NEC 701
OPTICAL COMMUNICATION
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.

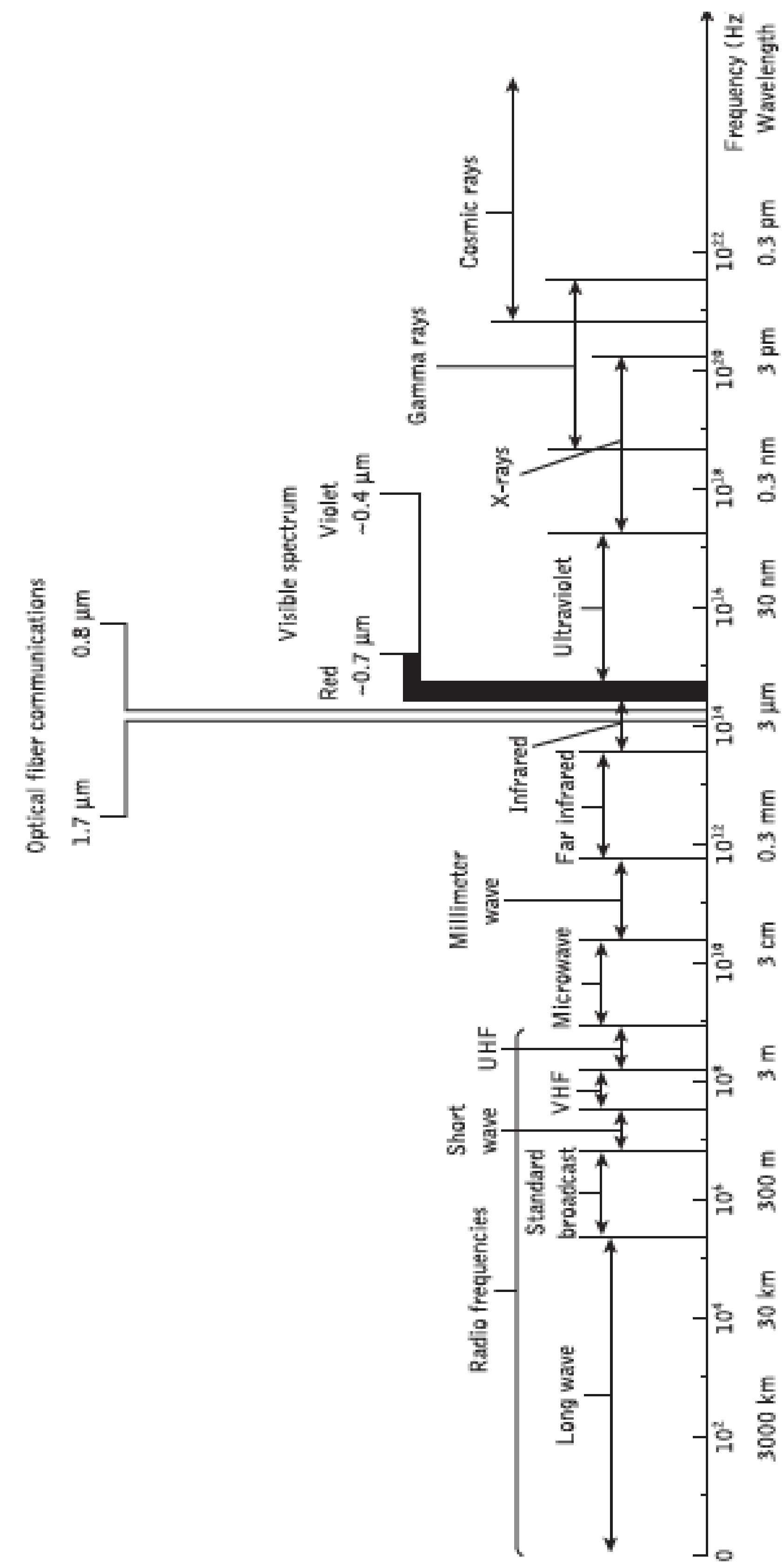


Figure 1.1 The electromagnetic spectrum showing the region used for optical fiber communications

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.

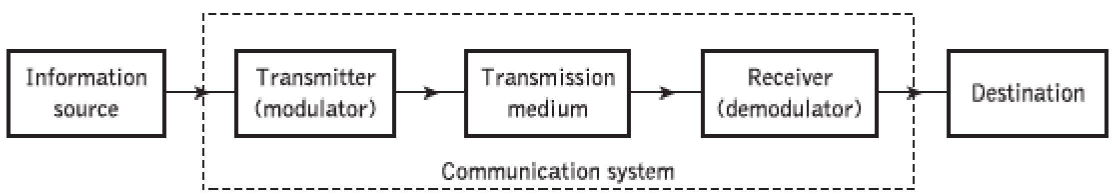


Figure 1.2(a): The General Communication System

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.

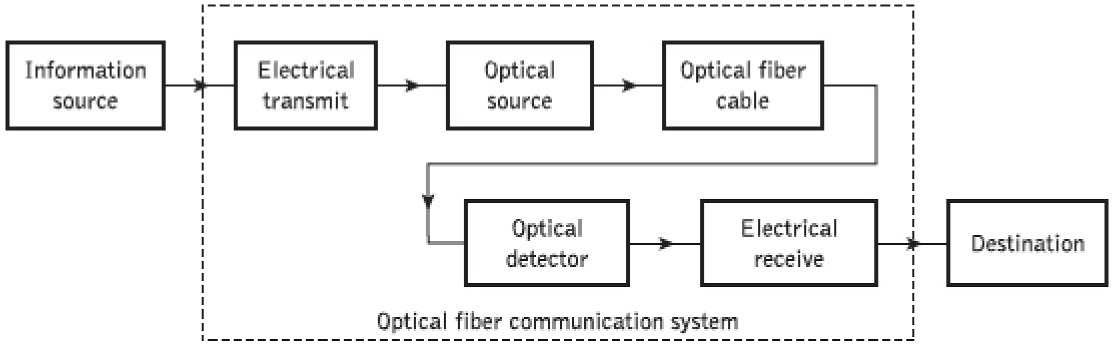


Figure 1.2(b): The Optical Fiber communication System

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.

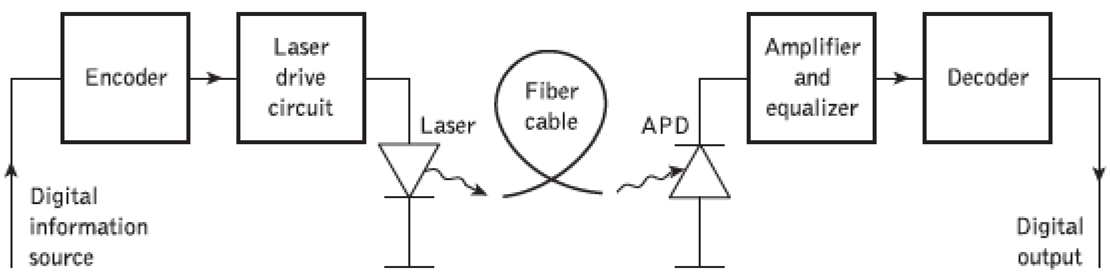


Figure 1.3: The Block diagram of digital optical communication system

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.**

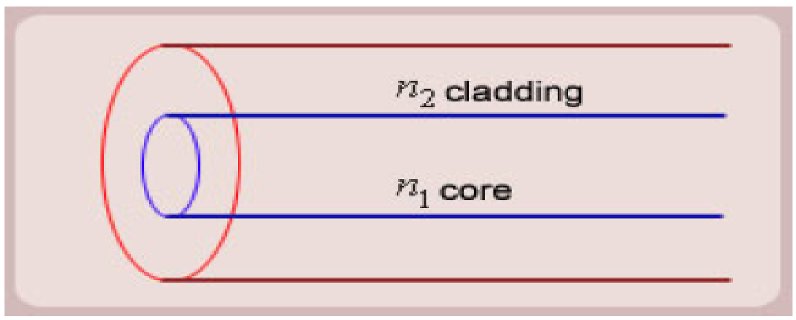
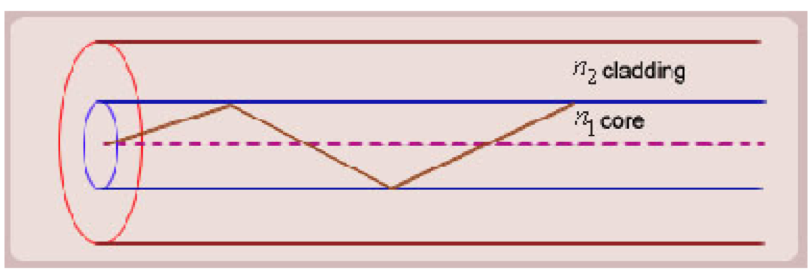


Figure 1.4: Schematic of Optical fiber

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

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

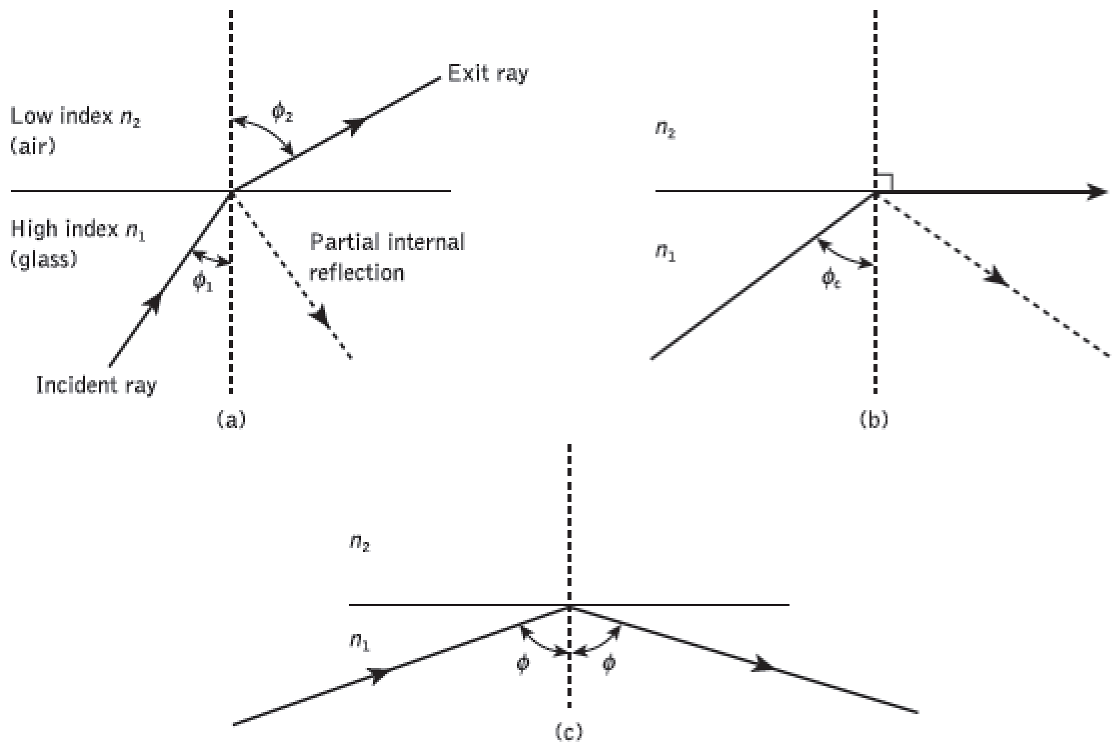


Figure 1.5 Light rays incident on a high to low refractive index interface (e.g. glass–air): (a) refraction; (b) the limiting case of refraction showing the critical ray at an angle ϕ_c; (c) total internal reflection where $\phi > \phi_c$

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.

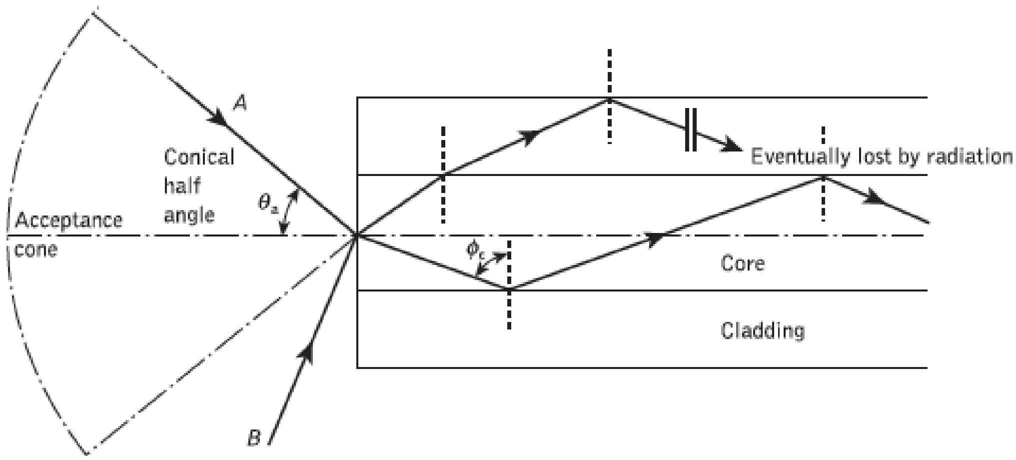


Figure 1.6 The acceptance angle θ_a when launching light into an optical fiber

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.

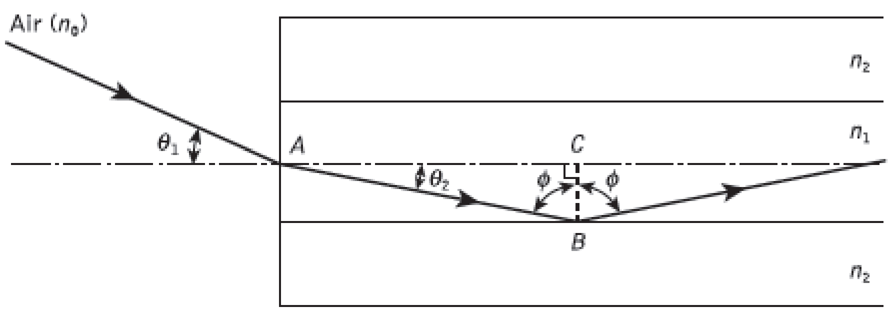


Figure 1.7 The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceptance angle for the fiber

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:

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

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

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

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

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

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

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

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

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

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:

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

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:

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

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

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

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

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:

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

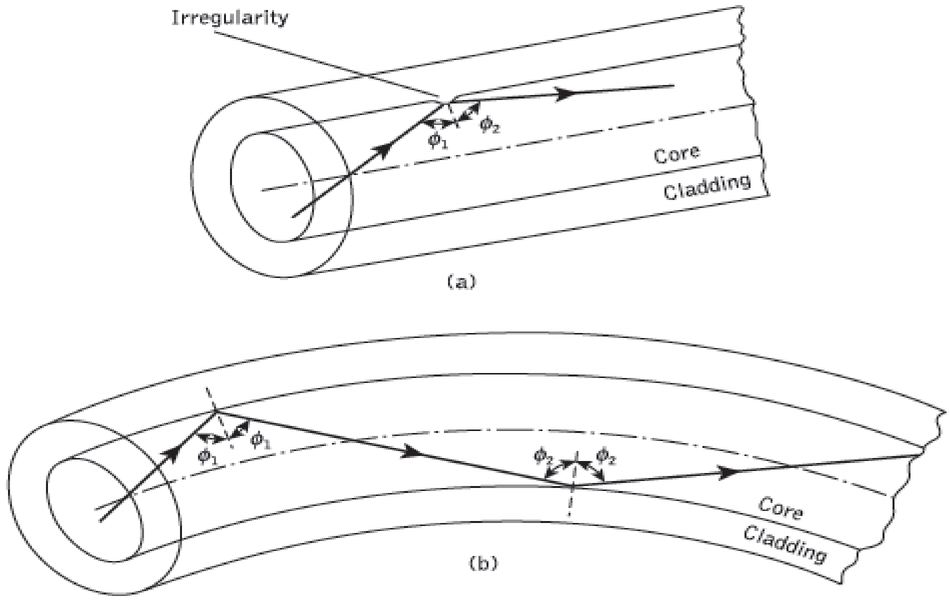


Figure 1.8 Ray theory illustrations showing two of the possible fiber perturbations which give mode coupling: (a) irregularity at the core–cladding interface; (b) fiber bend

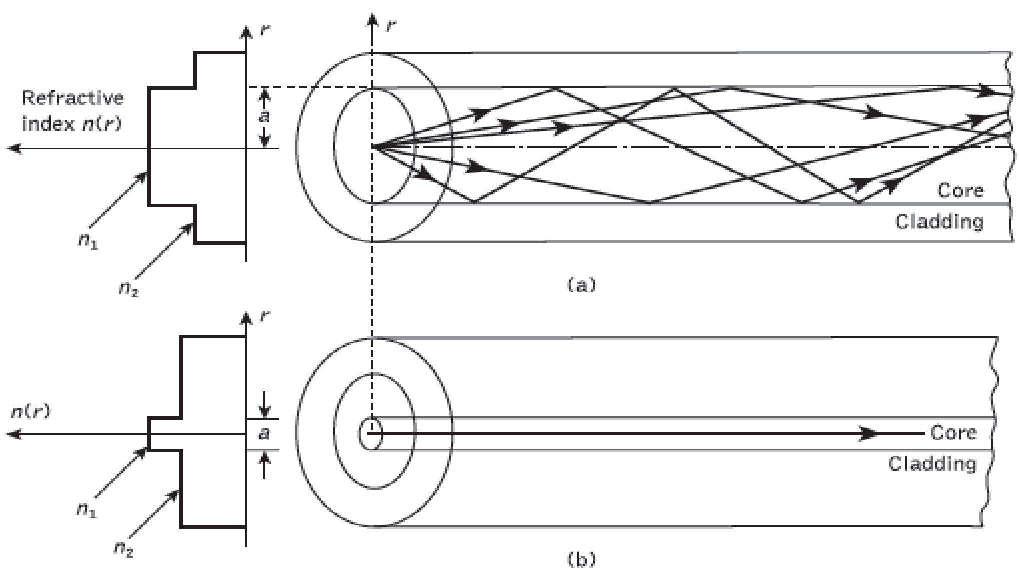


Figure 1.9 The refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber; (b) single-mode step index fiber

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.

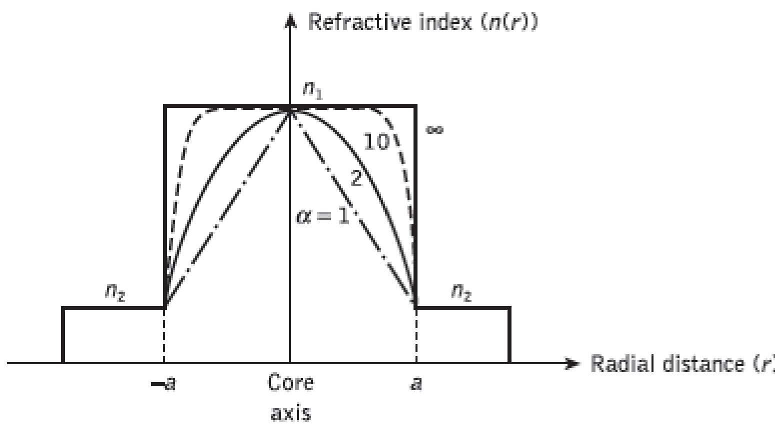


Figure 1.10 Possible fiber refractive index profiles for different values of α (given in Eq. (1.11))

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.

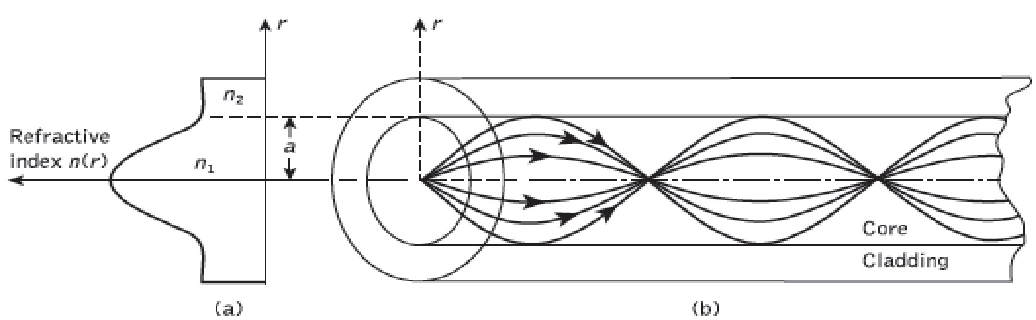


Figure 1.11 The refractive index profile and ray transmission in a multimode graded index fiber

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.

FIBER INDEX PROFILES

Single mode fibers can propagate only the fundamental mode while multimode fibers can propagate hundreds of modes. However, the classification of an optical fiber depends on the number of modes that a fiber can propagate.

The refractive index in the core material of the fiber varies due to variation in the composition of the core material which give rise to two types of optical fibers. These are:

- Step index fiber
- Graded index fiber

In a **step-index fiber**, the refractive index of the core is uniform and undergoes an abrupt change at the core-cladding boundary. Step-index fibers obtain their name from this abrupt change called the step change in refractive index. In graded- index fibers, the refractive index of the core varies gradually as a function of radial distance from the fiber center.

Single mode and multimode fibers can have a step- index or graded-index profile. The performance of multimode graded-index fibers is usually superior to multimode step-index fibers.

An optical fiber's refractive index profile and core size further distinguish single mode and multimode fibers. The refractive index profile describes the value of refractive index as a function of radial distance at any fiber diameter. Fiber refractive index profiles classify signal mode and multimode fibers as follows:

- Single mode step-index fibers
- Multimode step-index fibers
- Multimode graded-index fibers

However, for lower bandwidth applications multimode fibers have several advantages over single mode fibers these are:

- The use of spatially incoherent optical sources (e.g., mode LED's) which cannot be efficiently coupled to single mode fibers.
- Large numerical apertures, as well as core diameters, facilitating easier coupling to optical sources.
- Lower tolerance requirements on fiber connectors

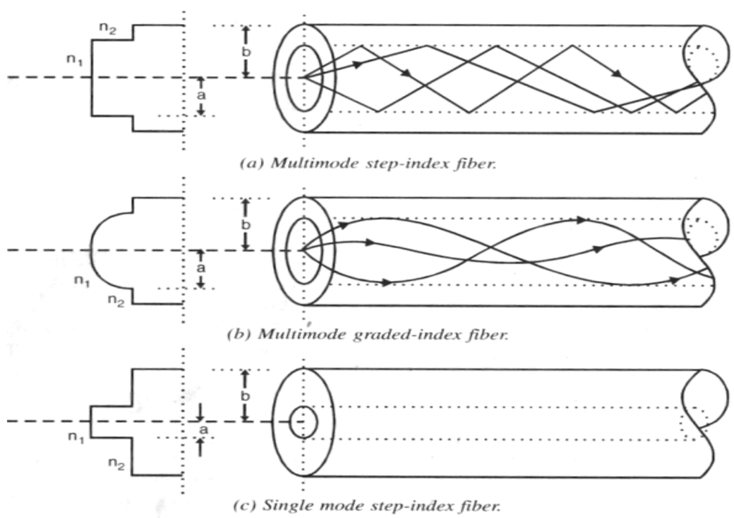


Fig. 1 the refractive index profiles and light propagation.

However, each type of multimode fiber can improve system design and operation depending on the intended application. Performance advantages for single mode graded- index fibers compared to single mode step-index fibers are relatively small. Therefore, single mode fiber production is almost exclusively step-index. Figure 1 shows the refractive index profile for a multimode step-index fiber and a multimode graded-index fiber. Figure 1 also shows the refractive index profile for a single mode step-index fiber. Since light propagates differently in each fiber type, figure1 shows the propagation of light along each fiber.

- Standard core sizes for multimode step-index fibers are 50 µm and 100 µm.
- Standard core sizes for multimode graded-index fibers are 50 µm, 62.5 µm 85 µm ad 100 µm .

- Standard core sizes for single mode fibers are between 8 µm and 10 µm

A particular optical fiber design can improve fiber optic system performance. Each single mode or multimode, step-index or graded-index, glass or plastic, or large or small core fiber has an intended application. The system designer must choose an appropriate fiber design that optimizes system performance in this application.

Multimode step-index fiber has a core of radius α and a constant refractive index n_1. A cladding of slightly lower refractive index n_2 surrounds the core.

But the diameters of the core is much larger (50-200 µm). The comparatively large central core makes it rugged and easily infused with light, as well as easily terminated and coupled. It is the best expensive but also the least effective of the lot, and for long range application, it has some serious drawbacks especially intermodal dispersion. It supports a large number of modes for propagation because of its large core diameter.

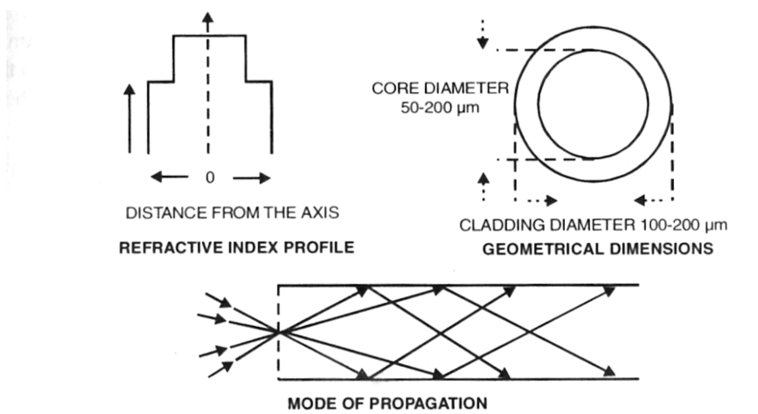


Figure 2 shows the refractive index profile n(r) for this type of fiber

$$n(r) = \begin{Bmatrix} n_1 r \leq a(core) \\ n_2 r \geq a(cladding \end{Bmatrix}$$

Notice that the step decrease in the value of refractive index at the core-cladding interface. This step decrease occurs at a radius equal to distance (a). The difference in the core and cladding refractive index is the parameter Δ:

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

Δ is the relative refractive index difference.

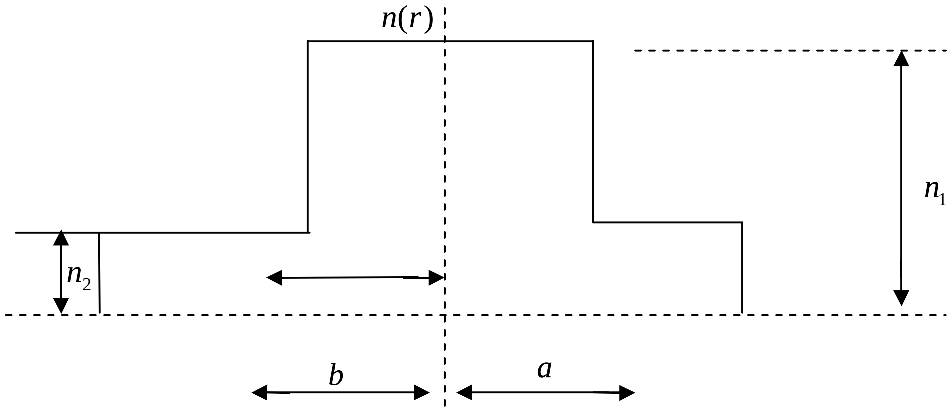


Fig 3 the refractive index profile for multimode step-index fibers.

The ability of the fiber to accept optical energy from a light source is related to Δ. Δ also results to the numerical aperture by

$$NA \cong n_1\sqrt{2\Delta}.$$

The number of mode that multimode step-index fibers propagate depends on Δ and core radius (α) of the fiber. The number of propagating modes also depends on the wavelength (λ) of the transmitted light. In a typical multimode step-index fiber, there are hundreds of propagating modes.

- Most modes in multimode step-index fibers propagate far from cutoff. Modes that are cut off cease to be bound to the core of the fiber.
- Modes that are farther away from the cutoff wavelength concentrate most of their light energy into tie fiber core.
- Modes that propagate close to cutoff have greater percentage of their light energy propagate in the cladding.
- Since most modes propagate far from cutoff, the majority of light propagates in the fiber core. Therefore, in multimode step-index fibers, cladding properties, such as cladding diameter, have limited affect on mode (light) propagation.

Multimode step-fibers have relatively:

- Large core diameters
- Large numerical apertures

A large core size and a large numerical aperture make it easier to couple light from a light-emitting diode(LED) into the fiber. Multimode step-index fiber core size is typically 50 µm or 100 µm. Unfortunately, multimode step-index fibers have limited bandwidth capabilities.

In addition multimode step index optical fibers:

- Accept either laser or a LED as the source of light.
- Are least expensive of all the three types of fibers.
- Are used in data links that have lower band width requirements.
- Not free form modal dispersion.
- Have higher information carrying capacity.

Multimode step-index section depends on system application and design. Short-haul, limited bandwidth, law-cost applications typically use multimode step-index fiber.

<u>Multimode Graded-index Fibers</u>

In consists of a core whose refractive index decreases gradually from its axis radially outward and becomes equal to the refractive index of the cladding at the core-index of the cladding at the core-cladding interface. The refractive index of the cladding remains uniform. Dimensions of the core and cladding are similar to that of step index multimode fibers. It supports a large number of modes for propagation because of its large core diameter.

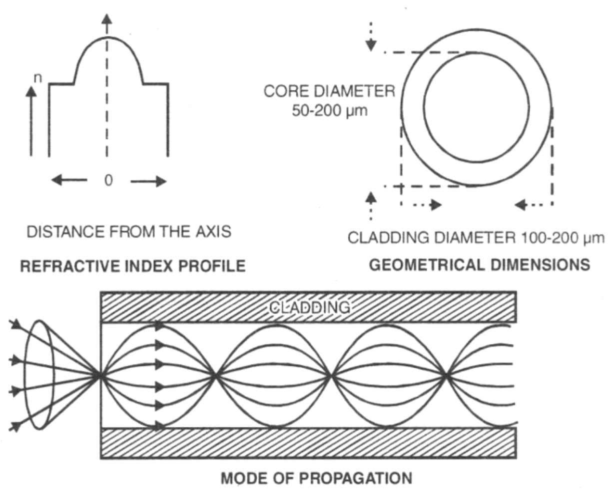


Figure 4

A multimode graded-index fiber has a core of radius α. Unlike step-index fibers, the value of the refractive index of the core n_1 varies according to the radial distance r. the index variation may be represented as:

$$n(r) = \begin{cases} n_1\left[1-2\Delta\left(\dfrac{r}{a}\right)^{\alpha}\right]^{1/2} & r \le a(core) \\ n_1(1-2\Delta 1/2 = n_2 & r \ge a(cladding) \end{cases}$$

The value of $n_1$decreases until it approaches the value of the refractive index of the cladding n_2. The value of n_1 must be higher than the value of n_2 to allow for proper mode for proper mode propagation. Like the step-index fiber, the value of n_2 is constant and has a slightly lower value than the maximum value of n_1. The relative refractive index difference (Δ) is determined using the maximum value of $n_1$and the value of n_2.

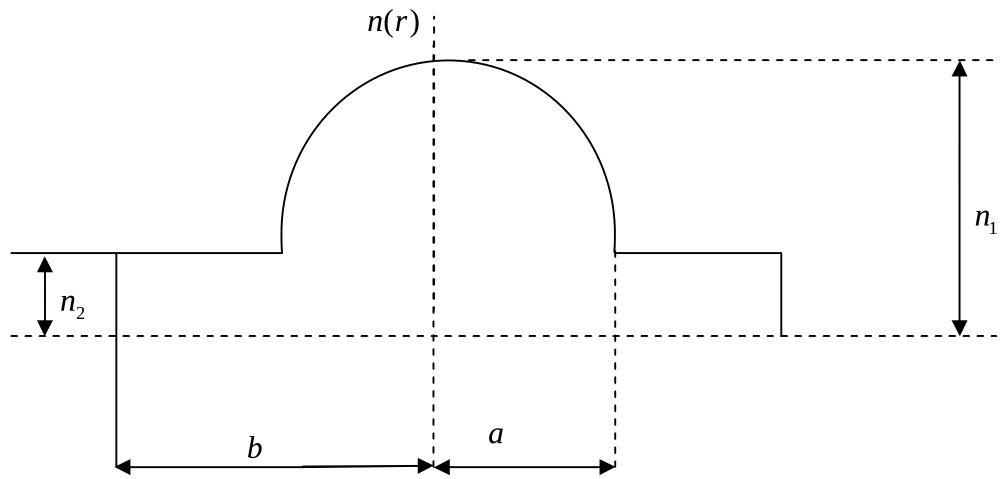


Figure 5. The refractive index profile for multimode graded-index fibers.

Figure 5 shows a possible refractive index profile n(r) for multimode graded-index fiber. Notice the parabolic refractive index profile of he core.

- The profile parameter (a) determines the shape of the core's profile. As the value of a increases, the shape of the core's profile changes from a triangular shape to step as shown in figure 6
- Most multimode graded-index fibers have a parabolic refractive index profile. Multimode fibers with near parabolic graded-index profiles provide the best performance.
- Unless otherwise specified, when discussing multimode graded-index fibers, assume that the core's refractive index profile is parabolic (a=2).

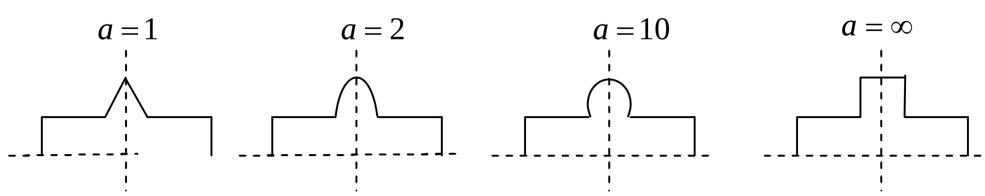


Fig. 6 the refractive index profiles for different values of α

- Light propagates in multimode graded-index fibers according to refraction and total internal reflection.
- The gradual decrease in the core's refractive index from the center of the fiber causes the light rays to be refracted many times.

- The light rays become refracted or curved, which increases the angle of incidence at the next point of refraction.

Most present day applications that use multimode fiber use graded-index fibers. The basic design parameters are the fiber's core and cladding size and Δ.

Standard multimode graded-index fiber core and cladding sizes are 50/125μm, 62.5/125μm, 85/125μm, and 100/125μm. Each fiber design has a specific Δ that improves fiber performance. Typical values of Δ are around 0.01 to 0.02. Although no single multimode graded-index fiber design is appropriate for all applications, the **62.5μm, fiber with a Δof 0.02 offers the best overall performance.**

A multimode graded-index fiber's source-to-fiber coupling efficiency and insensitivity to microbending and macrobending losses are its most distinguishing characteristics.

In addition to multimode graded index fiber:

- Accept either laser or a LED as the source of light.
- Are the most expensive of all the three types of fibers.
- Are used in telephone trunks between central offices.
- Have lower modal dispersion.
- Have higher information carrying capacity.

In most applications, **a multimode graded-index fiber with a core and cladding size of 62.5/125μm offers the best combination of the following properties:**

- Relatively high source-to-fiber coupling efficiency
- Low loss
- Low sensitivity to microbending and macrobending
- High bandwidth
- Expansion capability

Single mode step-index fibers

There are two basic types of single mode step-index fibers:

- Matched clad
- Depressed clad

Matched cladding means that the fiber cladding consists of a single homogeneous layer of dielectric material. Depressed cladding means that the fiber cladding consists of two regions: the inner and outer cladding regions. Matches -clad and depressed-clad single mode step-index fibers have unique refractive index profiles.

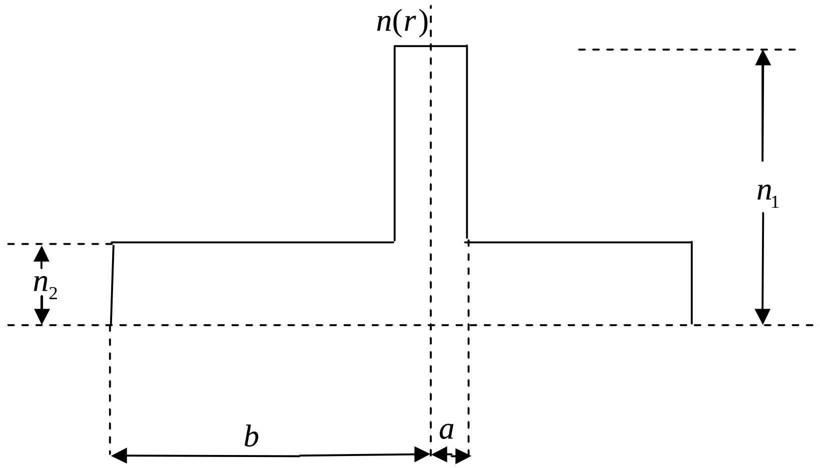


Fig. 7 Matched-clad refractive index profile.

A matched-clad single mode step-index fiber has a core of radius and a constant refractive is index n_1. A cladding of slightly lower refractive index surrounds the core. The cladding has a refractive index n_2. Figure7 shows the refractive index profile n(r) for the matches-clad single mode fiber.

Figure 8 shows the refractive index profile n(r) for the depressed-clad single mode fiber. A depressed-clad single mode step-index fiber has core of radius a with a constant refractive index n_1. A cladding, made of two regions, surrounds the core. An inner cladding refractive index n_2 is lower than the core's refractive index n_1. An outer cladding region surrounds the inner cladding region and has a higher refractive index n_3 than the inner cladding region. However, the outer cladding refractive index n_3 is lower than the core's refractive index n_1.

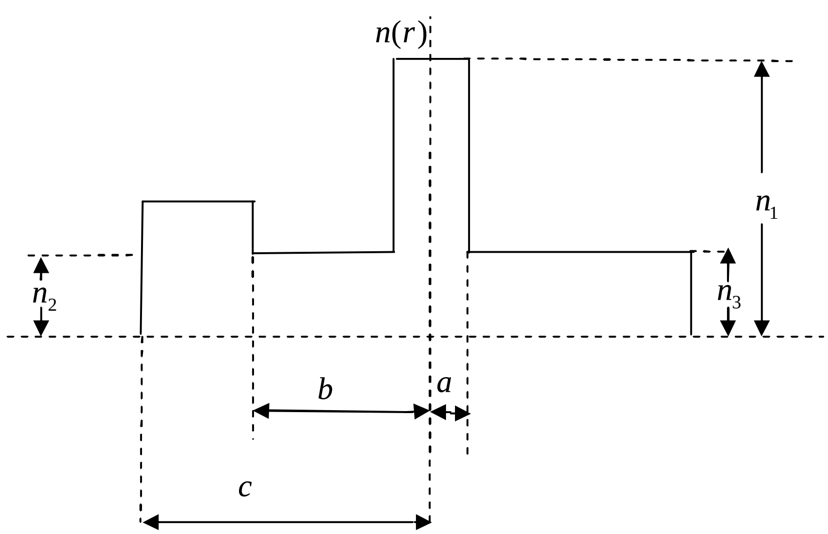


Figure 8 Depressed-clad refractive index profile.

Single mode step-index fibers propagate only one mode, called the fundamental mode. Single mode operation occurs when the value of the fiber's normalized frequency is between 0 and 2.405 ($0 \leq V < 2.405$). the value of V should remain near the 2.405 level. When the value of V is less than 1, single mode fibers carry a majority of the light power in the cladding material.

The total number of guided modes or mode volume M_s for step index fiber is related to the V value for the fiber y the approximate expression:

$$M_s = \frac{V^2}{2}$$

A single mode step-index fiber has low attenuation and high bandwidth properties. **Present applications** for single mode fibers include long-haul, high-speed telecommunication systems. Future applications include single mode fibers for sensor systems. However, the current state of single mode technology makes installation of single mode systems expensive and difficult. Several factors are there which make installation of single mode fiber shipboard system impractical:

- Short cable runs
- Low to moderate bandwidth requirements
- High component cost.

SINGLE MODE FIBERS

Single mode fibers are designed by taking the dimension of the core radius to a few wavelength (usually 4-6µm) and by having small index difference between core and cladding. The size of core in single mode fiber is very small, therefore to obtain a fiber of several kilometer is quite difficult.

$$V_C = 2.405\left[1 + \frac{2}{\alpha}\right]^{1/2}$$

In practical designing of single mode fiber, the core cladding index difference varies between 0.2% and 1.0%, and core diameter should be chosen to first below the cutoff of the first higher order mode. Thus V should be approximately 2.405. Example : A typical single mode fiber has a core radius of 3µm and numerical aperature of 0.1 at a wavelength of 0.8µm.

Graded index fibers may also be designed for single mode operation. The cutoff value of **normalized frequency V_C** to support a single mode in a graded index fiber is given by

Therefore as in the case of the step index, it is possible to determine the fiber parameters which give single mode operation.

Cutoff Wavelength

The cutoff normalized frequency (V_C) in terms of NA and the relative refractive index difference Δ is given by

$$V_C = \frac{2\pi}{\lambda_C}.a(NA) ------(1)$$

$$V_C = \frac{2\pi}{\lambda_C} an_1 (2\Delta)1/2 ------------(2)$$

The single mode operation only occur above a theoretical cutoff wavelength λ_C and is given by

$$\lambda_C = \frac{2\pi a n_1}{V_C}(2\Delta)1/2 --------(3)$$

Where, V_C = Cutoff normalized frequency.

Therefore, λ_C is the wavelength above which a particular fiber becomes single moded.

$$\frac{\lambda_C}{\lambda} = \frac{V}{V_C} ------------(4)$$

By dividing the Eqs. (2) by (3), we get an inverse relationship

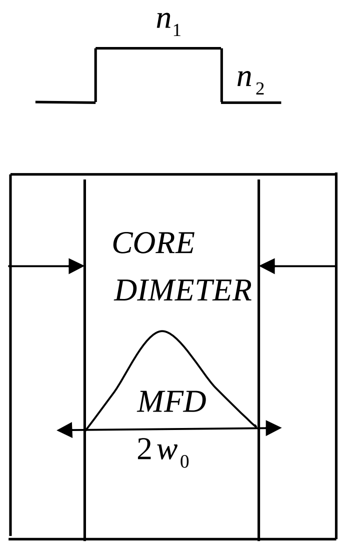
Thus for step index fiber where V_C = 2.405, the cutoff wavelength is given by

$$\lambda_C = \frac{V\lambda}{2.405} ----------(5)$$

CCITT defines an effective cutoff wavelength, which is obtained form a 2m length of fiber containing a single 14 cm radius loop.

Mode field diameter (MFD) and Spot Size

To describe single mode fibers, manufactures use parameter mode field diameter (MFD) in place of core diameter. The reason for using MFD as a parameter can be understood form fig. 9



$$(a)\Delta_{Typically} = \frac{n1 - n2}{n}$$

$< 0.4\%$

(b)

Fig. 9 Distribution of beam's intensity in a single mode fiber.
Core diameter : 8.3µm
MFD : Typically 9.3µm

Therefore mode field diameter is the cross-sectional dimension $2\omega_0$, where the beam's intensity drops to $1/e^2=0.135$ of its peak value.

Therefore, the mode field diameter of the propagating mode constitutes fundamental parameter characteristics of single mode fiber. This is also known as **mode spot size**.

Figure 10 shows the distribution of optical power across the diameter of a typical single-mode fiber. **The mode field** is defined as the distance between the points where the strength of the electric field is decayed to 0.37 (1/e) of the peak.

Optical power in single-mode fiber travels in both the core and the cladding. In many situations when we have to join two fiber we need a number that will give us a measure of the extent of the region that carries the optical signal. In single-mode fiber the core diameter is not sufficient.

The MFD of standard SMF at 1550 nm is between 10.5 microns and 11 microns depending on the fiber. In the 1310 nm band the MFD of standard fiber is 9.3 microns. Sometimes the spot size is also used to characterize single-mode fiber. The diameter of the spot is just the radius of the mode field.

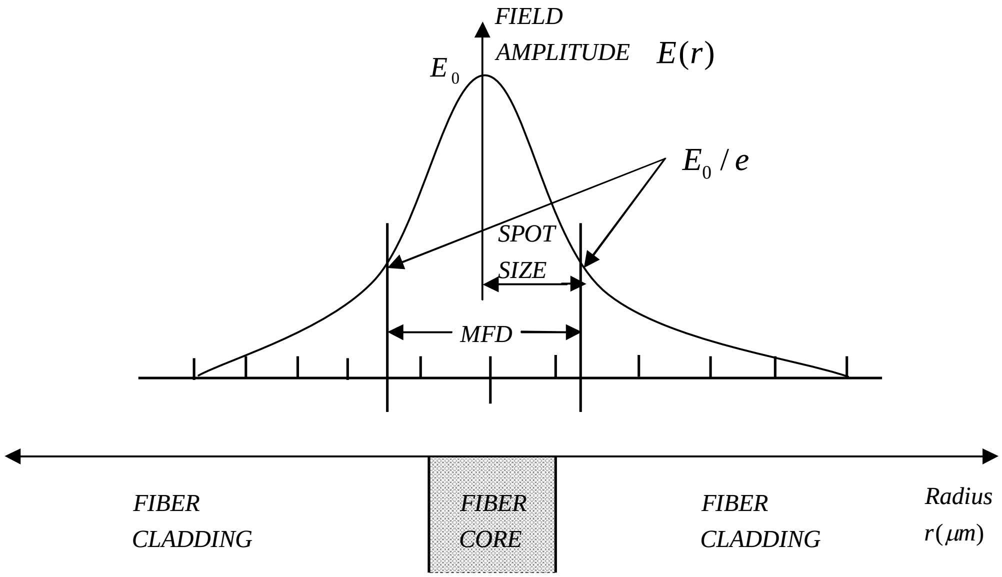


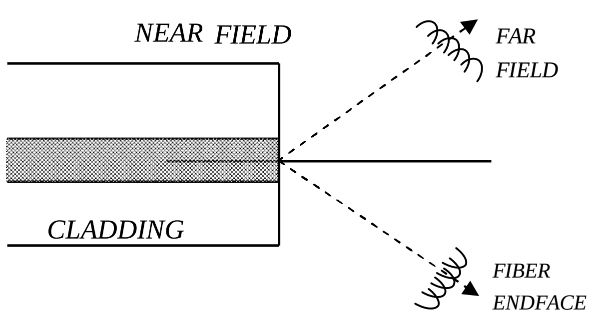
Figure. 10mode field definition.

If two fibers have different mode field diameters, we will have extra insertion loss. This insertion loss can be calculated by:

$$Loss\,coupling\;MFD(dB) = -10\log\left[\frac{4}{\left(\frac{MFD_1}{MFD_2}+\frac{MFD_2}{MFD_1}\right)^2}\right]$$

Field Strength at the Fiber End

When the intensity of light is measured at the end of a fiber there are two places at which it can be done- right at the end face itself and some distance away from it.



Fields at the end of the fiber.

Near Field

This is the electromagnetic field at the end face of the fiber itself. In a single-mode fiber this will usually be a profile of the bound mode but if the measurement is mode close to the transitter there may be cladding modes present as well.

Far Field:

It is extremely difficult to measure the near field directly. Thus the far field is measured and used to calculate the characteristics of the near field such as mode field diameter etc. The far field consists of a series of lobes spread out away from the axis of the fiber. This is due to the fact that light leaving the end face diffracts in many directions.

Bend Loss in Single-Mode Fiber: Let us consider light in SM fiber propagating along the fiber as a wave. There is a phase front which moves along the fiber perpendicular to the direction of travel. The wave front must be in-phase with itself across the diameter of the field. As the phase front movers into a bend the light at the inner radius of the bend must move more slowly than the light at the outer radius (considering a single wave occupying all of the mode field). This means that at the outer edge (of the core) the light must experience a lower R_τ than it would in a straight fiber.

Effective Refractive Index :

The **phase propagation constant β** is determined by the rate of change of phase of the fundamental LP_{01} mode propagating along a fiber. It is directly related to the wavelength of the LP_{01} mode λ_{01} by the factor 2π because β gives the increase in phase angle per unit length.

Hence $$\beta\lambda_{01} = 2\pi$$

$$\boxed{\lambda_{01} = \frac{2\pi}{\beta}}$$

Phase index of normalized phase change coefficient η_{eff} is defined by the ratio of the propagation constant of the fundamental mode to that of the vacuum propagation constant .

$$\boxed{\eta_{eff} = \frac{\beta}{K}}$$

Hence the fundamental mode (λ_{01}) wavelength is smaller than vacuum wavelength λ by a factor $\frac{1}{\eta_{eff}}$,

$$\boxed{\lambda_{01} = \frac{\lambda}{\eta_{eff}}}$$

Where,

The fundamental mode propagates in a medium with a refractive index n(r) which is dependent on the distance r from the fiber axis. The refractive index can be considered as an average over the refractive index of this medium.

At long wavelength within a normally clad fiber, the mode field diameter is large compared to the core diameter and hence the electric field extends far into the cladding region. In this case the propagation constant β will be approximately equal to n_2K and the effective index will be similar to the refractive index of the cladding n_2.

Physically most of the power is transmitted in the cladding material. However at short wavelengths, the field is concentrated in the core region and the propagation constant β approximates to the max. wave number n_1K.

Thus the propagation constant in single mode fiber varies over the interval $n_2K < \beta < n_1K$. Hence the effective refractive index will vary over the range $n_2 < \eta_{eff} < n_1$

A relation between the effective refractive index and the normalized propagation constant b is defined as

$$b = \frac{\left(\frac{\beta}{K}\right)^2 - n_2^2}{n_1^2 - n_2^2}$$

$$= \frac{\beta^2 - n_2^2 k^2}{n_1^2 K^2 - n_2^2 K^2}$$

$$= \frac{(\beta + n_2 K)(\beta - n_2 K)}{(n_1 K + n_2 K)(n_1 K - n_2 K)}$$

But $\beta \cong n_1 K, then$

$$b = \frac{\beta - n_2 k}{n_1 K - n_2 K}$$

$$\boxed{b = \frac{\beta / K - n_2}{n_1 - n_2} = \frac{\eta_{eff} - n_2}{n_1 - n_2}}$$

In single mode fibers, the parameter b varies between 0 and 1.

Group Delay and Mode Factor Delay

For a light pulse propagating along a unit length of fiber, the transit time or group delay τ_g is the inverse of the group velocity v_g. Therefore.

$$\tau_g = \frac{1}{v_g} = \frac{d\beta}{d\omega}$$
$$= \frac{1}{C} \cdot \frac{d\beta}{dK} \quad \text{....(2.45)}$$

The group index of a uniform plane wave propagating in a homogeneous medium can be determined by the following equation

$$\boxed{N_g = \frac{C}{v_g}} \quad \text{....(2.46)}$$

But for a single mode fiber effective group index N_{ge} is defined as

$$N_g = \frac{C}{v_g} \quad \text{....(2.47)}$$

Where, v_g = Group velocity of the fundamental fiber mode.

Hence the specific group delay of the fundamental fiber mode becomes:

$$\boxed{\tau_g = \frac{N_g}{C}}$$

The effective group index in terms of effective refractive index η_{eff} may be written as

$$\boxed{N_{ge} = \eta_{eff} - \lambda . \frac{d\eta_{eff}}{d\lambda}} \quad \text{....(2.48)}$$

β may be expressed in terms of the relative index difference Δ and the normalized propagation constant b by the following approximate equation.

$$\beta = K\left[(n_1^2 - n_2^2)b + n_2^2\right]^{1/2}$$
$$\approx Kn_2(1 + b\Delta) \quad \text{....(2.49)}$$

For a weakly guiding fiber where $\Delta \ll 1$, the relative refractive index as,

$$\frac{n_1 - n_2}{n_2} \approx \frac{N_{g1} - N_{g2}}{N_{g2}} \quad \text{....(2.50)}$$

Where, N_{g1} and N_{g2}= Group indices for the fiber core and cladding regions respectively.

Substituting the value of β in eqn. (2.45) and by using eqn. (2.50(, the group delay, per unit distance is given by

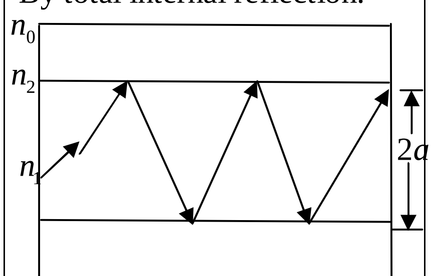
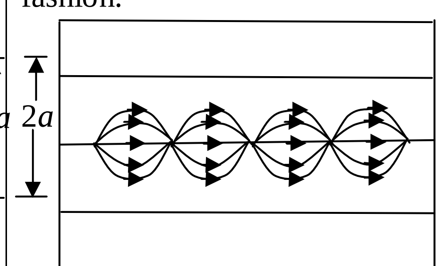
$$\tau_g = \frac{1}{C}\left[N_{g2} + (N_{g1} - N_{g2})\frac{d(Vb)}{dV}\right] \quad ….(2.51)$$

The wavelength dependence of Δ can be ignored because the dispersive properties of fiber core and the cladding are almost same.

Therefore the group delay can be written as

$$\tau_g = \frac{1}{C}\left[N_{g2} + n_2\Delta\frac{d(Vb)}{dV}\right] \quad ….(2.52)$$

- The first term is dependent on group delay an wavelength when uniform plane wave is propagating in an infinite extended medium.
- The second term results from the waveguiding properties properties of the fiber only and is determined by the mode delay factor $\frac{d(Vb)}{dV}$ which describes the change in group delay.

S. No.	Parameter	Stop Index fiber	Graded index fiber
1	Data rate	Slow	Higher
2	Coupling efficiency	Coupling efficiency with fiber is higher.	Lower coupling efficiency
3	Ray path	By total internal reflection. 	Light ray travels in oscillatory fashion. 
4	Index variation	$\Delta = \frac{n_1 - n_2}{n_1}$	$\Delta = \frac{n_1 - n_2}{2n_1^2}$
5	Numerical aperture	NA remains same.	Changes continuously with distance from fiber axis.
6	Material used	Normally plastic or glass is preferred.	Only glass is preferred.
7	Bandwidth efficiency	10-20MHz/km	1GHz/km

8	Pulse spreading	Pulse spreading by fiber length is more.	Pulse spreading is less
9	Attenuation of light	Less typically 0.34dB/km at 1.3µm.	More 0.6 to 1 dB/km at 1.3µm.
10	Typical light source	LED.	LED, Lasers
11	Applications	Subscriber local network communication.	Local and wide area networks.

Fiber material :-

Requirements of fiber Optic material

1. The material must be transparent for efficient transmission of light.
2. It must be possible to draw long thin fibers form the material.
3. Fiber material must be compatible with the cladding material.

Glass and plastics fulfills these requirements.

- Most fiber consists of silica (SiO_2) or silicate. Various types of high loss and low loss glass fibers are available to suit the requirements. Plastic fibers are not popular because of high attenuation they have better mechanical strength.

Glass Fibers

- Glass is made by fusing mixtures of metal oxides having refractive index of 1.458 at 580nm. For changing the refractive index different oxides such as B_2O_3, GeO_2 and P_2O_5 are added as figure 11 shows the dopants. Fig. shows variation of refractive index with doping concentration.
- The addition of dopants GeO_2 and P2O5 increases refractive index, wile dopants Fluorine (f) and B_2O_3 decreases refractive index. One important criteria is that the refractive index of core is grater than that of the cladding, hence some important compositions are used such as:

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

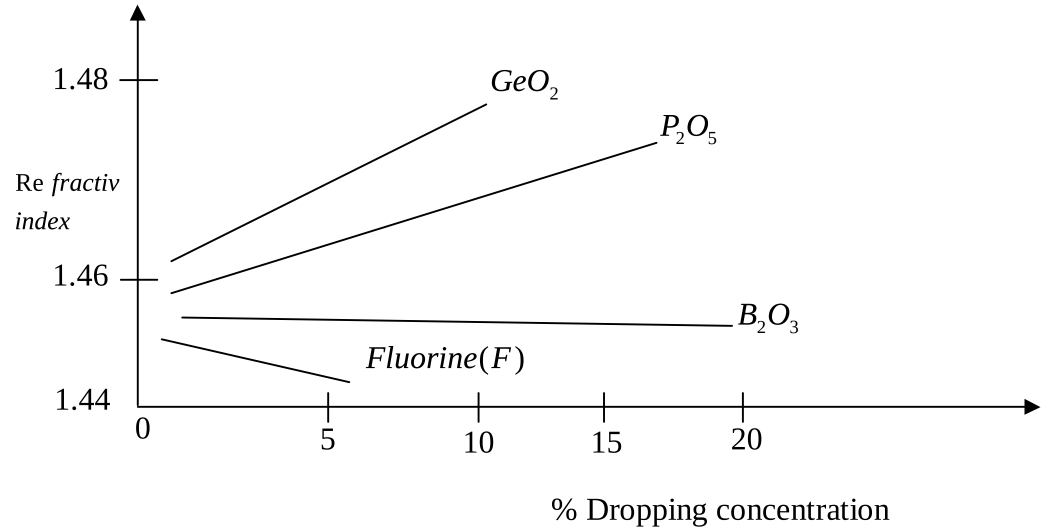


Fig. 11 Variation of refractive index with doping concentration

- The principal raw material for silica is sand and glass. The fiber composed of pure slica is called as silica glass. The desirable properties of silica glass are:-
  -Resistance to deformation even at high temperature.
  -Resistance to breakage from thermal shocks (low thermal expansion).
  - Good chemical durability.
  - Better transparency.
- Other types of glass fibers are:
  -Halide glass fibers
  -Active glass fibers
  - Chalgenide glass fibers
  -Plastic optical fibers

Fiber Fabrication Techniques:-

- The vapour-phase oxidation process is popularly used for fabricating optical fibers. In this process vapours of metal halides such as $SiCl_4$ and G_cCl_4 reactive with oxygen and forms powder of SiO_2 particles. The SiO_2 particles are collected on surface of bulk glass and then sintered to form a glass rod called preform. The preforms are typically 10-25 mm diameter and 60-120cm long from which fibers are drawn. A simple chaematic of fiber drawing equipment is shown in fig.12

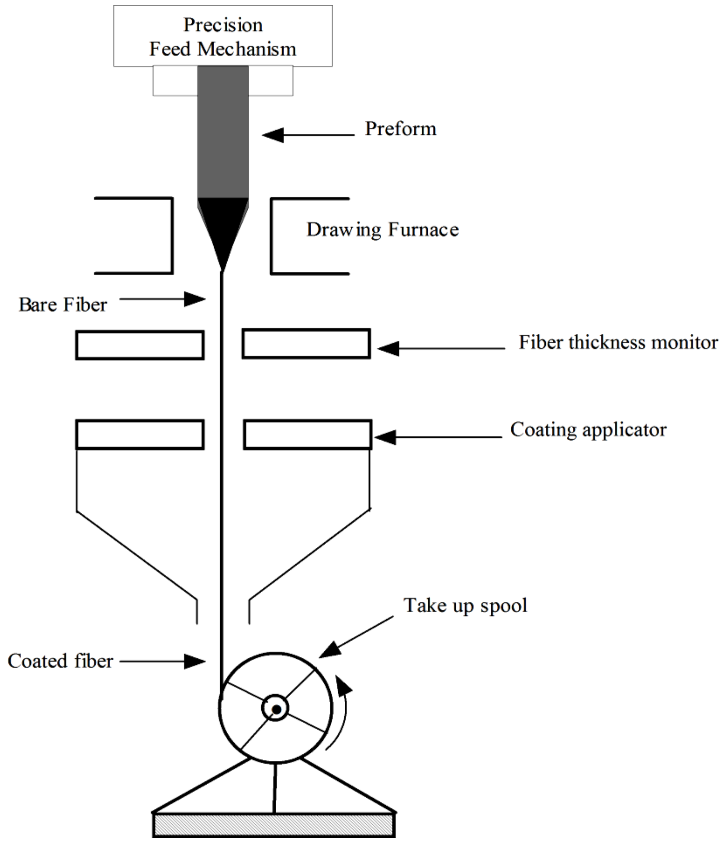


Fig.12 fiber drawing equipment

- The preform is feed to drawing furnace by precision feed mechanism. The perform is heated up in drawing furnace so that it becomes soft and fiber can be drawn easily.
- The fiber thickness monitoring decides the speed of take up spool. The fiber is then coated with elastic material to protect it from dust and water vapor.

Outside Vapour-Phase Oxidation (OVPO)

- The OVPO process is a lateral deposition process. In OVPO process a layer of SiO_2 (Soot)is deposited from a burner on a rotating mandrel so as to make perform. Fig.13 shown this process.

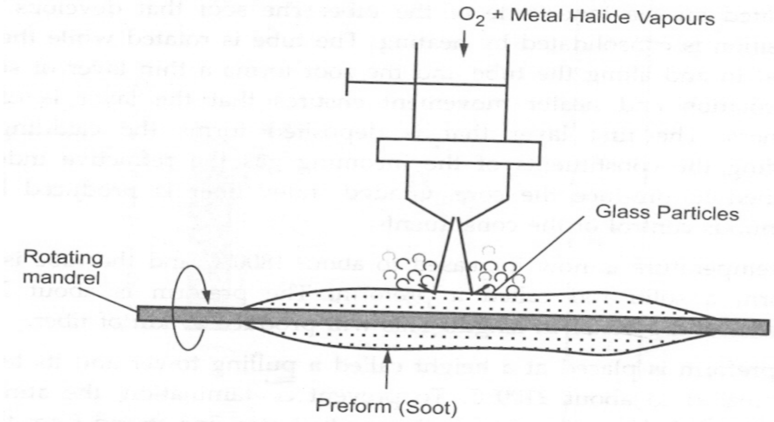


Figure 13 OVPO process

- During the SiO_2 deposition O_2 and metal halide vapours can be controlled so the desired core-cladding diameters can be incorporated. The mandrel is removed when deposition process is completed. This preform is used for drawing thin filament of fibers in fiber drawing equipment.

Vapour-phase Axial Deposition (VAD)

- In VAD process, the SiO2 particles are deposited axially. The rod is continuously rotated and moved upward to maintain symmetry of particle deposition.
- The advantages of VAD process are

  -Both step and graded index fibers are possible to fabricate in multi mode and signal mode.

  -The preforms does not have the central hole.

  -The preforms can be fabricated in continuous length.

  - Clean environment can be maintained.

Modified Chemical Vapour Deposition (MCVD):-

- The MCVD process involves depositing ultra fine, vaporized raw materials into a pre-made silica tube. A hollow silica tube is heated to about 1500°C and a mixture of oxygen and metal halide gases is passed through it. A chemical reaction occurs within the gas and glass '500t' is formed and deposited on the inner side of the tube. The tube is rotated while the heater is moved to and along the tube and the soot forms a thin layer of silica glass. The rotation and heater movement ensures that the layer is of constant thickness. The first layer that is deposited forms the cladding and by changing the constituents of the incoming gas the refractive index can be modified to produce the core. Graded index fiber is produced by careful continuous control of the constituents.

- The temperature is now increased to about 1800°C and the tube is collapsed to form a solid rod called a preform. The perform is about 25 mm in diameter and 1 meter in length. This will produce 25 km of fiber.
- The preform is placed at a height called a pulling tower and its temperature is increased to about 2100°C. To prevent contamination, the atmosphere is kept dry and clean. The fiber is then pulled as a fine strand from the bottom, the core and cladding flowing towards the pulling point. Laser gauges continually monitor the thickness of the fiber and automatically adjust the pulling rate to maintain required thickness of the fiber ajd automatically adjust the pulling rate to maintain required thickness. After sufficient cooling, the primary buffer is applied and the fiber is drummed.
- Figure 13 shown the overall MCVD process.

Plasma-Activated Chemical Vapour Deposition (PCVD)

- PCVD process is similar to MCVD process where the deposition occurs on silica tube at 1200°C. It reduced mechanical stress on glass films. There is no soot formation and hence sintering is not required. Non-isothermal microwave plasma at low pressure initiates the chemical reaction.

Double-Crucible Method

- Double-Crucible method is a direct melt process. In double-crucible method two different glass rods for core and cladding are used as feedstock for two concentric crucibles. The inner crucible is for core and outer crucible is for cladding. The fiber can be drawn from the orifice in the crucible. Fig. 14 shown double crucible method of fiber drawing.
- Major advantages of double crucible method is that it is a continuous production process.

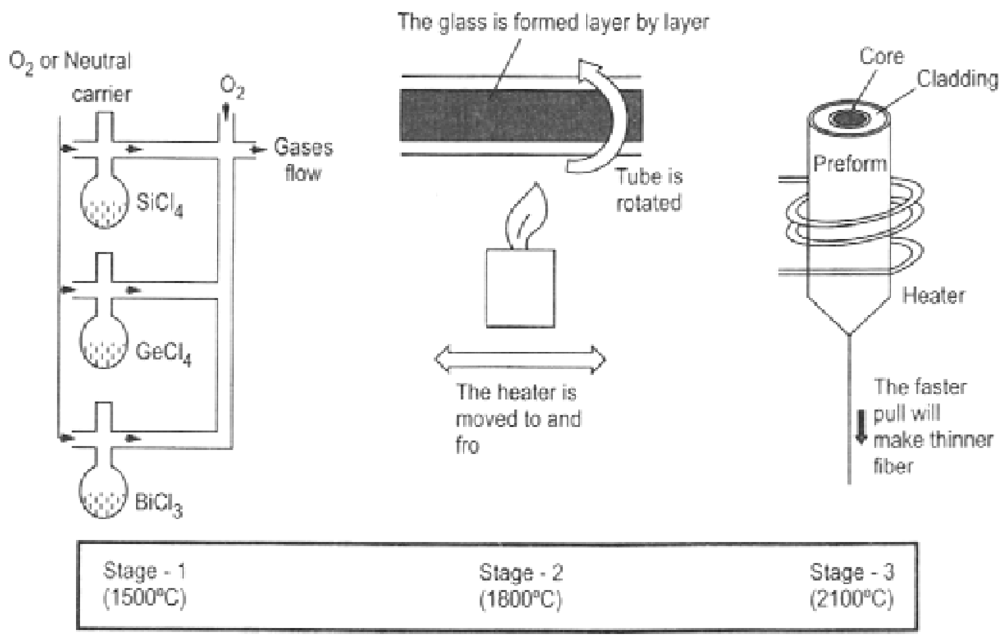


Figure 14 MCVD process

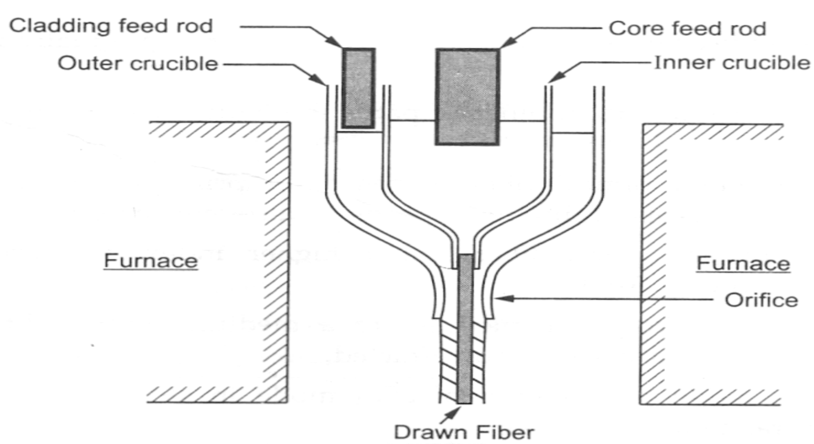


Figure 14 Double Crucible method