NEC 701
OPTICAL COMMUNICATIONS
Unit 1
OVERVIEW OF OPTICAL FIBER COMMUNICATION

1. The use of visible optical carrier waves or light for communication has been common for many years. Simple systems such as signal fires, reflecting mirrors and, more recently, signaling lamps have provided successful, if limited, information transfer. Moreover, as early as 1880 Alexander Graham Bell reported the transmission of speech using a light beam.
2. The photo phone proposed by Bell just four years after the invention of the telephone modulated sunlight with a diaphragm giving speech transmission over a distance of 200 m. However, although some investigation of optical communication continued in the early part of the twentieth century, its use was limited to mobile, low-capacity communication links.
3. This was due to both the lack of suitable light sources and the problem that light transmission in the atmosphere is restricted to line of sight and is severely affected by disturbances such as rain, snow, fog, dust and atmospheric turbulence. Nevertheless lower frequency and hence longer wavelength electromagnetic waves* (i.e. radio and microwave) proved suitable carriers for information transfer in the atmosphere, being far less affected by these atmospheric conditions. Depending on their wavelengths, these electromagnetic carriers can be transmitted over considerable distances but are limited in the amount of information they can convey by their frequencies (i.e. the information-carrying capacity is directly related to the bandwidth or frequency extent of the modulated carrier, which is generally limited to a fixed fraction of the carrier frequency).
4. In theory, the greater the carrier frequency, the larger the available transmission bandwidth and thus the information-carrying capacity of the communication system. For this reason radio communication were developed to higher frequencies (i.e. VHF and UHF) leading to the introduction of the even higher frequency microwave and, latterly, millimeter wave transmission. The relative frequencies and wavelengths of these types of electromagnetic wave can be observed from the electromagnetic spectrum shown in Figure 1.1. In may also be noted that communication at optical frequencies offers an increase in the potential usable bandwidth by a factor of around 10^4 over high-frequency microwave transmission. An additional benefit of the use of high carrier frequencies is the general ability of the communication system to concentrate the available power within the transmitted electromagnetic wave, thus giving an improved system performance
5. A renewed interest in optical communication was stimulated in the early 1960s with the invention of the laser. This device provided a powerful coherent light source, together with the possibility of modulation at high frequency. In addition the low beam divergence of the laser made enhanced free space optical transmission a practical possibility. However, the previously mentioned constraints of light transmission in the atmosphere tended to restrict these systems to short-distance applications. Despite the problems some modest free space optical communication links have been implemented for applications such as the linking of a television camera to a base vehicle and for data links of a few hundred meters between buildings. There is also some interest in optical communication between satellites in outer space using similar techniques.

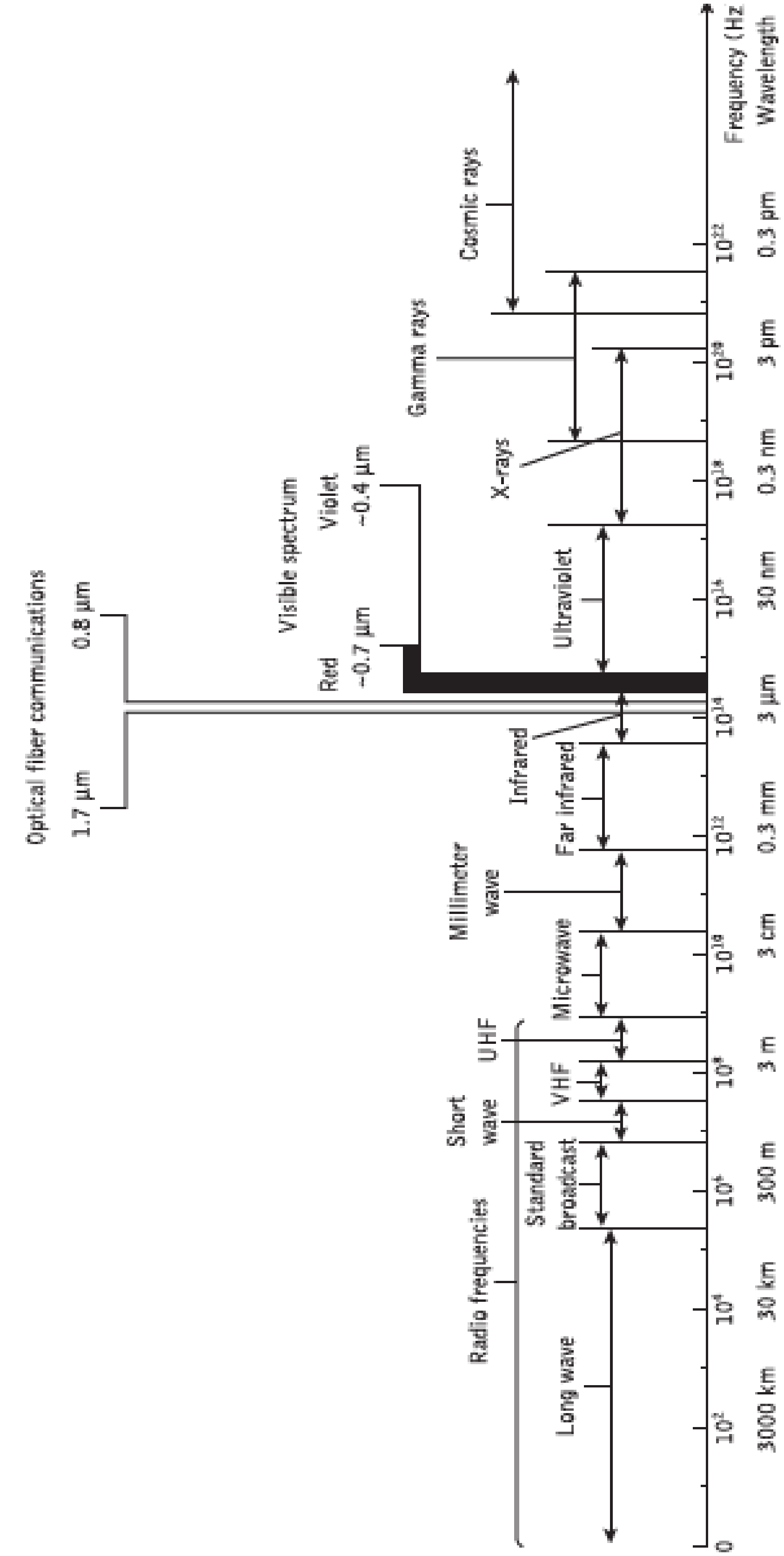


Figure 1.1 The electromagnetic spectrum showing the region used for optical fiber communications

THE GENERAL SYSTEM

1. An optical fiber communication system is similar in basic concept to any type of communication system. A block schematic of a general communication system is shown in Figure 1.2(a), the function of which is to convey the signal from the information source over the transmission medium to the destination.
2. The communication system therefore consists of a transmitter or modulator linked to the information source, the transmission medium, and a receiver or demodulator at the destination point. In electrical communications the information source provides an electrical signal, usually derived from a message signal which is not electrical (e.g. sound), to a transmitter comprising electrical and electronic components which converts the signal into a suitable form for propagation over the transmission medium.
3. This is often achieved by modulating a carrier, which, as mentioned previously, may be an electromagnetic wave. The transmission medium can consist of a pair of wires, a coaxial cable or a radio link through free space down which the signal is transmitted to the receiver, where it is transformed into the original electrical information signal (demodulated) before being passed to the destination.
4. However, it must be noted that in any transmission medium the signal is attenuated, or suffers loss, and is subject to degradations due to contamination by random signals and noise, as well as possible distortions imposed by mechanisms within the medium itself. Therefore, in any communication system there is a maximum permitted distance between the transmitter and the receiver beyond which the system effectively ceases to give intelligible communication. For long-haul applications these factors necessitate the installation of repeaters or line amplifiers at intervals, both to remove signal distortion and to increase signal level before transmission is continued down the link.

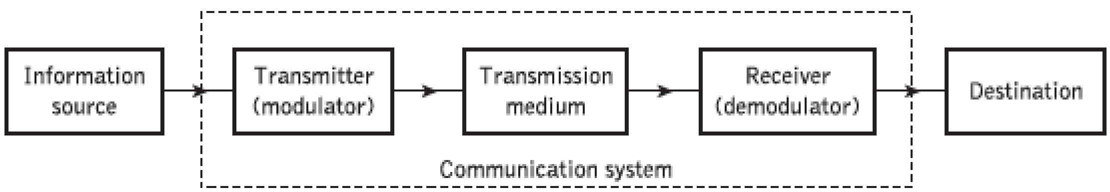


Figure 1.2(a): The General Communication System

5. For optical fiber communications the system shown in Figure 1.2(a) may be considered in slightly greater detail, as given in Figure 1.2(b). In this case the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the light wave carrier. The optical source which provides the electrical–optical conversion may be either a semiconductor laser or light-emitting diode (LED). The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier. Photodiodes (*p*–*n*, *p*–*i*–*n* or avalanche) and, in some instances, phototransistors and photoconductors are utilized for the detection of the optical signal and the optical–electrical conversion.
6. The optical carrier may be modulated using either an analog or digital information signal. In the system shown in Figure 1.2(b) analog modulation involves the variation of the light emitted from the optical source in a continuous manner. With digital modulation, however, discrete changes in

the light intensity are obtained (i.e. on–off pulses). Although often simpler to implement, analog modulation with an optical fiber communication system is less efficient, requiring a far higher signal-to-noise ratio at the receiver than digital modulation.

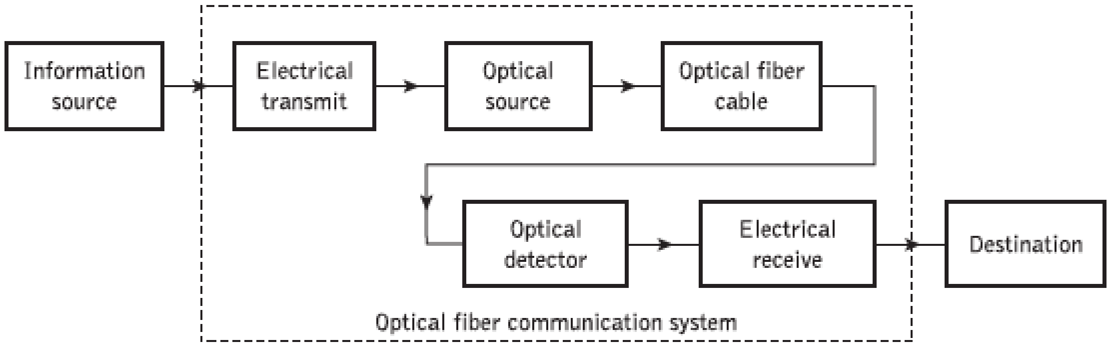


Figure 1.2(b): The Optical Fiber communication System

7. Figure 1.3 shows a block schematic of a typical digital optical fiber link. Initially, the input digital signal from the information source is suitably encoded for optical transmission. The laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence a digital optical signal is launched into the optical fiber cable. The avalanche photodiode (APD) detector is followed by a front-end amplifier and equalizer or filter to provide gain as well as linear signal processing and noise bandwidth reduction. Finally, the signal obtained is decoded to give the original digital information.

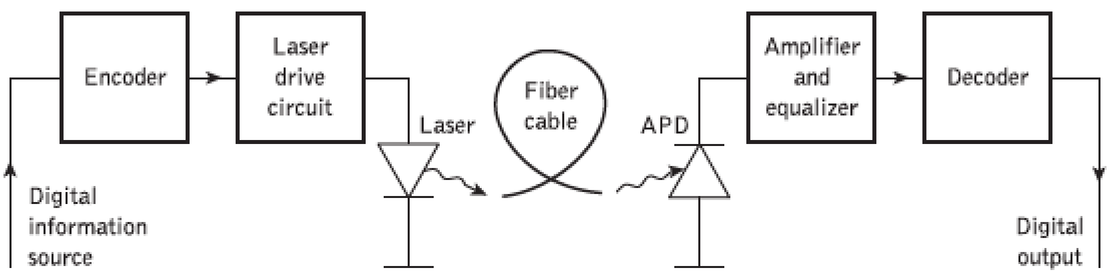


Figure 1.3: The Block diagram of digital optical communication system

ADVANTAGES OF OPTICAL FIBER COMMUNICATIONS

a) Enormous potential bandwidth.
b) Small size and weight.
c) Electrical isolation.
d) Immunity to interference and crosstalk.
e) Signal security.
f) Low transmission loss.
g) Ruggedness and flexibility.
h) System reliability and ease of maintenance.
i) Potential low cost.

OPTICAL FIBER WAVE GUIDES

INTRODUCTION

1. Optical fiber is basically a solid glass rod. The diameter of rod is so small that it looks like a fiber.
2. Optical fiber is a dielectric waveguide. The light travels like an electromagnetic wave inside the waveguide. The dielectric waveguide is different from a metallic waveguide which is used at microwave and millimeter wave frequencies.
3. In a metallic waveguide, there is a complete shielding of electromagnetic radiation but in an optical fiber the electromagnetic radiation is not just confined inside the fiber but also extends outside the fiber.
4. The light gets guided inside the structure, through the basic phenomenon of **total internal reflection.**
5. The optical fiber consists of two concentric cylinders; the inside solid cylinder is called the **core** and the surrounding shell is called the **cladding.**

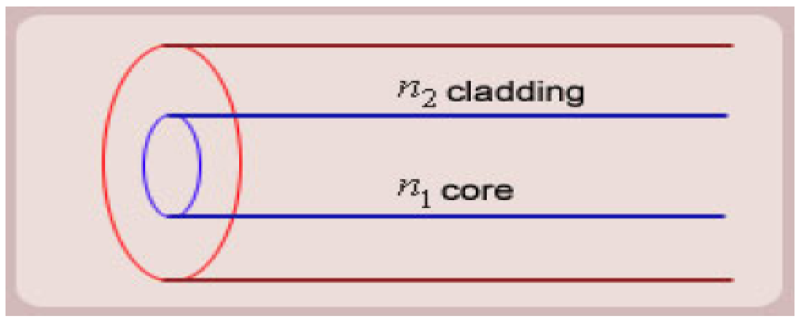
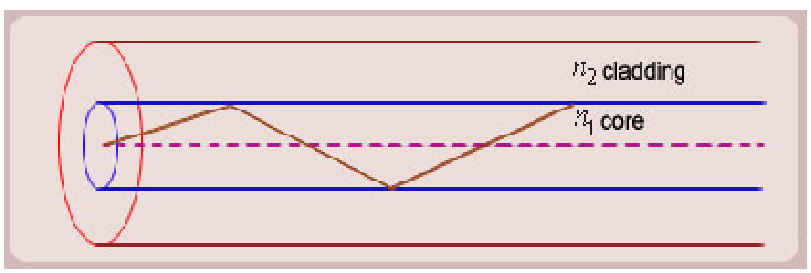


Figure 1.4: Schematic of Optical fiber

6. For the light to propagate inside the fiber through total internal reflections at core-cladding interface, the refractive index of the core must be greater than the refractive index of the cladding. That is $n_1 > n_2$.

RAY THEORY TRANSMISSION



1. The propagation of light within an optical fiber utilizing the ray theory model it is necessary to take account of the refractive index of the dielectric medium.
2. The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium
3. A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs.

4. It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index n_1 and is at an angle ϕ_1 to the normal at the surface of the interface. If the dielectric on the other side of the interface has a refractive index n_2 which is less than n_1, then the refraction is such that the ray path in this lower index medium is at an angle ϕ_2 to the normal, where ϕ_2 is greater than ϕ_1. The angles of incidence ϕ_1 and refraction ϕ_2 are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction

$$n_1 \sin \phi_1 = n_2 \sin \phi_1$$

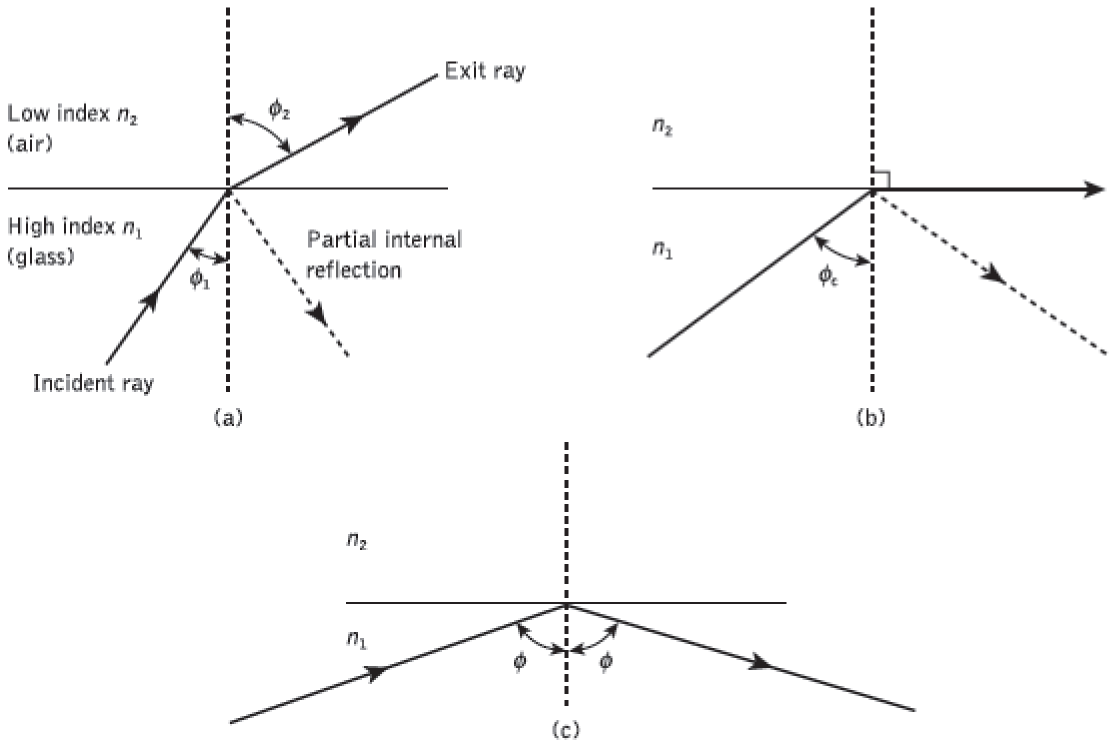


Figure 1.5 Light rays incident on a high to low refractive index interface (e.g. glass–air): (a) refraction; (b) the limiting case of refraction showing the critical ray at an angle ϕ_c; (c) total internal reflection where $\phi > \phi_c$

ACCEPTANCE ANGLE

The cone of acceptance is the angle within which the light is accepted into the core and is able to travel along the fiber.

The geometry concerned with launching a light ray into an optical fiber is shown in Figure 1.6, which illustrates a meridional ray A at the critical angle ϕ_c within the fiber at the core–cladding interface. It may be observed that this ray enters the fiber core at an angle θ_a to the fiber axis and is refracted at the air–core interface before transmission to the core–cladding interface at the critical angle. Hence, any rays which are incident into the fiber core at an angle greater than θ_a will be transmitted to the core–cladding interface at an angle less than ϕ_c, and will not be totally internally reflected.

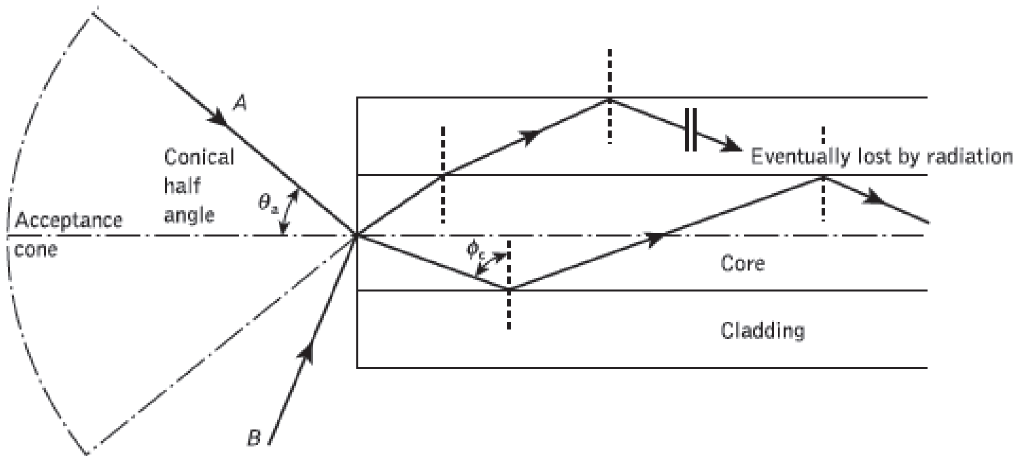


Figure 1.6 The acceptance angle θ_a when launching light into an optical fiber

This situation is also illustrated in Figure 1.6, where the incident ray B at an angle greater than θ_a is refracted into the cladding and eventually lost by radiation. Thus for rays to be transmitted by total internal reflection within the fiber core they must be incident on the fiber core within an acceptance cone defined by the conical half angle θ_a. Hence θ_a is the maximum angle to the axis at which light may enter the fiber in order to be propagated, and is often referred to as the acceptance angle for the fiber.

NUMERICAL APERTURE

The Numerical aperture (NA) of a fiber is a figure of merit which represents its light gathering capability. Larger the Numerical aperture, the greater the amount of light accepted by fiber.

The acceptance angle also determines how much light is able to be enter the fiber and hence there is a relation between the numerical aperture and the cone of acceptance.

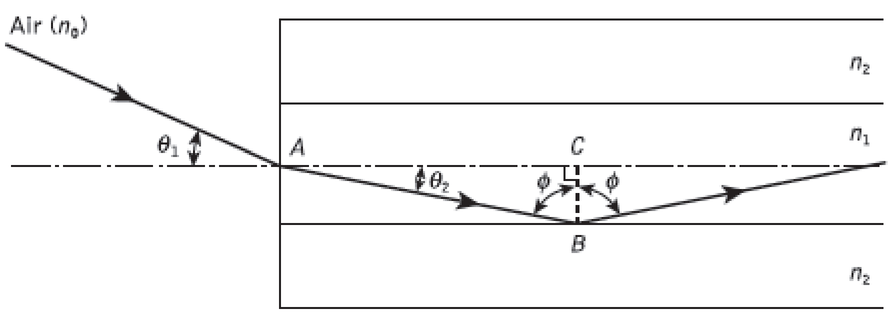


Figure 1.7 The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceptance angle for the fiber

Figure 1.7 shows a light ray incident on the fiber core at an angle θ_1 to the fiber axis which is less than the acceptance angle for the fiber θ_a. The ray enters the fiber from a medium (air) of refractive index n_0, and the fiber core has a refractive index n_1, which is slightly greater than the cladding refractive index n_2.

Using Snell's law:

$$n_0 \sin \theta_1 = n_1 \sin \theta_2 \quad \text{...... (1.1)}$$

Considering the right-angled triangle *ABC* indicated in Figure , then:

$$\phi = \frac{\pi}{2} - \theta_2 \quad \text{....... (1.2)}$$

where ϕ is greater than the critical angle at the core–cladding interface. Hence Eq. **1.1** becomes:

$$n_0 \sin \theta_1 = n_1 \cos \phi \quad \text{....... (1.3)}$$

Using the trigonometrical relationship $\sin^2 \phi + \cos^2 \phi = 1$, Eq. **1.3** may be written in the form:

$$n_0 \sin \theta_1 = n_1 (1 - \sin^2 \phi)^{\frac{1}{2}} \quad \text{..... (1.4)}$$

When the limiting case for total internal reflection is considered, ϕ becomes equal to the critical angle for the core–cladding interface.

$$n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \quad \text{..... (1.5)}$$

Equation **1.5** apart from relating the acceptance angle to the refractive indices, serves as the basis for the definition of the important optical fiber parameter, the numerical aperture (*NA*). Hence the *NA* is defined as:

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \quad \text{...... (1.6)}$$

The *NA* may also be given in terms of the relative refractive index difference Δ between the core and the cladding which is defined as:

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

$$\simeq \frac{n_1 - n_2}{n_1} \quad \text{for } \Delta \ll 1 \quad \text{......... (1.7)}$$

Hence combining Eq. **1.6** with Eq. **1.7** we can write:

$$NA = n_1 (2\Delta)^{\frac{1}{2}} \quad \text{........ (1.8)}$$

Example:

A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47.

Determine: (a) the critical angle at the core–cladding interface; (b) the *NA* for the fiber; (c) the acceptance angle in air for the fiber.

Solution: (a) The critical angle ϕ_c at the core–cladding interface is given by Eq. (2.2) where:

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.47}{1.50} = 78.5°$$

(b) From Eq. (2.8) the *NA* is:

$$NA = (n_1^2 - n_2^2)^{\frac{1}{2}} = (1.50^2 - 1.47^2)^{\frac{1}{2}} = (2.25 - 2.16)^{\frac{1}{2}} = 0.30$$

(c) Considering Eq. (2.8) the acceptance angle in air θ_a is given by:

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.30 = 17.4°$$

FIBER PROFILES

- A fiber is characterized by its profile and by its core and cladding diameters.
- One way of classifying the fiber cables is according to the index profile at fiber. The index profile is a graphical representation of value of refractive index across the core diameter.
- There are two basic types of index profiles:
  1) **Step index fiber**
  2) **Graded index fiber**

STEP INDEX FIBER

The optical fiber with a core of constant refractive index n_1 and a cladding of a slightly lower refractive index n_2 is known as step index fiber. This is because the refractive index profile for this type of fiber makes a step change at the core–cladding interface, as indicated in Figure 1.9, which illustrates the two major types of step index fiber. The refractive index profile may be defined as in both cases:

$$n(r) = \begin{cases} n_1 & r < a \quad \text{(core)} \\ n_2 & r \geq a \quad \text{(cladding)} \end{cases} \qquad \textbf{..... (1.9)}$$

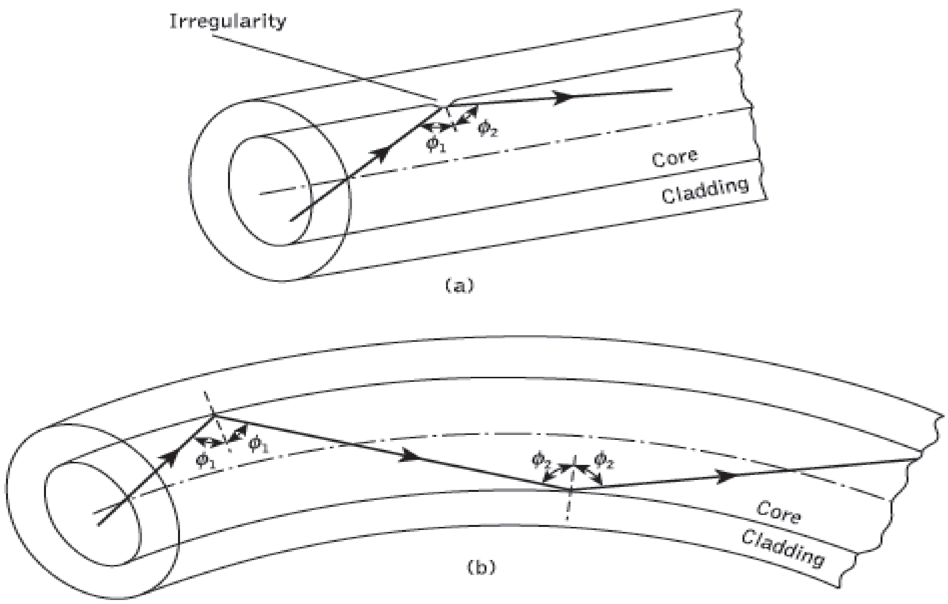


Figure 1.8 Ray theory illustrations showing two of the possible fiber perturbations which give mode coupling: (a) irregularity at the core–cladding interface; (b) fiber bend

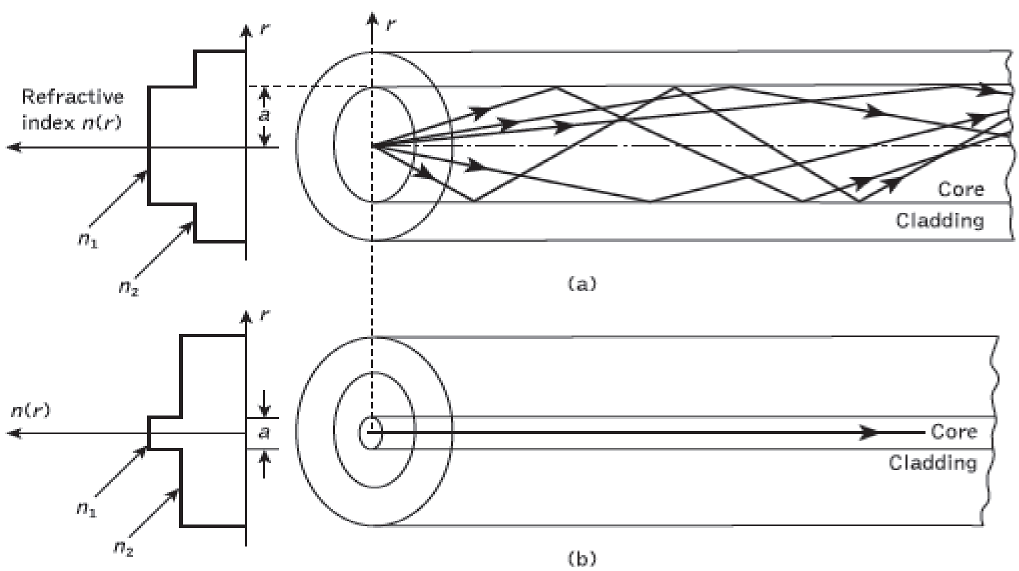


Figure 1.9 The refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber; (b) single-mode step index fiber

Figure 1.9(a) shows a multimode step index fiber with a core diameter of around 50 μm or greater, which is large enough to allow the propagation of many modes within the fiber core. This is illustrated in Figure 1.9 (a) by the many different possible ray paths through the fiber. Figure 1.9 (b) shows a single-mode or monomode step index fiber which allows the propagation of only one transverse electromagnetic mode, and hence the core diameter must be of the order of 2 to 10 μm.

The single-mode step index fiber has the distinct advantage of low intermodal dispersion (broadening of transmitted light pulses), as only one mode is transmitted, whereas with multimode step index fiber considerable dispersion may occur due to the differing group velocities of the propagating modes. This in turn restricts the maximum bandwidth attainable with multimode step index fibers, especially when compared with single-mode fibers. However, for lower bandwidth applications multimode fibers have several advantages over single-mode fibers. These are:

a) The use of spatially incoherent optical sources (e.g. most light-emitting diodes) which cannot be efficiently coupled to single-mode fibers;
b) Larger numerical apertures, as well as core diameters, facilitating easier coupling to optical sources;
c) Lower tolerance requirements on fiber connectors.

Multimode step index fibers allow the propagation of a finite number of guided modes along the channel. The number of guided modes is dependent upon the physical parameters (i.e. relative refractive index difference, core radius) of the fiber and the wavelengths of the transmitted light which are included in the normalized frequency V for the fiber.

There is a cutoff value of normalized frequency V_c for guided modes below which they cannot exist. However, mode propagation does not entirely cease below cutoff. Modes may propagate as unguided or leaky modes which can travel considerable distances along the fiber.

It can be noted that the total number of guided modes or mode volume M_s for a step index fiber is related to the V value for the fiber by the approximate expression:

$$M_s \simeq \frac{V^2}{2} \qquad \text{..... (1.10)}$$

: which allows an estimate of the number of guided modes propagating in a particular multimode step index fiber.

EXAMPLE

A multimode step index fiber with a core diameter of 80 μm and a relative index difference of 1.5% is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48, estimate: (a) the normalized frequency for the fiber; (b) the number of guided modes.

Solution: (a) The normalized frequency may be obtained where:

$$V \simeq \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}} = \frac{2\pi \times 40 \times 10^{-6} \times 1.48}{0.85 \times 10^{-6}} (2 \times 0.015)^{\frac{1}{2}} = 75.8$$

(b) The total number of guided modes is given by

$$M_s \simeq \frac{V^2}{2} = \frac{5745.6}{2} = 2873$$

Hence this fiber has a V number of approximately 76, giving nearly 3000 guided modes.

GRADED INDEX FIBER

Graded index fibers do not have a constant refractive index in the core but a decreasing core index $n(r)$ with radial distance from a maximum value of n_1 at the axis to a constant value n_2 beyond the core radius a in the cladding. This index variation may be represented as:

$$n(r) = \begin{cases} n_1(1 - 2\Delta(r/a)^{\alpha})^{\frac{1}{2}} & r < a \quad \text{(core)} \\ n_1(1 - 2\Delta)^{\frac{1}{2}} = n_2 & r \geq a \quad \text{(cladding)} \end{cases} \quad \text{........ } \mathbf{(1.11)}$$

; where Δ is the relative refractive index difference and α is the profile parameter which gives the characteristic refractive index profile of the fiber core. Equation 1.11 which is a convenient method of expressing the refractive index profile of the fiber core as a variation of α, allows representation of the step index profile when $\alpha = \infty$, a parabolic profile when $\alpha = 2$ and a triangular profile when $\alpha = 1$.

This range of refractive index profiles is illustrated in Figure 1.10.

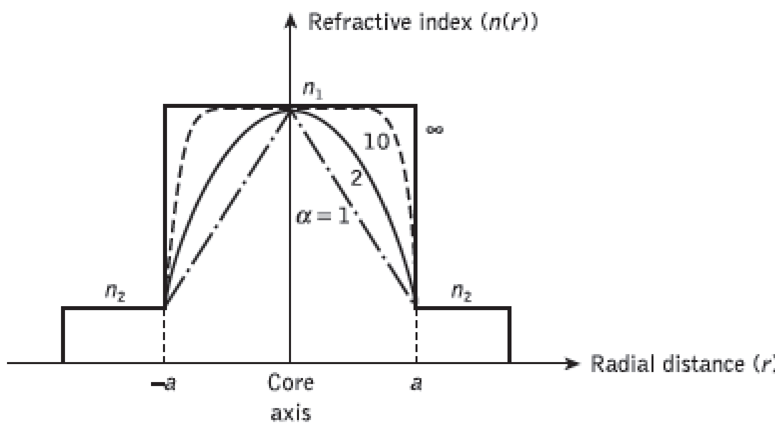


Figure 1.10 Possible fiber refractive index profiles for different values of α (given in Eq. (1.11))

The graded index profiles which at present produce the best results for multimode optical propagation have a near parabolic refractive index profile core with $\alpha \approx 2$. Fibers with such core index profiles are well established and consequently when the term 'graded index' is used without qualification it usually refers to a fiber with this profile.

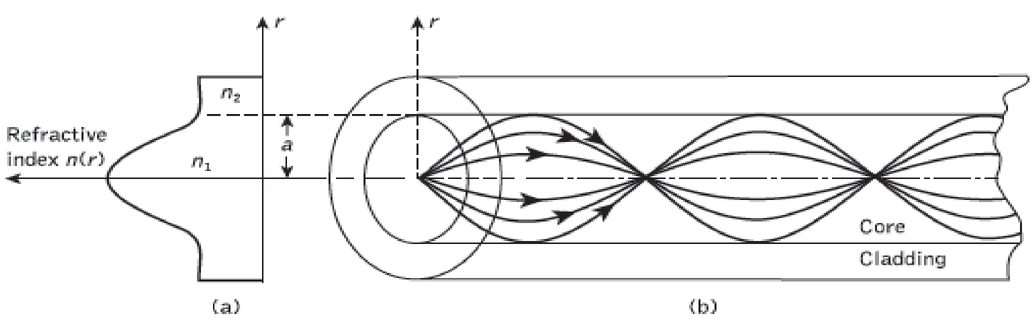


Figure 1.11 The refractive index profile and ray transmission in a multimode graded index fiber

EXAMPLE

A graded index fiber has a core with a parabolic refractive index profile which has a diameter of 50 μm. The fiber has a numerical aperture of 0.2. Estimate the total number of guided modes propagating in the fiber when it is operating at a wavelength of 1 μm.

Solution: the normalized frequency for the fiber is:

$$V = \frac{2\pi}{\lambda} a(NA) = \frac{2\pi \times 25 \times 10^{-6} \times 0.2}{1 \times 10^{-6}}$$

$$= 31.4$$

The mode volume may be obtained for a parabolic profile:

$$M_g \simeq \frac{V^2}{4} = \frac{986}{4} = 247$$

Hence the fiber supports approximately 247 guided modes.