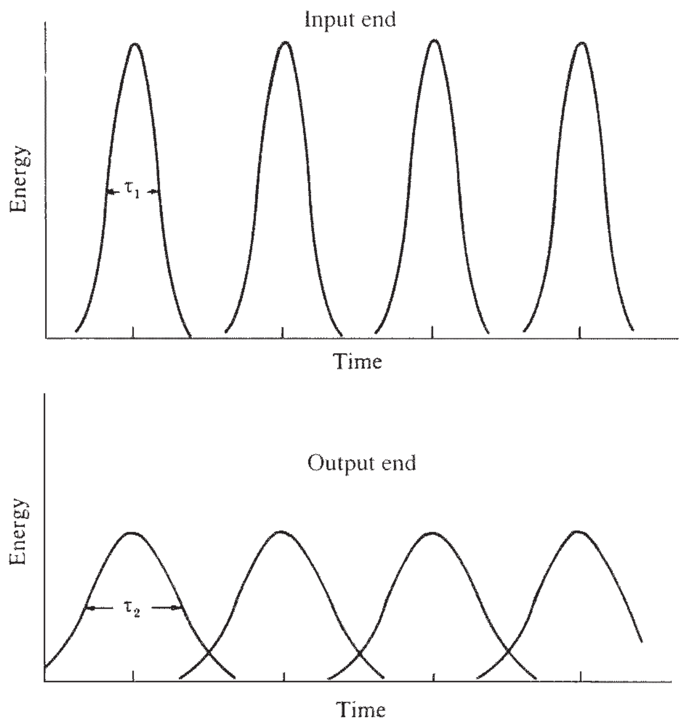


Fig. 3.10: A series of pulses, each of width τ_1 (at the input end of the fiber), after transmission through the fiber emerges as a series of pulses of width τ_2 (> τ_1). If the broadening of the pulses is large, then adjacent pulses will overlap at the output end and may not be resolvable. Thus, pulse broadening determines the minimum separation between adjacent pulses, which in turn determines the maximum information-carrying capacity of the optical fiber.

To understand the first mechanism causing pulse dispersion, we note that in the fiber shown in Figure 3.1, the rays making larger angles with the axis have to traverse a longer optical path length and they take a longer time to reach the output end. Consequently, the pulse broadens as it propagates through the fiber (see Figure 3.10). Hence, even though two pulses may be well resolved at the input end, because of broadening of the pulses they may not be so at the output end. When the output pulses are not resolvable, no information can be retrieved. Thus, the smaller the pulse dispersion, the greater the information-carrying capacity of the system.

We next calculate the amount of dispersion in a step index fiber. Referring to Figure 3.1 for a ray making an angle θ with the axis, the distance AB is traversed in time

$$t = \frac{AC + CB}{c/n_1} = \frac{n_1(AB)}{c\cos\theta} \tag{3.9}$$

where c/n_1 represents the speed of light in a medium of refractive index n_1, with c being the speed of light in free space. Because the ray path will repeat itself, the time taken by a ray to traverse length L of the fiber will be

$$t = \frac{n_1 L}{c\cos\theta} \tag{3.10}$$

The above expression shows that the time taken by a ray is a function of the angle θ made by the ray with the z-axis, which leads to pulse dispersion. If we assume that all rays lying between 0 and θ_c are present, then the time taken by rays corresponding, respectively, to $\theta = 0$ and $\theta = \theta_c = \cos^{-1}(n_2/n_1)$ will be

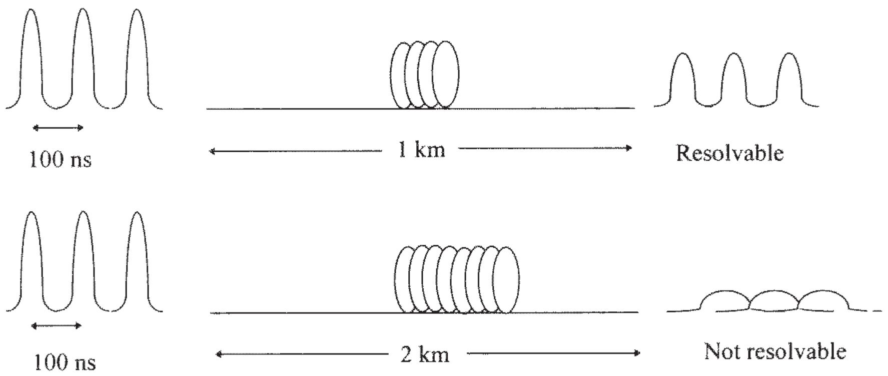


Fig. 3.11: Pulses separated by 100 ns, at the input end would be quite resolvable at the end of 1 km of the fiber. The same pulses would not be resolvable at the end of 2 km of the fiber.

given by

$$t_{\text{min}} = \frac{n_1 L}{c} \tag{3.11}$$

$$t_{\text{max}} = \frac{n_1^2 L}{c n_2} \tag{3.12}$$

Hence, if all the input rays were excited simultaneously, at the output end the rays would occupy a time interval of duration

$$T = t_{\text{max}} - t_{\text{min}} = \frac{n_1 L}{c}\left(\frac{n_1}{n_2} - 1\right) \tag{3.13}$$

For a typical fiber, if we assume

$$n_1 = 1.5, \quad \frac{n_1 - n_2}{n_2} \simeq 0.01, \quad L = 1\,\text{km}$$

one obtains

$$T \simeq 50\ \text{ns/km} \tag{3.14}$$

that is, an impulse after traversing through the fiber of length 1 km broadens to a pulse of about 50 ns duration. Thus, two pulses separated by say 100 ns at the input end would be quite resolvable at the end of 1 km of the fiber; however, they would be unresolvable at the end of 2 km (see Figure 3.11). Hence, in a 1-megabit-per-second (1 Mb/s) fiber optic system, where we have one pulse every 10^{-6} s, 50-ns/km dispersion would require repeaters to be placed every 3–4 km. On the other hand, in a 1000-Mb/s fiber optic communication system, where we require transmitting one pulse every 10^{-9} s, a dispersion of 50 ns/km would result in intolerable broadening even within 50 m or so, which would be highly inefficient and uneconomical from a system point of view.

As mentioned earlier, material dispersion that is due to the dependence of the refractive index of the fiber material on wavelength also leads to pulse dispersion that is due to the different traversal times taken by different wavelength components of the source (see Chapter 6). For optical fibers based on silica, material dispersion causes a pulse dispersion of around 90 ps/km for a source of spectral width 1 nm and operating at a wavelength of 0.85 μm. Thus, for an LED operating at a wavelength of 0.85 μm and having a spectral width of 30 nm, the contribution from material dispersion would be around 2.7 ns/km. Thus, for step index multimode fibers, the contribution from material dispersion is rather small and can be neglected. To achieve systems with very high information-carrying capacity, it is necessary to reduce pulse dispersion; two alternative solutions exist: one involving the use of graded index fibers and the other involving single-mode fibers. In Chapter 4 we discuss ray paths and pulse dispersion in graded index optical waveguides and in Chapter 10 we consider dispersion in single-mode fibers. We will see later that in graded index fibers, where the pulse dispersion that is due to different times taken by different rays can be minimized, material dispersion can play an important role. In single-mode fibers, where the first form of dispersion is absent, material dispersion plays a dominant role along with waveguide dispersion. These aspects are discussed in detail in later chapters.

We should mention here that a rigorous analysis of the propagation in fiber would involve the solution of Maxwell's equations, which are discussed in Chapter 8. Ray optics is valid when the waveguide parameter

$$V = \frac{2\pi}{\lambda_0} a \left(n_1^2 - n_1^2\right)^{1/2} \tag{3.15}$$

is greater than about 10; in the above equation λ_0 represents the wavelength of light in free space. For the parameters given in equation (3.2) and operating at $\lambda_0 = 0.8\,\mu$m

$$V \simeq 48$$

and the ray analysis should be very accurate. However, with the same values of n_1 and n_2 if the core radius was 2 μm, the value of V would have been 3.8 and the ray analysis would not be applicable at all. For such fibers the wave theory has to be used (see Chapter 8).

3.6 Loss mechanisms

The principal sources of attenuation in an optical fiber can be broadly classified into two groups: absorptive and radiative.

3.6.1 Absorptive losses

Absorptive losses can be further subdivided into intrinsic and extrinsic losses. Intrinsic absorption is caused by interaction of the propagating lightwave with one or more major components of glass that constitute the fiber's material composition. An example of such an interaction is the infrared absorption band of SiO_2. However, in the wavelength regions of interest to optical communication (0.8–0.9 μm and 1.2–1.5 μm), infrared absorption tails make negligible contributions (see Figure 3.12).

OPTICAL FIBER COMMUNICATION

FIBER TYPES:

Fibers are sub divided into two groups.

1.NUMBER OF MODES THEY CAN SUPPORT:

The light can propagate inside an optical fiber only as set of separated beams (or) rays. These rays (or) beams are called modes. Based on the number of modes that a fiber can support, it is classified into two types

- Single mode(only one exist within the fiber)
- Multi mode(many modes exist within the fiber)

2.BASED ON REFRACTIVE INDEX PROFILE:

- Step index fiber
- Graded index fiber

3.BASED ON NUMBER OF MODES AND REFRACTIVE INDEX PROFILE:

- Single mode step index fiber(SMSI)
- Multi mode step index fiber(MMSI)
- Single mode graded index fiber(SMGI)
- Multi mode graded index fiber(MMGI)

V-NUMBER (OR) NORMALISED FREQUENCY PARAMETER:

The number of modes in an optical fiber is determined by V-parameter (or) V-Number. It is dimension less and it is given by

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

d = core diameter of fiber

2a = where a is the radius of the optical Fiber λ = operating wave length

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

In terms of NA

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

$$\text{(or)} \qquad V = \frac{2\pi a n_1}{\lambda}\sqrt{2\Delta}$$

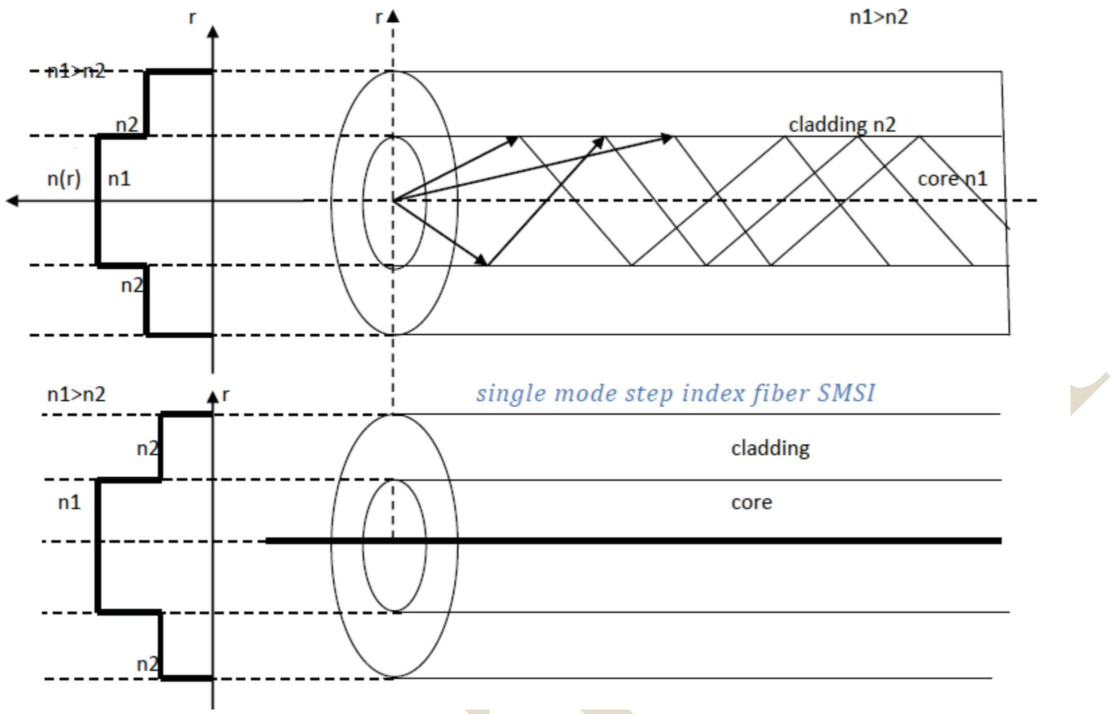
STEP INDEX FIBER:

- The optical fiber with a core of constant refractive index n1 , and a cladding of a slightly lower refractive index n2 is known as step index fiber.
- This is because the refractive profile for this type of fiber makes a step change at the core cladding interface.
- The refractive index profile may be defined as ,

$$n(r) = \begin{cases} n & r<a \quad \text{core} \\ n & r \quad \text{cladding} \end{cases}$$

r= radial distance from the center of the fiber. a = radius of core.

MULTIMODE STEP INDEX FIBER (MMSI):



In the above figure,

- The refractive index of the core is uniform throughout an undergoes an step change at the cladding boundary .
- The core diameter of MMSI is about 50 -200 m.
- The ray passing through the step index fiber is said to be meridional ray.
- Its core diameter is large enough to allow the propagation of many modes within the fiber core.
- Bandwidth of multimode fiber is 50 MHZ / km .
- Inter modal dispersion is high due to differing group velocities of propagating mode. This is inturn restricts the maximum bandwidth attainable with multimode step index fiber.
- NA is more for MMSI
- MMSI allow the propagation of a finite number of guided modes along the channel. The number of guided modes is dependent upon the V-parameter

Ms (no. of modes in step index) = $\frac{V^2}{2}$

ADVANTAGES OF MMSI

(1) The use of spatially incoherent optical sources (LED) which cannot be efficiently coupled to single mode fiber.

(2) Larger numerical aperture, as well as core diameter, facilitating easier coupling of optical sources.

(3) Lower tolerance requirements on fiber connectors.

SMSI:

Single mode or monomode step index fiber allows the propagation of only one transverse electromagnetic mode (typically HE_{00}), and hence the core diameter must be of the order of 2 to 10 micrometer.

Its core diameter is less.It allows only one mode which propagating along the core axis.

Bandwidth of SMSI is 1GHZ /km. (information carrying capacity is very high)

Low intermodal dispersion (broadening of transmitted pulse) as only one mode is transmitted

NA is very less for SMSI. Manufacturing was the mode field diameter, MED rather than the core diameter as a parameter that describes single mode fiber

V- parameter is less than (or) equal to 2.405 V< 2.405

ADVANTAGES OF SMSI:

(1) Used for higher bandwidth application

DISADVANTAGES :

(1) The small core diameter pose problems with

- Launching light into the fiber
- With field jointing
- Reduced relative refractive index difference present difficulties in the fabrication process

- Problem:
- A multimode step index fiber with core diameter of 80and a relative index difference of 1.5% is operating at a wavelength of 0.85 core R.I is 1.48, estimate (a) the normalized frequency for the fiber (b) the no. of guided modes.
- Solution:

(a) The normalized freq. (or) Vnumber

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

$$= \frac{2\pi a n_1}{\lambda}\sqrt{2\Delta}$$

$$= \frac{2\times3.14\times1.48\times40\times10^{-6}}{0.85\times10^{-6}}\sqrt{(2\times0.015)}$$

$$= 75.8$$

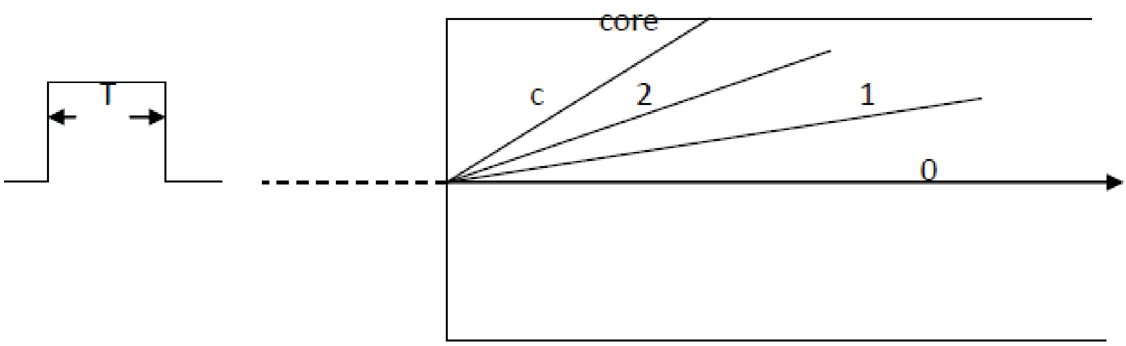
(b) Total no. of guided modes

$$Mstep\ index,\ Ms = \frac{V^2}{2} = \frac{75.8^2}{2} = 2873$$

- If V is approximately equal to 76, then nearly 3000 modes are guided by MMSI.

INTERMODAL DISPERSION:*(introduction)

- Pulse broadening or pulse widening caused by mode structure of a light beam inside the fiber is called modal dispersion or intermodal dispersion.



C= critical mode

2= second order mode

1= first order mode

0= zero order mode

The beams travel at the same velocity but over different distances, they arrive the receiver