MODULE 1

CHAPTER 1

Introduction and Basics of Optical Fiber Communication

Syllabus

1.1 Historical Development, Electromagnetic Spectrum, Optical Bands and Windows, Need for optical fiber communication, Fiber optic cable types and color codes, Block diagram, advantages and disadvantages of optical fiber cables, loss and bandwidth, applications and deployment.

1.2 Basics of Optical Fiber: Review of Ray theory, Wave theory, Light propagation in optical fiber Classification of optical fibers, Propagation modes, MFD in SMF.

1.3 Fiber material, Fabrication techniques for high quality fiber: MCVD, fiber joints, fiber connectors, splices. Brief introduction to Photonic Crystal Fiber and its types.

Syllabus Topic : Historical Development

1.1 HISTORICAL DEVELOPMENT

Year 1970

- The first optical communication system, known as the '*optical telegraph*', was invented in the **1790s** by French engineer Claude Chappe.

Year : 1972

- In **1792**, French scientist invented "Optical telegram". This system was in the form of series of semaphore mounted on towers. Semaphore is a system which is used to convey information in the visual form.

Year : 1880

- Later in **1880**, Alexander Graham Bell discovered optical telephone system, called as photo phone. But there were lot of disturbances, when the light was transmitted through air; so his invention of ordinary telephone became more popular.

Year 1900

- In the **1900s** inventors proved that bent quartz-rods can carry the light rays.

Year 1920

- In the year **1920s** A medical student in Munich, made use of optical cable bundles, to transmit medical images. His aim was to look inside in accessible parts of the body. But the transmission of images through unclad fibers was very poor.

Year 1951

- In **1951**, Lawrence Curtiss developed glass clad fibers. But such fibers were showing too much attenuation. For the use of communication. Basically he was working on the project to develop an endoscope to examine inside of the stomach.

Year 1960

- By **1960**, attenuation of the order of 1 dB/m was achieved with glass-clad fibers. This was acceptable for medical imaging applications but not for voice/data transmissions.
- The invention of the lasers in the 1960s marked the beginning of a new era in modern optics, called Photonics. Maiman developed an experimental optical amplifier by using lasers in the electromagnetic spectrum. However, the reliability of long-distance laser links operating in the millimeter-wave region was limited mainly due to various atmospheric turbulences like clouds, rains, and fog.

Year 1970

- In the year **1970**, glass fiber was developed, which was producing a minimum loss for signal transmission and it was 20 dB/km. That means, after losses, 1 % of light remained in the fiber, even travelling 1 km distance.

Year 1977

- The first commercial installation of optical cable was done in **1977** and then the telephone companies started replacing old copper wires with optical cables. In 1977, the development mainly focused on multi-mode fibers with core diameters of 50 nm or 62.5 mm, and having a refractive index gradient between fiber core and cladding. Such fibers having attenuation of about 2 dB/km were used to transmit optical signals at 850 nm wavelength from GaAlAs laser diodes up to several kilometers without the use of signal regenerators.
- This was followed by the use of InGaAsP lasers at 1300 nm wavelength having fiber attenuation of 0.5 dB/km only, and reduced pulse dispersion as compared to that at 850 nm.

Year 1980

- In the early **1980s**, the first long-distance transatlantic backbone networks were developed for telecommunication purpose using single-mode fiber as communication medium and optical sources at 1300 nm wavelength. This technology is followed as one of the standards for optical fiber communication networks even today.

Syllabus Topic : Electromagnetic Spectrum

1.2 ELECTROMAGNETIC SPECTRUM

- The propagation of an optical signal (or even an electrical signal) through any transmitting medium takes place in the form of electromagnetic waves or signals.
  - In a *wireline medium*, electromagnetic signals propagate along a metallic cable in the form of voltage (or current) waveforms.
  - In a *wireless medium* through free space, electromagnetic signals propagate in the form of radio waves, usually termed as electromagnetic waves.
  - In an *optical fiber medium*, the information signals propagate as electromagnetic light waves.
- Definition of electromagnetic wave: The analog combination of electrical voltage and magnetic field propagates through air or space, and is called an electromagnetic wave or simply an 'em wave'. By nature, radio signal transmissions take place on one radio frequency or with a very narrow bandwidth. Electromagnetic signal is distributed throughout an almost infinite range of frequencies.
- The discrete packet of energy called as photons, passes the electromagnetic radiation. And the energy contained by these photons is the electromagnetic energy. The motion of this electromagnetic energy is continuous in the space.
- This wave motion is in the form of an alternating electric filed in the space. The electric field produces the magnetic field which is perpendicular to it. And these two fields viz electric and magnetic fields are mutually perpendicular to the

direction of propagation of the electromagnetic energy wave.

- The full range of wavelengths of light emitted from the hot body is called is **'spectrum'**. This covers both visible and invisible regions.
- The electromagnetic spectrum covers the range of wavelengths from 10^4 meters to 1 A°. (1 A° referred as one Angstrom = 10^{-8} cm). This electromagnetic spectrum is shown in Fig. 1.2.1.
- The energy contained by the photons is given by,

$$E = hf = hc / \lambda$$

Where hf is the frequency of em wave , hc is velocity of propogation of light in free space (hc = 3×10^8 m/s) and λ is wavelength in meter.

- Thus energy and wavelength are inversely proportional to each other. So as the wavelength goes in increasing, the energy goes on decreasing.
- As shown in Fig. 1.2.1, 'X' rays and 'γ' rays are having very small wavelengths viz. 10^{-10} cm and 10^{-15} cm respectively.
- The visible light represents only a small portion of electromagnetic spectrum. It generally covers the range from 380 mμ to 780 mμ.

Note : 1 mμ (millimicron) or 1 nm (nanometer) = 10^{-7} cm.

- At nearly 4000 A° extreme violet region is present and at 8000 A° extreme red region is present.
- The ultraviolet region starts from 185 mμ upto the visible range.
- Infrared region covers wavelengths above the visible range. And after the infrared region the microwaves and radio waves are present.

1.2.1 Advantages of Electromagnetic Spectrum

1. By studying the spectrum of the element, the exact composition of the substance can be determined.

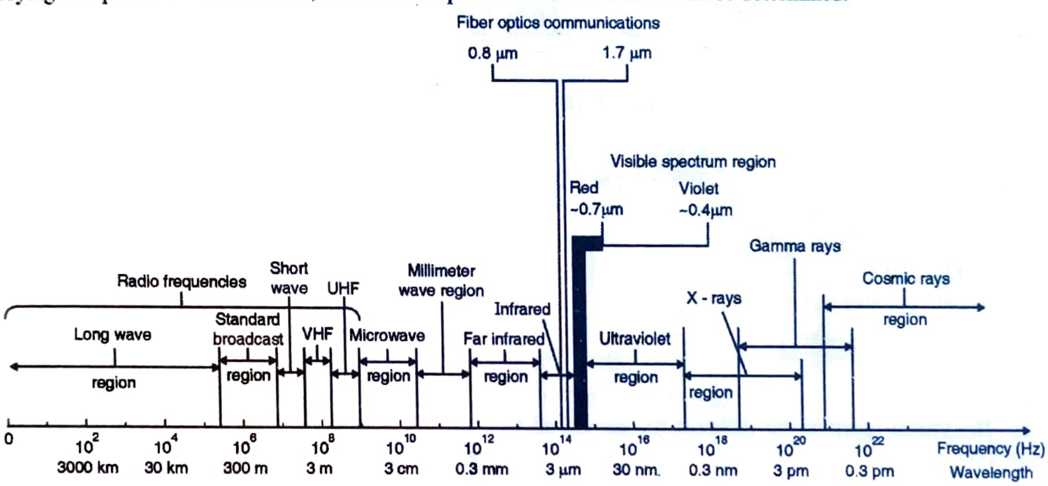


Fig. 1.2.1 : Electromagnetic spectrum

2. By studying the spectrum, the exact analysis of the mixture can be done.
3. The properties of the molecules can be studied by the use of spectrum.
4. In case of gases, the nature of vapour and the conditions under which it is excited can be determined by studying the spectrum.

1.2.2 Electromagnetic Spectrum Band and Applications

Designation	Frequency Range	Free-space Wavelength Range	Typical Applications
ELF (Extremely Low Frequency)	30–300 Hz	10,000–1000 km	Power line communications
VF (Voice Frequency)	300–3000 Hz	1000–100 km	Telephone system for analog subscriber lines
VLF (Very Low Frequency)	3–30 kHz	100–10 km	Long-range navigation; submarine communications
LF (Low Frequency)	30–300 kHz	10–1 km	Long-range navigation; submarine communication radio beacons

Designation	Frequency Range	Free-space Wavelength Range	Typical Applications
MF (Medium Frequency)	300–3000 kHz	1000–100 m	AM broadcasting; Maritime radio; Direction finding radio
HF (High Frequency)	3–30 MHz	100–10 m	Long-distance aircraft and ship communication; Military communication; Amateur radio
VHF (Very High Frequency)	30–300 MHz	10–1 m	FM broadcasting; Two-way radio; VHF television; Aircraft navigational aids
UHF (Ultra High Frequency)	300–3000 MHz	100–10 cm	UHF television; Cellular mobile telephone; Microwave links; Radar: Personal communications systems (PCS)
SHF (Super High Frequency)	3–30 GHz	10–1 cm	Wireless local loop; Satellite communication; Radar: Terrestrial microwave links
EHF (Extremely High Frequency)	30–300 GHz	10–1 mm	Wireless local loop; specialized laboratory experiments
Infrared Light	300 GHz–300 THz	1 mm–1 nm	Infrared LANs; Consumer electronic applications; Astronomy
Visible Light	400–750 THz	0.75–0.40 nm	Optical fiber communications

1.2.3 Visible Electromagnetic Spectrum

(1) Whenever an electron falls from higher energy level to lower energy level, a photon of definite energy is emitted. This amount of energy contained by photon depends on the energy level difference between the two orbits, in which the electron transition is taking place.

(2) Since wavelength is related with the energy as,

$$E = \frac{hc}{\lambda};$$

So, as energy changes the wavelength of light also goes on changing. The visible spectrum for different wavelength of light is as shown in Fig. 1.2.2.

(3) Here since with change in the energy, the wavelength goes on changing; the radiation or emission of different wavelength produces different colors. Thus the human eye can sense the different colors.

(4) Here the maximum sensitivity of the eye is at approximately 5500 A°. This lies between green and yellow colors. But this maximum sensitivity is not fixed. It varies from person to person. The eye sensitivity curve becomes asymptotic at both ends of spectrum as shown in Fig. 1.2.2

(5) So the range of visible spectrum is increased over the wavelengths where the eye sensitivity becomes 1% of its maximum value. So the visible spectrum ranges from 4000 A° to 8000 A°.

(6) But the ultraviolet region is smaller than the visible region and infrared region is greater than visible region; so the part of ultraviolet region and infrared region can be covered into the visible region. This visible spectrum is also affected by the temperature variations.

(7) Because light is a part of radiant energy from a hot body which produces the visible sensation, so it is the part of energy. And as temperature (or energy) goes on increasing the wavelength becomes shorter.

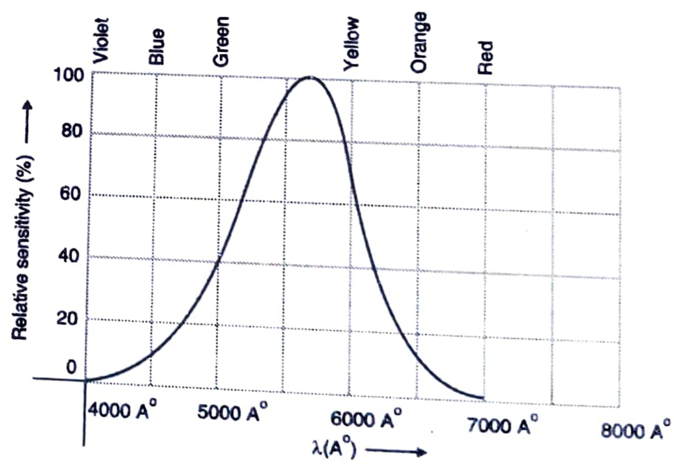


Fig. 1.2.2 : Visible spectrum

(8) When the emitted light becomes white then it includes all the visible wavelengths from extreme red to extreme violet. So as the temperature goes on increasing, the wavelengths become shorter and enters into the ultraviolet region. This is the invisible region for the human eye.

1.3 GENERATIONS OF LIGHT WAVE SYSTEMS

Since development of Optical fiber communication systems or light wave systems over several years in a series of generations, generations are differentiated based on its operating wavelength and improved performance.

1. **First Generation**

- In the 1970s, the earliest optical fiber communication systems were developed using infrared LED and GaAs semiconductor lasers as optical sources, a silica-based optical fiber as transmission medium and low-cost photodetectors at operating wavelength of near 850-nm region.
- These systems provided 50–100 Mbps data transmission rates with repeater spacings of the order of 10 km. But due to its relatively high attenuation (≈ 3 dB/km), it became less attractive subsequently.

2. **Second Generation**

- In the early 1980s, optical fiber systems were developed to operate near 1300 nm wavelength region, with lower fiber loss (less than 1 dB/km, typically 0.5 dB/km).
- The development of InGaAsP semiconductor lasers with simultaneous oscillation of several longitudinal modes and detectors alongwith single-mode fibers, exhibiting low dispersion, offered 1–2 Gbps transmission data rates with repeater spacings higher than that of 40–50 km.

3. **Third Generation**

- In the 1990s, the silica fibers were developed at 1550 nm wavelength which offered theoretical minimum attenuation of approximately 0.2 dB/km.
- These optical fiber communication systems offered data speeds over 2.4 Gbps with repeater spacings of 100 km or more. Systems using InGaAsP lasers operating in a single longitudinal mode and dispersion- shifted fibers could operate at 10 Gbps date rate.

4. **Fourth Generation**

- With the advent of the wavelength-division multiplexing (WDM) technique for increased data rate capability and of optical amplification methods for employing greater repeater spacings, a revolution began in the development of optical fiber communication in the spectral region extending from 1450–1620 nm.
- By the year 2001, the light wave WDM systems used in-line erbium-doped fiber amplifiers with 60–80 km spacing for compensation of fiber losses and operation at 10 Tbps data rate.

5. **Fifth Generation**

- Subsequent availability of dry fibers (single-mode dispersion-shifted), Raman amplification techniques, and optical solitons (very short optical pulses that counteract the dispersion effect due to fiber nonlinearity and thereby preserve their shape) enabled to extend the wavelength region from 1300–1650 nm for simultaneous working of thousands of WDM channels at the rate of 40–160 Gbps.
- Table 1.3.1 shows five generations of light wave systems.

Table 1.3.1 : Five generations of light wave systems

Generation	Wavelength (µm)	Fiber Type	Bit Rate	Fiber Losses (dB/km)	Repeater Spacings
1st (1970s)	0.85	Multimode (graded core)	2–45 Mbps	≥ 1	≈ 10 km
2nd (Early 80s)	1.3	Multimode (graded core)	45–90 Mbps	0.5–1.0	≈ 40 km
3rd (Late 80s)	1.55	Single mode	≥1.7 Gbps	≈0.3	≈ 60–70 km
4th (Early 90s)	1.45–1.62 (Typical 1.55)	Single mode (dispersion- shifted)	2.4 Gbps	≈ 0.2	≈ 80 km
5th (In 2000s)	1.50–1.57 (Typical 1.55)	Single mode (dispersion- shifted/soliton) + Fiber Amplifier	≥2.4 Gbps	0.1–0.2	≥ 100 km

1.4 ADVANTAGES OF OPTICAL FIBER LINK OVER CONVENTIONAL COPPER SYSTEMS

UQ. Draw the block diagram of optical communication and state its advantages and disadvantages. **(MU – Q. 2(a), Dec. 15, 10 Marks)**

There are several advantages of optical fiber communication over conventional communication methods. These are as follows :

1. Fiber optic cables are light in weight.
2. The size of fiber optic cable is small. The diameter is comparable to the diameter of human hair.
3. Since the data is passing through the fiber optic cable in the form of light rays and not in the form of electrical signals. There is no hazards of short circuits.
4. No cross talk generation inside the fiber optic cable.
5. Electromagnetic interference is absent.
6. It is not affected by an electrical noise.
7. The fiber optic cables doesn't get affected by drastic environment conditions.
8. The cost of cable per unit length is less as compared to conventional links.

9. Signal can be sent upto hundred times faster in fiber optic cables than conventional copper cables.
10. Intermediate amplifiers are not required.
11. Ground loops are not present.
12. A low installation and handling cost.
13. Information carrying capacity is very high.
14. Fiber optic cables are flexible, so installation is easier compared to conventional cables.
15. It possesses a wide band transmission property.

1.5 DISADVANTAGES OF OPTICAL FIBER COMMUNICATION

The disadvantages of optical fiber communication over conventional communication techniques are as follows :

1. Due to small size, connecting and splicing of optical cable is difficult.
2. Usually LED or laser is used as light source in optical communication. These light sources are having nonlinear response.
3. It is difficult to distinguish between positive and negative signals.
4. Efficiency of light source is poor; so the efficiency of total system is reduced.
5. Testing procedure and fault location in optical cable is a complex process.

1.6 OPTICAL BANDS AND WINDOWS

UQ. Explain three operating windows in optical communication. **(MU – Q. 1(a), May 18, 4 Marks)**

- An optical region forms an important region in electromagnetic spectrum. The light frequency spectrum can be divided into three general frequency bands:
  - Infrared
  - Ultraviolet
  - Visible
- **Infrared Band.** Infrared is the band of light frequencies which is quite high and cannot be seen by the human eye. Typical useful wavelengths range between 770 nm and 1600 nm. In the infrared spectrum, there are three regions (850 nm, 1300 nm, and 1550 nm) in which silica glass fibers are relatively efficient. Optical fiber systems generally operate in the infrared band.
- **Visible Band.** It is the band of light frequencies (typically 390–770 nm wavelength range) which is visible to the human eye. Silica glass fibers are not very good transmitters of light in the visible spectrum. They attenuate the light waves to such an extent that only short optical transmission links are useful.
- **Ultraviolet Band.** It is the band of light frequencies which cannot be seen by the human eye. Typical wavelengths range between 10 nm and 390 nm. The fiber losses in the ultraviolet spectrum are even greater. This band is used in medical applications
- Early technology made the use of wavelength from 800 nm to 900 nm. Because for this band of wavelength; an optical sources and detectors were easily available. Similarly an attenuation of data passing through optical fiber was also low. This particular band of wavelength is also called as **first window.**
- Later on the manufactures were able to fabricate optical waveguides in the 1100 nm to 1600 nm region. These waveguides were having very low losses. Here two windows are present. The **second window** is centered around 1300 nm and the **third window** is centered around 1500 nm.
- Now-a-days, new types of fiber materials are used in the 3 μm to 5 μm wavelength band. These materials are having very low losses.
- But it is difficult to manufacture the long lengths of these fibers. The total optical spectrum is ranging from 300 GHz to ∞. This optical spectrum is again subdivided into the sub spectrums as shown in Table 1.6.1.

Table 1.6.1

Designation		Frequency range
(a)	Infra-red	300 GHz to 375×10^3 GHz
(b)	Visible	375×10^3 GHz to 790×10^5 GHz
(c)	Ultraviolet	790×10^5 GHz to 225×10^5 GHz
(d)	X-rays	225×10^5 GHz to 450×10^8 GHz
(e)	γ - rays	450×10^8 GHz to 270×10^9 GHz
(f)	Cosmic rays	270×10^9 GHz to ∞

1.6.1 Units of Wavelengths with Light Frequencies

- It is customary to express the wavelength in *microns* (1 micron = 10^{-6} m, or 1μm), or in nanometers (1 nm = 10^{-9} m) with light frequencies.
- With optical spectrum, the unit *angstrom* is sometimes used to express the wavelength (1 angstrom = 10^{-10} m, or 0.0001 micron).

1.6.2 Expressing Wavelength in Angstroms

Ex. 1.6.1 : Expressing Wavelength in Angstroms Determine the wavelength in angstroms units for the light wave signal having frequency equal to 3.45×10^{14} Hz.

☑ **Soln. :**

We know that wavelength,

$$\lambda(\text{m}) = \frac{c\ (\text{m/s})}{f\ (\text{Hz})}\ ; \text{ and } 1 \text{ angstrom } \mathring{A} = 10^{-10} \text{ m}$$

For given $f = 3.45 \times 10^{14}$ Hz,

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{3.45 \times 10^{14} \text{ Hz}} \times 10^{10} = 8695 \text{ Å}$$

Ex. 1.6.2 : Converting Wavelength Å to nm Determine the light wave frequency corresponding to specified wavelength as 780 Å.

☑ **Soln. :**

We know that the wavelength, $\lambda(\text{m}) = \frac{c \text{ (m/s)}}{f \text{ (Hz)}}$

Or, the frequency, $f(\text{Hz}) = \frac{c \text{ (m/s)}}{\lambda \text{ (m)}}$

First we have to convert the given wavelength in angstrom (Å) in meters.

We know that $1 \text{ Å} = 10^{-10}$ m

Therefore, $780 \text{ Å} = 780 \times 10^{-10} \text{ m} = 7.8 \times 10^{-8}$ m

Hence, $f \text{ (Hz)} = \frac{3 \times 10^8 \text{ (m/s)}}{7.8 \times 10^{-8} \text{ (m)}} = 3.85 \times 10^{15}$ Hz

1.7 NEED FOR OPTICAL FIBER COMMUNICATION

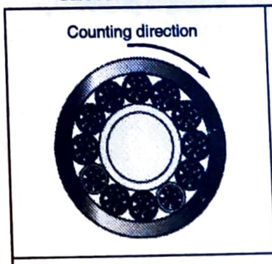
- The information-carrying capacity of any electronic communications system is directly proportional to the channel bandwidth. In an electronic communications system, the transmitter superimposes (modulates) low-frequency information signal on a radio frequency carrier signal. The modulated RF carrier signal is then transmitted through wireless or guided medium.
- The receiver retrieves the original information from the carrier signal. The carrier frequencies, in fact, restrict the information carrying capacity as well as the rate of transfer of information. Increasing the carrier frequency, therefore, increases the transmission bandwidth which helps to eliminate these limitations.
- The optical frequency is typically 1014 Hz, as compared to that of microwave frequency of 109 Hz. Thus, the optical carrier can offer 100,000 times more bandwidth.
- In addition, the optical region of the electromagnetic spectrum ranges from 50 nm (ultraviolet radiation) to about 100 μm; the visible portion lies in the 400–700-nm region. In optical fiber communication systems, the carrier frequencies are selected from the optical region (particularly the infrared part, ranging between 1700–800 nm).
- Consequently, the only practical type of optical communications system is one that uses optical fibers as transmitting medium. For all practical purposes, optical fiber cables have an infinite bandwidth. In other words, they have the capacity to carry much more information than metallic cables or even the wireless communications.

1.8 FIBER OPTIC CABLE TYPES AND COLOR CODES

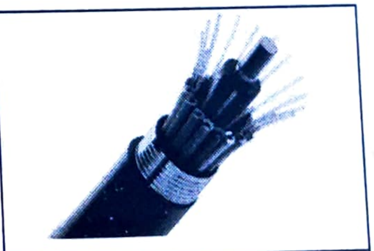
- Color coding of indoor **fiber optic cable** help users to easily and accurately identify which types of fiber optic cables are used in fiber optic cabling systems.
- The color coding of the indoor optical fiber cable distinguishes the fire resistance of different kinds of optical cables and optical cables according to the color of each optical fiber in the sleeve and the color of the optical cable sheath.
- These different colors of optical fiber cable are generally used in indoor applications, and the TIA-598C standard and EIA/TIA 568 standard specify the color coding of the indoor optical cable.
- Outdoor cables are generally black jacketed to protect the cable from damage caused by sunlight and ultraviolet radiation.
- Jacketed optical fibers are color coded according to fiber type. Color coding enables technicians to quickly determine whether a particular cable is multimode (e.g. orange or aqua) or single mode (e.g. yellow or blue).
- The jacket imprint provides additional information, such as fiber size, fire code rating, and so forth. Be aware that the colors of some jacketed fiber varies from this standard. Also note that bare fibers within buffer tubes are color coded differently than jacketed fiber.

1.8.1 Inner Cable Optical Fiber Color Code

- Inside a multi-fiber cable, individual fibers are compliant with fiber color code as well. They are often distinguished from one another by color-coded jackets, buffers or tubes on each fiber.
- According to EIA/TIA-598, inner fibers are color coded in a group of 12 fibers and they are counted in a clockwise direction.



(a) Counting direction of a group of 12 fibers



(b) Colored jackets of multi-fiber cable

Fig. 1.8.1

There are two situations for multi-fiber cables:

- Each fiber in the sleeve has its own unique fiber number, color, beam tube, etc.
- Generally, 12 fibers or less are a bundle of tubes, and each tube will be numbered or colored according to the same fiber color code. For example, the first tube is blue and the second is orange.

- For cables consisting of more than 12 strands, the cable color code will appear repeatedly. Each group of 12 fibers was determined by other methods.
- For example, the fiber color codes of the 24 chain sets repeat some variations, for example, the first set of 12 is a solid color, and the second set is a solid color with stripes or other identifying marks.

The color sequence for inner fibers is as follows:

Fiber Position	Jacket Color	Fiber Position	Jacket Color
1	Blue	13	Blue with black tracer
2	Orange	14	Orange with black tracer
3	Green	15	Green with black tracer
4	Brown	16	Brown with black tracer
5	Slate	17	Slate with black tracer
6	White	18	White with black tracer
7	Red	19	Red with black tracer
8	Black	20	Black with yellow tracer
9	Yellow	21	Yellow with black tracer
10	Violet	22	Violet with black tracer
11	Rose	23	Rose with black tracer
12	Aqua	24	Aqua with black tracer

1.8.2 Outer Jacket Color Code

- Colored outer jackets or print may be used on outside plant and premises fiber cables, e.g., fiber distribution cables, fiber optic patch cords, etc.
- In EIA/TIA-598, the fiber color code defines the jacket color codes for different fiber types. So for optical fiber cable that contains only one type of fiber we can easily identify it by its jacket color;
- Unless otherwise specified, the outer jacket of premises cable containing more than one fiber type shall use a printed legend to identify the quantities and types of fibers within the cable, for example "12 Fiber 8 x 50/125, 4 x 62.5/125."
- Here are the jacket color codes for different fiber types:

Fiber Type	Color Code		
	Non-military Applications	Military Applications	Suggested Print Nomenclature
OM1 62.5/125µm Multimode	Orange	Slate	62.5/125
OM2 50/125µm Multimode	Orange	Orange	50/125
OM3 50/125 µm (850 nm Laser-Optimized) Multimode	Aqua	Undefined	850 LO 50/125
OM4 50/125µm (850 nm Laser-Optimized) Multimode	Aqua/Violet	Undefined	850 LO 50/125
100/140µm Multimode	Orange	Green	100/140
OS1/OS2 Single Mode	Yellow	Yellow	SM/NZDS, SM
Polarization Maintaining Single Mode	Blue	Undefined	Undefined

- Besides the jacket colors specified in fiber color code standard, other colors may also be used if the print on the outer jacket can tell the fiber classifications. Such colors should be agreed upon between manufacturer and user.

1.8.3 Connector Color Code

- Connectors are also a part of the fiber color code. Since there are different polish styles of fiber end-face, the connectors of fiber jumpers and the mating adapters are color coded for identification.
- However, the advent of metallic connectors like the FC(ferrule connector or fiber channel) and ST(straight tip) made connector color coding difficult, so colored strain relief boots are also used. The boot color may vary among manufacturers.

Fiber Types	Polish Style	Connector Body	Strain Relief/Mating Adapter
OM1 62.5/125	UPC	Beige/Grey	Beige/Grey
OM2 50/125	UPC	Black	Black
OM3/OM4 50/125 laser optimized	UPC	Aqua	Aqua

Fiber Types	Polish Style	Connector Body	Strain Relief/Mating Adapter
Single Mode	UPC	Blue	Blue
Single Mode	APC	Green	Green

1.9 BASIC STRUCTURE OF OPTICAL FIBER

- Always through the fiber optic cable the signal gets transmitted in the form of light rays. The light is having electromagnetic nature and the frequency of light is about 3×10^4 Hz. This is 10^5 times the ultra high frequency used for transmission of TV signals.
- So the information carried by light is much more than TV signals. The wavelength of light is very small so the diameter of fiber optic cable is also very small. This diameter is comparable to the diameter of human hair. The basic structure of fiber optic cable is as shown in Fig. 1.9.1.

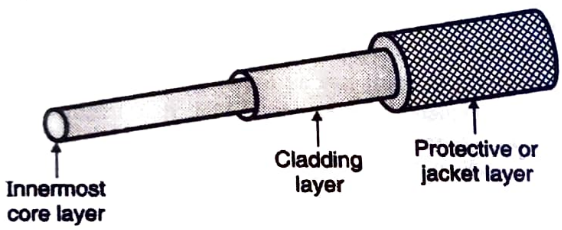


Fig. 1.9.1 : Basic structure of fiber optic cable

- As shown in Fig. 1.9.1, the core is an innermost layer. Through the core layer the light rays are travelling. This layer is covered by the cladding layer. The refractive index of the cladding layer is made less than that of core layer.
- This is achieved while manufacturing the fiber optic cable. The thickness of cladding layer is made one or two times than the wavelength of light to be guided.
- **The cladding layer is used to perform following functions :**
  1. It gives strength to the fiber optic cable.
  2. This layer acts as a mirror. So the light rays gets reflected from it with no power loss.
  3. When the fiber optic cables are used in bundle then cladding layer avoids the light rays to get escaped to nearby fiber optic cable.
- The last layer is called as jacket or **protecting layer**. This provides the strength to the fiber optic cable. Also this layer provides protection against variations in the environmental conditions.
- Many time a **Kevlar layer** is added with the jacket layer. This gives added strength to the fiber optic cable. Thus in the fiber optic cable the light rays gets reflected from the boundary of cladding wall and enters into the core layer. So total internal reflections of the light rays takes place inside the fiber optic cable.

1.10 BLOCK DIAGRAM OF LIGHT WAVE COMMUNICATION

Fig. 1.10.1 shows simplified block diagram of a light wave communication system, also known as optical fiber communication system.

System consist of following blocks,

1. Information System
2. Voltage-to-current Converter
3. Optical Source
4. Optical Couplers
5. Optical fiber cable
6. Optical signal Generator
7. Optical Detector
8. Current-to-voltage converter
9. Destination Output

- **1. Information Source :** The source information may be in the form of non-electrical, physical form such as voice or image/video. An input transducer is a device that converts physical information into an electrical signal. The input signal can either be an analog or digital (computer data).
- **2. Voltage-to-current converter :** It serves as an electrical interface between the information source circuit and the optical (light) source. The amount of light emitted by the light source is generally proportional to the amount of its drive current. Thus, the voltage-to-current converter is necessary to convert an input signal voltage to a current that is used to drive the light source.
- **3. Optical source :** In an optical transmitter, the optical carrier signal generated by optical source is modulated by an analog or a digital signal. The optical source is either a light-emitting diode (LED) or an injection laser diode (ILD), which generates an electromagnetic wave in the infrared region of the optical spectrum. In essence, the light intensity is modulated by the input signal. The optical sources are generally compact, lightweight, consume moderate amount of power, and are relatively easy to modulate.
- **4. Optical couplers :** The function of source-to-fiber coupler is to collect the light signals from the optical source and send it efficiently to the optical fiber cable. Similarly, the fiber-to-detector coupler is used at the other end of the fiber cable to direct the received light signals onto the photodetector.
- **5. Optical fiber cable :** It is the guided transmission medium, which is either an ultrapure glass or a plastic cable. The optical fiber consists of a glass or plastic fiber core surrounded by a cladding and then encapsulated in a protective jacket. Techniques have been developed for the production of fibers with very low transmission losses (a few tenths of a dB/km at 1300 nm and 1550 nm optical wavelengths).

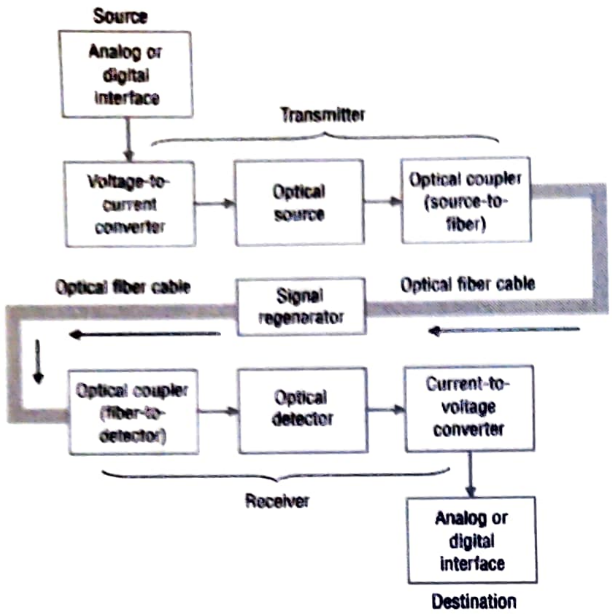


Fig. 1.10.1 : Block Diagram of Light wave communication System

- 6. **Optical signal regenerators :** As the optical signals (in the form of intensity-modulated light pulses) propagate along the lengths of the optical fiber cable from the source to destination, they get attenuated (due to absorption, scattering, etc.) as well as broadened (due to dispersion). As a result, the signals may become weak and indistinguishable after a certain distance. Optical regenerators (or optical amplifiers, such as erbium-doped fiber amplifiers) are used at appropriate distances from the transmitter along the length of the fiber cables which help to restore the strength and shape of transmitted signal.
- 7. **Optical detector :** The optical detector is generally a *p–i–n* (*p*-type-intrinsic-*n*-type) diode, an avalanche photodiode (APD), or a phototransistor which converts an input optical signal into an equivalent electrical signal, usually in the form of electric current. The resultant output current is normally proportional to the incident optical signal level and hence to the input information signal. The optical detectors are generally compact, consume low power, and have flat spectral response, and long operating life.
- 8. **Current-to-voltage converter :** It transforms variations in photodetector current to corresponding variations in voltage. It produces an output voltage which is proportional to the original source information.
- 9. **Destination output :** Finally, the received information is presented in a form similar to that of input information source and suitable for destination device such as loud speaker, computer, or other machines.

1.11 ADVANTAGES AND DISADVANTAGES OF OPTICAL FIBER

(A) Advantages of Optical Fiber

(i) **Larger bandwidth and greater information capacity :** Due to inherently available wider bandwidths at light frequencies, optical fibers have greater information-carrying capacity than that can be obtained with metallic cables as transmission medium. Typically, bandwidths up to several thousand GHz are available with optical fibers.

(ii) **Lower transmission loss :** Typical signal loss in modern sophisticated optical fibers is as small as a few-tenths-of-a-dB loss per km. As a result, optical amplifiers and regenerators can be spaced considerably farther apart as that can be offered by metallic transmission lines.

(iii) **Security :** Due to inherent property of optical fiber cable for propagation of light through it, it is almost impossible to tap the data flowing into an optical fiber cable without the knowledge of the user. Thus, we can say that optical fiber cables provide much higher data integrity and security than metallic cables. Moreover, it is not possible to detect the presence of optical fiber cables installed under the ground with metal detectors provided steel is not used alongwith fiber cables for reinforcement.

(iv) **Immunity to static noise :** Static noise usually occurs due to electromagnetic interference (EMI). It is mainly caused by various sources of man-made noise that include lightning, fluorescent lights, electric motors, relays, and other electrical appliances. Since fiber cables are nonconductors of electrical current, they do not radiate electromagnetic energy as well.

(v) **Immunity to crosstalk.** Optical fibers are made of glass and plastic materials which fibers are known to be nonconductors of electricity. Therefore, they are immune to crosstalk.

(vi) **Immunity to environmental variations.** Optical fiber cables tend to be more resistant to environmental and climatic conditions (including weather variations) than metallic cables. Optical fiber cables can also operate over a wider temperature range.

(vii) **Reliability.** Optical fiber cables are more reliable than metallic cables and last longer because they exhibit higher tolerance to changes in environmental conditions and are immune to corrosive materials including liquids and gases.

(viii) **Easier to install and maintain.** Optical fiber cables, in general, are quite easier to install as well as to maintain than metallic cables. Optical fibers are compact and much more lightweight than metallic cables. Consequently, they are more flexible, require less storage space, cheaper to transport, and easier to work with.

(ix) **Cheap :** Long, continuous miles of optical fiber cable can be made cheaper than equivalent lengths of copper wire. With numerous vendors swarm to compete for the market share optical cable price would sure to drop.

(x) **Thinner and light-weighted :** Optical fiber is thinner, and can be drawn to smaller diameters than copper wire. They are of smaller size and light weight than a comparable copper wire cable, offering a better fit for places where space is a concern.

(xi) **Less signal degradation** : The loss of signal in optical fiber is less than that in copper wire.

(xii) **Long lifespan** : Optical fibers usually have a longer life cycle for over 100 years.

(xiii) **Longer Distances :** Fiber optic cables are created to carry signals over much higher distances than traditional cabling as they provide low power loss.

(xiv) **Flexibility :** An optical fiber has more accurate strength than copper or steel fibers of equal diameter. It is flexible, bends simply, and continues the most serious components attacking copper cable.

(b) Disadvantages of Fiber Optic Cable

(i) **Lower tensile strength.** Glass fiber is quite fragile as compared to copper wire, making it cumbersome to transport. As such optical fiber cables have considerably lower tensile strength than that exhibited by RF coaxial cables, which can be improved by Kevlar coating and a protective PVC jacket.

(ii) **Susceptible to bending losses.** Bending the optical fiber cable causes irregularities in the cable dimensions. Since electromagnetic waves propagate through it by total internal reflection, slight bending of cable results in a loss of signal power.

(iii) **Prone to manufacturing defects.** Excessive loss of optical signal power is experienced even with the minor manufacturing defect of the optical fiber cable. As a result, this may cause imperfect total internal reflection mechanism.

(iv) **Interfacing with electronic devices.** Optical fiber cables must be connected to standard electronic devices for communication purposes, which make the interfacing expensive.

(v) **Difficulty in locating faults.** Because of no electrical continuity, it is extremely difficult to locate physical or technical faults in optical fiber cables and maintain its proper functioning throughout the operating period.

(vi) **Need of specialized tools.** Special tools are needed to splice and repair optical fiber cables. In addition, special measuring test equipment is needed for making regular measurements by trained professional

(vii) **Reaction by chemicals.** The glass fiber is easily affected by number of chemicals such as hydrogen gas. This is really a serious concern while deploying optical fiber cables in underwater applications.

(viii) **Equipment :** For the functioning of fiber optics technology, it needed several elements besides cables. An independent transmitter and a receiver should be installed along with a repeater to increase the signal. In some instances where transmission distance tends to be high, an optical amplifier might be required to deepen the signal.

1.12 LOSS AND BANDWIDTH

- For fiber optic cable, theoretically speaking, its bandwidth is infinitely high, transmission capacity is infinitely large and the transmission distance is infinitely far.
- Besides, optical fiber cable is also light in weight, and all of these features make it an ideal medium for data transmission, which is capable of transmitting unlimited telephone and TV signal. However, in the current application of optical cable, the result is far from the theory. Regardless of the fragile physical properties of silicon, the transmission capability of fiber optic cable has opened a few windows.

1.12.1 Bandwidth and Window of Fiber Optic Cable

- In May 2002, the ITU-T organization divided the fiber optical communication system into six bands as O, E, S, C, L and U6.
- Multi-mode optical fiber at 850nm is known as the first window, single-mode optical fiber at O band is referred to as the second band.
- C band is called as the third window, L band is the forth window and E band is the fifth window. The following table shows the wavelength bands for both multimode fiber optic cable and single-mode fiber optic cable.

Frequency band	Window	Wavelength range (nm)	Frequency range (THz)
/	1	850(770-910)	/
Original band	2	1260-1360	237.9-220.4
Extended band	5	1360-1460	220.4-205.3
Short wavelength band	/	1460-1530	205.3-195.9
Conventional band	3	1530-1565	195.9-191.6
Longer wavelength band	4	1565-1625	191.6-184.5
Ultralength wavelength band	/	1625-1675	184.5-179.0

The frequency range in the table above refers to the frequency of light. According to the formula speed = wavelength x frequency, we can easily figure out the frequency of light. Its relation to the transmission loss of fiber optic cable and wavelength has been displayed as follow:

Optical Transmission windows and Wavelength

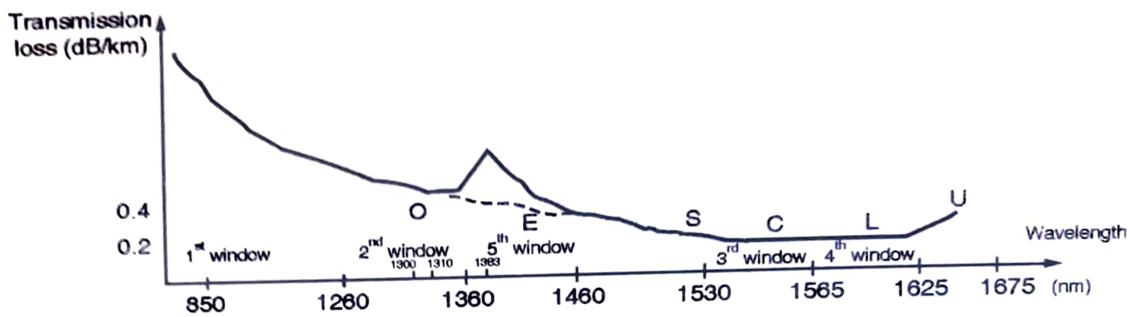


Fig. 1.12.1 : Optical Transmission window and wavelength

- In the early days of fiber optic communication the LED was employed as a light source due to its low price. Multi-mode fiber optic cables that operate at 850nm and 1300nm became the first choice for building small network, while single-mode optical fiber cables, working at 1310nm and 1550nm with laser as the light source, were the foundation for constructing large network.
- If there were more windows available for single-mode optic cable, one fiber optic cable would achieve ultra high speed transmission by transmitting signals at different wavelength at the same time by employing WDM (wavelength division multiplexing) technology, thus maximizing the potential of single mode fiber.
- Telephone and network and be using at the same time via ADSL (asymmetric digital subscriber line) modem. That's because voice and data use different frequency. And this principle is similar with WDM and ADSL technology, which are usually applied in main networks that require higher bandwidth.

1.12.2 The Bandwidth and Window of Fiber Optic Cable in Application

- For intelligent building, the mainly adopted fiber optic cable are multi-mode optical cable which supports short distance transmission, such as multi-mode optical fiber cable that operates at 850nm or 1300nm with LED as the light source, or multi-mode optical fiber cable working at 850nm with VCSEL laser. Single-mode fiber optic cable is often adopted in buildings that with a longer distance to each other.
- Intelligent building applications, fiber optic cable is often close to support multi-mode-based, such as multi-mode fiber optic cable with the emission wavelength of 850nm or 1300nm LED light source, or 850nm VCSEL laser wavelength. Single-mode used in long distance system buildings, single-mode fiber optic cable with emission wavelength 1310nm or 1550nm FP or DFB laser, means that most of the fiber optic cable is only open a window. Single-mode fiber optic cable works together with FP or DFB which transmit wavelength of 1310nm or 1550nm. That's to say most optical cable only open one window.

1.13 APPLICATIONS OF FIBER OPTIC TRANSMISSION SYSTEMS :

1. Optical fiber cable has wide bandwidth and is widely used in backbone networks because it is capable of transferring data at a rate of 1600 Gbps. Moreover, it provides a cost-effective solution as transmission medium.
2. A hybrid CATV network is creating by using a combination of RF coaxial cable and optical fiber cable by some cable TV companies. RF coaxial cable is used to connect the end user directly. On the other hand, optical fiber cable is used as the backbone configuration. This type of arrangement offers an economical solution because the end user usually requires narrow bandwidth as compared to relatively very high bandwidth of an optical fiber cable.
3. The small size and large information-carrying capacity of optical fibers make them viable alternatives to traditional twisted-pair copper cables as trunk lines in modern telecommunication networks.
4. Optical fiber cables are also used in several types of local area networks (LANs). Examples of such LANs include 100Base- and 1000Base- Fast Ethernets.
5. Usually optical fiber cables have lower attenuation than that in a coaxial cable. This leads to greater repeater spacing in an optical fiber communication links. This is the reason that underwater optical fiber links are designed to span the oceans. More advanced systems use lower-loss fibers and optical amplifiers to reduce (or eliminate) the need for repeaters.
6. Because of the relative ease of transporting and laying the fibers due to low-weight as compared to coaxial cables, optical fiber cables have distinct edge for their use in submerged cable applications.
7. Due to availability of very large bandwidth, "fibered city" such as Hi-OVIS (Highly Interactive Optical Visual Information

System) can provide reliable connectivity to home computers and video equipment provide live TV programs, recorded audio/video programs, etc by using optical fiber cables.

8. Optical fiber links are compatible with electrified railway tracks because they do not suffer from electromagnetic interference.
9. Optical fiber video transmission successfully competes with coaxial cable for surveillance and remote monitoring systems due to its EMI rejection and low susceptibility to lightning damage. Examples of such applications include surveillance of power-generating stations, parking areas, critical control points along railroad pathways, and the perimeter of military installations.
10. Fiber sensors have been used to measure temperature, pressure, linear and rotary positions, and liquid levels; for examples, the Optic Gyroscopes and Fiber Hydrophones.

1.14 REVIEW OF RAY THEORY

- Ray theory describes only the direction a plane wave takes in a fiber. Ray theory eliminates any properties of the plane wave that interfere with the transmission of light along a fiber. In reality, plane waves interfere with each other. Therefore, only certain types of rays are able to propagate in an optical fiber. Two types of rays can propagate along an optical fiber.
- The first type is called **Meridional rays.** Meridional rays are rays that pass through the axis of the optical fiber. Meridional rays are used to illustrate the basic transmission properties of optical fibers.
- The second type is called **Skew rays.** Skew rays are rays that travel through an optical fiber without passing through its axis. An optical fiber communications system is one that uses light (optical signal) as the carrier of analog or digital information signal.
- Propagating light waves, carrying information, through the earth's atmosphere is difficult and often impractical. The optical energy in a light wave follows narrow paths, called light rays or beams.
- For most practical applications, the light rays are used to describe a number of optical phenomena geometrically. Ray theory is known as geometric optics. It is these rays (geometrical paths traversed by light) which actually carry the optical energy.

1.14.1 Velocity of Propagation

- Light waves, travels at a speed or velocity of $c = 3 \times 10^8$ m/sec approximately in free space (a vacuum).
- The velocity of propagation is the same for all light frequencies in free space. All light frequencies are not propagated with the same velocity.
- Materials are denser (possess higher refractive index) than free space, electromagnetic waves travel slower in materials than in free space.
- Velocity of an electromagnetic wave is reduced as it travels from one medium to another medium of denser material, the light ray refracts (i.e., bends or changes direction) toward the normal.
- Also when an electromagnetic wave travels from a denser material into a lighter one, it gets refracted away from the normal.

1.15 REFRACTION

- When the light ray travels from one medium (air) to another medium (glass) then bending of light ray takes place as shown in Fig. 1.15.1. It is called as refraction.
- Fig. 1.15.1 shows how a light ray is refracted (bent) as it passes from a less denser material into a denser one it may be of the same type with different refractive indexes.
- Infact light rays does not bent, but changes its direction of propagation at the interface of two different materials, not bent.)

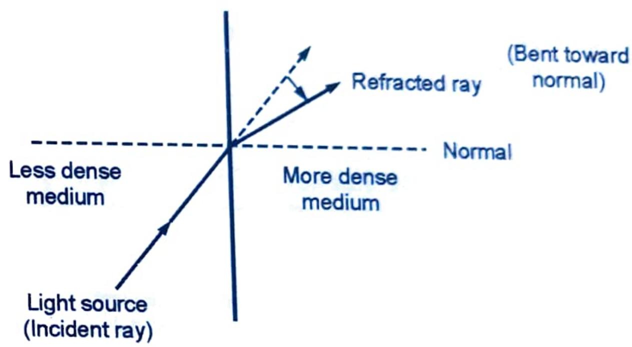


Fig. 1.15.1 : Refraction of Light

1.15.1 Refractive Index (n)

❒ **Definition :** It is defined as the ratio of speed of light in air (c) to the speed of light in another medium like glass (v).

- The extent of refraction that occurs at the intersection of two different materials having different values of index of refraction can be exactly predicted. Mathematically, refractive index, *n* is expressed as

$$\therefore \quad n = \frac{c}{v}$$

where, c = velocity of propagation of a light ray travelling in a free space (3×10^8 m/sec)

v = velocity of propagation of a light ray travelling in a specified material (m/sec)

Table 1.15.1 : Typical values of index of refraction

S. No.	Type of Material	Index of Refraction (dimensionless)
1.	Vacuum	1.0
2.	Air	1.0003 (approximately 1)
3.	Water	1.33
4.	Ethyl alcohol	1.36
5.	Fused silica	1.46
6.	Silica glass	Typical ≈1.5
7.	Diamond	2.0 – 2.42
8.	Indium phosphide (InP)	3.21
9.	Gallium arsenide (GaAs)	3.35
10.	Silicon (Si)	3.5
11.	Indium gallium arsenide phosphide (InGaAsP)	3.51
12.	Aluminum gallium arsenide (AlGaAs)	3.6
13.	Germanium (Ge)	4.0

1.16 LAW OF REFLECTION

Laws of reflection

(1) The first law of reflection states that the incident ray, the reflected ray, and the normal to the surface of the mirror, **all lie in the same plane.**

(2) The second law of reflection states that the **angle of reflection is equal to the angle of incidence**. Both angles are measured with respect to the normal to the mirror.

❒ **Definition** : The **law of reflection** defines that upon reflection from a smooth surface, the angle of the reflected ray is equal to the angle of the incident ray, with respect to the normal to the surface that is to a line perpendicular to the surface at the point of contact.

- The reflected ray is always in the plane defined by the incident ray and the normal to the surface at the point of contact of the incident ray.
- As shown in Fig. 1.16.1, the angle made by incident ray with respect to normal is called as angle of incidence (ϕ_1).

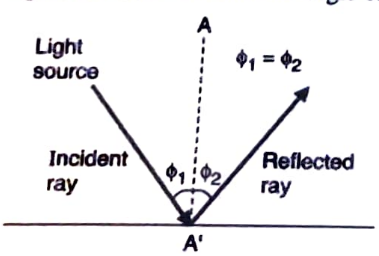


Fig. 1.16.1 : Law of Reflection

- Similarly the angle made with vertical line, at which the light is reflected from the surface; is called as angle of reflection (ϕ_2).

So $\phi_1 = \phi_2$ is called as the law of reflection.

1.17 SNELL'S LAW

- When the light ray meets the interface of two media having different index of refraction then part of light ray is reflected back into the first medium and other part is refracted into the second medium. It is shown in Fig. 1.17.1.

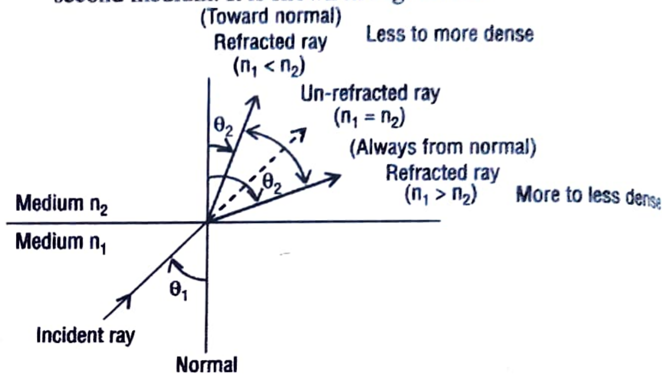


Fig. 1.17.1 : Snell's Law

- At the intersection of two different mediums—medium 1 and medium 2, the incident ray may be refracted toward the normal or away from it, depending on whether refractive index n_1 of the first medium is greater or less than refractive index n_2 of the second medium.

❒ **Definitions : Angle of Incidence :** It is defined as the angle at which the light ray strikes the intersection of two different materials with respect to the normal in the first medium.

- **Angle of Refraction :** It is defined as the angle formed between the refracted light ray and the normal in the second medium.
- **Normal :** The normal is a straight line drawn perpendicular to the intersection of two different mediums at the point where the incident ray strikes it.
- Hence, the angle of refraction can be either smaller or larger than the angle of incidence, depending on the values of index of refraction of the two mediums under consideration.
- Mathematically, Snell's law is represented as ,

$$\therefore \; n_1 \sin \phi_1 = n_2 \sin \phi_2.$$

1.17.1 Problems based on Snell's Law

Ex. 1.17.1 : A light ray is refracted as it travels from a more dense (higher refractive index) material (Glass with $n_1 = 1.5$) into a less dense (lower refractive index) material (ethyl alcohol with $n_2 = 1.36$). If the angle of incidence made by the ray at the point of intersection of two materials is 30°, then determine the angle of refraction. Also interpret the results with the help of suitable illustration.

Soln. :

According to Snell's law, we know that $n_1 \sin q_1 = n_2 \sin q_2$

For the given $n_1 = 1.5$, $q_1 = 30°$, and $n_2 = 1.36$, we have

$1.5 * \sin 30 = 1.36 * \sin q_2$

$\Rightarrow \sin q_2 = \frac{1.5}{1.36} * \sin 30 = 0.5515$

$\Rightarrow q_2 = \sin^{-1} 0.5515 = 33.47°$

Conclusion

Since $q_2 > q_1$, states that the incident light ray is refracted further away from the normal at the intersection surface of two materials. These is because the light was incident in a more dense material (having higher refractive index) and travelling into a less dense material (having lower refractive index). As shown in Fig. Ex. 1.17.1.

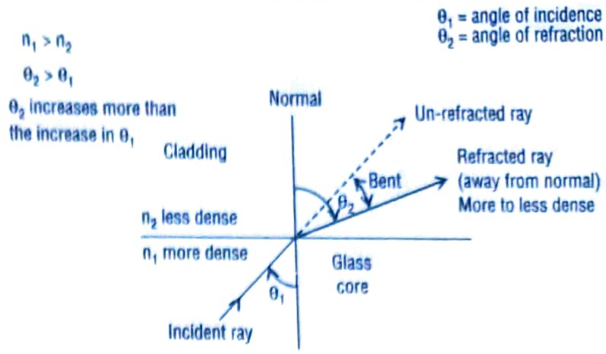
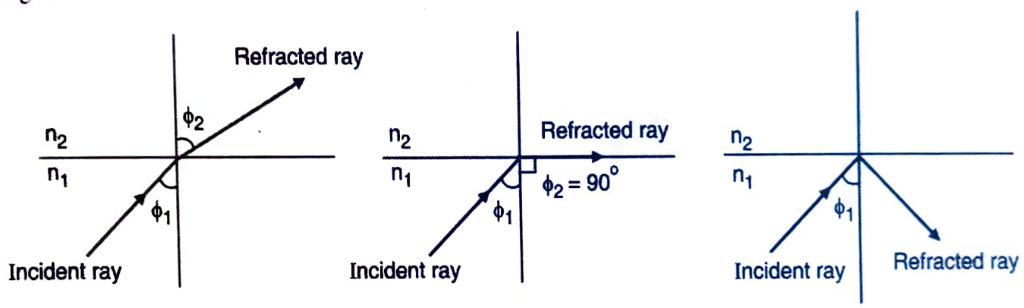


Fig. Ex. 1.17.1 : Refraction of Light from Denser to Lighter Medium

1.18 CRITICAL ANGLE

UQ. Define Critical Angle, **(MU – Q. 1(b), May 17, Q. 1(c), May 19, 5 Marks)**

Definition of Critical Angle : It is the minimum possible angle of incidence at which if a light ray is incident at the intersection of two different mediums, then it gets refracted with an angle of refraction exactly equal to 90°. This phenomenon is usually called the critical angle refraction.



Consider the light ray making an angle of incident 'ϕ_1' as shown in Fig. 2.5.1(a)

(a) Incident angle less than critical (b) Critical angle

(c) Incidence angle greater than critical angle

Fig. 1.18.1

- The light ray gets reflected by making an angle of refraction (ϕ_2). Here n_1 and n_2 are the refractive indices of two medium.
- Now according to Snell's law,

$$n_1 \sin \phi_1 = n_2 \sin \phi_2 \quad ...(1.18.1)$$

- Now as the value of 'ϕ_1' goes on increasing the value of 'ϕ_2' also gets increased.
- At one particular stage the value of 'ϕ_1' is such that it makes angle 'ϕ_2' equal to 90°. This is called as the **critical angle** of incidence (ϕ_c). This is as shown in Fig. 1.18.1(b).
- Thus using Snell's law,

$$n_1 \sin \phi_c = n_2 \sin 90° \quad ...(1.18.2)$$

where, ϕ_c = Critical angle of incidence

$$\therefore n_1 \sin \phi_c = n_2$$

$$\therefore \sin \phi_c = \frac{n_2}{n_1}$$

$$\therefore \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \quad ...(1.18.3)$$

1.18.1 Problems based on Critical Angle

Ex. 1.18.1 : A light ray is refracted as it travels from a denser medium (with higher refractive index, n_1) into a less dense medium (with lower refractive index, n_2). Determine the critical angle of incidence if the ratio of two refractive indexes is

(a) $\frac{n_2}{n_1} = 0.77$ (b) $\frac{n_2}{n_1} = 0.63$

☑ Soln. :

Critical angle of incidence $\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

(a) $\phi_c = \sin^{-1}(0.77) = 50.35^\circ$

(b) $\phi_c = \sin^{-1}(0.0.63) = 39^\circ$, $\phi_c = \sin^{-1}(0.77) = 50.35^\circ$

Ex. 1.18.2 : Critical Angle, Refraction and Reflection A typical optical fiber cable has specification of refractive index of 1.6 and 1.4 for the core and the cladding, respectively. Determine the following:

(a) the critical angle of incidence

(b) n_2 for $n_1 = 30^\circ$ (c) n_2 for $n_1 = 75^\circ$

☑ Soln. :

Critical angle of incidence $\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

(a) For given $n_1 = 1.6$ and $n_2 = 1.4$

$$\phi_c = \sin^{-1}\frac{1.4}{1.6} = 61^\circ$$

(b) The given angle of incidence $\phi_1 = 30^\circ$ is less than the calculated above in (a) critical angle, $\phi_c = 61^\circ$, the phenomenon of refraction will take place.

Therefore, the Snell's law is applicable, that is, $n_1 \sin\phi_1 = n_2 \sin\phi_2$

For the given $n_1 = 1.6$ and $n_2 = 1.4$, and $q_1 = 30^\circ$, we have

$$1.6 \sin(30) = 1.4 \sin\phi_2$$

$$\phi_2 = \sin^{-1}\frac{1.6 \sin(30)}{1.4}$$

$$\phi_2 = 34.8^\circ$$

Since, $\phi_2 > \phi_1$ since it is given that $n_1 > n_2$. The ray will be refracted away from the normal.

(c) The given angle of incidence $\phi_1 = 75^\circ$ is greater than the calculated above in (a) critical angle, $\phi_c = 61^\circ$, the phenomenon of refraction will not take place. Instead, the resultant ray will be reflected back in the same medium as per the laws of reflection and the angle of reflection in the first medium will be exactly equal to the angle of incidence

Hence $\phi_2 = 75^\circ$

1.19 LIGHT PROPAGATION IN OPTICAL FIBER

- An optical fiber is a very thin long cylinder that consists of two circularly symmetric coaxial elements with
  - o **Higher Refractive Index** - the inner one (the core) is made of glass material.
  - o **Lower Refractive Index** - the outer one (cladding) is made of either glass or plastic material
- The light rays (optical signals) are indecent into the cylindrical fiber which can be automatically guided (travel) over long distance by an optical phenomenon known as total **internal reflection.**

1.19.1 Total Internal Reflection (TIR)

MU - May 2011, May 2014

- If angle of incidence is increased than critical angle, then the light ray gets reflected rather than causing refraction. This is as shown in Fig. 1.19.1. Now inside the fiber optic cable the incident light ray should cause the total internal reflections.
- If the refraction of light ray occurs, then the light rays will not enter into the fiber optic cable. In this case the light rays will get escaped.
- Thus, the total internal reflection occurs at the interface between two dielectrics having different refractive indices; when the light is incident on dielectric of lower index from the dielectric of higher index and angle of incidence is greater than critical angle.
- Consider a light ray having angle of incidence ϕ at the interface of core and cladding as shown in Fig. 1.19.1.
- This ray is reflected at the same angle ϕ and it causes the total internal reflection. In this case, the light ray propagates through optical fiber by keeping the shallow angle (less than $90^\circ - \phi_c$). This is called as meridional ray and it passes through the axis of fiber core.

- The total internal reflection occurs only in materials in which the speed of light is slower than in air.

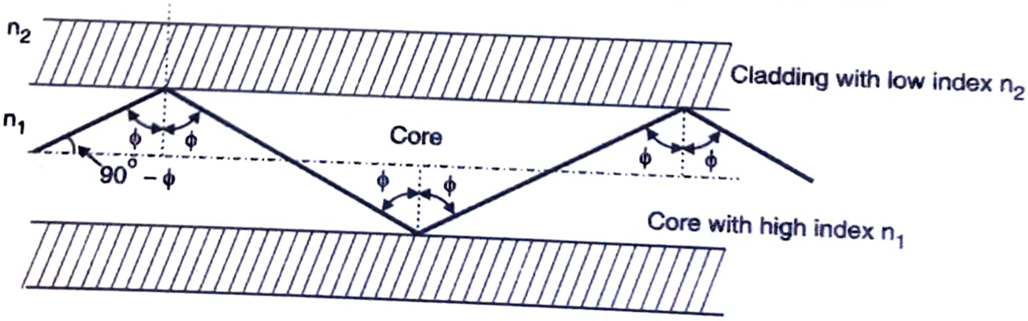


Fig. 1.19.1 : Total Internal Reflection (TIR)

❒ **Definition :** When a ray (or beam) of light travels from a medium with a higher refractive index (such as fiber core) to another medium with a lower refractive index (such as fiber cladding) and it happens to strike (incident) the core–cladding intersection at more than the known critical angle of incidence (at which the angle of refraction is 90°), then total light will be reflected back to the medium of incidence (i.e., the fiber core). **This particular phenomenon is known as Total Internal Reflection(TIR).**

Significance of Total Internal Reflection(TIR)

- Internal Reflection means when the light beam when incidented at the core – cladding junction of an optical fiber cable with angles of incidence greater than the critical incidence angle, ϕ_c, then all the light gets reflected back into the fiber core with high efficiency (as high as 99.9%).
- No portion of the incident light will propagate in the cladding material without this crucial need. It denotes that only the optical fiber core is where light propagates (with very low loss of propagating optical signal).
- **Hence, the phenomenon of total internal reflection(IR) keeps light propagating within an optical fiber.**

1.19.2 Problems based Total Internal Reflection(TIR)

Ex. 1.19.1 : Consider a light ray traveling from a denser (i.e., higher refractive index, $n_1 = 1.5$) material into a less dense (lower refractive index, $n_2 = 1.47$) material. Show that the desired criterion of total internal reflection phenomenon is completely satisfied.

☑ **Soln.:**

As per Snell's law, $n_1 \sin\phi_1 = n_2 \sin\phi_2$

For total internal reflection , Critical angle of incidence

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

$$\phi_c \text{ (for } \phi_2 = 90) = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Given $n_1 = 1.5$ and $n_2 = 1.47$

$$\phi c(\text{for } \phi_2 = 90) = \sin^{-1}\frac{1.47}{1.5}$$

$$\phi_c = 78.5^o$$

- When $\phi_c = 78.5°$, $\phi_2 = 90°$ States that refraction will not take place and the refracted ray will travel along the intersection of two materials.
- When $\phi_c > 78.5°$, $\phi_2 > 90°$ which means total internal reflection.
- Thus the condition of total internal reflection (TIR) is fully satisfied with the given situation that the ray of light happens to cross a less dense material to a denser material.

1.19.3 Fresnel Reflection

UQ. Define Fresnel Reflection.
MU - May 17, Dec. 17, 5 Marks

☑ **Ans. :**

- The reflection of a portion of light resulting when light is incident upon the surface between materials that have different refractive indices is called as **Fresnel Reflection.** This Fresnel reflection depends upon the index difference and the angle of incidence.
- For example, at input side there is interface of air and optical cable and at the output side there is interface optical cable and air. Due to change in refractive index, reflection of light takes place. Such reflection occurs at the air-glass interfaces at entrance and exit ends of an optical waveguide.
- Resultant transmission losses (on the order of 4 percent per interface) can be virtually eliminated by the use of antireflection coatings or index-matching materials.
- For the simplest case with normal incidence on the interface, the Fresnel reflectivity can be calculated with the following equation:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

☞ Examples for Fresnel Reflections

Fresnel reflections occur in many situations; some examples:

- When a laser beam is sent through an optical window with a single sheet of glass, there are reflections from both sides of the glass. Typical reflectivity's of such interfaces (if they are not coated) are a few percent.
- For non-perpendicular incidence of the beam, one can easily see multiple reflections: primary reflections from the two interfaces, leading to two parallel reflected beams, plus additional weak beams related to multiple reflections of light.
- Fresnel reflections sometimes lead to parasitic lasing, e.g. in fiber amplifiers and slab lasers. In light emitting diodes (LEDs), Fresnel reflections make it difficult to efficiently extract the generated light; special LED designs have been developed to overcome that problem.
- Fresnel reflections also occur at the ends of optical fibers. When the ends of two fibers are fitted together (e.g. in a mechanical splice), but with a small air gap in between, there are Fresnel reflections from both sides of the gap. They can largely cancel each other if the width of the gap is far below one optical wavelength, but for larger gap sizes the effective reflectivity can be up to four times that of a single interface due to constructive interference.
- Dielectric mirrors utilize Fresnel reflections at multiple optical interfaces, often with constructive interference of such reflections.

1.19.4 External Reflection

UQ. Define External Reflection.
(MU – Q. 1(b), May 17, 5 Marks)

- It is the phenomenon in optical cable when the light ray, at certain angle, gets totally reflected from interface of core and cladding.
- External reflection is the situation where the light starts in air and vacuum (refractive index 1), and bounces off a material with index of refraction less than 1.
- Some materials have an index of refraction that is less than one at the frequency of the incident field. This is rare in the visible light spectrum, but common for x-rays.
- Total External reflection occurs for low grazing angles when the index of refraction of the medium the field is incident upon is less than that index of refraction of the medium the light is in. That occurs for most optical materials in air to result in total internal refraction (light stays in the glass). If that is the case from the air to the material, then you have total external reflection.
- For example, in X-rays, the refractive index is frequently slightly less than 1, and therefore total external reflection can happen at a glancing angle. It is called external because the light bounces off the exterior of the material. This makes it possible to focus X-rays.

1.20 ACCEPTANCE ANGLE

UQ. Define Acceptance Angle.
(MU – Q. 1(b), May 17, Q. 1(c), Dec. 18, May 19, 5 Marks)

Definition of Acceptance Angle : It is defined as the maximum (not minimum) external angle of incidence at which the external light rays must strike the air/glass (fiber core) intersection and enters the fiber core and propagate within it.

- For the propagation of signal through the fiber; there must be total internal reflection of light rays. The total internal reflection of light ray takes place if angle of incidence is greater than the critical angle.
- The maximum angle at which light enters the fiber and causes internal reflection is called as acceptance angle of an optical fiber. Consider the geometry shown in Fig. 1.20.1. Here light ray 'x' makes an angle θ_a with the core axis. It enters into the fiber cable. It is called as meridional ray.
- The same ray makes an angle ϕ_c at the core-cladding interface, inside the optical cable. Here ϕ_c is the critical angle. It and it is the limiting angle for total internal reflection. If angle of incidence will be greater than θ_a then the corresponding angle at core cladding interface, inside the cable, will be less than ϕ_c.

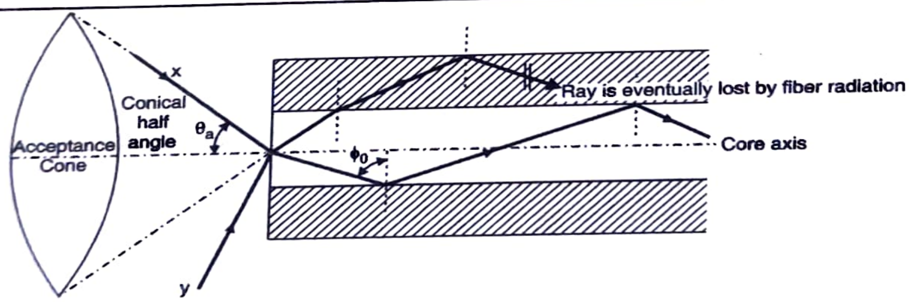


Fig. 1.20.1 : Acceptance Angle

- In this case, the ray will not cause internal reflection. Consider a ray 'y' shown in Fig. 1.20.1. It makes an angle greater than θ_a; so the corresponding angle inside the cable will be less than ϕ_c and there is refraction, instead of reflection.
- So, this ray enters into the cladding layer and it is eventually lost due to radiation.
- Thus acceptance angle is the maximum angle of incoming light ray, with respect to the fiber axis, at which the light may enter into optical cable and gets propagated.

1.20.1 Derivation of Angle of Acceptance

- In order for a ray of light to propagate down the cable (i.e. for total internal reflection to take place), it must strike the internal core/cladding interface at an angle that is greater than the critical angle ϕ_c. The core of the fiber has a refractive index n_1 and is surrounded by a cladding of a material with a lower refractive index n_2.
- Applying Snell's law to the external angle of incidence yields, the following relation.
- Light is launched into the end of the fiber from a launch region with a refractive index n_0. If the launch region is air then $n_0 = 1$. When light rays enter the fiber, they strike the air/glass interface at its axis point A, with an angle of incidence ϕ_{in}.

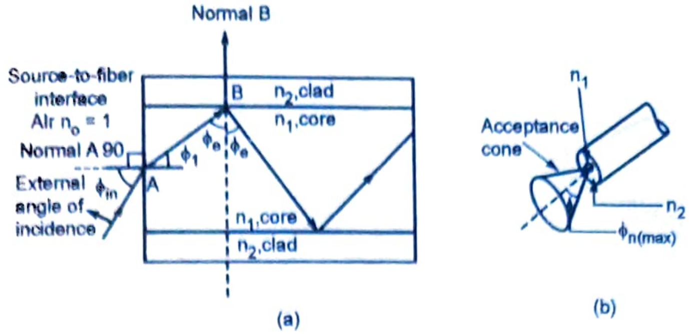


Fig. 1.20.2 : Acceptance Angle

- Consequently, the light entering the air/glass interface propagates from a less dense medium into a more dense medium. Under these conditions and according to Snell\s law, the light rays will refract towards the normal (i.e. normal B). **The angle of refraction is denoted as ϕ_1.**
- It is then reflected from the core/cladding interface at point B with an internal incidence angle ϕ_c. [This is different from the external angle of incidence at the air/glass interface ϕ_{in}.]
- In order for a ray of light to propagate down the cable (i.e. for total internal reflection to take place), it must strike the internal core/cladding interface at an angle that is greater than the critical angle ϕ_c.
- Applying Snell's law to the external angle of incidence yields, the following relation

$$n_0 \sin \phi_{in} = n_1 \sin \phi_1 \qquad \text{but,} \quad \phi_1 = 90° - \phi_c$$

$$n_0 \sin \phi_{in} = n_1 \sin \phi m \qquad \text{...(1.20.1)}$$

$$\text{but} \quad \phi_1 = 90° \qquad \text{...(1.20.2)}$$

Therefore, substituting Equation (1.20.2) in (1.20.1) we get,

$$n_0 \sin \phi_m = n_1 \sin 90 - \phi_c$$

$$n_0 \sin \phi_m = n_1 \cos \phi_c \text{ since } \sin(90 - \phi_c)$$

$$= \cos(\phi_c) \qquad \text{...(1.20.3)}$$

- If we consider the point B in above figure, the critical angle value for ϕ_c is

$$\sin \phi_c = \frac{n_2}{n_1} \qquad \text{...(1.20.4)}$$

- Expressing the term $\cos\phi_c$, in equation (3), in terms of $\sin \phi_c$, then equation (1.20.3) modifies to the form,

$$n_0 \sin \phi_{in} = n_1(1 - \sin^2 \phi_c)^{1/2} \qquad \text{...(1.20.5)}$$

Substituting for $\sin \phi_c$ from equation (1.20.4)

$$n_0 \sin \phi_{in} = n_1 \left[1 - \left(\frac{n_2}{n_1}\right)^2\right]^{1/2}$$

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

or

$$n_0 \sin \phi_{in} = \frac{n_1}{n_1}\sqrt{n_1^2 - n_2^2} \qquad \text{...(1.20.6)}$$

where, $\phi_{in}(max)$ = acceptance angle (in degrees) = ϕ_a

n_1 = refractive index of glass fiber core (dimensionless, typical value = 1.5)

n_2 = refractive index of quartz fiber cladding (dimensionless, typical value = 1.46)

n_0 = refractive index of air (dimensionless, typical value = 1)

- Because light rays generally enter the fiber from the air medium. $n_0 = 1$. Therefore, the maximum value of $\sin\phi_{in}$ is given as,

$$\sin \phi_{in(max)} = \sqrt{n_1^2 - n_2^2}$$

$$\text{or} \quad \phi_{in(max)} = \sin^{-1}\sqrt{n_1^2 - n_2^2} \qquad \text{...(1.20.7)}$$

$$\text{or} \quad \phi_{in(max)} = \sin^{-1} \text{NA} \qquad \text{...(1.20.8)}$$

- Thus, ϕ_{in} is called the acceptance angle or acceptance cone half-angle.

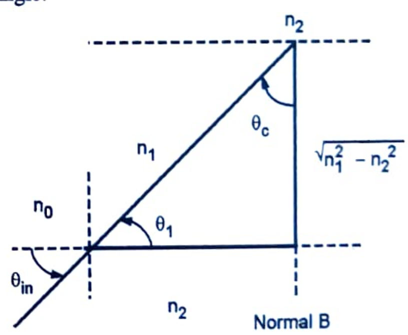


Fig. 1.20.3 : Geometric relation Ship acceptance angle and critical angle

Thus,

(1) The acceptance angle of the fiber is the maximum angle with a light ray can enter into the fiber and still be totally internally reflected.

(2) A cone of light incident at the entrance end of the fiber will be guided through the fiber, provided the semi-vertical angle of the core is less than or equal to $\phi_{in(max)}$.

Note : The angle $\phi_{in(max)}$ is unique only for a particular fiber. it differed from fiber to fiber and depends on the material and the core diameter.

- Rotating the acceptance angle around the fiber core axis describes the cone of acceptance at the input of the fiber. Fig. 1.20.4. depicts the acceptance cone.

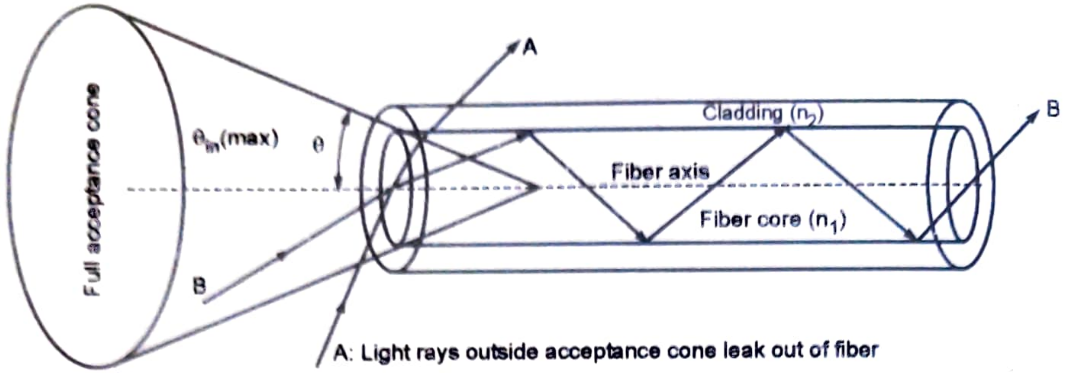


Fig. 1.20.4 : Acceptance cone

- Any light entering the cone of acceptance illustrated will be reflected internally and may propagate along the fiber length.
- Light entering from outside the cone of acceptance is merely refracted into the cladding and will not propagate at all.

1.20.2 Relationship between the critical incidence angle and the acceptance angle

- Fig. 1.20.5. shows the relationship between the critical incidence(ϕ_c) angle and the acceptance (ϕ_{in}) angle for total internal reflection to take place in optical fiber cable.

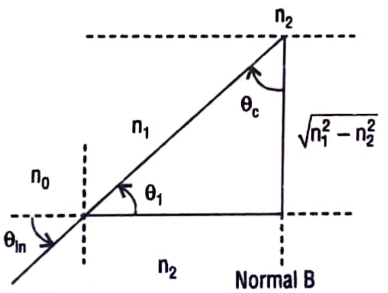


Fig. 1.20.5 : Relationship between acceptance angle and critical angle

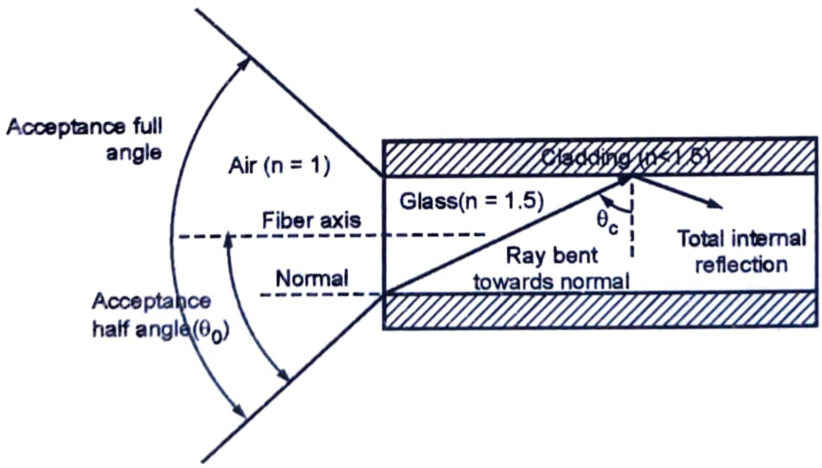


Fig. 1.20.6

1.21 NUMERICAL APERTURE

UQ. Derive an expression for Numerical Aperture. **(MU – Q. 3(a), May 17, 10 Marks)**

UQ. Define Numerical Aperture **(MU – Q. 1(a), Dec. 17, 5 Marks)**

- **Definition:** The numerical aperture (NA) is defined as the sine (sinusoidal) of the maximum angle which a light ray (being incident into the optical fiber) can make with the central axis of the fiber core and can travel through the fiber using the principle of total internal reflection (tir).
- Numerical aperture is the figure of merit which is used to describe the capability of an optical fiber to gather the light efficiently.
- Numerical aperture is closely linked with the acceptance angle. The value of numerical aperture can be used to measure the magnitude of the acceptance angle.

Derivation

- Consider the light ray enters inside the fiber optic cable by making an angle θ_a with respect to the axis of the fiber optic cable. This light rays strikes to the boundary of core cladding interface and make an angle equals to critical angle. This situation is as shown in Fig. 1.21.1.

Here n_0 = Refractive index of air = 1

n_1 = Refractive index of the core

n_2 = Refractive index of cladding

and θ_a = Angle of incidence.

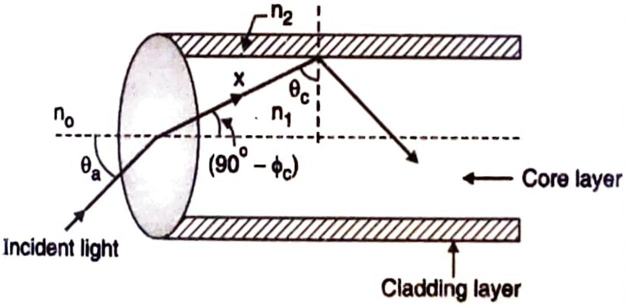


Fig. 1.21.1 : Maximum acceptance angle

Now according to Snell's law,

$$n_0 \sin\theta_a = n_1 \sin(90 - \phi_c) \quad ...(1.21.1)$$

where ϕ_c = Critical angle.

But $\sin(90 - \phi_c) = \cos\phi_c$

$$\therefore n_0 \sin\theta_a = n_1 \cos\phi_c \quad ...(1.21.2)$$

- Since the value of n_0 that means refractive index of air is always 1, so the value of $n_0 \sin\theta_a$ is not dependent on n_0.
- This is called as **numerical aperture** of fiber optic cable.

$\therefore$ From Equation (1.21.2) we have,

$$NA = n_1 \cos\phi_c \quad ...(1.21.3)$$

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

$$\therefore NA = n_1\left[1 - \sin^2\phi_c\right]^{1/2} \quad ...(1.21.4)$$

We have the equation of ϕ_c in terms of n_1 and n_2 as,

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

$\therefore$ Equation (1.21.4) becomes,

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

$$\therefore NA = \left[n_1^2 - n_2^2\right]^{1/2} \quad ...(1.21.5)$$

But from Equations (1.21.1) and (1.21.2),

$$NA = n_0 \sin\theta_a$$

Since $n_0 = 1$,

$$NA = \sin\theta_a$$

Angle of acceptance $\theta_a = \sin^{-1}(NA)$

$$\therefore NA = \sin\theta_a = \sqrt{n_1^2 - n_2^2} \quad ...(1.21.6)$$

$$\therefore NA = \sqrt{(n_1 + n_2)(n_1 - n_2)}$$

Now if $n_1 \approx n_2$ then $n_1 + n_2 \approx 2n_1$

$$\therefore NA = \sqrt{2n_1(n_1 - n_2)} \quad ...(1.21.7)$$

- The relative refractive index difference between core and cladding is given by,

$$\Delta = \frac{n_1 - n_2}{n_1} \quad \text{for } \Delta << 1$$

$$\therefore \Delta n_1 = n_1 - n_2 \quad ...(1.21.8)$$

- Putting Equation (1.21.8) in Equation (1.21.7) we get,

$$NA = \sqrt{2n_1 \cdot \Delta n_1} = n_1\sqrt{2\Delta} \quad ...(1.21.9)$$

Note : For small angles, the solid acceptance angle in air is given by,

$$\xi = \pi \sin^2\theta_a \approx \pi\theta_a^2$$

$$\therefore \xi = \pi(NA)^2 \quad .....(1.21.10)$$

Conclusions

- Thus, numerical aperture can be calculated from the given values of refractive index of the fiber core and cladding used in the optical fiber cable. It may be noted that it is independent of the diameter of the fiber core.
- In other words, a larger diameter core does not necessarily produce a larger numerical aperture. However, in practice, larger core fibers tend to have larger numerical apertures.
- Numerical aperture (a property concerned at the input of the fiber) is generally measured by looking at the output of the

fiber because of the simple reason that the light guiding properties of an optical fiber cable are symmetrical. It means that the light leaving a fiber cable spreads out (i.e., scattered) over an angle which is almost same as that of the acceptance angle.

1.21.1 Problem based on Numerical Aperture

Ex. 1.21.1 : An optical fiber cable has values of refractive index of 1.50 for the fiber core and 1.47 for the cladding. Determine the numerical aperture.

☑ **Soln. :**

Numerical aperture is $NA = \sin\theta_a = \sqrt{n_1^2 - n_2^2}$

$$\text{Given } n_1 = 1.50 \text{ and } n_2 = 1.47,$$

$$NA = \sqrt{1.5^2 - 1.44^2}$$

$$NA = 0.30$$

1.21.2 Problem based on NA and Acceptance Cone

Ex. 1.21.2 : An optical fiber cable has specified refractive index values of 1.6 and 1.4 for the fiber core and cladding, respectively. Determine the numerical aperture and the total width of the acceptance cone.

☑ **Soln. :**

Numerical aperture is $NA = \sin\theta_a = \sqrt{n_1^2 - n_2^2}$

$$\text{Given } n_1 = 1.50 \text{ and } n_2 = 1.4,$$

$$NA = \sqrt{1.5^2 - 1.4^2} = 0.775$$

$$\text{Acceptance angle } \theta_a = \sin^{-1}(NA)$$

$$\text{Therefore Acceptance angle } \theta_a = \sin^{-1}(0.775) = 50.8^0$$

$$\text{Total width of the cone of acceptance} = 2 * \theta_a = 2 * 50.8° = 101.6°$$

Ex. 1.21.3 : 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.

☑ **Soln. :**

(a) The critical angle Φ_c at the core–cladding interface is given by Eq. 1.18.3.

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

Eq. (1.21.6.) where NA is:

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

(c) Considering Eq. (1.20.7) the acceptance angle in air θ_a is given by :

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

UEx. 1.21.4 : (MU – Q. 2(b), Dec. 18, 10 Marks)

A typical relative refractive index difference for an optical fiber designed for long distance transmission is 1%. Estimate the *NA* and the solid acceptance angle in air for the fiber when the core index is 1.46. Further, calculate the critical angle at the core – cladding interface within the fiber. It may be assumed that the concepts of geometric optics hold for the fiber.

☑ **Soln. :** Using Eq. (1.21.9.) with $\Delta = 0.01$ gives the *NA* as:

$$NA = n_1 (2\Delta)^{1/2} = 1.46(0.02)^{1/2} = 0.21$$

- For small angles the solid acceptance angle in air ξ is given by:

$$\xi \simeq \pi\theta_a^2 = \pi \sin^2\theta_a$$

Hence from Eq. (1.21.10):

$$\xi \simeq \pi(NA)^2 = \pi \times 0.04 = 0.13 \text{ rad}$$

- Using Eq. (1.21.8.) for the relative refractive index difference Δ gives:

$$\Delta \simeq \frac{n_1 - n_2}{n_1} = 1 - \frac{n_1}{n_1}$$

Hence

$$\left(\frac{n_2}{n_1}\right) = 1 - \Delta = 1 - 0.01 = 0.99$$

- From Eq. (1.18.3.) the critical angle at the core–cladding interface is:

$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1} 0.99 = 81.9°$$

1.22 SKEW RAYS

- If incoming light ray falls in the cone of acceptance then internal reflection takes place inside the cable. The **meridional rays** enter the core and causes internal reflection by passing through the centre of core.
- Some, incoming light rays, enter the core and passes along the axis of core. Throughout the optical cable; the

propagation of such rays is along the axis of core. Such rays are called as **axial rays**.

- Some of rays follow the helical path inside the core layer as shown in cross section of fiber in Fig. 1.22.1. Such rays are called as **skew rays** and these rays are not transmitted through the axis of optical cable.
- Due to the helical path; tracking of skew rays is difficult. As shown in Fig. 1.22.1, β is the angle made by light ray with the radius.

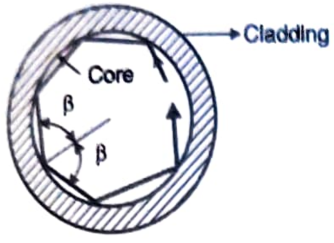


Fig. 1.22.1

- At each reflection, the helical path gives a change in direction of 2β. The point from which, helical rays comes out of the fiber, depends on the number of reflections inside the cable.
- Even if the input light is non-uniform; skew rays produce the smoothing effect. Skew rays change the power losses when they are travelling through the optical cable. Due to the helical path followed by skew rays; the light acceptance ability of the fiber is changed.

1.23 SOLVED NUMERICALS ON TOTAL INTERNAL REFLECTION

Ex. 1.23.1 : An optical fiber has core and cladding refractive indices 1.48 and 1.46 respectively. Calculate numerical aperture. Also calculate the maximum angle of entrance of light into air.

☑ **Soln. :**

Given : core $n_1 = 1.48$, cladding $n_2 = 1.46$

$$\therefore \text{NA} = \left(n_1^2 - n_2^2\right)^{1/2} = ((1.48)^2 - (1.46)^2)^{1/2}$$

$$= 0.2424$$

Acceptance angel θ_a is given by

$$\theta_a = \sin^{-1} \text{NA} = \sin^{-1}(0.2424)$$

$$= 14.028°$$

Ex. 1.23.2 : Find core radius necessary for single mode operation at 820 nm of step index fiber with $n_1 = 1.480$ and $n_2 = 1.478$. What is NA and maximum acceptance angle of fiber ? Also calculate corresponding solid angle.

☑ **Soln. : Given :**

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

$$= [(1.48)^2 - (1.478)^2]^{1/2}$$

$$= [2.19 - 2.184]^{1/2} = [0.006]^{1/2}$$

$$= \mathbf{0.077}$$

(ii) $$\theta_a = \sin^{-1} \text{NA} = \sin^{-1} 0.077$$

$$= 4.41°$$

(iii) Solid acceptance angle $= \pi (\text{NA})^2 = \pi \times (0.077)^2$

$$= 0.0186 \text{ radians}$$

UEx 1.23.3 : MU- May 2016, 10 Marks

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 cladding refractive index of 1.47.

Determine :

(i) The critical angle at the core-cladding interface,

(ii) The numerical aperture for fiber,

(iii) The acceptance angle in air for the fiber.

☑ **Soln. :**

Given : Core refractive index = 1.50

Cladding refractive index = 1.47

(i) Critical angle is, $\phi_c = \sin^{-1} \frac{n_2}{n_1} = \sin^{-1} \frac{1.47}{1.5}$

$$= \mathbf{78.5°}$$

(ii) $$\text{NA} = \left(n_1^2 - n_2^2\right)^{1/2} = (1.5^2 - 1.47^2)^{1/2}$$

$$= 0.2984$$

(iii) Acceptance angle is, $\theta_a = \sin^{-1} \text{NA} = \sin^{-1} 0.2984$

$$= 17.3673°$$

UEx. 1.23.4 : MU - Dec. 2012, 6 Marks

The velocity of light in the core of a step index fiber is 2.01×10^8 m/s, and the critical angle at the core-clad interface is 80°. Determine the numerical aperture and the acceptance angle for the fiber in air, assuming it has a core diameter suitable for consideration by ray analysis.

☑ **Soln. :**

Critical angle = 80°

$$\therefore \phi_c = \sin^{-1} \frac{n_2}{n_1}$$

$$\therefore 80° = \sin^{-1} \frac{n_2}{n_1}$$

$$\therefore \frac{n_2}{n_1} = \sin 80° = 0.9848$$

We have to determine NA for fiber in air that means for $n_2 = 1$

$$\therefore n_1 = \frac{n_2}{0.9848} = \frac{1}{0.9848} = 1.015$$

(i) NA = Numerical aperture

$$= \left(n_1^2 - n_2^2\right)^{1/2} = [(1.015)^2 - 1^2]^{1/2}$$

$$= \mathbf{0.1738}$$

(ii) Acceptance angle $= \sin^{-1}\sqrt{n_1^2 - n_2^2} = \sin^{-1}(NA)$

$$= \sin^{-1} 0.1738 = \mathbf{10.01°}$$

Ex. 1.23.5 : Calculate the refractive indices of the core and the cladding materials of an optical fiber whose NA = 0.35 and $\Delta = 0.01$.

☑ **Soln. :**

$$NA = n_1 (2\Delta)^{1/2}$$

$$\therefore 0.35 = n_1 (2 \times 0.01)^{1/2}$$

$$= n_1 (0.02)^{1/2}$$

$$\therefore n_1 = \frac{0.35}{0.141} = 2.48$$

Now $\Delta \simeq \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$

$$\therefore 0.01 = 1 - \frac{n_2}{n_1}$$

$$\therefore \frac{n_2}{n_1} = 1 - 0.01$$

$$\therefore n_2 = n_1 (0.99) = 2.48 \times (0.99)$$

$$= 2.45$$

∴ Core refractive index = **2.48**

and Cladding refractive index = **2.45**

Ex. 1.23.6 : Calculate the aperture of a step index fiber having $n_1 = 1.48$, $n_2 = 1.46$. What is the maximum entrance angle if outer medium has $n = 1$?

☑ **Soln. :**

(a) $\theta_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.46}{1.48}$

$$= 80.56°$$

Now, $NA = \left(n_1^2 - n_2^2\right)^{1/2}$

$$= [(1.48)^2 - (1.46)^2]^{1/2}$$

$$= \mathbf{0.242}$$

(b) Acceptance angle $\theta_a = \sin^{-1} NA = \sin^{-1} 0.242$

$$= \mathbf{14.033°}$$

1.24 OPTICAL FIBER MODES AND CONFIGURATIONS (MODE THEORY)

- In case of an optical fiber, the innermost layer is core layer. This layer is covered by another layer called as cladding.
- For the proper propagation of light through an optical fiber the refractive index of cladding layer is made less than that of core layer.
- The light rays coming from one end of optical fiber entered into it. For this an angle of incidence should greater than the critical angle (θ_c). Then it is possible for light rays to cause the total internal reflections in an optic fiber.
- In case of metal waveguides, the metal walls are acting waveguides. Here the carriers are electrons. But in case optical fiber the fiber layers are acting as waveguides. He the carriers are photons. The fiber optic cable acts **cylindrical waveguide**. Because the structure of an optic fiber is cylindrical in nature.
- The light rays undergoes the different modes when they a travelling through an optical fiber. Here fiber optic cable acting as waveguide for these light rays. Because, optic fiber cable guides the light wave passing through it. Now t order of mode means the number of field zeros across t mode.
- If we will consider the Transverse Electric (TE) mode, th the lower order modes are TE_0, TE_1 and TE_2 modes.
- Electric field distribution across the waveguide for the lower order modes is as shown in Fig. 1.24.1.

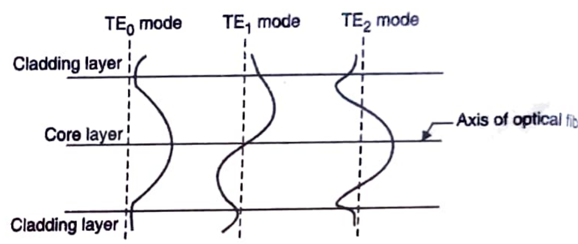


Fig. 1.24.1 : Electric field distribution across the waveguide for lower order modes

- As shown in Fig. 1.24.1, the field concentration is mostly distributed along the core layer. But this electric field is not becoming zero at the core-cladding interface.
- Some portion of an electric field is entering in the cladding layer. Here TE_0 mode is having the lowermost order. The field concentration for this mode is completely confined to the axis of optical fiber.
- For another lower order mode, that means for TE_1 and TE_2 modes, the fields are distributed at the core cladding interface. Thus for higher modes electric field gets penetrated more in cladding layer. This is the power loss for the core layer.
- In case of optical fiber if an incident light rays are in the acceptance cone of optical fiber, then the total internal reflections takes place. So the light rays cause several reflections and appears at the output.
- Some of the light rays may fall at the interface of core cladding layer. These light rays starts travelling through the cladding layer.
- Now the core layer is designed in such a way that all the light rays (input signals) can pass only through it. But as discussed earlier, some of the light rays are passing through the cladding layer.

- The modes corresponding to these light rays passing through cladding layer, are called as **cladding modes**. Like the core modes, the cladding modes also enters into the core layer. Thus as the light rays travels through optical fiber, at many place the coupling of modes takes place. That means the coupling of core and cladding modes takes place. Thus the diffusion of optical power between core and cladding layer takes place.

Note : Optical power is the power related to the light rays. Because the light rays are optical signals.

- This means at one instant the optical power from core layer gets diffused into cladding layer. While at another instant optical power from cladding layer gets diffused into core layer. This is because the light rays are passing both through the core layer and cladding layer.
- For fiber optic cable, one more layer is used above the cladding layer. This is called as jacket or protecting layer. Many times this protecting layer suppresses the cladding modes. If certain irregularities are present in the cladding layer, then the scattering of light rays takes place.
- The modes travelling through core layers are bounded by this layer. These modes are called as **bottom modes**. While the modes created because of refraction of light at core-cladding interface are called as **refracted modes.**

Leaky modes

- Some of the modes passing through the core layer continuously looses their energies. That means these modes get attenuated after travelling certain distance through core layer. So a continuous power loss is taking place for such modes.
- The radiation of power from these modes outside the core layer takes place because of **tunnel effect**. This modes are called as **leaky modes.**

1.24.1 Conditions for Guided Modes

- The propagation constant is denoted by β.
- For a mode, to remain as guided mode in the core layer the condition is,

$$n_2 K < \beta < n_1 K \qquad \text{...(1.24.1)}$$

Here n_2 = Refractive index of cladding,

n_1 = Refractive index of core

β = Propagation constant,

and $K = 2\pi/\lambda$

where λ is the wavelength of light

- The cut-off condition for such modes is defined as,

$$\beta = n_2 K \qquad \text{...(1.24.2)}$$

- n_2 is the refractive index of cladding layer.
- So when β becomes less than n_2 K then there is a leak of power from core layer to cladding layer. Thus at this stage the leaky mode starts.
- To summarize we can write the conditions for different modes as follows :

(i) $n_2 K < \beta < n_1 K$; for guided modes

(ii) $n_2 K = \beta$; for cutoff

(iii) $\beta < n_2 K$; for leaky modes.

1.25 PHASE AND GROUP VELOCITY

MU - May 2015

Phase velocity

- When optical waves are propagating through optical fibers, there are certain points having constant phase. These points of constant phase travels with a phase velocity (V_P) as,

$$V_P = \frac{\omega}{\beta} \qquad \text{...(1.25.1)}$$

Here, ω = Angular frequency $= 2\pi f = \frac{2\pi c}{\lambda}$

and β = Propagation constant

- The propagation constant for core layer is given as,

$$\beta_1 = n_1 \frac{2\pi c}{\lambda} \qquad \text{...(1.25.2)}$$

Here, n_1 = Refractive index of core layer

c = Velocity of light

- Similarly the propagation constant is also given by,

$$\beta_g = \omega\sqrt{\mu_0 \epsilon_0} \qquad \text{...(1.25.3)}$$

- This is the propagation constant for free space

Here, ϵ_0 = Permittivity of free space

μ_0 = Permeability of free space

- In case of dielectric having permittivity and permeability as ϵ_1 and μ_1, the propagation constant for core layer is given as,

$$\beta_1 = \omega\sqrt{\mu_1 \epsilon_1} \qquad \text{...(1.25.4)}$$

- Similarly for cladding layer having permeability and permittivity as μ_2 and ϵ_2, the propagation constant is given by,

$$\beta_2 = \omega\sqrt{\mu_2 \epsilon_2} \qquad \text{...(1.25.5)}$$

Group velocity

- Optical waves are travelling as wave packets. These wave packets have a group velocity.
- It is denoted by V_g. It is given by,

$$V_g = \frac{d\omega}{d\beta}$$

$$\therefore V_g = \frac{c}{N_g} \qquad \text{...(1.25.6)}$$

Here c = Velocity of light ,

N_g = Group index of the guide.

1.25.1 Transverse Propagation Constant

- The transverse propagation constant in core layer is denoted by K_a. It is given by,

$$K_a = \sqrt{\beta_1^2 - \beta_g^2} \quad ...(1.25.7)$$

Here β_1 = Propagation constant for core layer

β_g = Propagation constant of free space

- Similarly, the transverse propagation constant for cladding layer is denoted by K_b. It is given as,

$$K_b = \sqrt{\beta_g^2 - \beta_2^2} \quad ...(1.25.8)$$

Here β_2 = Propagation constant for cladding layer

β_g = Propagation constant of free space

1.25.2 'V' Number

MU – Dec. 2013

- The number of propagating modes in an optical fiber is decided by **'V' number**. This value also decides at which point, mode cutoff condition is occurring.
- The 'V' number is given as,

$$V = \sqrt{U^2 + W^2} \quad ...(1.25.9)$$

Here U = Radial propagation constant

W = Cladding decay parameter

- The radial propagation constant is given as,

$$U = a\sqrt{n_1^2 K^2 - \beta^2} \quad ...(1.25.10)$$

Here, a = Radius of core,

n_1 = Refractive index of core layer

$K = 2\pi/\lambda$,

β = Propagation constant

- The cladding decay parameter is given by,

$$W = a\sqrt{\beta^2 - n_1^2 K^2} \quad ...(1.25.11)$$

Here, n_2 = Refractive index of cladding layer

- Now from Equation (1.25.9) we have,

$$V^2 = U^2 + W^2 \quad ...(1.25.12)$$

- Putting the values of U and W we get,

$$V^2 = a^2\left(n_1^2 K^2 - \beta^2\right) + a^2\left(\beta^2 - n_2^2 K^2\right)$$

$$\therefore V^2 = a^2 n_1^2 K^2 - a^2\beta^2 + a^2\beta^2 - a^2 n_2^2 K^2$$

$$= a^2 n_1^2 K^2 - a^2 n_2^2 K^2$$

$$= a^2 K^2\left(n_1^2 - n_2^2\right)$$

$$\therefore V = K \cdot a\sqrt{n_1^2 - n_2^2} \quad ...(1.25.13)$$

- But we have, numerical aperture of optical fiber (NA) as,

$$NA = \sqrt{n_1^2 - n_2^2} \quad ...(1.25.14)$$

- Thus Equation (1.25.13) becomes,

$$V = K \cdot a \cdot (NA) \quad ...(1.25.15)$$

- Putting the value of k we get,

$$V = \frac{2\pi}{\lambda} \cdot a \cdot (NA) \quad ...(1.25.16)$$

- This is equation of V in terms of NA. Now the relative refractive index of an optical fiber is denoted by Δ. It is given as,

$$\Delta = \frac{n_1^2 - n_2^2}{2 n_1^2} \quad ...(1.25.17)$$

But, $$n_1^2 - n_2^2 = (NA)^2$$

$$\therefore \Delta = \frac{NA^2}{2 n_1^2}$$

$$\therefore NA^2 = 2 n_1^2 \cdot \Delta$$

$$\therefore NA = n_1\sqrt{2\Delta} \quad ...(1.25.18)$$

- Putting this value in Equation (1.25.16) we get,

$$V = \frac{2\pi}{\lambda} \cdot a \cdot n_1 (2\Delta)^{1/2} \quad ...(1.25.19)$$

- This is equation of V in terms of Δ.
- The number of modes that can exists in a waveguide is a function of 'V' number. These number of modes that can exist in a waveguide is also represented by a **normalized propagation constant** (b).
- It is defined as,

$$b = \frac{W^2}{V^2} \quad ...(1.25.20)$$

- Putting Equations (1.25.11) and (1.25.13) in Equation (1.25.20) we get,

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

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

- Dividing numerator and denominator by K^2 we get,

$$\therefore \quad b = \frac{(\beta / K)^2 - n_2^2}{n_1^2 - n_2^2} \quad ...(1.25.21)$$

1.26 CLASSIFICATION OF OPTICAL FIBER

- There are various ways to classify optical fibers. These can be based on different characteristics related to the nature (or types) of refractive index profiles of the fiber core, modes of propagation of light in the fiber, and the improvement in the propagation properties.
- One way is to classify the fiber optic cables according to the type of material used. That means whether the material is plastic or pure silica.

- According to the requirements of the bandwidth the fiber optic cables are classified as having low, medium, high or ultrahigh.

Different classification are :

1. Based on **the refractive index profiles** of the fiber core, there can be two types of optical fibers, namely,
   - Step-index optical fiber
   - Graded-index optical fiber
2. Based on **the number of modes** (rays or light wave patterns) propagated within the optical fiber, there can be two types of optical fibers. These are
   - Single-mode optical fiber
   - Multi-mode optical fiber
3. Based on the **improvement in propagation properties**, there can be three different types of optical fibers, such as
   - Polarization-maintaining optical fiber
   - Dispersion-shifted optical fiber
   - Dispersion-flattened optical fiber

1.26.1 Classification based on Number of Modes

According to the operating modes fiber optic cables are classified as :

1. Single mode fiber optic cables.	2. Multimode fiber optic cables.

1. Single mode fiber optic cables

- These fiber optic cables carries only one mode. Single mode fiber has a much smaller core which forces the light to travel in one ray or mode (a single mode) with little light reflection so the signal will travel further. Shown in Fig. 1.26.1.
- These are designed for a single specific wavelength, so that the attenuation losses are minimum. In case of these fiber optic cables microbending losses are also minimum. Microbending losses are the losses occurring in the fiber optic cable due to lateral displacement of the fiber optic cable.
- Single-mode fiber is also known as a single-mode optical fiber, uni-mode fiber, mono-mode optical fiber and single-mode optical waveguide.

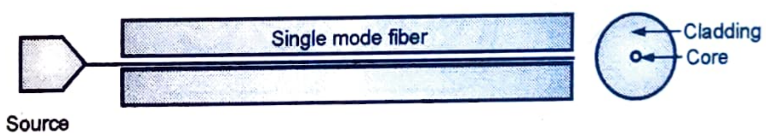


Fig.1.26.1 : Single Mode Fiber

2. Multimode fiber optic cables

- Light travels through a large core in many rays called modes (multiple modes). Due to refraction, the rays are reflected from the cladding surface back into the core as they move through the fiber. Shown in Fig. 1.26.2.
- These fiber optic cables allow different wavelengths to pass through it. Because of this the dispersion losses takes place. That means all the wavelength of light signal doesn't appear at the output, at the same time. There is a transit time difference between these signals. These wavelengths are called intermodally dispersed wavelengths.
- We discussed that the refractive index of cladding layer is made less than that of core layer. That means there is a variation in the refractive index while passing from core layer to the cladding layer. The differences between single mode and multimode fiber optic cable mainly lie in fiber core diameter, wavelength & light source, bandwidth, color sheath, distance and cost.

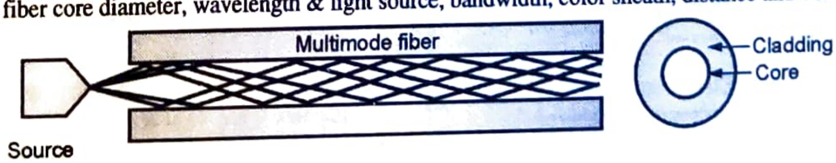


Fig. 1.26.2 : Multimode Fiber

1.26.2 Classification based on Refractive Index Profile

- Depending upon this there are again two types :

1. Step index fiber optic cables.
2. Graded index fiber optic cables.

Disadvantages

1. Since the core diameter is very small, the coupling of light ray from light source in the core layer is difficult.
2. The relative refractive index difference between core and cladding is less; so fabrication of such fibers is difficult.

1.27.5 Based on the Improvement in Propagation Properties

Dispersion modified or dispersion shifted single mode fibers

> **GQ.** What do you mean by dispersion ? How it is minimized ?

- Dispersion is basically broadening of the output pulse. In case of single mode fiber; if the spreading of pulse at the output takes place then it is called as **intramodal dispersion**.
- It may happen that, the refractive index of core layer, changes with the wavelength of signal. It is called as the material dispersion. Due to the variation in core radius, index profile and refractive index difference; again the dispersion takes place. It is called as waveguide dispersion. By changing the design parameters; the dispersion can be minimized.
- Usually to minimize the dispersion; two types of modifications are done in the designing of single mode step index fibers. These are :

Dispersion shifted single mode fibers
- (i) Matched cladding
- (ii) Depressed cladding

Fig. 1.27.2 : Dispersion shifted single mode fiber

(i) Matched cladding

- The refractive index profile of matched clad single mode step index fiber is shown in Fig. 1.27.3.

n(r) = refractive index profile

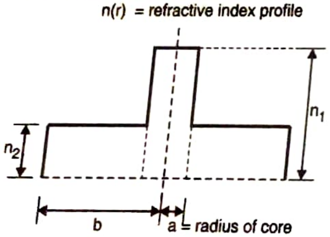


Fig. 1.27.3

- Here 'a' is the core radius and n_1 is the refractive index of core, which is uniform. The index difference from core to cladding is 37 %.
- The refractive index of cladding is denoted by n_2 and the refractive index is also uniform throughout the cladding.

(ii) Depressed cladding

- The depressed cladding single mode step index fiber has two cladding layers. The refractive index profile of such fiber is shown in Fig. 1.27.4. The core to cladding refractive index difference is 25 %. The core radius is 'a' and it has uniform refractive index n_1.
- The core is surrounded by two cladding layers. The inner cladding is having radius 'b'. The refractive index of inner cladding is n_2, which is slightly less than refractive index of core n_1.
- Inner cladding is surrounded by outer cladding layer, having radius 'c'.

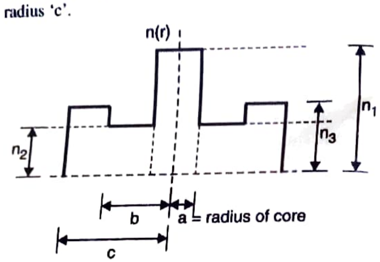


Fig. 1.27.4 : Depressed Cladding

- It has refractive index n_3, which is greater than n_2 but less than n_1. Such a matched cladding and depressed cladding design fibers are called as dispersion shifted fibers or dispersion modified fibers.
- In some fiber optic designs; the dispersion is distributed over a wide spectral range. Such fibers are called as dispersion flattened fibers.

1.28 MULTIMODE STEP INDEX FIBER

> **UQ.** Derive an expression for number of modes in SIF. **MU - May 17, 3 Marks**
>
> **UQ.** Sketch the Refractive Index Profile of SIF and GIF. Derive an expression for Numerical Aperture and Number of Modes in SIF. **(MU – Q. 3(a), May 17, 10 Marks)**

- Multimode step index fiber with a core diameter of around 50 μm or greater allows the propagation of a finite number of guided modes along the channel. The total number of guided modes Ms for a step index fiber is given by

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

Where, V denotes the V-number which is a normalized frequency parameter.

- In multimode step index fiber dispersion is high due to the differing group velocities of the propagating modes. Due to high dispersion the information carrying capacity is less.
- It cannot be used for long distance communication as dispersion is a function of length. Simple to fabricate than single mode fiber and LED can be used as light source.
- As the name indicates; the number of modes travel through the core layer. The number of modes that can propagate through the fiber, depends on following factors :
  (i) Wavelength of incoming light
  (ii) The diameter of core
  (iii) The refractive indices of core and cladding layers.
- Mathematically, the number of modes, that propagate through the fiber is given by,

$$M = \left[\frac{\pi d}{\lambda}\right]^2 \left(n_1^2 - n_2^2\right)$$

Here λ = Wavelength of incoming light
d = Diameter of core layer
n_1 = Refractive index of core
n_2 = Refractive index of cladding

1.28.1 Propagation in Multimode Step Index Fibers

- Basically the 'V' number of multimode fiber is greater than 1.1505; so the fiber supports different modes. The refractive index profile and number of modes propagating through multimode step index fiber, is shown in Fig. 1.28.1.
- The core diameter is larger than single mode fibers and the core to cladding refractive index ratio is efficient.
- The number of guided modes depend on relative refractive index difference, core radius and wavelengths.
- There is a cut off value of normalized frequency (V_C) below which the guided modes do not exists. It does not mean that, the propagation will be stopped; but the propagation takes place in the form of leaky modes.

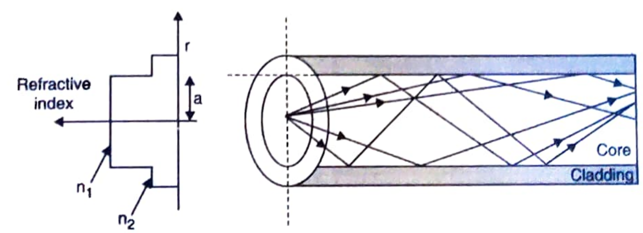


Fig. 1.28.1 : Propagation in Multimode Step Index Fibers

- In case of multimode fibers; the different modes follow, the different paths in the core layer. Because of this, all the modes do not arrive at the output; at the same time. It produces dispersion.
- In case of multimode step index fiber, the cut off condition is given by,

$$n_2K < \beta < n_1K$$

Here, K = $2\pi/\lambda$
n_1 = Refractive index of core
n_2 = Refractive index of cladding
β = Propagation constant.

- Cut off is the condition at which the normalized frequency (V) becomes equal to the normalized cut off frequency (V_c). At this condition the propagation of waves through optical waveguide stops.
- But in practical cases, the propagation of waves is not stopped. In this case the guided modes are converted into leaky modes.

1.28.2 Advantages of Multimode Propagation

> **GQ.** State advantages of multimode propagation.

1. Due to large core radius; the launching of optical power in the fiber is easy.
2. Connecting two fibers is easy compared to single mode fibers.
3. LED can be easily coupled to the fiber; as a light source.
4. Compared to single mode fiber; there is large refractive index difference between core and cladding layers. So, fabrication of such fibers is easy.

Disadvantages

GQ. State disadvantages of multimode propagation.

1. The different mode follow the different paths. They are not reaching the output at same type. It produces intermodal dispersion.
2. The spreading of output pulse takes place.
3. For multimode step index fiber, bandwidth is limited. It is only 6 to 50 MHz/km.
4. Due to large amount of intermodal dispersion; multimode fibers are not suitable for long distance communication.

1.29 COMPARISON BETWEEN SINGLE MODE AND MULTIMODE FIBER

GQ. Differentiate single mode and multimode fibers.

Sr. No.	Parameters	Single mode fiber	Multimode fiber
1.	Propagating Mode	Propagation of only one mode takes place.	Many modes propagate at the same time.
2.	Diameter	Due to small core diameter; launching of optical power is difficult.	Due to large core diameter, launching of optical power is easy.
3.	Intermodal Dispersion	Due to single mode, there is no intermodal dispersion.	Many modes travel with different speeds; so intermodal dispersion occurs.
4.	Pulse Duration	Duration of input and output pulse is same.	Output pulse is spreadout compared to input pulse.
5.	Source	LED cannot be used as light source.	LED can be used as light source.
6.	Attenuation	At 850 nm; attenuation is about 2 to 5 dB/km.	At 850 nm; attenuation is about 2.6 to 50 dB/km.
7.	Bandwidth	Higher bandwidth (greater than 400 MHz / km)	Less bandwidth (6 to 50 MHz / km)
8.	V Number	V number is less than 1.15.	V number is greater than 1.15.
9.	Distance	Applicable to long distance communication.	Applicable for short distance communication.
10.	Application	**Applications :** Long distance telephony, multichannel television broadcasting.	**Applications :** LAN networks and video surveillance.

1.30 GRADED INDEX FIBER

UQ. Sketch the Refractive Index Profile of GIF. **MU - May 17, 2 Marks**

UQ. Sketch the Refractive Index Profile of SIF and GIF. Derive an expression for Numerical Aperture and Number of Modes in SIF. **(MU - Q. 3(a), May 17, 10 Marks)**

- The refractive index of core layer is not constant. It varies smoothly and continuously over the diameter of core layer. The refractive index changes proportionally as the distance varies from core axis to the cladding layer.
- Since the refractive index of core is varying; it is called as inhomogeneous core fiber. On the axis of core; the refractive index is maximum. It is denoted by n_1.
- The refractive index goes on decreasing with the radial distance as shown in Fig. 1.30.1. In graded-index multimode fiber, the light travels forward in the form of sinusoidal oscillation.
- Like step-index multimode fibers, different lights in a graded-index multimode fiber travel along different paths. However, the speed of light propagation in graded-index multimode fibers is different because the speed of guided light varies with the refractive index of the fiber core.
- The farther the light goes from the center of the fiber, the faster its speed is. The speed difference compensates for the longer paths followed by the light rays that go farthest from the center of the fiber.
- This equalization of the transmission time of different modes reduces the mode dispersion greatly, making a higher bandwidth in graded-index fiber than step-index fiber. Therefore, most of the multimode fiber today is graded-index fiber. Compared to step-index fiber, the graded-index fiber is usually used in medium-distance (10~20 km) and relatively higher-speed (34~140 Mb/s) communication systems with higher cost.

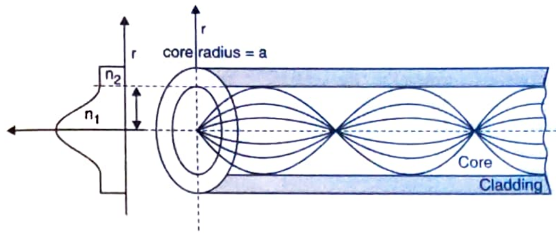


Fig. 1.30.1 : Graded Index Fiber

- The reduction in refractive index takes place from core axis to the cladding layer. But in the cladding layer; the refractive index is constant.
- It is denoted by n_2. Due to continuously changing refractive index; the propagation of light rays is not along straight line paths.
- Consider the propagation through multimode graded index fiber as shown in Fig. 1. 30.2.

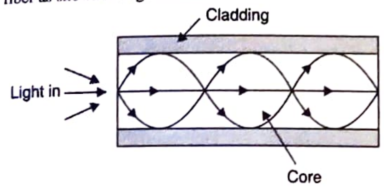


Fig. 1.30.2 : Propagation through multimode graded index fiber

- For the curved path; the velocity of propagation goes on changing with respect to change in refractive index. At the centre of core; the refractive index is maximum. So, axial ray passing along centre of core is having slowest speed.
- Due to the difference in speeds of different paths; even though the distance travelled by each path is different, all paths reach the output at the same time. Let 'α' denotes the profile parameter, which gives the characteristic refractive index profile of core layer. The value of α decides the shape of the refractive index profile curve.
- The relative refractive index difference is denoted by Δ. Then index variation in graded index fiber is given by,

$$n(r) = \begin{cases} n_1\sqrt{1-2\Delta\left(\frac{r}{a}\right)^{\alpha}}, & r \le a \quad \text{(core layer)} \\ n_2 = n_1\sqrt{1-2\Delta}, & r > a \quad \text{(cladding layer)} \end{cases}$$

- As the value of α changes, the shape of refractive index profile also changes as shown in Fig. 1.30.3.

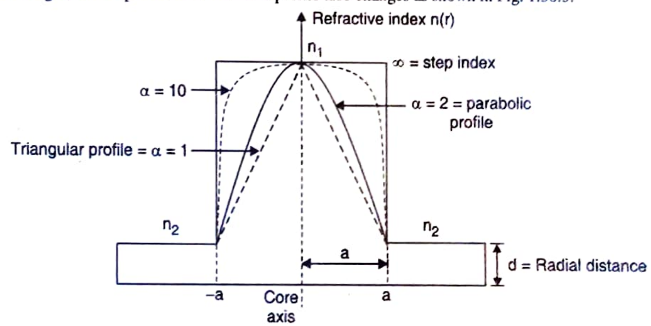


Fig. 1.30.3 : shape of refractive index profile

- For $\alpha = 1$; the refractive index profile is triangular. For $\alpha = 2$; the profile is parabolic and when α becomes ∞, we will get step index profile instead of graded index profile.

1.31 PROPAGATION MODES

❑ **Definition of mode:** In fiber-optics terminology, the word '**mode**' simply means '**path**', the path that is traversed by the propagation of light within the fiber. This path can be best described by a well defined set of guided electromagnetic (em) waves. These are known as the propagation modes, or simply modes, of the optical fiber.

- Modes are distinguished by their propagating angles (incidence or reflected). The extent of propagating angle is directly related with the order of the mode of an optical fiber. It implies that the **smaller the propagating angle the lower will be the order of the propagating mode**. Thus, it say that:
- The **fundamental mode**, also called the **zero-order mode**, is the propagating mode of the light that travels precisely along the **central axis** of the optical fiber.
- The **highest-order mode** is the propagating mode of the **light that travels at critical angle**, φc, of incidence.
- In an optical fiber cable, the light rays can be propagated using the **law of total internal reflection**. In reality, an optical fiber can be considered as a waveguide. Therefore, the light can propagate in a **number of specific modes** only. For example,
- if the diameter of a fiber is **sufficiently narrow**, then it may support only **one mode of propagation** of light;
  - o if the diameter of a fiber is **relatively large**, light entering at different angles will excite **different modes** of propagation of light.
- Fiber-optic technology supports mainly **two types of propagation modes** of light along the optical fiber cable, namely,
  - o single mode and
  - o multimode.
- In multimode type of light propagation through the optical fiber can be supported in **two different categories** of optical fibers (depending on nature of index profiles of fiber core):
  - o step-index optical fiber, and
  - o graded-index optical fiber.
- Various types of modes are shown in Fig. 1.31.1.

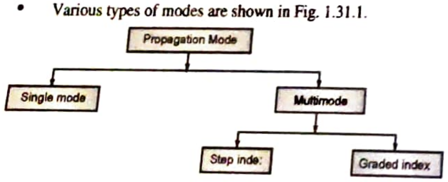


Fig. 1.31.1 : Modes in Fiber Optics

1.31.1 Single Mode Propagation

❑ **Definition:** It is defined as if there is only one possible path for light rays to travel through an optical fiber cable, it is called single mode propagation.

- Fig. 1.31.2 shows single mode propagation of light rays through an optical fiber.

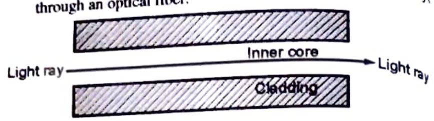


Fig. 1.31.2 : Single mode propagation

- Single-mode propagation of light, there is **one and only one path** for light rays to travel, which is directly along the axis of the fiber cable. Single-mode propagation uses **step-index configuration** of optical fiber cable.
- A highly focused optical source that emits light beam with a **very narrow beam width** is required.
- The single- mode optical fiber cable itself is manufactured with **lower refractive index** and much **smaller diameter** as compared to that of multimode optical fiber cable.
- The lower refractive index results in a **critical angle of incidence that is approximately equal to 90°**, due to which the propagation of light rays almost horizontal to the central axis of the fiber core. Hence different light rays propagate through the optical fiber with negligible propagation delays.
- **Core and cladding diameter** are the key parameters on which the maximum allowable diameter for a single mode fiber depends. Obviously, it varies directly with the wavelength of the propagating light and inversely with the numerical aperture of the given optical fiber cable. The relationship among these parameters is given as

$$D_{max} = \frac{0.766\,\lambda}{NA}$$

where, d_{max} = the maximum diameter of the core

λ = wavelength

NA = numerical aperture

Note that d_{max} and λ should have same units.

1.32 MULTI MODE PROPAGATION

❑ **Definition:** If there is more than one path for light rays to travel through an optical fiber cable, it is called multimode propagation.

- The term '**multimode**' refers to '**multiple light rays**' from an optical source that propagate through the fiber core following different paths.
- The movement of light rays within the optical fiber cable depends on the core structure. The light rays, following several paths, propagate within the optical fiber cable in a zigzag manner. Fig. 1.32.1 shows multimode propagation of light rays through an optical fiber.

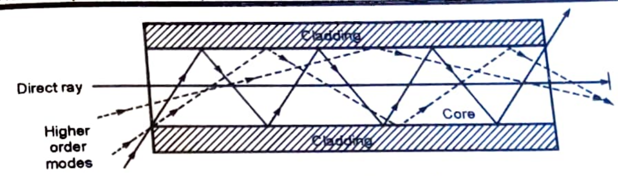


Fig. 1.32.1 : Multimode Propagation

- In terms of propagation of light through fiber, modes can be categorized in the following three types :
  1. **Guided mode :** which experiences total internal reflection.
  2. **Radiation mode :** which experiences total refraction in the cladding and propagate outside the fiber core.
  3. **Leaky mode :** in which some light rays are partially reflected within the fiber core and some are partially refracted toward the cladding.

1.32.1 Multimode Step-index Fiber

- Multimode step-index fiber has a larger core diameter (typically of the order of 50 µm or more) than that of single-mode step-index fiber.
- It allows the propagation of several modes (different possible paths) of light rays within the fiber core.
- Fig. 1.32.2 shows the core index profile of a multimode step index fiber.

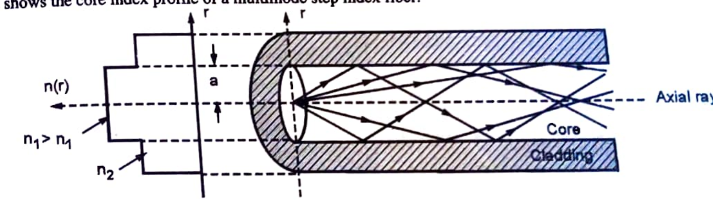


Fig. 1.32.2 : Core profile of Multimode Step Index Fiber

- In multimode step-index fiber source-to-fiber aperture is greater, due to which more external light is allowed to be coupled with the fiber cable. This is shown in Fig. 1.32.3.

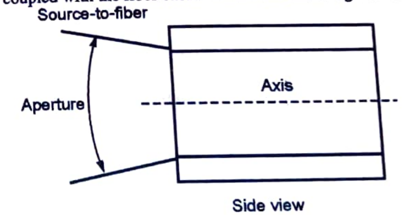


Fig. 1.32.3 : Multimode Step index Fiber

- The light rays that enter the intersection of the core and cladding at an angle more than the specified critical angle of incidence are propagated down the fiber core in a random manner, continuously getting reflected from the core-cladding interface boundary.
- The light rays that strike the intersection of the fiber core and cladding at an angle less than the specified critical angle of incidence will not experience total internal reflection.
- Instead, they will be refracted in the cladding and are likely to be lost. Fig. 1.32.4 shows the phenomena of total internal reflection happening in a typical multimode step-index type of optical fiber.

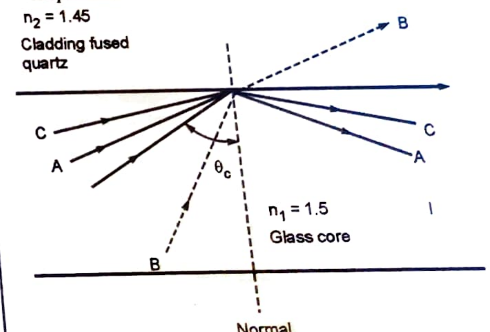


Fig. 1.32.4 : Total Internal Reflection in Multimode Step Index Fiber

- From Fig. 1.32.4. it is clear that there are several propagation paths followed by a light ray as it propagates down the multimode step-index fiber.
- It States that all light rays may not follow identical paths—some paths may be shorter and some may be longer.
- Hence, different light rays may take different amount of time to travel the given length of the optical fiber cable.

1.33 RELATIONSHIP BETWEEN NUMBER OF MODES AND 'V' NUMBER

GQ. Derive relation between number of modes and 'V' number.

The number of modes is denoted by M. In case of multimode fibers the value of M is large.

Now the numerical aperture is given as,

$$NA = \sqrt{n_1^2 - n_2^2} \quad ...(1.33.1)$$

But, $NA = \sin\theta_a$;

Here θ_a = Angle of acceptance ...(1.33.2)

$$\therefore \sin\theta_a = \sqrt{n_1^2 - n_2^2} \quad ...(1.33.3)$$

But generally θ_a is small

$$\sin\theta_a \approx \theta_a \quad ...(1.33.4)$$

- Now the solid acceptance angle of an optical fiber is denoted by Ω. It is given as,

$$\Omega = \pi\theta_a^2 \quad ...(1.33.5)$$

But we have, $\theta_a = \sqrt{n_1^2 - n_2^2}$

Thus Equation (1.33.5) becomes,

$$\Omega = \pi\left(n_1^2 - n_2^2\right) \quad ...(1.33.6)$$

- Let A be the area of mode. That means it is the cross sectional area of core. Thus

$$A = \pi a^2 \quad ...(1.33.7)$$

Here, a = Radius of core layer

- The plane waves are having two polarized conditions. The number of modes (M) per unit solid angle is given by $2A/\lambda^2$.

$$\therefore M = \frac{2A}{\lambda^2} \cdot \Omega \quad ...(1.33.8)$$

Here, λ = Wavelength of light coming from source

A = Area of mode

Ω = Solid acceptance angle.

- Putting value of Ω from Equation (1.33.6) in Equation (1.33.8) we get,

$$M = \frac{2A}{\lambda^2} \cdot \pi \cdot \left(n_1^2 - n_2^2\right) \quad ...(1.33.9)$$

But $A = \pi a^2$

$$\therefore M = \frac{2\pi^2 a^2}{\lambda^2}\left(n_1^2 - n_2^2\right) \quad ...(1.33.10)$$

Now $n_1^2 - n_2^2 = (NA)^2$

$$M = \frac{2\pi^2 a^2}{\lambda^2} \cdot (NA)^2 \quad ...(1.33.11)$$

The equation of V is,

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

$$\therefore M = \frac{V^2}{2} \quad ...(1.33.12)$$

This is the relationship between the number of modes and V number in case of multimode step index fiber.

1.34 PROPAGATING MODES IN MULTIMODE GRADED INDEX FIBER

GQ. Derive an expression for Propagating Modes in Multimode Graded Index Fiber.

- We have, the equation of 'V' number

$$V = \frac{2\pi}{\lambda} \cdot a \cdot n_1 \cdot \sqrt{2\Delta} \quad ...(1.34.1)$$

- The total number of guided modes in multimode graded index fiber is given by,

$$M_g = \left(\frac{\alpha}{\alpha+2}\right)(n_1 K \cdot a)^2 \Delta \quad ...(1.34.2)$$

But $K = \frac{2\pi}{\lambda}$

$$\therefore M_g = \left(\frac{\alpha}{\alpha+2}\right)\left(n_1 \frac{2\pi}{\lambda} \cdot a\right)^2 \cdot \Delta \quad ...(1.34.3)$$

Putting Equation (1.34.1) in Equation (1.34.3) we get,

$$\therefore M_g = \left(\frac{\alpha}{\alpha+2}\right)\left(\frac{V^2}{2}\right) \quad ...(1.34.4)$$

- For a parabolic refractive index profile, $\alpha = 2$

$$\therefore M_g = \left(\frac{2}{2+2}\right) \cdot \frac{V^2}{2}$$

$$\therefore M_g = \frac{V^2}{4} \quad ...(1.34.5)$$

- This is the equation of number of modes in terms of 'V' number for multimode step index fiber.

1.35 NUMBER OF MODES

- The modal volume, or simply the number of modes, guided by a multi-mode fiber, depends on the following parameters:
  1. the radius of the fiber core
  2. the operating wavelength of the light rays

  3. the index of refraction of the fiber core and the cladding
  4. the optical characteristic of the fiber cable
  5. the geometrical characteristic of the fiber cable

- The number of modes, or the modal volume designated by M_s for a step-index fiber can be expressed as

$$M_s = \frac{1}{2}\left[\frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}\right]^2 \quad ...(1.35.1)$$

But we know that $v = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$

$$M_s = \frac{V^2}{2} \quad ...(1.35.2)$$

The number of modes, or the modal volume designated by M_g for a graded-index fiber can be expressed as

$$M_g = \frac{1}{2}\left(\frac{\alpha}{\alpha+2}\right)\left[\frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}\right]^2 \quad ...(1.35.3)$$

where, α is the profile parameter of the graded-index fiber. It may be noted here that n_1 represents the index of refraction of the fiber core at its axis (which decreases gradually towards the intersection of the fiber core and the cladding, as defined by the profile parameter).

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

We have

$$M_g = \frac{1}{2}\left(\frac{\alpha}{\alpha+2}\right)\frac{V^2}{2} \quad ...(1.35.4)$$

For a parabolic profile, a = 2. Therefore

$$M_g = \frac{V^2}{4} \quad ...(1.35.5)$$

In order to support a single mode in a graded-index fiber, the cut-off value of the normalized frequency parameter, designated by V_c, is given by the expression

$$V_c = 2.405\sqrt{\left(1 + \frac{2}{\alpha}\right)} \quad ...(1.35.6)$$

Note : In practical optical fibers, $(n_1 - n_2) << 1$. Natural modes will combine (degenerate) into linear–polarized (LP) modes.

Ex. 1.35.1 : Number of Propagating Modes

A multimode step-index fiber cable has the following specifications :

- the fiber core diameter = 50 μm
- the index of refraction of a fiber core = 1.6
- the index of refraction of cladding = 1.584.

If the wavelength of light propagating through it is 1300 nm, determine the approximately number of propagating modes.

☑ Soln. :

We know that the number of propagating modes is given as

$M_s \approx \frac{V^2}{2}$ in a multimode step-index fiber.

Where $V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$ also d = 2a

For the given d = 50 μm, l = 1300 nm, n_1 = 1.6, and n_2 = 1.584, we have

$$V = \frac{\pi \times 50 \times 10^{-6}}{1300 \times 10^{-9}}\sqrt{1.6^2 - 1.584^2} = 27.27$$

Therefore $M_s = \frac{27.27^2}{2} = 372$

1.36 MODE FIELD DIAMETER

- A single-mode optical fiber cable is designed in such a way that it supports only the fundamental mode of propagation of light rays, and all higher-order propagation modes are cut-off at the specified wavelength of operation.
- In a step-index fiber the single mode operation is possible over a normalized frequency parameter range specified as $0 < V < 2.405$. However, for a particular value of λ, the V-parameter can be made lower than its cut-off value of $V_c = 2.405$, by reducing either the core diameter (2a), or the relative refractive index difference (Δ).
- Practically it is not recommended because of the following reasons :
  - With small core diameter, it becomes difficult not only to launch the light into the optical fiber but also to join two pieces of fibers in the field (splicing).
  - It is extremely difficult to manufacture fibers with very low values of Δ.
  - A higher value of V_c (and hence larger core diameter) is possible with graded-index fiber in which,

$$V_c = 2.405\left(\sqrt{1 + \frac{2}{\alpha}}\right);$$

where, α is its profile parameter

  - For a triangular index profile ($\alpha = 1$), V_c increases by a factor of √3
  - For a parabolic index profile ($\alpha = 2$), V_c increases by a factor of √2
- It is observed that with low values of V-parameter and Δ for the single-mode operation, the modal field distribution of the fundamental mode of propagation (due to the radial distribution of the optical power) is approximately Gaussian for step-index optical fibers as well as for parabolic profile graded-index optical fibers that operate near the specified cut-off wavelength, λ_c.
- Therefore, the mode field diameter (MFD), or the mode spot size, of the propagating mode constitutes a key parameter characteristic of a single-mode fiber. It may be noted here that the mode field diameter for single-mode fibers is analogous to the fiber core diameter in multimode fibers, except that all the light propagated through the fiber is not carried within the fiber core in single-mode fibers.

- For a step-index fiber, the mode field diameter (MFD), designated by 2w, is given by

$$MFD = 2w = 2a\left(0.65 + \frac{1.619}{\sqrt{V^3}} + \frac{2.879}{V^6}\right)$$

where, w represents the mode field radius, and a represents the fiber core radius.

- This expression gives the value of MFD to within about 1% of accurate value for V-parameter in the range of 0.8–2.5. It is obvious that for a fiber of given diameter, the normalized mode spot size increases as V becomes smaller (or as λ becomes longer).

Note : At longer operating wavelength, the modal field is less confined within the fiber core. Therefore, the design of a single-mode fiber should be such that the cut-off wavelength is not too far away from the operating wavelength.

Ex. 1.36.1 : Mode Field Diameter

The core diameter of a typical step-index fiber is specified as 8 μm. The values of core refractive index and relative refractive index difference are specified as 1.46 and 0.3%, respectively. Calculate : the mode field diameter (MFD) at operating wavelength of 1550 nm.

☑ **Soln. :** We know that

$$MFD = 2a\left(0.65 + \frac{1.619}{\sqrt{V^3}} + \frac{2.879}{V^6}\right)$$

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

For the given $2a = 8$ μm, $\lambda = 1550$ nm, $n_1 = 1.46$, and $\Delta = 0.3\%$, or 0.003, we have

Therefore,

$$V = \frac{\pi \times 8 \times 10^{-6}}{1550 \times 10^{-9}} \times 1.46\sqrt{2 \times 0.003} = 1.834$$

1.37 COMPARISON BETWEEN MULTIMODE STEP INDEX AND MULTIMODE GRADED INDEX

GQ. Compare between multimode step index and multimode graded index fibers.

Sr. No.	Parameter	Multimode step index fiber	Multimode graded index fiber
1.	Refractive Index	There is a step change in the refractive index at the core cladding interface.	There is continuous change in refractive index.
2.	Dispersion	More modal dispersion.	Less modal dispersion.
3.	Bandwidth	Less bandwidth capabilities.	More bandwidth capabilities.
4.	Bit Rate	Transmission bit rate is low.	Transmission bit rate is high.
5.	Propagation	The propagation of light rays is in zigzag manner.	The propagation paths are predicable and orderly.
6.	Coupling	Coupling of light rays is simple.	Coupling of light rays is difficult.
7.	Core Diameter	Typical core diameter is 125 to 400 μm.	Typical core diameter is 50 to 100 μm.
8.	Manufacturing	Easy to manufacture.	Due to continuously changing refractive index; manufacturing is difficult.

1.38 LINEARLY POLARIZED (LP) MODES

- Basically optical fiber cable acts as cylindrical waveguide. In case of other waveguide structures, like metallic waveguides; the tangential components of electric and magnetic fields are separate.
- But in optical cables; the tangential components of electric and magnetic fields are coupled. That means, in optical cable, we cannot separate out the modes as Transverse Electric (TE) or Transverse Magnetic (TM) modes.

GQ. Define and explain Linearly Polarized (LP) Modes.

❒ **Definition**

If the value of relative refractive index difference (Δ) is small that means $\Delta << 1$ the modes propagating in fiber optic cable are called as; Linearly Polarized (LP) modes.

Explanation

- LP modes are basically combination of magnetic (H) and electric (E) modes.
- LP modes are denoted by LP_{mn} modes. Here 'm' represents the number of angular nodes in the electric field distribution and 'n' represents the number of radial nodes. As an approximation the mode HE_{11} from the wave theory becomes the mode LP_{01} in optical cable.
- If the 'V' number is less than 1.1505 then only LP_{01} made propagates. If 'V' is greater than 1.1505 then next higher mode can also propagate. So, in this case, both LP_{01} and LP_{11} modes propagate through the fiber.

- LP modes are also called as degenerate modes and these modes are useful in analysing the transmission characteristics of optical cable.
- The classification of LP modes is dependent on light intensity distribution in optical cable. The concept of LP modes is applicable only for weakly guided optical cables ($n_1 - n_2 << 1$).

1.39 SOLVED PROBLEMS ON MODE THEORY

Ex. 1.39.1 : 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.

☑ **Soln. :**

Given, core diameter = 50 μm, thus core radius = 25 μm

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 for parabolic profile is

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

Fiber has 247 guided modes.

Ex. 1.39.2 : Design a single mode fiber with V = 2.3 for operation at 1.55 micron with a fused silica core ($n_1 = 1.458$) and a numerical aperture of 0.1.

(a) Find the cladding index n_2 and radius of the fiber.

(b) Calculate the approximate number of modes for operation at 1200 nm.

☑ **Soln. :**

(a) (i)

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

$$0.1 = [(1.458)^2 - (n_2)^2]^{1/2}$$

Taking square of both sides,

$$\therefore 0.01 = (1.458)^2 - (n_2)^2$$

$$\therefore (n_2)^2 = (1.458)^2 - 0.01$$

$$= 2.125 - 0.01 = 2.1157$$

$$\therefore n_2 = \mathbf{1.454}, \text{ cladding index}$$

(ii) Now

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

$$2.3 = \frac{2 \times 3.14 \times a \times 0.1}{1.55 \times 10^{-6}}$$

$$\therefore a = \frac{2.3 \times 1.55 \times 10^{-6}}{2 \times 3.14 \times 0.1}$$

$$= \frac{3.565 \times 10^{-6}}{0.628} = 5.676 \times 10^{-6}$$

$$= \mathbf{5.676\ \mu m}$$

(b) For 1200 nm wavelength, 'V' number is

$$V = \frac{2\pi a}{\lambda}(NA) = \frac{2 \times \pi \times 5.676 \times 10^{-6}}{1200 \times 10^{-9}} \times 0.1$$

$$= \frac{2 \times 3.14 \times 5.676 \times 10^{-6}}{1.2 \times 10^{-6}} \times 0.1 = 2.97 \simeq 3$$

$$\therefore M = \frac{V^2}{2} = \frac{9}{2} = \mathbf{4.5} \text{ guided modes.}$$

Ex. 1.39.3 : A graded index fiber has a core diameter of 45 μm. Core has parabolic refractive index profile. The fiber has NA of 0.22 and operating at wavelength of 1.2 μm. Estimate total number of guided mode propagating in the fiber.

☑ **Soln. :**

$$V = \frac{2\pi}{\lambda} a\,(NA) = \frac{2\pi \times 45 \times 10^{-6}}{1.2 \times 10^{-6} \times 2} \times 0.22$$

$$\therefore V = 25.91$$

where core diameter = 45 μm

$$\therefore \text{radius} = a = \frac{45}{2} = 22.5\ \mu m$$

The mode volume for parabolic profile is

$$M_g = \frac{V^2}{4} = \frac{(25.91)^2}{4}$$

$$= 167.93 \simeq \mathbf{168 \text{ modes}}$$

UEx. 1.39.4 : MU - May 2013, 10 Marks

Find the core radius necessary for single mode operation at 820 nm of step index fiber with $n_1 = 1.482$ and $n_2 = 1.474$. What is the numerical aperture and maximum acceptance angle of this fiber ? Also calculate the corresponding solid angle.

☑ **Soln. :**

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

$$= (1.482^2 - 1.474^2)^{1/2}$$

$$NA = \mathbf{0.1537} \qquad ...(1)$$

Acceptance angle $\theta_a = \sin^{-1} NA$

$$= \sin^{-1} 0.1537$$

$$\theta_a = \mathbf{8.84°} \qquad ...(2)$$

Solid angle

$$\zeta = \pi (NA)^2$$

$$\zeta = \mathbf{0.075 \text{ radians}} \qquad ...(3)$$

Assuming,

$$V = 2.405$$

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

Here 'a' is core radius

$$2.405 = \frac{2\times\pi\times a}{820\times 10^{-9}}\times 0.1537$$

$$\therefore a = \frac{2.405\times 820\times 10^{-9}}{2\times\pi\times 0.1537}$$

$$\therefore \mathbf{a = 2.04\ \mu m}$$

Ex. 1.39.5 : Compute the cut-off parameter and the number of modes supported by a GIF $n_1 = 1.54$ and $n_2 = 1.5$. Core radius is 25 μm and operating wavelength is 1300 nm.

☑ **Soln. :**

Given : $n_1 = 1.54$, $n_2 = 1.5$, $a = 25\ \mu m$ and $\lambda = 1300$ nm

$$\therefore NA = \left(n_1^2 - n_2^2\right)^{1/2} = \left(1.54^2 - 1.5^2\right)^{1/2}$$

$$= 0.3487$$

Now, $V = \frac{2\pi}{\lambda}a\,(NA)$, where a = radius = 25 μm

$$= \frac{2\pi\times 25\times 10^{-6}\times 0.3487}{1300\times 10^{-9}}$$

$$= 42.13 \simeq 43$$

The total number of guided modes

$$M_g = \frac{V^2}{4} = \frac{(42.13)^2}{4} = 443.73 \simeq \mathbf{444}$$

Ex. 1.39.6 : A step index fiber in air has a numerical aperture of 0.16, a core refractive index of 1.45 and a core diameter of 60 μm. Determine the normalized frequency for the fiber when light at a wavelength of 0.82 μm. is transmitted. Estimate the number of guided modes propagating in the fiber.

☑ **Soln. :**

Given, core diameter = 60 μm ∴ core radius = a = 30 μm

The normalized frequency,

$$V \approx \frac{2\pi}{\lambda}a\,n_1\,(2\Delta)^{1/2}$$

$$= \frac{2\times\pi\times 30\times 10^{-6}}{0.82\times 10^{-6}}\times 1.45\times(2\times\Delta)^{1/2} \quad ...(1)$$

Now, $NA = n_1\,(2\Delta)^{1/2}$

$$\therefore \frac{0.16}{n_1} = (2\Delta)^{1/2}$$

$$\therefore \frac{0.16}{1.45} = 0.11 = (2\Delta)^{1/2}$$

Putting this value in Equation (1)

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

$$= 36.76 \simeq 37$$

The total number of guided modes in $\frac{V^2}{2}$.

$$\therefore M_g = \frac{36.76^2}{2} = 675.64 \simeq \mathbf{676}$$

Ex. 1.39.7 : A multimode step index fiber has a relative refractive index difference of 1% and a core-refractive index of 1.5. The number of modes propagating at a wavelength of 1.3 μm is 1100. Estimate the diameter of the fiber core.

☑ **Soln. :**

Given : Relative refractive index = 1% = 0.01, $n_1 = 1.5$

Number of modes = 1100, λ = 1.3 μm

$$M_g = \frac{V^2}{2} = 1100$$

$$\therefore V = 46.9$$

Now $V = \frac{2\pi}{\lambda}a\,n_1\,(2\Delta)^{1/2}$

$$46.9 = \frac{2\pi\times a\times 1.5\times(0.02)^{1/2}}{1.3\times 10^{-6}}$$

$$\therefore a = \frac{46.9\times 1.3\times 10^{-6}}{2\pi\times 1.5\times(0.02)^{\frac{1}{2}}}$$

$$\therefore a = 45.74\ \mu m$$

$$\therefore \text{Diameter} = 45.74\times 2 = \mathbf{91.48\ \mu m}$$

Ex. 1.39.8 : Determine the normalized frequency at 850 nm for a step index fiber has a core radius of 25 μm, core refractive index of 1.48 and cladding refractive index of 1.46. How modes propagate in this fiber at 1320 nm and 1550 nm ?

☑ **Soln. :**

Given, Step index fiber : core radius = 25 μm

$n_1 = 1.48$, $n_2 = 1.46$, $\lambda_1 = 1320$ nm, $\lambda_2 = 1550$ nm

$$NA = \sqrt{n_1^2 - n_2^2}$$

$$\therefore NA = \sqrt{1.48^2 - 1.46^2}$$

$$\therefore NA = 0.2424$$

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

$$= \frac{2\times\pi}{850\times 10^{-9}}\times 25\times 10^{-6}\times 0.2424$$

$$= 44.81$$

$$M_g = \frac{V^2}{2} = 1004 \text{ modes at 850 nm}$$

For $\lambda_1 = 1320$ nm, $V = 28.84$, ∴ $M_g = \mathbf{416\ modes}$

For $\lambda_2 = 1550$ nm, $V = 24.56$,

∴ $M_g = 301.72 \approx \mathbf{302\ modes}$

Ex. 1.39.9 : If a multimode step index fiber having the core refractive index of 1.5, cladding refractive index of 1.38, core radius of 25 μm operates at a wavelength of 1300 nm. Calculate :

(i) Numerical aperture.

(ii) Normalized frequency.

(iii) Solid acceptance angle.

(iv) Total no. of modes entering the fiber.

☑ **Soln. :**

Given : multimode SIF

$n_1 = 1.5$, $n_2 = 1.38$, $a = 25\ \mu m$, $\lambda = 1300$ nm

(i) NA = numerical aperture

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

$$= [(1.5)^2 - (1.38)^2]^{1/2}$$

$$\therefore NA = 0.5878$$

(ii) Normalized frequency $V = \frac{2\pi}{\lambda}a\,(NA)$

$$= \frac{2\pi\times 25\times 10^{-6}\times 0.5878}{1300\times 10^{-9}}$$

$$\therefore V = \mathbf{71.024}$$

(iii) Acceptance angle

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.5878$$

$$\theta_a = \mathbf{36°}$$

(iv) Solid acceptance angle $= \xi = \pi\sin^2\theta_a$

$$\therefore \xi = \pi\sin^2(36°)$$

$$\xi = \mathbf{1.0854\ rad}$$

(v) Total number of modes $= \frac{V^2}{2} = \frac{(71.024)^2}{2}$

$$= 2522.2 \simeq \mathbf{2523\ modes}$$

UEx. 1.39.10 MU - May 18, Q. 2(c), May 17, 5 Marks

Calculate the number of modes at 1.3 μm wavelength in GIF having index profile α = 2, core radius 25 μm, core refractive index 1.48 and cladding refractive index 1.46.

☑ **Soln. :**

Given, $\lambda = 1.3\ \mu m$, $\alpha = 2$, $a = 25\ \mu m$, $n_1 = 1.48$, $n_2 = 1.46$

Total modes in GIF,

$$M_g = \frac{\alpha}{\alpha+2} = \frac{V^2}{2}$$

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

and $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} = \frac{(1.48)^2 - (1.46)^2}{2\,(1.48)^2}$

$$= 0.0134$$

$$\therefore V = \frac{2\pi}{1.3\times 10^{-6}}\times 25\times 10^{-6}\times 1.48\sqrt{2\times 0.0134}$$

$$\therefore V = 29.2756$$

∴ Total modes,

$$M_g = \frac{2}{2+2} = \frac{(29.2756)^2}{2}$$

$$= 214.26 \simeq \mathbf{215}$$

Ex. 1.39.11 : A single mode step index fiber which is designed for operation at a wavelength of 1.3 μm has core and cladding refractive indices of 1.447 and 1.442 respectively. When the core diameter is 5.2 μm, confirm that the fiber will permit single mode transmission and estimate the range of wavelengths over which this will occur.

☑ **Soln. :**

Given : $\lambda = 1.3\ \mu m$, $n_1 = 1.447$, $n_2 = 1.442$, $a = 2.6\ \mu m$

(i) $NA = \left[\left(n_1^2 - n_2^2\right)\right]^{1/2}$

$$= \left[(1.447)^2 - (1.442)^2\right]^{1/2} = 0.120$$

Now, $V = \frac{2\pi}{\lambda}a\;n_1\,(2\Delta)^{1/2} = \frac{2\pi}{\lambda}a\,(NA)$

$$= \frac{2\pi\times 2.6\times 10^{-6}\times 0.120}{1.3\times 10^{-6}}$$

$$= \mathbf{1.5079}$$

This is less than 2.405 the fiber will permit single mode transmission.

(ii) The single mode operation only occurs above a theatrical cut off wave length λ_C

$$\therefore \frac{\lambda_C}{\lambda} = \frac{V}{V_C} \text{ for step index fiber } V_C$$

$$= 2.405$$

$$\therefore \lambda_C = \frac{V\lambda}{2.405}$$

$$= \frac{1.5079\times 1.3\times 10^{-6}}{2.405}$$

$$= 0.956\times 10^{-6}$$

$$= \mathbf{815.11\ nm}$$

Ex. 1.39.12 : An installed fiber has following specifications : Core diameter = 62.5 μm; NA = 0.275 and its operating wavelength is 1310 nm. Calculate, the V number, the number of modes if the fiber is graded index and has a parabolic refractive index profile. What number of modes would be supported if instead, the fiber is of step index type ?

☑ **Soln. :**

Core diameter = 62.5 μm, ∴ Core radius = 31.25 μm

NA = 0.275 ; λ = 1310 nm

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

$$= \frac{2\times\pi\times 31.25\times 10^{-6}\times 0.275}{1310\times 10^{-9}} = 41.21 \simeq 42$$

For step index type,

$$M_g = \frac{V^2}{2} = \frac{(41.21)^2}{2}$$

$$= 849.47 \approx \mathbf{850\ modes}$$

For parabolic graded index fiber

$$M_g = \frac{V^2}{4} = \frac{(41.21)^2}{4}$$

$$= \mathbf{424.73 \approx 425\ modes}$$

Ex. 1.39.13 : A graded index fiber with a parabolic index profile supports the propagation of 742 guided modes. The fiber has a numerical aperture in air of 0.3 and a core diameter of 70 μm. Determine the wavelength of the light propagating in the fiber. Further, estimate the new maximum core diameter for single mode operation at the same wavelength.

☑ **Soln. :**

A graded index fiber with parabolic index profile has

$$M_g = \frac{V^2}{4}$$

$$\therefore 742 = \frac{V^2}{4}$$

$$\therefore V = 54.47 \approx 55$$

Given → $n_2 = 1$; NA = 0.3

Core diameter = 70 μm

∴ Core radius = 35 μm

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

$$0.3 = \left[n_1^2 - 1\right]^{1/2}$$

$$\therefore 0.09 = n_1^2 - 1$$

$$\therefore n_1 = 1.04$$

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

For GIF, $55 = \frac{2\pi}{\lambda} \times 35 \times 10^{-6} \times 0.3$

$$\therefore \lambda = \frac{2\pi \times 35 \times 3 \times 10^{-7}}{55} = \frac{659.4}{55} \times 10^{-7}$$

$$= 1.1995\ \mu m$$

It must be noted that single mode operation in SI fiber $\mathbf{0 \le V \le 2.405}$ for step index or the cutoff wavelength is

$$\lambda_C = \frac{V\lambda}{2.405}$$

Where as in GIF, the cutoff value of normalized frequency V_C to support a single mode is,

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

For parabolic profile $\alpha = 2$

$$\therefore V_C = 2.405\,(1 + 1)^{1/2}$$

$$\mathbf{V_C = 2.405\sqrt{2}} \quad \textbf{graded index}$$

The maximum core radius for SM operation

$$a = \frac{V\lambda}{2\pi n_1 (2\Delta)^{1/2}} = \frac{2.405\sqrt{2} \times 1198}{2\pi \times 1.04\,(2\Delta)^{1/2}}$$

Where $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} = \frac{1.08 - 1}{2 \times 1.08} = \frac{0.08}{2.16}$

$$\Delta = 0.037$$

$$\therefore 2\Delta = 0.074$$

$$\therefore a = \frac{2.405 \times 1.41 \times 1198 \times 10^{-9}}{2\pi \times 1.04 \times 0.27}$$

$$= 2.28\ \mu m$$

Thus the normalized frequency of the fiber can be adjusted for single mode operation by reducing the core diameter.

Core radius = 2.28 μm

∴ Core diameter = 4.567 μm

Ex. 1.39.14 : A graded index fiber with a core axis refractive index of 1.5 has a refractive index profile 1.90, a relative refractive index difference of 1.3% and a core diameter of 40 μm. Estimate the number of guided modes propagating in the fiber when the transmitted light has a wavelength of 1.55 μm.

☑ **Soln. :** Normalized frequency

$$V \simeq \frac{2\pi}{\lambda} a \cdot n_1 \cdot (2\Delta)^{1/2}$$

$$= \frac{2\pi \times 40 \times 10^{-6} \times 1.5 \times (2 \times 0.013)^{1/2}}{1.55 \times 10^{-6}}$$

$$V = 39.21 \approx 40$$

$$M_s = \frac{V^2}{2} = \frac{(40)^2}{2} = 800$$

Hence there are about 800 guided modes (approximated).

Ex. 1.39.15 : A step index fiber in air has a numerical aperture of 0.16, a core refractive index of 1.45 and a core diameter of 60 μm. Determine normalized frequency for the fiber when light at a wavelength of 0.9 μm is transmitted. further estimate the number of guided modes propagating in the fiber.

☑ **Soln. :**

Given, Core diameter = 60 μm, ∴ Core radius = a = 30 μm

The normalized frequency is,

$$V = \frac{2\pi}{\lambda} a\,NA = \frac{2\pi}{0.9 \times 10^{-6}} \times 30 \times 10^{-6} \times 0.16$$

$$\therefore \mathbf{V = 33.51 \approx 34}$$

The number of guided modes,

$$M_g = \frac{V^2}{2} = \frac{(33.51)^2}{2} = 561.46 \approx \mathbf{562}$$

Ex. 1.39.16 : Determine the cut-off wavelength for a step index fiber to exhibit single mode operation when the core index and radius are 1.46 and 4.5 μm respectively, with the relative index difference being 0.25 %.

☑ **Soln. :** **Given,** $n_1 = 1.46$, a = 4.5 μm, Δ = 0.25 % = 0.0025

We have, $V = \frac{2\pi}{\lambda} a\, n_1 (2\Delta)^{\frac{1}{2}}$ ...(1)

But for step index fiber, V = 2.405

Thus from Equation (1), cut-off wavelength can be written as,

$$\lambda_C = \frac{2\pi}{V} a\, n_1 (2\Delta)^{\frac{1}{2}}$$

$$\lambda_C = \frac{2\pi}{2.405} \times 4.5 \times 10^{-6} \times 1.46 \times (2 \times 0.0025)^{\frac{1}{2}}$$

$$\therefore \lambda_C = \mathbf{1.2137\ \mu m}$$

Ex. 1.39.17 : An engineer selects a fiber with a 25 μm core radius, a core index $n_1 = 1.48$ and Δ = 0.01.

(i) If λ = 1310 nm, what is the value of normalized frequency V and how many modes propagate in the fiber ?

(ii) What percent of optical power flows in the cladding ?

(iii) If the core - cladding difference is reduced to Δ = 0.003, how many modes does the fiber support and what fraction of the optical power flows in the cladding ?

☑ **Soln. :**

(i) **Given :** a = 25 μm, $n_1 = 1.48$, Δ = 0.01

$$V = \frac{2\pi a n_1 (2\Delta)^{1/2}}{\lambda}$$

$$= \frac{2 \times \pi \times 25 \times 10^{-6} \times 1.48 \times (2 \times 0.01)^{1/2}}{1310 \times 10^{-9}}$$

$$\therefore \mathbf{V = 25.09 \approx 25}$$

Total number of guided modes is given by,

$$M_S = \frac{V^2}{2} = \frac{25 \times 25}{2} = \frac{625}{2} = 312.5$$

∴ **Number of modes = 312**

(ii) The total average cladding power is approximated given by,

$$\left(\frac{P_{Clad}}{P}\right)_{Total} = \frac{4}{3} \times M_S^{-1/2} = \frac{4}{3} \times (312)^{-1/2}$$

$$= \frac{4}{3} \times 0.0566 = 0.075$$

Where, M_S = Total number of modes

Thus **7.5** percent of the power propagates in the cladding.

(iii) $V = \frac{2\pi a\, n_1 (2\Delta)^{1/2}}{\lambda}$

$$= \frac{2 \times \pi \times 25 \times 10{-}6 \times 1.48 \times (0.003 \times 2)1/2}{1310 \times 10{-}9}$$

$$\therefore V = 13.74 \approx 14$$

$$\therefore \text{Modes} = \frac{V^2}{2} = \frac{14^2}{2} = \mathbf{98}$$

and $\left(\frac{P_{Clad}}{P}\right)_{Total} = \frac{4}{3} \times M^{-1/2} = \frac{4}{3} \times (98)^{-1/2} = \mathbf{0.13}$

13 percent optical power flows in the cladding.

Ex. 1.39.18 : A graded index fiber with a parabolic refractive index profile core has a refractive index at the core axis of 1.5 and refractive index difference of 1%. Estimate the maximum possible core diameter which allows single mode operation at wavelength of 1.55 μm.

☑ **Soln. :**

The maximum V value for a fiber which gives single mode operation is 2.4.

$$\therefore a = \frac{V\lambda}{2\pi n_1 (2\Delta)^{1/2}} = \frac{2.4 \times 1.55 \times 10^{-6}}{2\pi \times 1.5 \times (0.02)^{1/2}}$$

where λ = 1.55 μm Δ = 1%

n_1 = 1.5 ∴ 2Δ = 0.02

a = core radius = 2.8 μm

∴ **Core diameter = 5.6 μm**

Ex. 1.39.19 : A step index fiber has core refractive index 1.5 and Δ = 1.3% with core diameter of 100 μm. The operating wavelength is 850 nm. Calculate assuming that the fiber is kept in air, the :

(i) Numerical aperture of fiber and acceptance angle.

(ii) V parameter and number of modes

(iii) Does the number of modes in the fiber increase or decrease if

(A) n_1 increases and (B) if wave length increases.

☑ **Soln. :**

Given : n_1 = 1.5, Δ = 1.3%, a = 100 μm, λ = 850 nm

Since Δ = 1.3%

$$\therefore \Delta = 0.013 \qquad \therefore 0.013 = \frac{n_1 - n_2}{n_1}$$

$$0.013 \cdot n_1 = n_1 - n_2$$

$$n_2 = n_1 - (0.013 \cdot n_1) = 1.5 - (0.013 \times 1.5)$$

$$n_2 = 1.48$$

(i) N.A. $= \sqrt{n_1^2 - n_2^2} = \sqrt{(1.5)^2 - (1.48)^2}$

$$= \sqrt{2.25 - 2.19}$$

$$= 0.245$$

Acceptance angle,

$$\theta_a = \sin^{-1}\sqrt{n_1^2 - n_2^2} = \sin^{-1} NA$$

$$= \sin^{-1} 0.245 = 14.18^\circ$$

(ii) V parameter

$$V \simeq \frac{2\pi}{\lambda} \cdot a \cdot n_1 (2\Delta)^{1/2} \qquad ...(1)$$

$$= \frac{2 \times \pi \times 100 \times 10^{-6} \times 1.5 \times (2 \times 0.013)^{1/2}}{850 \times 10^{-9}}$$

$$\mathbf{V = 178.7}$$

Number of modes, $M_s = \frac{V^2}{2} = \frac{(178.7)^2}{2} = \mathbf{15966.8}$

Hence there are about 16000 guided modes (approximated).

(iii) (A) If n_1 increases the number of modes will also increase according to Equation (1)

(B) If wavelength increases the number of modes will decrease.

Ex. 1.39.20 : A single mode step index fiber has core and cladding refractive indices of 1.498 and 1.495 respectively. Determine the core diameter required for the fiber to permit its operation over the wavelength range 1.48 to 1.60 μm. Calculate the new fiber core diameter to enable single mode transmission at a wavelength of 1.30 μm.

☑ Soln. :

(i) We have, $V = \frac{2\pi}{\lambda} a\,NA$

$\therefore a = \frac{V\lambda}{2\pi \cdot NA}$ ...(1)

For step index fiber, V = 2.405

The step index operation starts at wavelength 1.48 μm.

$\therefore \lambda = 1.48\ \mu m$ and

$NA = \sqrt{n_1^2 - n_2^2}$

$\therefore NA = \sqrt{(1.498)^2 - (1.495)^2}$

$\therefore NA = 0.09476$

Putting these values in Equation (1) we get,

$a = \frac{2.405 \times 1.48 \times 10^{-6}}{2\pi \times 0.09476}$

$= 5.9782 \times 10^{-6}$

Thus core **diameter = 2a = 11.96 μm**

(ii) Given, λ = 1.30 μm. Thus from Equation (1),

$a = \frac{2.405 \times 1.30 \times 10^{-6}}{2\pi \times 0.09476} = 5.25\ \mu m$

Thus core diameter = 2a = **10.5 μm**

Ex. 1.39.21 : A multi mode step index fiber with core diameter of 80 μm and relative index difference of 1.5% is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48 estimate the normalized frequency for the fiber and the number of modes guided.

☑ Soln. :

Given, Core radius = 40 μm = 40×10^{-6} m

$\Delta = 1.5\,\% = 0.015$

$n_1 = 1.48$

$\lambda = 0.85\ \mu m = 0.85 \times 10^{-6}$ m

The normalized frequency is,

$V = \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}}$

$\therefore V = \frac{2\pi}{0.85 \times 10^{-6}} \times 40 \times 10^{-6} \times 1.48\,(2 \times 0.015)^{\frac{1}{2}}$

$\therefore V = 75.795$

Number of guided modes, $M_s = \frac{V^2}{2} = 2872.44 \approx$ **2873**

Ex. 1.39.22 : A graded index fiber has a core with a parabolic refractive index profile which has a diameter of 45 μm. The fiber has numerical aperture of 0.25. Estimate the total number of guided modes propagating in the fiber when it is operating at a wavelength of 1.5μm.

☑ Soln. :

Here, core radius (a) $= \frac{45}{2} = 22.5\ \mu m$.

NA = 0.25, λ = 1.5 μm.

The normalized frequency,

$V = \frac{2\pi}{\lambda} a\,(NA) = \frac{2\pi}{1.5 \times 10^{-6}} \times 22.5 \times 10^{-6} \times 0.25$

$\therefore V = 23.56 \approx 24$

Number of guided modes, $M_g = \frac{V^2}{4} =$ **144 modes.**

Ex. 1.39.23 : For a single mode fiber with core and cladding refractive indices 1.49 and 1.47 respectively, calculate

(i) Cut off wavelength if core radius is 2 μm.

(ii) Maximum core diameter for cut off wavelength of 1310 mm wavelength of 1310 mm

☑ Soln. :

Given, $n_1 = 1.49,\ n_2 = 1.47$

(i) Core radius, a = 2 μm

We have, $v = \frac{2\pi}{\lambda} a\,N\,A$

$\therefore \lambda = \frac{2\pi}{v} a\,N\,A$

For step index fiber, v = 2.405

Here $NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.49^2 - 1.47^2}$

$= 0.2433$

∴ Cut-off wavelength,

$\lambda_c = \frac{2\pi}{2.405} \times 2 \times 10^{-6} \times 0.2433$

$\therefore \lambda_c =$ **1.2712 μm**

We have, $V = \frac{2\pi}{\lambda} a\,N\,A$

$\therefore a = \frac{V\lambda}{2\,\pi\,nA}$

Given, λ = 1310 nm

$\therefore a = \frac{2.405 \times 1310 \times 10^{-9}}{2\pi \times 0.2433}$

$= 2.0609\ \mu m$

∴ Maximum core diameter

$= 2a = 4.1219\ \mu$

1.40 FIBER MATERIAL

UQ. Explain any one Fiber Fabrication Technique. **(MU – Q. 3(b), May 17, 5 Marks)**

UQ. Explain in brief any two Fiber Fabrication techniques. **(MU – Q. 3(a), Dec. 17, 10 Marks)**

UQ. Explain any one fiber fabrication process with neat diagram. Compare the different methods of fabrication. **(MU – Q. 3(b), May 18, 10 Marks)**

UQ. A typical relative refractive index difference for an optical fiber designed for long distance transmission is 1%. Estimate NA and solid acceptance angle in the air for the fiber when the core index is 1.46. Further calculate the critical angle at the core cladding interface within the fiber. It may be assumed that the concept of geometric optics hold for the fiber. **(MU – Q. 2(b), Dec. 18, 10 Marks)**

- The core part of the cable is made from glass or plastic optical fiber, while the cladding is usually made from fluoride-doped silica. Typically, the buffer is manufactured from a material called acrylate, which is a type of plastic.
- **Glass fiber optic cables** are made from a material called silica, which is very pure and has a very low index of refraction. This means it can carry data over longer distances with less signal loss. However, glass is more fragile than plastic and can be difficult to work with.
- Alternatively, **plastic fiber optic cables** are made from materials such as acrylate and polyimide. These plastics have a higher index of refraction than glass, meaning they're not suitable for long-distance data transmission. However, they are much more flexible than glass and easier to work with.
- The core is surrounded by a layer of cladding. The cladding surrounds and reflects light back into the core. Together, the core and cladding make up what is generally referred to as the fiber.

The material used for production of fiber optic cable should possess following properties :

1. Dielectric that is used in the cladding layer should have lower refractive index than that of core layer.
2. In the infrared region of electromagnetic spectrum, the dielectric material should have low loss. This loss should be less than 10 dB/km.
3. Material used should provide a high bandwidth.
4. The dielectric material used should be able to draw into the fibers.
5. The dielectric material should have good thermal and mechanical properties.

- Generally to fulfil the requirements, plastic or glass materials are used. But the hydrogen present in the plastic gives more losses. So the glass materials are preferred.
- ***Two types of glass materials are used.*** That are :
  (i) High silica glass-also called as high temperature glass.
  (ii) Compound silica glass-also called as low temperature glass.

1.40.1 Mechanical and Thermal Characteristics of glass

- The glass used for the production of fiber optic cable is as amorphous material. All the atoms in the glass are loosely bonded. There is no fixed melting point for a glass. And as the temperature provided to the glass goes on increasing; it's viscosity will also go on changing.
- The thermal expansion coefficients for both the core and cladding layers should be same. If there is a difference in thermal expansion coefficients; the thermal expansion stresses will be created. Usually silica consists of SiO_2 with other metal oxides, in order to obtain the required refractive index difference between core and cladding layers.
- To increase the refractive index of silica, TiO_2, Al_2O_3, GeO_2 and P_2O_5 are used as dopant material. The glass fibers have refractive index of 1.458 at the operating wavelength 850 nm.
- For short distance (upto 100 m), plastic multimode step index fibers are preferred. Plastic cables are tough and durable. The different variations in plastic cables are as follows :
  (i) Glass core with plastic cladding.
  (ii) Plastic core with plastic cladding.
  (iii) Plastic core with glass cladding.

1.41 PREPARATION OF THE PERFORM

- Instead of directly drawing the optical cable; first the perform is prepared. The perform contains both core and cladding layers.
- The perform is a cylindrical structure about 25 mm in diameter and it contains silica composition. Once the perform is prepared then it becomes easy to draw the fiber optic cable from it. Initially pure silica is obtained in the form of small particles, which is called as soot. The different layers of soot are deposited on the glass rod to form cladding layer.
- Using dopant material, the refractive index of cladding can be adjusted. For the core material, the soot is prepared by mixing three gases $SiCl_4$, O_2 and $GeCl_4$. By changing the percentage of dopant material, required refractive index of cladding is obtained. In this case, the deposition is done layer by layer and it is possible to control the refractive index of each layer separately. Thus the desired refractive index profile of entire cable can be precisely controlled.
- The different methods used to prepare the perform are as follows :

(i) Outside Vapour Deposition.
(ii) Vapour Phase Axial Deposition.
(iii) Modified Chemical Vapour Deposition.
(iv) Plasma Chemical Vapour Deposition.

1.41.1 Outside Vapour Deposition (Outside Vapour Phase Oxidation)

- One of many variations of vapour deposition technique for fabricating optical fiber. Silicon chloride($SiCl_4$), germanium chloride($GeCl_4$) Boron Chloride (BCl_3)are oxidised to form silica and germania particles for the deposition.
- This produces a soot perform and it is deposited on the rotating ceramic rod called as mandrel. This deposition is done layer by layer, on the rotating rod. By changing the percentage of dopant material, the refractive index of core and cladding can be adjusted. Then, this perform is removed from the rod and it is placed in high temperature furnace. The high temperature furnace, removes any water vapour content present in the perform.
- After processing in high temperature furnace; the perform is converted into solid mass of material. This process is called as sintering. Now the different fiber strands can be drawn from it.
- The Outside Vapour Phase Oxidation (OVPO) process is shown in Fig. 1.41.1.

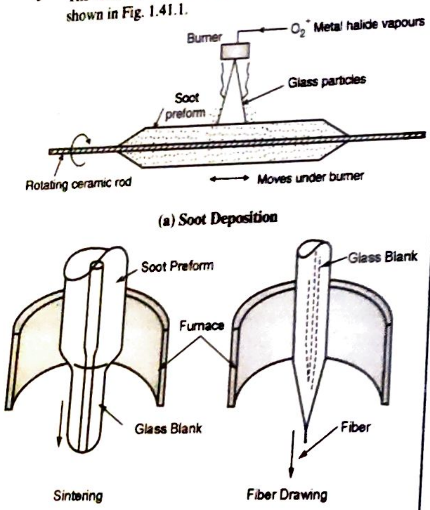


Fig. 1.41.1 : Outside Vapour Phase Oxidation

1.41.2 Vapour Phase Axial Deposition

UQ. Explain in brief VAD and MCVD fiber fabrication techniques. **(MU - Q. 2(a), Dec. 19, 10 Marks)**

- In this process a simultaneous flame deposition of both core and cladding material is done. Shown in Fig. 1.41.2.
- Silicon chloride, $SiCl_4$ and germanium chloride, $GeCl_4$ are oxidized to form silica and germania particles. These glass soots are formed axially on a rod. The porous soot perform grows and then it is drawn through a heating furnace.
- Then a transparent glass perform is made by zone sintering.

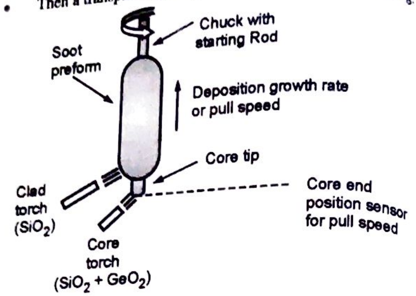


Fig. 1.41.2 : Vapour phase Axial deposition

☞ Advantages

The axial deposition has following advantages compared to the Outside Vapour Phase Oxidation (OVPO) process.

1. All types of fiber can be produced.
2. The perform has no holes like OVPO process.
3. The deposition and sintering takes place in the same heating chamber.

1.41.3 Modified Chemical Vapour Deposition (MCVD)

UQ. Explain modified chemical Vapour phase deposition method of fiber fabrication. **(MU - Q. 3(a), Dec. 18, May 19, 10 Marks)**

UQ. Explain in brief VAD and MCVD fiber fabrication techniques. **(MU - Q. 2(a), Dec. 19, 10 Marks)**

- The modified chemical vapor depostion (MCVD) process was pioneered at Bell laboratories and widely adopted elsewhere to produce very low-loss graded index fibers.
- It is also called as Inner Vapour Phase Deposition (IVPD) since the soot is deposited inside the target rod tube as opposed to outside in the Outer Vapour Phase Deposition (OVPO) process.
- The MCVD technique was developed to increase the deposition rates as compared to conventional CVD process and also to reduce the OH^-contamination due to the use of hydride reactants.

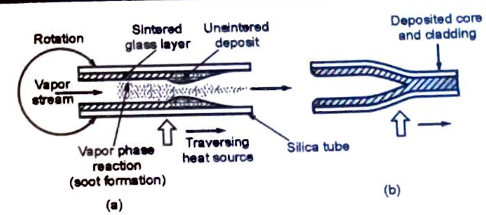


Fig. 1.41.3 : MCVD method (a) Deposition (b) Collapse to produce a perform

- As in Outside Vapour Phase Deposition, Modified Chemical Vapour Deposition also produces the preform in two steps.
- First, reactant gases flow through a rotating glass tube made from fused silica while a burner heats its narrow zone by travelling back and forth along the tube. Silica and dopants form soot that is deposited on the inner surface of the target tube.
- A burner heats a narrow zone of this deposit and sintering (heating without melting) occurs within this zone. The result is a layer of sintered glass. Operating temperature is kept at around 1600°C.
- The second step involves heating the soot perform to 2000°C, thus collapsing the tube into solid glass perform.
- The fiber that is subsequently drawn from this preform rod will have a core that consists of the vapor-deposited material and a cladding that consists of the original silica tube.
- The tube is then collapsed to give a solid preform which may then be drawn into fiber at temperatures of 2000 to 2200 °C.
- A graded refractive index profile can be created by changing the composition of the layers as the glass is deposited. This technique is the most widely used at present as it allows the fabrication of fiber with the lowest losses.
- Apart from the reduced OH^- impurity contamination the MCVD process has the advantage that deposition occurs within an enclosed reactor which ensures a very clean environment.
- MCVD has produced GeO2GeO2 doped silica single-mode fiber with minimum losses of only 0.2 dB/km at a wavelength of 1.55μm. Although it is not a continuous process, the MCVD technique has proved suitable for the widespread mass production of high-performance optical fibers. Moreover, it can be scaled up to produce preforms which provide 100 to 200 km of fiber.
- The cross section of the soot perform is as shown in Fig. 1.41.4.

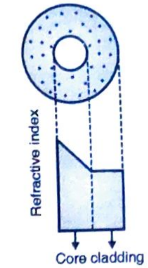


Fig. 1.41.4 : cross section of the soot perform

☞ Advantages

1. The raw materials are available in high purity form.
2. This is the process taking place inside the tube. So water content causes very less deposition of the glass layers. So water bubbles present in the glass layers are reduced.

☞ Disadvantage

This method is based on the deposition process and a starting tube is required. So the cost of the system is more.

1.41.4 Plasma Chemical Vapour Deposition (PCVD)

- The PCVd process is very similar in principle to the MCVD process. Instead of heating the outside of the silica tube the energy source is provided by a high power microwave field (the same principle as a microwave oven).
- The microwave field is provided through a magnetron cavity which surrounds the silica tube. This microwave field can be moved very quickly along the tube as it heats the gas plasma directly and doesn't have to heat up the silica tube itself.
- This means that you can traverse the tube thousands (instead of hundreds) of times depositing extremely thin layers at each pass. The result is much better control of the RI profile using MCVD.

- As it happens the tube is kept hot by another set of heaters but this is only at 1000°C rather than the 1600°C used in MCVD. Heating to create the gaseous reaction comes from the microwave field not from the tube. Silica is deposited on the inside of the tube uniformly without the need to rotate it.
- The reaction is nearly 100% efficient and proceeds several times faster than MCVD. In addition the process can produce large preforms capable of producing a few hundred km of fibre. In this method, soot formation is not required.
- The clear glass is deposited inside a silica tube, similar to MCVD process. But instead of using a torch or flame; oxidation is done by using non isothermal plasma. This plasma is used in the microwave frequency range around 2.45 GHz.
- Compared to earlier methods; the temperature is low. So there is no mechanical stress. Due to lower temperatures (1000 to 1200°C); thin layers are deposited inside the tube.
- The PCVD method is shown in Fig. 1.41.5.

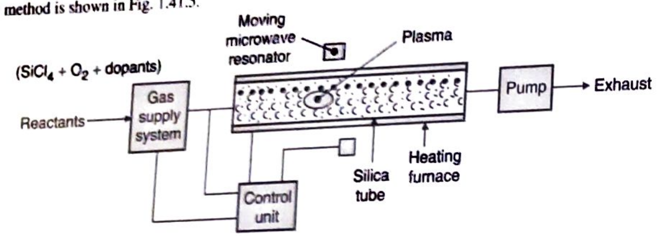


Fig. 1.41.5 : PCVD Method

Advantages

(i) Low loss fibers are produced.

(ii) There is no formation of soot, so sintering is not required.

(iii) Operating temperature is low, so there is no mechanical stress.

(iv) Mass production is possible.

1.42 COMPARISON BETWEEN OVPO PROCESS AND MCVD PROCESS

UQ. Explain any one fiber fabrication process with neat diagram. Compare the different methods of fabrication. **(MU - Q. 3(b), May 18, 10 Marks)**

Sr. No.	Parameter	OVPO process	MCVD process
1.	Fabrication	The soot perform is deposited outside the rotating rod.	The chemical reactions takes place inside the tube and soot is deposited inside the tube.
2.	Reactant	The reactions of $SiCl_4$, $GeCl_4$ and O_2 in a hot flame produces soot.	The major reactants used are $SiCl_4$ and O_2.
3.	Holes	The perform has holes which gets collapsed during drawing of fiber.	Perform does not contain hole.
4.	Temperature and Process	Oxidation takes place around 1900°C.	Sintering takes place around 1500°C.
5.	Flame for Heating Purpose	Methane oxygen flame is used for heating purpose.	Oxy-hydrogen flame is used for heating.

1.43 COMPARISON BETWEEN MCVD AND PCVD PROCESS

UQ. Explain any one fiber fabrication process with neat diagram. Compare the different methods of fabrication. **(MU - Q. 3(b), May 18, 10 Marks)**

Sr. No.	Parameter	MCVD	PCVD
1.	Oxidation Temperature	Oxidation takes place at high temperature.	Oxidation takes place at low temperature.
2.	Oxidation Flame	A flame is used for oxidation.	Non isothermal plasma is used for oxidation.
3.	Operating Temperature	Higher operating temperature.	Lower operating temperature.
4.	Stress	Mechanical stresses are developed.	No mechanical stresses.
5.	Soot Formation	There is soot formation.	No soot formation.
6.	Sintering	Sintering is required.	Sintering is not required.

1.43.1 Comparison Table for Fabrication

UQ. Explain any one fiber fabrication process with neat diagram. Compare the different methods of fabrication. **(MU - Q. 3(b), May 18, 10 Marks)**

	OVPO	MCVD	PCVD	VAD
Reaction Type	Flame Hydrolysis	Chemical Vapor Dimension	Chemical Vapor Dimension	Flame Hydrolysis
Dimensional Direction	Outside Layer Deposition	Inside Layer Deposition	Inside Layer Deposition	Axial Layer Deposition
Refractive index Profile formation	Layer Approximation	Layer Approximation	Layer Approximation	Simultaneous Formation
Process	Batch	Batch	Batch	Continuous

1.44 FIBER DRAWING PROCESS

- The Fiber draw process takes a specialty fiber preform that may measure one meter in length and stretches it into hundreds of meters or even multiple kilometers of fiber.
- The preform is designed and fabricated with dopants and other elements carefully placed so that the drawn fiber will have the correct index of refraction, chemical, mechanical, and geometric characteristics.
- Then, the drawing process must follow rigorous, high-accuracy procedures so that the finished and coated fiber has the desired properties that were "baked into" the preform. Specifically, the draw process has the following objectives:
  - getting high-strength fiber; e.g., meeting the specification for tensile strength;
  - achieving geometric specifications – fiber outside diameter, and for some specialty fibers, the shape;
  - applying and curing the fiber's coating with the right adhesion, thickness, concentricity; and mechanical properties;
- Once the perform is formed it is drawn into fibers. The procedure of fiber drawing process is as shown in Fig. 1.44.1.
- The perform is feed vertically into the furnace as shown in Fig. 1.44.1. Through this furnace the perform passes slowly and gets heated. So the lower end of the perform is melted. Now from this end the fiber can be drawn.
- A continuous diameter monitoring is necessary in this case. This is activated by providing a diameter gauge. This diameter monitoring is provided by using a non-contact type laser. At the lower end of this system a pulling capstan is used to pull the fiber from furnace.
- Many times the flaws are created in the fiber while passing through the pulley; so to avoid these flaws a coating is provided to the fiber when it is drawn from the furnace.
- The coating cap provides this coating on the fiber. The curing of this coating is done by using a curing oven. The fiber is allowed to pass through the ultraviolet light bath.
- The feedback signal is given from diameter gauge to the pulling capstan to control the pulling action of fiber.

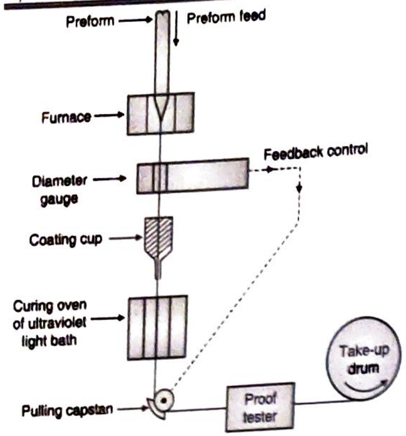


Fig. 1.44.1 : Fibre drawing process

- Before the fiber passes to the take-up drum, in order to check the strength of fiber proof tester is used as shown in Fig. 1.44.1.

1.45 DOUBLE CRUCIBLE METHOD

MU - May 2011, Dec. 2011, Dec. 2012, Dec. 2013, Dec. 2014, May 2015

- Silica, chalgenide and halide glass fibers can all be made using a direct double-crucible technique. In this method, glass rods for the core and Cladding materials are first made separately by melting mixtures of purified powders, to make the appropriate glass composition.
- These rods are then used as feedback for each of two concentric crucibles. The inner crucible contains molten core glass and the outer one contains the cladding glass.
- Subsequent development in the drawing of optical fibers (especially graded index) produced by liquid-phase techniques has concentrated on the double-crucible method.
- In this method the core and cladding glass in the form of separate rods is fed into two concentric platinum crucibles.
- The assembly is usually located in a muffle furnace capable of heating the crucible contents to a temperature of between 800 and 1200°C.
- The fibers are drawn from the molten state through orifices in the bottom of the two concentric crucibles in a continuous production process.
- The crucibles have nozzles in their bases from which the cladding fiber is drawn directly from the melt as shown in Fig. 1.45.1.

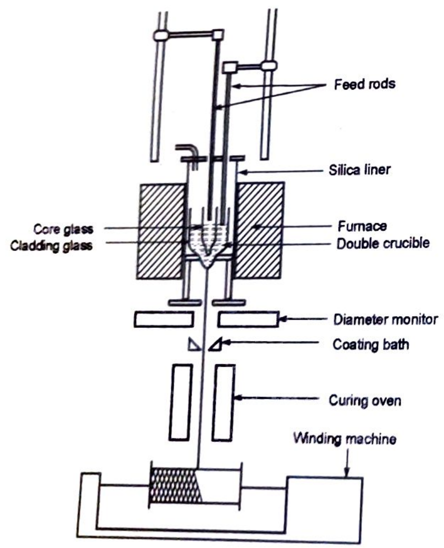


Fig. 1.45.1 : Double Crucible Method

- Although this method has the advantage of being a continuous process (both melting and drawing), careful attention must be paid to avoid contaminants during the melting.
- The main sources of contamination arise from the furnace environment and from the crucible. Silica crucibles are normally used in preparing the glass feed rods, whereas the double concentric crucibles used in the drawing furnace are made from platinum.
- This method has disadvantage of obtaining and maintaining extremely pure glass which limits their ability to produce low loss fibers.

Advantages

1. The rate of production is high.
2. There is no dimension restriction.
3. It can be used for large scale production.
4. It has higher glass compositions.

Disadvantages

1. Purity of glass is low.
2. Absorption loss is more.

1.46 FIBER CABLES AND JACKET

- The structure of fiber cable depends on the application for which it is designed. It consists of one, two or several layers around the central structural member.
- The structural element consists of solid or stranded steel wire, dielectric like kelvar and other glass elements. The smaller units are bunched together; so the flexibility is improved.
- Normally a stranded strength member is coated with coating of plastic which prevents microbending losses. It is called as buffer jacket. To prevent flaws in the material a coating of teflon material having a thickness of 5 μm to 10 μm is applied.
- There are different types of buffer jackets used to prevent the microbending losses. These are :

(i) Tight buffer jacket
(ii) Loose tube buffer jacket
(iii) Filled loose tube buffer jacket.

1.46.1 Tight Buffer Jacket

- It is basically a hard plastic material like Nylon and it is in direct contact with primary coated fiber.
- It is shown in Fig. 1.46.1.

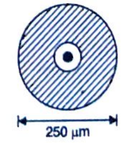


Fig. 1.46.1 : Tight Buffer Jacket

1.46.2 Loose Tube Buffer Jacket

- It produces over sized cavity as shown in Fig. 1.46.2.
- Usually a polyester or polyamide material is selected; it gives some kind of free movement to the fiber.
- It is smooth from inside, so it produces low resistance to fiber movement.
- It can be easily stripped for jointing or fiber termination.

Fig. 1.46.2 : Loose Tube Buffer Jacket

1.46.3 Filled Loose Tube Buffer Jacket

- It consists of a loose tube filled with moisture resistance compound.
- The filling material gives stability over wide range of temperatures.

1.47 CLASSIFICATION OF CABLES

Depending on the material used; fiber optic cables are classified as follows :

(i) Glass Fiber Optic Cable (GFOC)
(ii) Plastic Fiber Optic Cable (PFOC)
(iii) Plastic Clad Silica Fiber Optic Cable (PCSFOC).

1.47.1 Glass Fiber Optic Cable (GFOC)

- Glass optical fibers are constructed of tiny strands of glass. In this case, both the core and cladding layers are made from glass material.
- It posses lowest attenuation compared to other cables. Using dopant materials; the refractive index can be varied, during the manufacturing process.
- Ge and P increases the refractive index while Boron and Fluorine (B and F) decreases the refractive index.
- The main applications for glass fiber are communication, sensor, and measurement system. Some types of glass optical fiber cables can also be used in harsh environments such as corrosive and wet environments.

Advantages of Glass Optical Fiber

(1) Glass fiber cables can be used in high-temperature applications like furnaces, ovens, and condensers in large engines, as well as in extremely low-temperature areas such as cold storage warehouses.

(2) Since glass cores are efficient at transmitting light and allow for significantly higher transfer speeds, glass optical fibers can be used over long sensing distances.

(3) Glass optical fiber enables you to use a photoelectric sensor in areas where you wouldn't normally be able to use them. With this advantage, you can choose sensors with a wide range of housings, mounting styles, and features for your specific application. Since glass fiber optic cables are thin and light, they are optimized for small spaces and small targets.

Disadvantages of Glass Optical Fiber

(1) The installation of glass optical fibers requires highly trained technicians, and the tools and equipment for fiber termination are usually expensive.

(2) The core diameter of glass fiber is very small, hence it has higher technology requirements to couple light into the core region, such as light sources.

(3) Glass optical fibers are fragile and more possible to break if not handled properly.

1.47.2 Plastic Fiber Optic Cable (PFOC)

- Plastic optical fiber (POF) is introduced to optical links later than glass optical fiber. It is an optical fiber in which the core and cladding are both made out of plastic or polymeric materials rather than glass.
- It is typically made up of PMMA (acrylic), coating is made from fluropolymer material, a general-purpose resin as the core material, thus it is also referred to as PMMA optical fiber. Similar to the glass optical fiber, POF transmits the light through the core of the fiber. POFs are usually multimode fibers with large core (diameter from 0.15-2 mm).
- Made from just one acrylic monofilament, plastic fiber optic cables are efficient when used with visible red status indicator light sources. This types of cable is rugged in nature, but it has more attenuation.

Plastic Clad Silica Fiber Optic Cable (PCSFOC)

- It consists of glass core and plastic cladding. For cladding silicone elastomer material is used.
- The attenuation of this cable is moderate, which is between GFOC and PFOC.
- Due to the plastic cladding, the connection of cable to the connectors becomes difficult as well as the bonding is difficult.

Advantages of Plastic Optical Fiber

(1) The materials which POF is made up of are low-cost and the installation with associated assemblies is not expensive.

(2) It is flexible and solid, able to bend farther without breakage.

(3) The network using plastic optical fiber can be installed by untrained personnel. Even home users can handle and install these fibers.

(4) Plastic optical fibers use harmless green or red light that is easily visible towards the eye. They are safe when installed in a house without risk to inquisitive children.

Disadvantages of Plastic Optical Fiber

(1) The signal attenuation and dispersion of POF are typically very high, hence it is limited to short distances.

(2) POF cannot withstand the extreme temperature as glass optical fiber does.

1.47.3 Difference Between Glass Optical Fiber and Plastic Optical Fiber

Item	Glass optical fiber	Plastic optical fiber
Core diameter	More narrow (about 50-100μm for multimode fiber and 8-10μm for single mode fiber)	Wider (about 150-2000μm and even up to 20000μm)
Numerical aperture	Larger	More narrow
Cost	More expensive	Less expensive
Signal strength	Poorer	Better
Extreme temperatures	Sustainable	Unsustainable
Flexibility	Less flexible	More flexible
Consumability	More complex	Easier
Transmission distance	Longer	Shorter

1.48 FIBER JOINT

- A major issue with all types of fiber–fiber connection is the optical loss which occurs at the interface.
- Even when the two joined fiber ends are smooth and perpendicular to the fiber axes, and the two fiber axes are perfectly aligned, a small proportion of the light may be **reflected back into the transmitting** fiber causing **attenuation** at the joint. This phenomenon, known as **Fresnel reflection**, is associated with the **step changes** in **refractive index** at the jointed interface (i.e. glass–air–glass).
- The magnitude of this partial reflection of the light transmitted through the interface may be estimated using the classical **Fresnel formula** for light of normal incidence and is given by

$$r = \left(\frac{n_1 - n}{n_1 + n}\right)^2 \qquad ...(1.48.1)$$

where r is the fraction of the light reflected at a single interface, $n1$ is the refractive index of the fiber core and n is the refractive index of the medium between the two jointed fibers (i.e. for air $n = 1$).

- To determine the amount of light reflected at a fiber joint, Fresnel reflection at both fiber interfaces must be taken into account. The loss in decibels due to Fresnel reflection at a single interface is given by:

$$Loss_{Fres} = -10 \log_{10} (1 - r) \qquad (1.48.2)$$

Using in Eqns (1.48.1) and (1.48.2) the optical attenuation due to Fresnel reflection at a fiber–fiber joint can be determined.

- Fresnel reflection may give a significant loss at a fiber joint even when all other aspects of the connection are ideal.
- However, the effect of Fresnel reflection at a fiber–fiber connection can be reduced to a very low level through the use of an index-matching fluid in the gap between the jointed fibers.
- When the index-matching fluid has the same refractive index as the fiber core, losses due to Fresnel reflection are reduced.

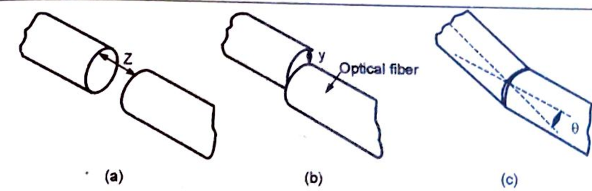


Fig. 1.48.1 : Three types of misalignment (a) Longitudinal misalignment (b) Lateral misalignment (c) angular misalignment

- Fresnel reflection is only one possible source of optical loss at a fiber joint. A potentially greater source of loss at a fiber–fiber connection is caused by misalignment of the two jointed fibers.
- Any deviations in the geometrical and optical parameters of the two optical fibers which are jointed will affect the optical attenuation (insertion loss) through the connection.
- It is not possible within any particular connection technique to allow for all these variations. Hence, there are inherent connection problems when jointing fibers with, for instance
  - o different core and/or cladding diameters;
  - o different numerical apertures and/or relative refractive index differences;
  - o different refractive index profiles;
  - o fiber faults (core ellipticity, core concentricity, etc.).
- The losses caused by the above factors together with those of Fresnel reflection are usually referred to as **intrinsic joint losses**. The best results are therefore achieved with compatible (same) fibers which are manufactured to the lowest tolerance.
- In this case there is still the problem of the quality of the fiber alignment provided by the jointing mechanism. Examples of possible misalignment between coupled compatible optical fibers are illustrated in Fig. 1.48.1.
- It is apparent that misalignment may occur in three dimensions:
  - o the separation between the fibers (longitudinal misalignment),
  - o the offset perpendicular to the fiber core axes (lateral/radial/ axial misalignment) and
  - o the angle between the core axes (angular misalignment).
- Fig. 1.48.2 Insertion Losses characteristics for jointed optical Fibes with various types of misalignment (a) Insertion loss due to lateral and longitudinal misalignment forgraded index fiber of 50μm core diameter
- Optical losses resulting from these three types of misalignment depend upon
  - o the fiber type, core diameter and
  - o the distribution of the optical power between the propagating modes.

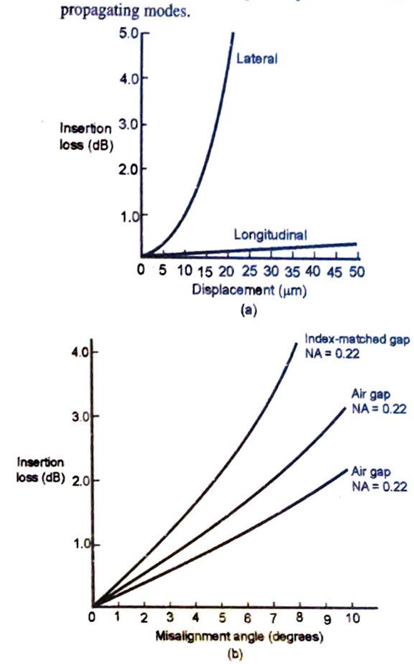


Fig. 1.48.2

- Examples of the measured optical losses due to the various types of misalignment are shown in Fig. 1.48.2. Fig. 1.48.2(a) shows the attenuation characteristic for both longitudinal and lateral misalignment of a graded index fiber of 50 μm core diameter.
- It is clear from Fig. 1.48.2 that the lateral misalignment gives significantly greater losses per unit displacement than the longitudinal misalignment. For instance, in this case a lateral displacement of 10 μm gives about 1 dB insertion loss whereas a similar longitudinal displacement gives an insertion loss of around 0.1 dB.
- Fig. 1.48.2(b) shows the attenuation characteristic for the angular misalignment of two multimode step index fibers with numerical apertures of 0.22 and 0.3. An insertion loss of around 1 dB is obtained with angular misalignment of 4° and 5° for the NA = 0.22 and NA = 0.3 fibers respectively.
- Also in Fig. 1.48.2(b) it is seen that the effect of an index-matching fluid in the fiber gap causes increased losses with angular misalignment. Therefore, it is clear that relatively small levels of lateral and/or angular misalignment can cause significant attenuation at a fiber joint. This is especially the case for fibers of small core diameter (less than 150 μm) which are currently employed for most telecommunication purposes.

1.49 FIBER JOINT LOSSES

UQ. Explain sources of loss at fiber joint. **(MU - Q. 3(a), May 18, 10 Marks)**

- These losses takes place while coupling the light sources to optical fiber or while splicing the two optical fibers.
- The different types of these losses are as follows :

1. Core misalignment
2. Lateral misalignment
3. Gap losses
4. Angular losses
5. Losses due to difference in diameter
6. Losses due to change in numerical aperture

1. Core misalignment

- If the core layers of two optical fibers to be joined are not exactly at the centres then the data may lost while connecting the two optical fibers. This situation is as shown in Fig. 1.49.1.

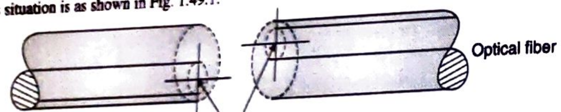


Fig. 1.49.1 : Core misalignment

- Similarly in case of single optical fiber after certain length the core is at OFF-axis then there may be small stretches of core.

2. Lateral misalignment

This situation occurs if there is a lateral displacement of core layer as shown in Fig. 1.49.2.

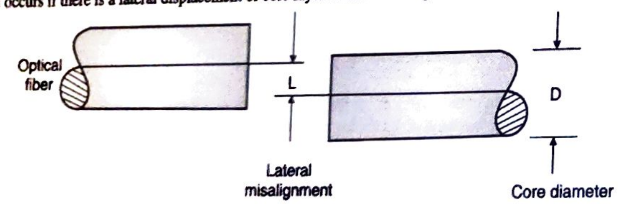


Fig. 1.49.2 : Lateral misalignment

Here, L = Lateral misalignment , D = Diameter of core

In this case all the light rays coming from one optical fiber may not enter into the second; some of them may get escaped into the environment.

3. Gap losses

- This situation is as shown in Fig. 1.49.3. These losses takes place if certain gap is present between the two optical to be joined. The allowable gap losses are 0.0002 to 0.0003.

- Gap losses are proportional to the value of numerical aperature of optical fiber. If the value of NA is less the gap losses are also less.

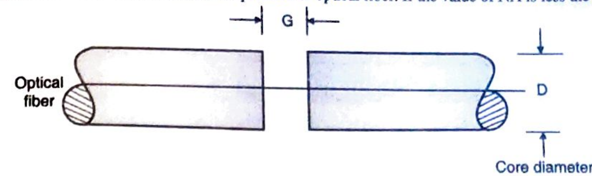


Fig. 1.49.3 : Gap losses

4. Angular losses

- If the ends of the optical fibers are not symmetrically cut then these losses takes place. These losses are expressed in decibels. The allowable angle should be less than 0.25°.

This schematic is as shown in Fig. 1.49.4. Here θ is an angular displacement.

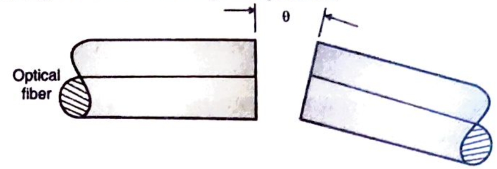


Fig. 1.49.4 : Angular losses

5. Losses due to difference in diameter

- If the two optical fibers to be joined are having different diameters then some of the light rays may gets escaped into the environment.
- This loss is expressed in dB and is given by,

$$\text{loss in dB} = -10 \log \frac{Dr}{Dt}$$

Where Dr = Diameter of receiving optical fiber.

Dt = Diameter of transmitting optical fiber.

6. Losses due to change in numerical aperture

- If the values of numerical aperatures of two optical fibers are different then there is a loss in the optical energy.
- This loss is given by,

$$\text{loss in dB} = -10 \log \frac{NAr}{NAt}$$

Where NAr = Numerical aperature of receiving fiber.

NAt = Numerical aperature of transmiting fiber.

1.50 FIBER CONNECTORS

- With many electronics that require fiber optic connections, several types of terminations exist. The most common fiber connectors are LC and SC. SC and LC connector types are so common that many systems have designs to accommodate them.
- The connectors are used to join the optical sources as well as detectors to the optical fiber. Similarly the connectors are used to join the two optical fibers.
- The main criteria about the connectors is that the connectors should be **aligned properly** in order to reduce the losses.
- The **separable connectors** are used to join the two optical fibers. Here the care should be taken that the two fiber optic ends should not be joined.
- And the vibrations that may be taking place in one optical fiber should not be transferred to the another optical fiber.

1.50.1 Requirements of Good Connector

MU - Dec. 2011, May 2013, Dec. 2013, May 2014, Dec. 2014

While connecting two fiber optic cables or while connecting components to the fiber optic cable; the connectors should satisfy the following requirements :

1. The connectors should have **low coupling loss**.
2. The design of connector should be such that the **repeated connection and disconnection** is possible without affecting the fiber alignment.
3. The **demountable connector** must provide reproducible accurate alignment of the fiber.
4. The connectors should **not get affected** by environmental factors.
5. The design of connector should provide **ease of connection**.
6. The connectors must **protect the fiber ends**, while making the connectors. It should not damage the fiber ends.
7. Connectors should provide the **strength to the joint**.

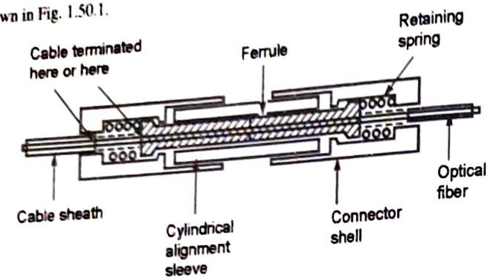
1.50.2 Types of Connectors

The two major types of connectors are :

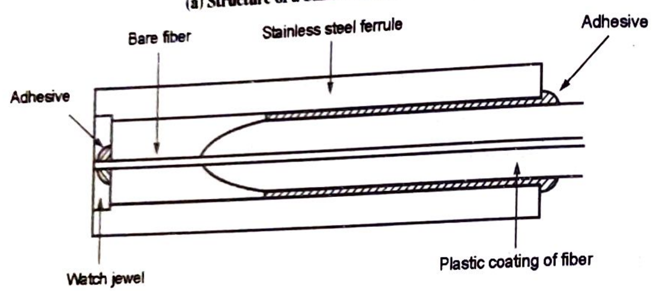
1. Ferrule type connectors	2. Lensed type connectors

1. Ferrule type connectors

The schematic is as shown in Fig. 1.50.1.



(a) Structure of a basic ferrule connector



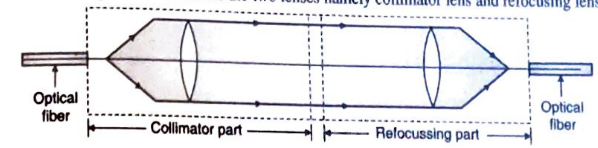
(b) Structure of a watch jewel connector ferrule

Fig. 1.50.1 : Ferrule type connector

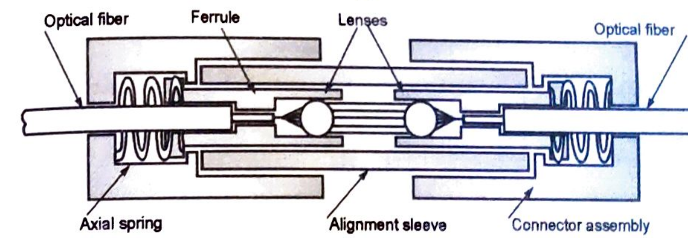
- Fiber optic ferrules are mechanical fixtures, generally rigid tubes, which are used to confine the stripped end of a fiber or a fiber bundle.
- They align and polish optical fibers to prevent the scattering and dampening of the light signal. Most fiber optic ferrules are made of metals such as stainless steel, ceramics such as alumina or zirconia, or plastic materials.
- Fiber optic ferrules made of borosilicate glass and glass are also available. Then the two ferrules are brought in contact under the cylindrical sleeve as shown in Fig. 1.50.1.
- Selecting fiber optic ferrules requires a careful analysis of product specifications and features. Fiber optic components for both single-mode and multi-mode fibers are commonly available. For both types of optical fibers, ferrule specifications such as
  - inner diameter (ID),
  - outer diameter (OD),
  - length,
  - concentricity,
  - radius, and
  - bore style are important to consider.
- Choices for bore style include :
  - single bore,
  - double bore, and
  - racetrack bore.
- Fiber optic ferrules with square and rectangular bores are also available. In terms of features, some fiber optic ferrules have a multi-step ID or a multi-step OD.
- Others have countersinks, anti-rotation notches, flats, slots, grooves, epoxy vent holes, and any-angle chamfers.

2. Lensed type connectors MU - May 2013

- The schematic is as shown in Fig. 1.50.2. This uses the two lenses namely collimator lens and refocusing lens.



(a)



(b)

Fig. 1.50.2 : Lensed type connectors

- Fig.1.50.2 shows a connector consisting of two lenses for collimating and refocusing the light from one fiber into the other.
- The use of these interposed optics makes the achievement of lateral alignment much less critical than with a butt-jointed fiber connector. By adjusting the two lens the optic signal from one optical fiber is connected to the other optical fiber. Here the radial alignment of two parts to be connected is not critical as compared to other connectors. But an angular alignment is difficult in this case.

1.51 OTHER TYPES OF CONNECTORS

1.51.1 Subminiature Type-A (SMA) Connector

- The SMA connector is a sub-miniature coaxial cable connector and it takes its name from the words Sub-Miniature A connector shown in Fig. 1.51.1.
- It finds many applications for providing connectivity for RF assemblies within equipments where coaxial connections are required.
- It is often used for providing RF connectivity between boards, and many microwave components including filters, attenuators, mixers and oscillators, use SMA connectors.
- It is preferred in data communication and instrumentation connections. It is very common type of connector, but it has limited uses in new systems due to its difficulty in pairing.

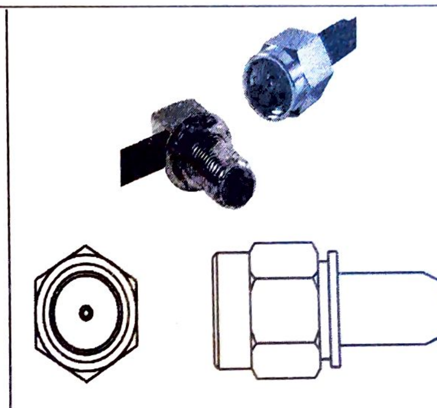


Fig. 1.51.1 : SMA Type Connector

- There are also reverse-polarity ("RP") SMA connectors in which the pin and sleeve are swapped; so that the "male" RP-SMA has a centre sleeve surrounded by an inside-threaded barrel, and the "female" RP-SMA has a centre pin and an outside-threaded barrel.

1.51.2 SC Connector

- The SC was developed by the laboratories at Nippon Telegraph and Telephone (NTT) in the mid-'80s, and was one of the first connectors to hit the market following the advent of ceramic ferrules.
- It is also called as the 'Square Connector' the SC has a push-pull coupling end face with a spring-loaded ceramic ferrule. Shown on Fig. 1.51.2.

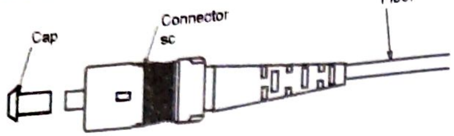


Fig. 1.51.2 : SC Connector

- Initially intended for Gigabit Ethernet networking, it was standardized into the telecommunications specification TIA-568-A in 1991 and slowly grew in popularity as manufacturing costs came down.
- Due to its excellent performance, it dominated fiber optics for over a decade with only the ST rivaling it. The SC is ideally suited for datacoms and telecoms applications including point to point and passive optical networking.

1.51.3 LC (Lucent or Little) Connector

- LC Connectors were invented by Lucent Technologies (hence the LC name). It is type of small form factor (SFF) line of connectors. Shown in Fig. 1.51.3.
- These SFF connectors were initially invented to fill a need for large fiber count applications.
- It contains plastic housing and a ceramic ferrule. These connectors provide precise alignment for single mode and multimode fibers.

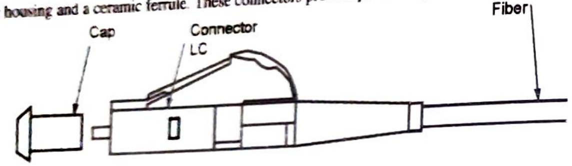


Fig. 1.51.3 : LC Connector

- They are basically used for high density, inter connections. These connectors are also used for connecting different instruments to optical cable. In some installations there are dozens of connectors being plugged in and these connectors make life much easier.
- The LC connector uses a 1.2mm ferrule and has about half the footprint size of the other connectors. It does share the same non optical disconnect as the SC and FC share. They are suitable for single mode or multimode fibers and it is widely used for LAN.

1.51.4 FC (Fiber Connector) Connectors

- The FC was the first optical fiber connector to use a ceramic ferrule, but unlike the plastic-bodied SC and LC, it utilizes a round screw-type fitment made from nickel-plated or stainless steel.
- The connector end face relies on an alignment key for correct insertion and is then tightened into the adapter/jack using a threaded collet. Shown in Fig. 1.51.4. Despite the additional complexity both in manufacturing and installation, it's still the connector of choice for precise measuring equipment such as OTDRs.
- Initially intended for datacoms and telecoms applications, its use has reduced since the introduction of the SC and LC.

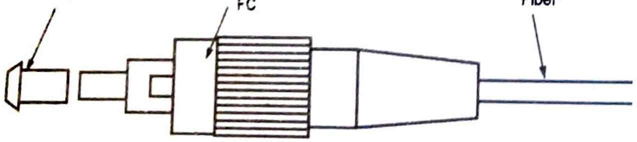


Fig. 1.51.4 : FC Connector

- These deliver similar performance to the FC, but both have less expensive components and are quicker to connect.
- However, the screw-on collet of the FC does make it particularly effective in high vibration environments, ensuring that the spring-loaded ferrule is firmly mated.
- It is basically push on-off type metallic connector having a provision of locking tab. It contains ceramic ferrule. Such connectors are especially used for single mode fibers. These connectors provide extremely precise position for the connection of source and detector.

1.51.5 Straight Tip (ST) Connector

- The ST connecter was developed by AT&T . The ST uses a bayonet fitment rather than a screw thread. These connectors are push in, twisted type metallic connectors shown in Fig. 1.51.5. They are constructed having a single metal housing and can be easily connected and removed from the fiber optic cable.
- It cannot be terminated with an angled polish, which limits its use in single-mode fiber and FTTH applications.

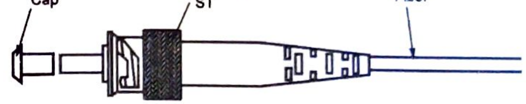


Fig. 1.51.5 : ST Connector

- It is used in multi-mode datacoms, it is most common in network environments such as campuses, corporate networks and in military applications where the quick connecting bayonet had its advantages at the time.
- They are mostly used in networking devices as well as in data communication. It is typically installed into infrastructures that were built at the turn of the century; when retro-fitting, STs are typically swapped out for more cost-effective SC and LC connectors.

1.51.6 Jack or Media Termination – Recommended Jack (MT - RJ) Connectors

- Mechanical Transfer Registered Jack (MT-RJ) connector is a duplex connector that uses pins for alignment and has male and female versions.
- Constructed with plastic housing and provide for accurate alignment via their metal guide pins and plastic ferrules. Shown in Fig. 1.51.6.
- Compared to a standard phone jack, the size of MT-RJ connector is slightly smaller, making it easier to connect and disconnect.
- In addition, MT-RJ fiber optic connector provides a lower termination cost and greater density for both electronics and cable management hardware compared to other singer-fiber terminations.

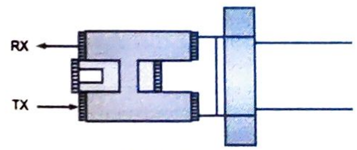
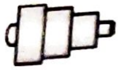


Fig. 1.51.6 : MT-RJ Connector

- These are push on, pull off 74ype suitable for duplex multimode connections. These connectors are having plastic housing, metal guide pins and plastic ferrules. They can connect almost 72 fibers, so these connector are suitable for high density local area networks.

1.52 SUMMARY OF DIFFERENT TYPES OF CONNECTORS

Name/Parameter	FC	ST	LC	SC
Full Form	Ferrule Connector	Straight Tip	Lucent Connector or Little Connector	Suscriptor Connector or Square Connector
History	It was the first optical connector using a ceramic ferrule, developed by Nippon Telephone and Telegraph. Its use is becoming less common in favor of SC and LC connectors.	Developed in the USA by AT&T and used in professional environments such as corporate networks as well as the military field.	Developed by Lucent Technologies and released in 1997.	Developed by Nippon Telegraph and Telephone, it has become the most popular because of its decreasing production costs.

Name/Parameter	FC	ST	LC	SC
Feature	The screwed fitting of the connector is vibration-proof; therefore it is used in applications under motion. It is also used in precision instruments (such as OTDR) and it is very popular in CATV.	**Its shape reminds of the Japanese FC connector, except for its BNC-type fitting system (twist lock also called bayonet style fitting).**	Push-and-pull fitting (it reminds an RJ45). Safer and more compact that the SC-type, allowing even more density of connectors in racks, panels and FTTH.	Quick push-and-pull fitting. It is compact, allowing a big density of connectors per instrument. It is used in FTTH, telephony, CATV, etc.
Optical Feature	**For single mode fibers. Its insertion losses reach the 0.3 dB.**	**For multimode fibers. Losses of about 0.25 dB.**	For monomode and multimode fibres. Losses of 0.10 dB.	**For single mode and multimode fibers. Losses of 0.25 dB.**
Example	 FC Connector	 ST Connector	 LC Connector	 SC Connector

⏭ 1.53 SPLICES

MU - May 2011, Dec. 2011, Dec. 2012, May 2013, Dec. 2013, May 2014, Dec. 2014

- The disadvantages of optical fiber connectors is overcomed by splicing of optical fibers is used to maintain permanent connections between the two optical fiber cables.
- The fiber optic cables of various lengths like more than 5kms, 10kms, etc., are not capable of the permanent connection and can't run for a longer run.
- And also not suitable for repeated connections and disconnection of cable connections. So, it is necessary to splice the fiber optic cables with two lengths to join the cables together that can provide sufficient permanent connection for a longer run.
- The splicing of optical fibers is one of the techniques used to join two optical fiber cables for permanent connection. This technique is also known as termination or connecterization.
- This method is mostly preferred when two types of cables (for example 48-fiber cable and 12-fiber cable) are joined together for a longer run with a single length of fiber cable.

⏭ 1.54 SPLICING TECHNIQUES OF OPTICAL FIBERS

UQ. Define Splicing, Mention its types and limitations. **(MU - Q. 1(c), Dec. 17, 5 Marks)**

UQ. Draw and explain fusion splicing. **(Q. 1(c), Dec. 19, 5 Marks)**

- The splices are used to connect the two fiber optic cables permanently. The basic requirements of splices are :
  (i) Splices should cause the minimum power loss.
  (ii) They should be easy to install.
  (iii) They should cause a low attenuation.
  (iv) They should be strong and having light weight.
- There are two techniques in splicing of optical fibers depending on the insertion loss, cost, and performance characteristics.
- This splicing technique are :

  (i) Fusion splicing
  (ii) Mechanical splicing.

- The mechanical splicing is again divided as :

  1. Precision tube splice
  2. Loose tube splice
  3. V-groove splice
  4. Elastomeric splice
  5. Precision pin splice
  6. Spring groove splice.

- The two optical fiber cables should be aligned properly while splicing and at the same time its geometrical factors and the mechanical strength should be considered.

1.54.1 Fusion Splicing

- Fusion Splicing is used to make permanent connection between the two optical fiber cables and gives a longer life with less attenuation.
- The two cores of fiber cables are joined or fused electrically or thermally. That means an electric device or an electrical arc is used to fuse the two fiber optic cables and produces a connection between them.
- This technique is very costly and works for a longer period. The Fig.1.54.1. shows of the fusion splicing of optical fiber technology.

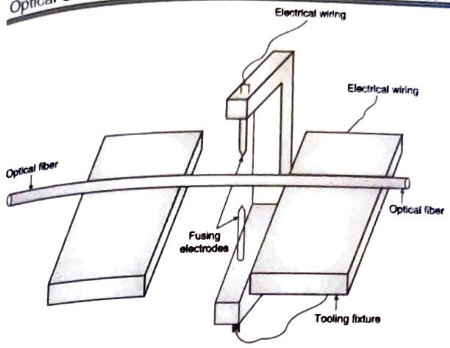


Fig. 1.54.1 : Fusion splicing

- The two fiber cables are aligned together by using a device called a fusion splicer. Those cables can be fused or joined together to form a connection with the help of an electric arc more precisely.
- The heat produced by the electric arc can give a transparent and continuous non-reflective connection between the two optical fiber cables with less attention, and insertion losses.
- The light loss will be low in this technique. So, it is most widely used and expensive than mechanical splicing of optical fiber cable.

1.54.2 Functions of the Fusion Splicer

The functions of the fusion splicer used in the splicing of optical fiber are,

1. It helps to align the optical fibers with more precision
2. It helps to create an electric arc or heat to fuse or join or weld the optical fibers together. This method has less attention loss of 0.1dB, and also black reflection loss is low. The insertion losses (<0.1dB) are less in both multimode and single-mode optical fiber splicing.

1.54.3 Advantages and Dis-advantages of Fusion Splicing

Advantages

1. It provides lowest attenuation.
2. It provides high quality joint.
3. It has small size of splice.
4. It is very compact
5. It has the lowest insertion loss
6. It has the lowest back reflection (optical return loss ORL)
7. It has the highest mechanical strength
8. It is permanent
9. It can withstand extreme high temperature changes
10. It prevents dust and other contaminants from entering the optical path

Disadvantages

1. The heat is used for splicing, so makes the fiber ends weak.
2. After splicing, the tensile strength becomes low.
3. The cost of fusion splicing is very high mainly because of expensive fusion splicing device.
4. It requires a constant power supply and some special tools.
5. There are some situations where fusion splicing is not practical or we can say it is impossible, so as an alternative, we have to use mechanical splicing.
6. It is a time consuming process and can't be used for temporary connections.
7. Fusion splicers need periodic maintenance which involves regular cleaning, electrode alignment and occasional replacement.
8. It is mainly used with single mode fiber unlike mechanical splicing which works for single mode fiber, as well as, multi mode fiber

⏭ 1.55 MECHANICAL SPLICING

- It uses index matching fluid to hold and align the single or more fiber cables assembled in a place to join them together.
- The mechanical splicing acts as a junction to join the optical cables more precisely. When the optical fiber cables are joined together to pass the light from one to another, the loss of light will be low if we use the mechanical splicing technique. Insertion loss, splicing loss will be nearly 0.3dB.
- It produces high back reflection when compared to fusion splicing. It is very easy to repair and install for both multimode and single-mode optical fiber cables. In this method, the fiber ends are aligned and then they are locked in position using various positioning devices.
- The different types of mechanical splicing are :

  1. Precision tube splice
  2. Loose tube splice
  3. V-groove splice
  4. Elastomeric splice
  5. Precision pin splice
  6. Spring groove splice.

1.55.1 Precision Tube Splice

- In this case a precision tube is used to splice the two fiber optic cables. The schematic of this splice is as shown in Fig. 1.55.1.
- Initially the ends of optical fiber to be joined are polished. A splicing compound is added in the precision tube. This compound is having the same refractive index as the fibers to be joined.

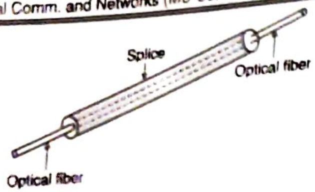


Fig. 1.55.1 : Precision tube splice

- Then the two optical fibers are inserted into the precision tube from two ends. The two ends of optical fibers are joined and the outer jacket is crimped.

1.55.2 Loose Tube Splice

- This type of splice is as shown in Fig. 1.55.2. Here a rectangular tube is used for splicing. The tube has a square hole as shown in Fig. 1.55.2.
- An adhesive material is added in the tube to join the ends of optical fiber. Then the optical fibers are inserted from two ends of the tube.
- Because of adhesive material the two ends of optical fiber are joined. The adhesive material is having the same refractive index as that of the fiber optic cables.

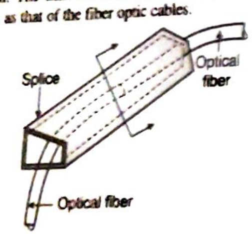


Fig. 1.55.2 : Loose tube splice

1.55.3 V - groove Splice

- It is one of the types of mechanical splicing, which uses a substrate in a V-shape made up of ceramic, silicon, plastic, or any other metal. This is also called as surface groove splice.
- The ends of two optical fiber cables are placed in the groove as shown in Fig. 1.55.3. Here the two metal places are used and a ' V ' shaped groove is made at the centre of each metal plate.
- The dimensions of the grooves are such that the two optical fibers can be easily placed in the grooves.
- Then the adhesive epoxy material is placed in the 'V' grooves. The fiber optic ends are placed in one of the metal plate ' V ' groove. Then they are butted together.
- The second metal plate is aligned and placed on the first metal plate. Then the two metal plates are fastened. In this type, the fiber losses are more because of cladding diameter, core diameter, and position of the core to the center.

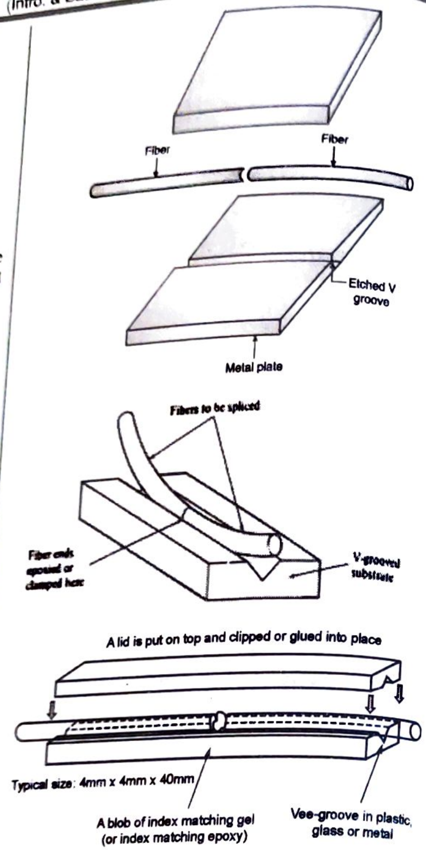


Fig. 1.55.3 : Double metal plate splice or V Groove Splice

- It doesn't form a permanent connection. Hence, it is used for Semi-permanent connections. This type of splice is as shown in Fig. 1.55.3.

1.55.4 Elastomeric Splice

- It is another variation in V groove splice. It has two elastomeric internal parts and one of the parts has a V groove.
- Using an outer sleeve, two elastomeric parts are held in compression and the fibers are aligned in V groove.
- This splice is shown in Fig. 1.55.4.

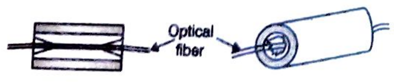


Fig. 1.55.4 : Elastomeric Splice

1.55.5 Precision Pin Splice

- The arrangement of precision pin splice is shown in Fig. 1.55.5. The heat shrink tube is used to held three steel pins together.
- The fibers tube joined are inserted in the openings between three pins. Using index matching epoxy, splicing is done.

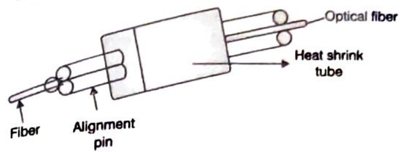


Fig. 1.55.5 : Precision pin Splice

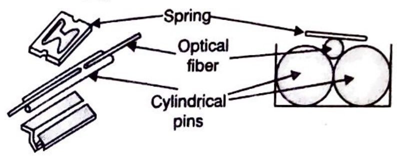


Fig. 1.55.6 : Spring groove Splice

1.55.6 Spring Groove Splice

- Two cylindrical pins are used as alignment guide for two prepared fiber ends.
- Using the spring, the fiber is pressed in the groove and alignment is maintained.
- Epoxy resin is used for splicing. This type of splice is shown in Fig. 1.55.6.

1.55.7 Advantages and Disadvantages of Mechanical Splicing

Advantages

1. Mechanical splices require no power supplies.
2. Many mechanical fiber splice designs require no extra tools beyond a fiber stripper and fiber cleaver.
3. They can be used in situations where fusion splicing is not practical or impossible.
4. Mechanical splices can be made within a couple of minutes, this makes it ideal for temporary connections.

Disadvantages

1. Higher insertion loss. The typical insertion loss for a mechanical splice is about 0.2dB which is significantly higher than the 0.02dB loss for a typical fusion splice.
2. Mechanical splices are typically for multimode fibers. The tough alignment tolerance for single mode fibers makes it hard for mechanical splices to meet.
3. Mechanical splice is more expensive than fusion splices. But if you take into account the expensive fusion splicing machines that fusion splices need, the average cost is actually much lower for mechanical splice if you just do a few splices.
4. Since the refractive index of most index matching compounds varies with temperature, so the optical performance of a mechanical splice can be sensitive to ambient temperature.
5. Mechanical splices are not thought to be as reliable as fusion splices over long periods of time.
6. Mechanical splices are used only in relatively benign environments such as inside an office building.

1.56 COMPARISON BETWEEN FUSION AND MECHANICAL SPLICING

UQ. Compare different types of splicing techniques. **(MU - Q. 1(d), Dec. 15, 5 Marks)**

The major types of splices are fusion splicing and mechanical splicing. The following table shows comparison between these techniques.

Sr. No.	Parameters	Fusion splicing	Mechanical splicing
1.	**Process**	By applying heat, the two ends of optical cables got fused and two cables are connected.	The fiber ends are aligned and then they are locked in position using various positing devices.
2.	**Size**	Small in size	Size is large.
3.	**Attenuation**	Provides lowest attenuation.	Attenuation is about 0.5 dB.
4.	**Usage of Heat**	Heat is used for splicing, so it makes the fiber ends weak.	Heat is not applied.
5.	**Tensile Strength**	After splicing, tensile strength becomes low.	After splicing, tensile strength is unaffected.

1.57 PHOTONIC CRYSTAL FIBER(PCF)

- Pioneered by the research group of Philip St. J. Russell in the 1990s, the development of photonic crystal fibers.
- An optical fibers comprised of solid silica core and cladding regions in which the light is guided by a small increase in refractive index in the core facilitated through doping the silicon with germanium.
- A new class of microstructured optical fiber containing a fine array of air holes running longitudinally down the fiber cladding has been developed.
- The microstructure within the fiber is often highly periodic due to the fabrication process, these fibers are usually referred to as photonic crystal fibers (PCFs), or sometimes just as holey fibers.

- In conventional optical fibers electromagnetic modes are guided by total internal reflection in the core region, which has a slightly raised refractive index, in PCFs two distinct guidance mechanisms arise.
- The guided modes can be trapped in a fiber core which exhibits a higher average index than the cladding containing the air holes by an effect similar to total internal reflection, alternatively they may be trapped in a core of either higher, or indeed lower, average index by a photonic bandgap effect.
- In optical fiber the effect is often termed modified total internal reflection and the fibers are referred to as index guided, while in the latter they are called photonic bandgap fibers.
- The existence of two different guidance mechanisms makes PCFs versatile in their range of potential applications.
- For example, PCFs have been used
  - to realize various optical components and devices including long period gratings,
  - multimode interference power splitters,
  - tunable coupled cavity fiber lasers,
  - fiber amplifiers,
  - multichannel add/ drop filters,
  - wavelength converters and
  - wavelength demultiplexers
- As with conventional optical fibers, however, a crucial issue with PCFs has been the reduction in overall transmission losses which were initially several hundred decibels per kilometer even with the most straightforward designs.
- Increased control over the homogeneity of the fiber structures together with the use of highly purified silicon as the
- base material has now lowered these losses to a level of a very few decibels per kilometer for most PCF types, with a loss of just 0.3 dB km-1 at 1.57 Ím for a 100 km span being recently reported.

1.57.1 Types Photonic Crystal Fiber Designs

Depending on the design, substantially different physical mechanisms providing the guidance of light may be obtained. The most important designs are.

(a) Triangular Hole Patterns

Fig. 1.57.1 : Solid-Core photonic crystal fiber design

- The simplest (and most often used) type of photonic crystal fiber has a triangular pattern of air holes, with one hole missing. Shown on Fig. 1.57.1., i.e. with a solid core surrounded by an array of air holes.
- The guiding properties of this type of PCF can be roughly understood with an *effective index model*: the region with the missing hole has a higher effective refractive index, similar to the fiber core in a conventional fiber.
- That guiding principle can work in a very wide range of wavelengths; even single-mode guidance may be obtained in a very wide spectral region (*endlessly single-mode fibers*).

(b) Photonic Bandgap Guiding

- There are also so-called photonic bandgap fibers (PBG fibers) with a totally different guiding mechanism, based on a photonic bandgap of the cladding region, which is considered as a two-dimensional photonic crystal. Based on that mechanism, one can even obtain guidance in a hollow core (i.e. in a low-index region), such that most of the power propagates in the central hole (→ *hollow-core fibers*). Such *air-guiding hollow-core photonic crystal fibers* (or *air core bandgap fibers*) can have a very low nonlinearity and a high damage threshold.
- Photonic bandgap fibers typically guide light only in a relatively narrow wavelength region with a width of e.g. 100–200 nm and can be used e.g. for pulse compression with high optical intensities, as most of the power propagates in the hollow core.

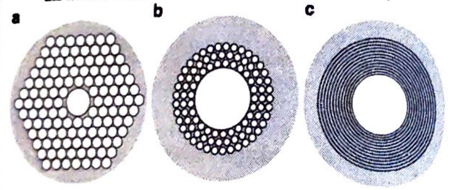


Fig. 1.57.2 : Types of Photonic Bandgap fibers

Various types of hollow-core photonic bandgap fibers shown in Fig. 1.57.2.

(a) Photonic crystal fiber featuring small hollow core surrounded by a periodic array of large air holes.

(b) Microstructured fiber featuring medium-sized hollow core surrounded by several rings of small air holes separated by nano-size bridges.

(c) Bragg fiber featuring large hollow core surrounded by a periodic sequence of high and low refractive index layers

Active Fibers for Amplifiers and Lasers

- Laser-active PCFs for fiber lasers and amplifiers can be fabricated, e.g., by using a rare-earth-doped rod as the central element of the preform assembly. Shown in Fig. 1.57.3.
- Rare earth dopants (e.g. ytterbium or erbium) tend to increase

the refractive index, but this can be accurately compensated, e.g. with additional fluorine doping of the core or with germanium doping of the cladding, so that the guiding properties are determined by the photonic microstructure only and not by a conventional-type refractive index difference. With rare-earth-doped PCFs, it is possible to realize, for example, soliton mode-locked fiber lasers operating in the 1-μm region, where a fiber's chromatic dispersion would usually be in the normal dispersion regime, but can be anomalous for suitable designs .

- However, one may also implement dispersion management by incorporating dispersion-modified passive fibers in the laser resonator.

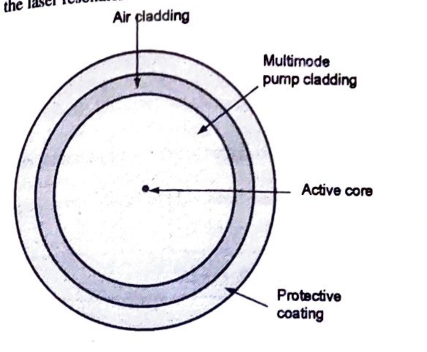


Fig. 1.57.3 : Structure of a photonic crystal fiber with an air cladding

- For high-power fiber lasers and amplifiers, double-clad PCFs shown in fig. can be used, where the pump cladding is surrounded by an air cladding region (*air-clad fiber*).
- Due to the very large contrast of refractive index, the pump cladding can have a very high numerical aperture (NA), which significantly lowers the requirements on the pump source with respect to beam quality and brightness.
- Such PCF designs can also have very large mode areas of the fiber core while guiding only a single mode for diffraction-limited output, and are thus suitable for very high output powers with excellent beam quality.
- Another advantage is that the pump light is kept away from any polymer coating, thus avoiding possible problems with overheating of a coating.
- Doped photonic crystal fibers have favorable properties also for use in fiber-based chirped-pulse amplification systems with very high output peak power.

1.58 TYPES OF PHOTONIC CRYSTAL FIBER

Photonic crystal fibers are generally divided into two main categories:

- **Index-Guiding Fibers:** Have a solid core like conventional fibers. Light is confined in this core by exploiting the modified total internal reflection mechanism.
- **Photonic Bandgap (Air Guiding) Fibers:** Have periodic micro structured elements and a core of low-index material (hollow core). The core region has a lower refractive index than the surrounding photonic crystal cladding. The light is guided by a mechanism that differs from total internal reflection in that it exploits the presence of the photonic bandgap (PBG).

1.58.1 Index Guiding Fiber

- Index guiding PCFs transport light through a solid core by total internal reflection. The microstructured air-filled region in PCFs effectively lowers the index of the cladding – effectively creating a step-index optical fiber.
- The fiber behaves in many ways like standard step-index fibers, but it has a number of advantages. Index guiding PCFs are made of undoped silica that provides very low losses, sustains high powers and temperature levels, and may withstand nuclear radiation.
- Depending on PCF design, the air in the cladding may be utilized to yield fibers with extremely low or extremely high index steps.

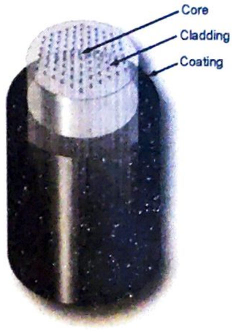


Fig 1.58.1 : Schematic of an index guided PCF

- A typical cross section of an index guided PCF is shown in Fig. 1.58.1. The PCF consists of a triangular lattice of air holes where the core is defined by a "missing" air hole. The pitch is labeled Λ, and measures the period of the hole structure (the distance between the centers of neighboring air holes). The hole size is labeled d, and measures the diameter of the holes.

- Some PCFs have a cladding refractive index that exhibits a strong wavelength dependence. Together with the inherently large design flexibility, PCFs allow for a whole range of novel properties to be explored.
- Such properties include endlessly single-mode fibers (F-SM Series), extremely nonlinear fibers and fibers with anomalous dispersion in the visible wavelength region (F-NL Series).
- A unique feature of PCFs is that a single fiber may support single-mode operation over a wavelength range from around 300 nm to beyond 2000 nm - even for large mode field areas (of several hundred μm^2).

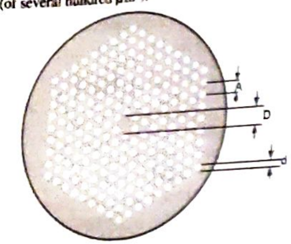


Fig. 1.58.2 : Cross section of triangular cladding photonic crystal fiber (PCF)

- This allows PCFs to be utilized for transmission of very high powers with high beam quality without running into nonlinear or damage barriers (several hundred Watts for CW operation).
- The highly nonlinear fibers made as single-mode fibers have extremely small mode field areas (typically around 3 μm^2) and confine light to the core region efficiently.

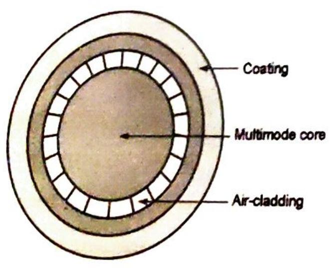


Fig. 1.58.3 : Cross section of air-clad photonic crystal fiber

- Compared to standard fiber technology, where the light is guided using solid glasses with different refractive indices, several new properties may be realized using PCF technology.
- For example:
  - Fibers that are single-mode in a very broad spectral range (in principle all wavelengths)
  - Very small mode sizes may be obtained (down to approx. 1 μm)
  - Very large mode sizes may be obtained (up to 25 μm or larger)
  - Zero dispersion wavelengths below 1300 nm is possible (down to approx. 600 nm)
  - Exceptionally large birefringence close to 10-2 can be realized
  - Very high numerical apertures up to 0.9 may be obtained
- Hence, PCFs are ideally suited for applications requiring large non-linearities, broadband operation with single-mode guidance, large mode areas, light collection from a large solid angle, etc.

1.59 RF OVER FIBER

UQ. Write short note on RF over Fiber. (MU - Q. 6(i), Dec. 2019, 5 Marks)

- **RF over fiber (RFoF)** or **Radio over fibre (RoF)** is a way of transmitting radio waves over a fiber optic cable by converting the RF signal into light by modulating the intensity of a light source (Laser or LED) with the RF signal. At the other end, the RF signal is recovered using an Optical-Electrical modulator (O/E).
- RF over Fiber transmission is an analog process that provides high bandwidth, low-loss communication links to transport RF energy at optical frequencies/wavelengths. Unlike traditional copper coax cables whose losses limit their transmission distance to around 300 ft., RoF is not distance limited.

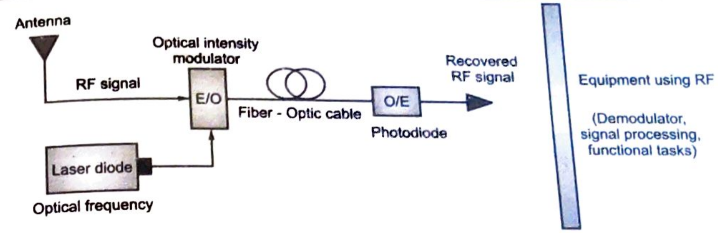


Fig. 1.59.1 : RF over Fiber Optical Link

- An RF Over Fiber (RoF) Link receives an RF Signal, converts it to an optical signal, transmits it over a distance and then converts its back to an RF signal which is then processed as required. A RoF Link consists of the following parts shown in Fig. 1.59.1 :
  - **Light Source/Laser Diode** - That acts as an optical carrier, usually provided by a laser diode. This laser diode is controlled by forward-biasing the semiconductor junction.
  - **Electrical-optical Modulator (E/O)** - To convert/modulate the light beam using the RF signal.
  - **Transmission Medium** - A single-mode fiber-optic cable. Single-mode has a lower number of light reflections, which lowers attenuation and allows the signal to go further than multimode.
  - **Optical-electrical Modulator (O/E)** - To recover the RF signal at the receiver side, usually by using a photodiode or avalanche photodiode (APD).
- At this point, the original RF signal is recovered and can then be processed as required.

The benefits of RFoF are

- Very low signal loss (less than 0.5 dB/km) allowing for connections of several kilometers without the need for amplification (see graph comparing RFoF to coax over frequency).
- Flat frequency response across the entire frequency band, meaning there is no need for slope compensation
- Immunity to EMI and RFI due to fiber being a non-conductive medium
- Security against signal interception
- Flexible and lightweight for ease of deployment
- Low maintenance – install and forget technology
- Simple installation
- Cost effective compared to high end, low loss coax cable and slope compensation amplifiers.
- Due to the physical properties of fiber-optic cables, certain frequencies have less attenuation. The optical frequencies used most often for LEDs are 780nm, 850nm, 1300nm and for Laser Diodes are 1310, 1550nm, 1625nm.

1.60 DIFFERENT TYPES OF FIBERS

UQ. Explain different types of fibers with their refractive index profile and-mention its dimensions. (MU - Q. 2(b), Dec. 15, Q. 1(b), Dec. 19, 5 Marks)

Based on the refractive index classification of fiber is as follows:

- **Step Index Fibres:** It consists of a core surrounded by the cladding, which has a single uniform index of refraction.
- Graded Index Fibres: The refractive index of the optical fibre decreases as the radial distance from the fibre axis increases.

(A) Step index fiber

(i) 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.

(ii) This is because the refractive index profile for this type of fiber makes a step change at the core–cladding interface, as indicated in Fig 1.60.1, which illustrates the two major types of step index fiber.

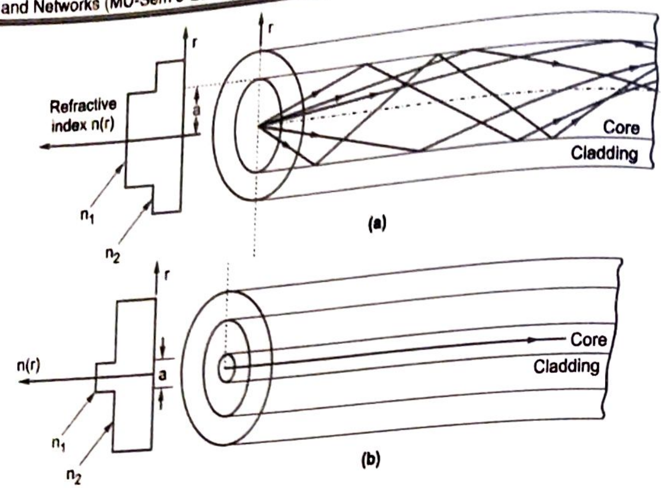


Fig. 1.60.1 : The refractive index profile and ray transmission in step index

(a) Multimode step index fiber (b) Single-mode step index fiber

The refractive index profile may be defined as :

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

For Multimode Step Index Fiber

- Core diameter: 100 to 300 μm
- Cladding diameter: 140 to 400 μm
- Buffer jacket diameter: 400 to 1000 μm
- Numerical aperture: 0.16 to 0.5

(B) Graded Index fibers

i. 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. shown in Fig. 1.60.2.

ii. This index variation may be represented as:

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

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.

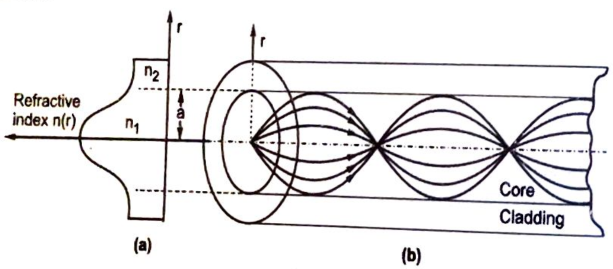


Fig. 1.60.2 : The refractive index profile and ray transmission in a multimode graded index fiber

For Multimode Graded Index Fiber

- Core diameter: 50 to 100 μm
- Cladding diameter: 125 to 150 μm
- Coating diameter: 200 to 300 μm
- Buffer jacket diameter: 400 to 1000 μm
- Numerical aperture: 0.2 to 0.3

iii. Above equation 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 α = ∞, a parabolic profile when α = 2 and a triangular profile when α = 1.

iv. This range of refractive index profiles is illustrated in Fig 1.60.3.

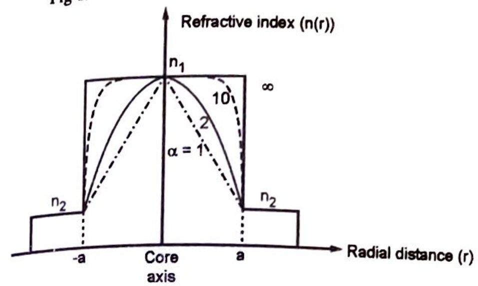


Fig. 1.60.3

Standard single-mode fiber

- Cladding diameter: generally 125 μm
- Coating diameter: 200 to 300 μm
- Buffer jacket diameter: 500 to 1000 μm
- Numerical aperture: 0.08 to 0.15, usually around 0.10.

UEx. 1.60.1 : (MU – Q. 6(b), May 16, 10 Marks)

A silica optical fiber with core diameter large enough to be considered by Ray theory has a core refractive index of 1.5 and cladding refractive index of 1.47.

Determine:

(i) The critical angle.

(ii) The NA

(iii) The acceptance angle

☑ **Soln. :**

Given : $n_1 = 1.5, \; n_2 = 1.47$

To Find:

1 Critical angle (θ_c)

2. Numerical aperture (N.A)

3. Acceptance angle (θ_a)

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.47}{1.5}\right)$$

$$\theta_c = 78.52°$$

$$\text{Critical angle } (\theta_c) = 78.52°$$

$$N.A = \sqrt{n_1^2 - n_2^2} = \sqrt{1.5^2 - 1.47^2}$$

$$N.A = 0.2984$$

Numerical aperture (N. A) = 0.2984

$$N.A = \sin\theta_a$$

$$0.2984 = \sin\theta_a$$

$$\theta_a = 17.36°$$

Acceptance angle (θ_a) = 17.36°

UEx 1.60.2 (MU - Q. 2(a), May 18, 10 Marks)

A silica optical fiber has core refractive index of 1.4 and the cladding index of refraction is 1.35. Determine :

(i) The critical angle (ii) Numerical aperture

(iii) The acceptance angle

☑ **Soln. :**

Given : $n_1 = 1.4, \; n_2 = 1.35$

(i) The critical angle ϕ_c at the core–cladding interface is given by Eq. 1.18.3.

$$\phi_c = \sin^{-1}(n_2/n_1) = \sin^{-1}(1.35/1.4)$$

$$= 74.64°$$

(ii) The Numerical Aperture (NA) is given by Eq.1.21.5:

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

$$= (1.4^2 - 1.35^2)^{1/2}$$

$$= (1.96 - 1.82)^{1/2}$$

$$= 0.37$$

(c) Considering Eq. (1.20.8) the acceptance angle in air θ_a is given by :

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.37$$

$$= 21.71°$$

Chapter Ends...

❑❑❑