CHAPTER- 1

INTRODUCTION TO OPTICAL FIBER COMMUNICATION

CONTENTS

1. TECHNICAL TERMS

1. **Numerical Aperture:**Numerical aperture (N.A) of the fiber is the light collecting efficiency of the fiber and is the measure of the amount of light rays that can be accepted by the fiber.
2. **Acceptance Angle**: The maximum angle with which a ray of light can enter through the entrance end of the fiber and still be totally internally reflected is called acceptance angle of the fiber.
3. **Relative refractive Index Difference**: Relative refractive index difference is the ratio between the refractive index difference (of core and cladding) and refractive index of core.
4. **Meridional rays**: Meridional rays are the rays following Zig Zag path when they travel through fiber and for every reflection it will cross the fiber axis.
5. **Skew rays**: Skew rays are the rays following the helical path around the fiber axis when they travel through the fiber and they would not cross the fiber axis at any time.
6. **Intra Modal Dispersion**: Intra Modal dispersion is pulse spreading that occurs within a single mode. The spreading arises from finite spectral emission width of an optical source. This phenomenon is also called as group velocity dispersion.
7. **Splices:** The splices are generally permanent fiber joints, whereas connectors are temporary fiber joints. Splicing is a sort of soldering.
8. **Modes** :The number of paths for the light rays in the fiber
9. **Numerical aperture:** The light gathering or light collecting ability of an optical fiber.
10. **Step index:** Refractive index of core is uniform throughout & undergoes a abrupt change at cladding is called step-index fiber.
11. **Graded index:** The core of refractive index is made to vary as a function of radial distance from the center of fiber.

2. INTRODUCTION

2.1 History of Optical Fiber Communication

Optical fiber communication owes its discovery to many researchers from 1880 until today. In 1977, a small city in Italy, by the name of Torino, was the first to get a metropolitan fiber optic communication system. Today the technology has been developed to provide data transfer speeds of 1 Petabit per second. To put that in perspective, that kind of speed will allow you to transfer 5000 HD movies in one second.

2.2 What is optical fiber communication?

If you have seen one of the following decorative pieces in your house or anywhere, then you have seen a very basic fiber optic cable. The light is brighter at the end because that is the opening of the cable. The same principle of light transmission is used to transfer data, giving rise to a whole new field of communication.

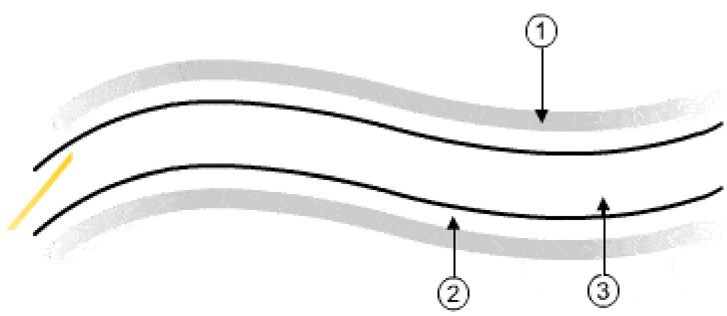
Fancy fiber optic lamp

The cables used for actual communication are a bit different from your fancy lamp. They are protected within a thick cable and are manufactured using unique processes to increase their lifespan.

Optic fiber cable

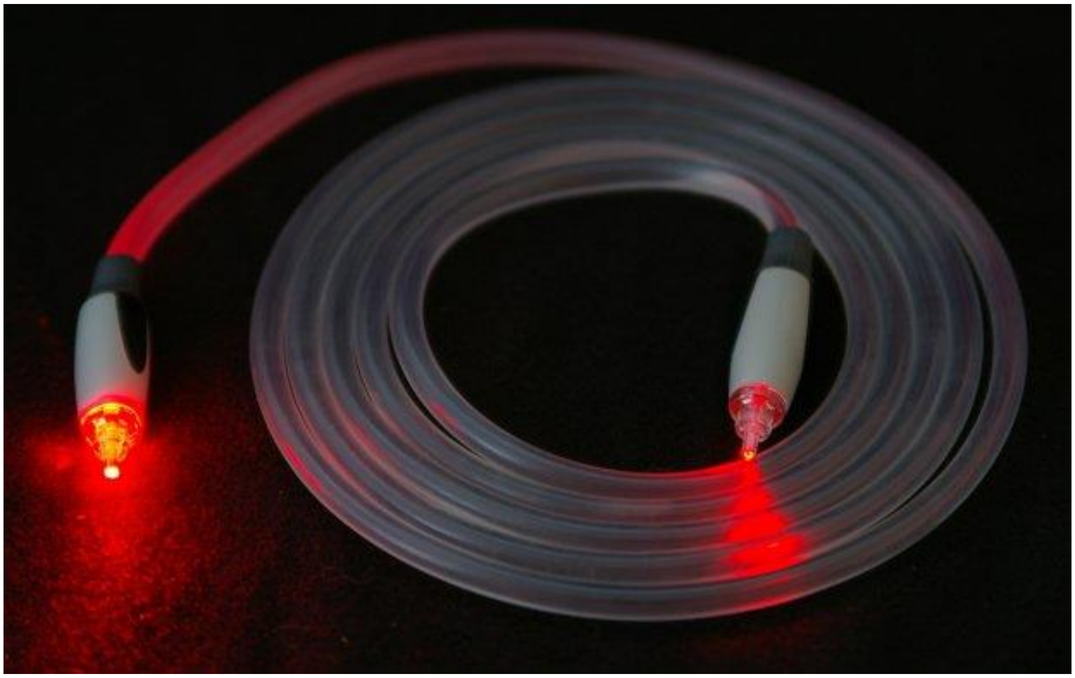
Optical fiber communication is a method of transmitting data in the form of light using special cables, or fibers, made out of glass. The *light source* is usually a laser or an LED.

Imagine a flexible tube entirely made out of a cylindrical mirror. Take a flashlight and flash it through one end of the tube. The light entering the tube is almost entirely received at the other end. This principle is the basis of total internal reflection.



Total internal reflection

Fiber optic cables are made out of glass instead of mirrors. These glass tubes are extremely thin and flexible. They will carry light from one end to the other, even if they are twisted. If you are a college student, you are most likely to use a fiber optic cable like the one shown below during your practical sessions.



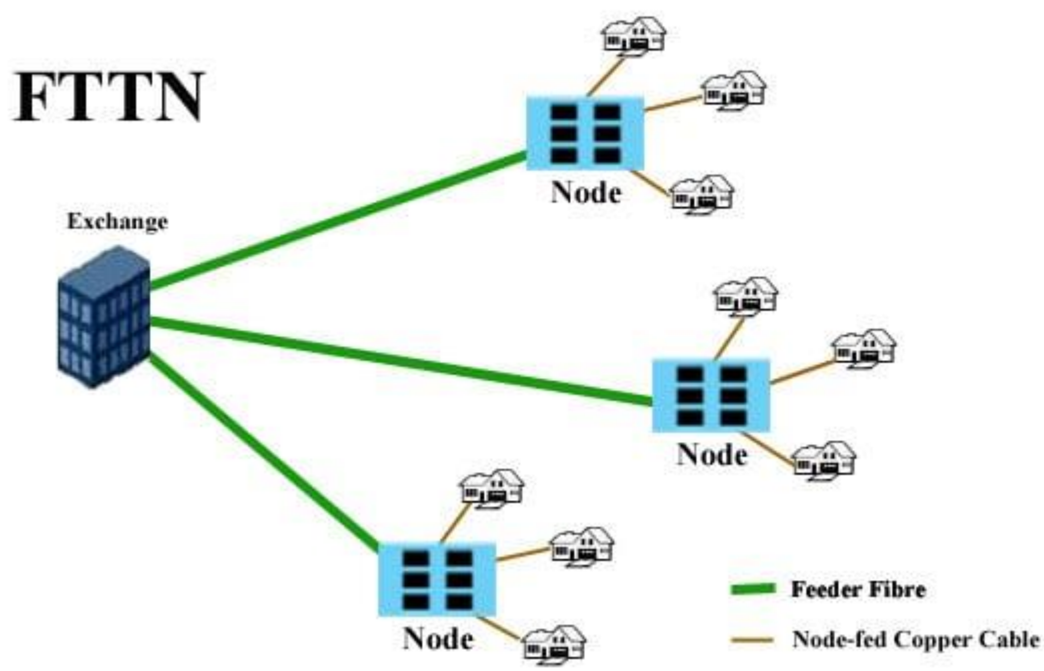
2.3 How is it better than copper?

Since it uses light to transfer data via a hollow cable, it doesn't need to experience the kind of resistance an electrical signal would encounter in a metallic wire. This means less power to function, no heat dissipation, and mostly no recurring costs.

The most alluring factor that trumps fiber optics over copper wires is the fact that it can handle way more bandwidth. Imagine you are on a highway. Think of bandwidth as a highway lane. In a copper wire, the electrical signal can have, let's say, a highway of 5 lanes. In a fiber optic cable, the light signal can have 100 highway lanes. Thus it allows more transmission of data, resulting in faster speeds.

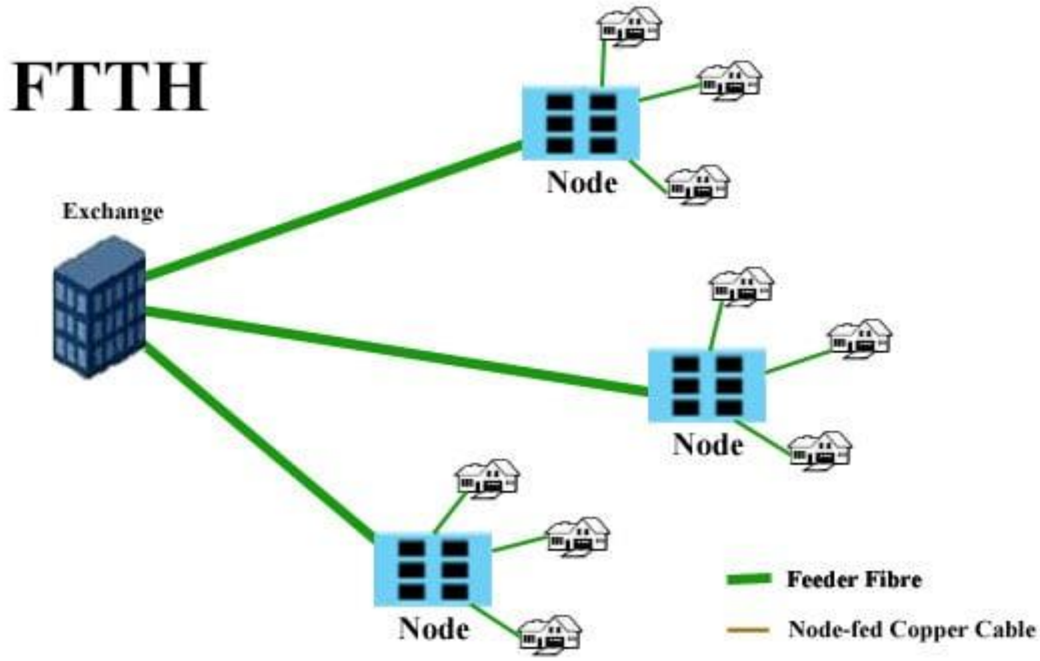
2.4 Do I have an optical fiber communication network providing connectivity to my house?

Yes and no. It is costly to replace all the traditional copper wire networks with optical fibers. It will happen gradually. The chances are that your ISP (Internet Service Provider), has a vast network of optical fibers in your area, but it does not exactly get to your house. The 'last mile' of many optical fiber communication networks are usually copper. In plain language, this means that your connection is a combination of both fiber and copper. The fiber network reaches your residential area and then branches out into copper wires. These copper wires then provide connectivity to individual residences/offices. This kind of connection is called Fiber To The Node (FTTN).



Fiber To The Node (Source)

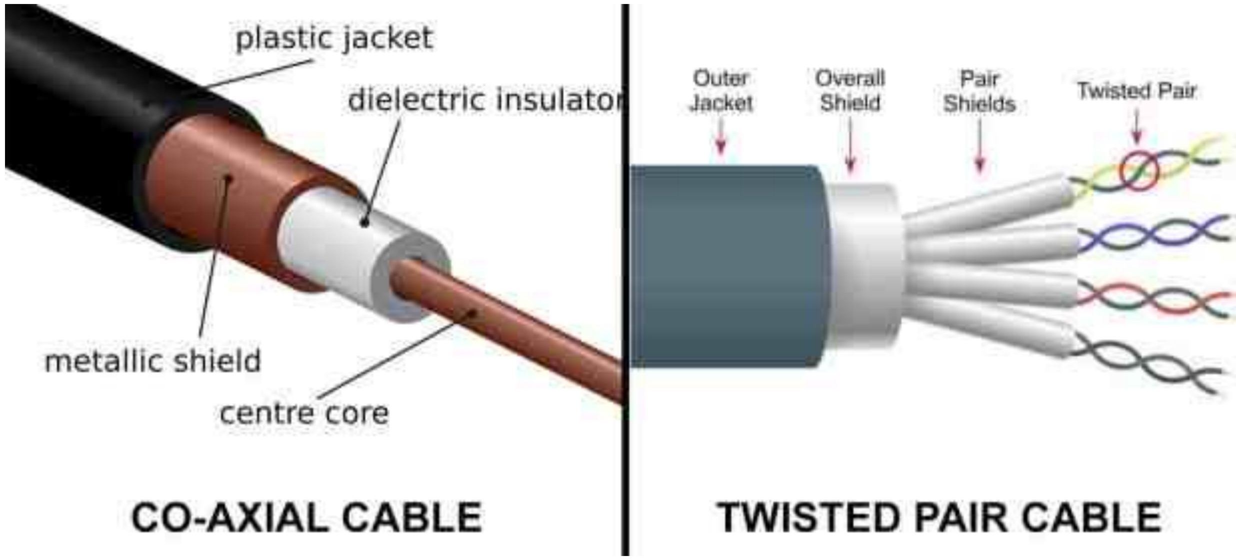
Some ISPs provide a fiber-optic connection to their consumers' doorsteps. This kind of connection is called Fiber To The Home (FTTH).



Fiber To The Home

2.5 What is going to happen to copper wires, and what is the future of optical fiber communication?

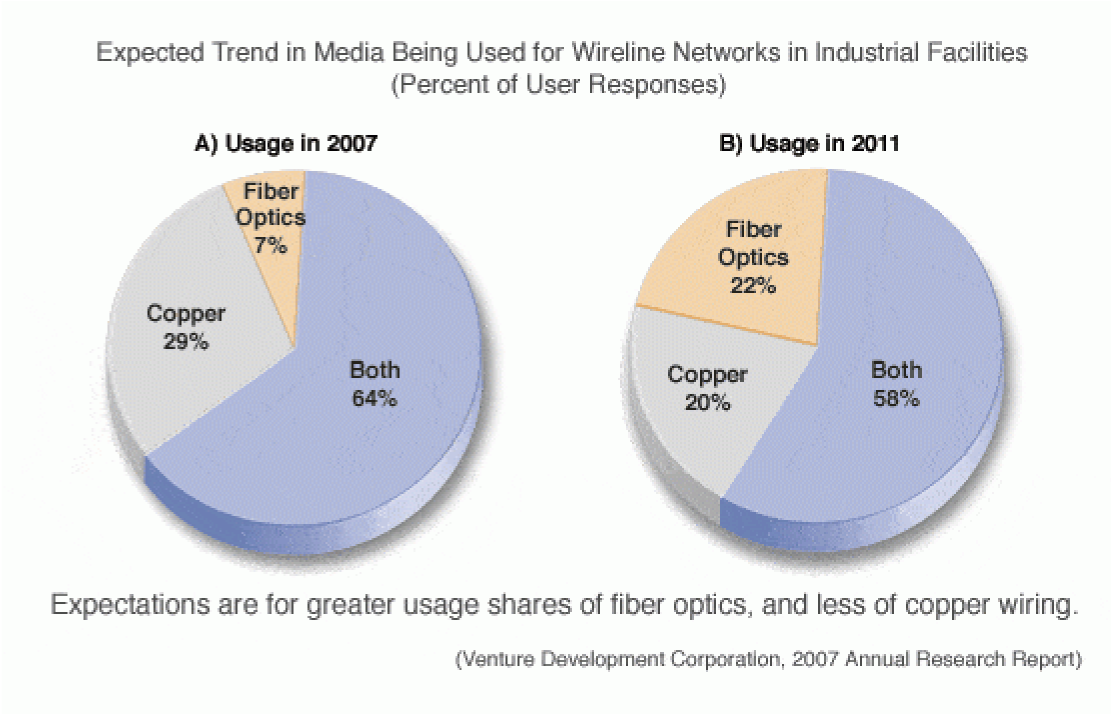
The copper cable industry is putting up a good fight. To begin with, the industry came up with the co-axial copper wires (see image below) in the early 1930s to increase the number of channels that could be transmitted to TV. They have continually upgraded their technologies and are now trying to launch Category 8 of the twisted pair copper wire technology, which would give an increased bandwidth of 2000MHz and speeds more than 10Gbps.



Co-axial and twisted pair cables

But the problem is more inherent. It cannot be overcome with simple upgrades to existing techniques. On a basic level, copper cables use electrons to transmit data, whereas optical fiber cables use photons. As a result, electrons face resistance, which means they need more power to cover larger distances. This issue is omnipresent.

In contrast, the optical fiber communication industry has had it relatively easy. It didn't face a lot of issues in upgrading its technology. There has been a gradual increase in bandwidth. Methods to decrease losses have been devised, and the costs of installation are decreasing.



2.6 Why should I study optical fiber communication? What are the job requirements to be an Optical Communications Engineer?

The simple answer would be because internet traffic has and will grow at a tremendous rate. The size of the content that we are consuming is also increasing. 4k video streaming is a prime example of that fact. This means that new networks need to be established in new, previously untapped areas to provide connectivity. Similarly, existing copper networks need to be upgraded to provide customers a high-speed, low latency, high bandwidth connection. If you would like to work on this technology that can provide fast connectivity to people, then take a look at a sample entry-level job requirement for the post of Optical Communications Engineer.

2.7 Advantages:

- High speed.
- Low loss
- Flexibility

- Wide channel
- Low size & weight
- Low interruption(interference & crosstalk)
- Broad bandwidth

2.8 Disadvantages:

- High cost
- Maintenance is difficult
- Brittleness

2.9 WDM:

To use multiple sources operating at slightly different wavelengths to transmit several independent information streams over the same fiber.

3. EVOLUTION OF FIBER OPTICS SYSTEMS:

In 1880, Alexander Graham Bell experimented with an apparatus called Photo phone. It was a device constructed from mirror that transmitted sound waves over a beam of light.
There are three generations in fiber optics:

3.1 First Generation:

- In 1977 ,GTE in Los Angeles & AT & T in Chicago were introduced. In transmitter side they used LASER, it has high output power, high frequency of operation, wide bandwidth.
- The operating wavelength is 800 to 900nm i.e., around 850nm.
- Fiber material is GaAS and bit rate is 45 to 140 Mbps and repeater spacing is 10kms.

3.2 Second Generation:

- The operating wavelength is around 1300nm.

- Fiber material is Indium Gallium Arsenide, Phosphorus and bit rate is 155 to 622 Mbps and repeater spacing is 40kms.
- Both single mode and multimode fibers are used in LAN, & its bit rate is 10 to 100Mbps.
- In 1984, Single mode fibers were used for larger bandwidth.

3.3 Third Generation:

- The operating wavelength is around 1550nm.
- Bit rate is 2.5 Gbps and repeater spacing is 90kms.
- In 1970’s start to use WDM to boost the transmission capacity. In 1990’s combination of EDFA & WDM was used to boost fiber capacity
- In 1996 onwards bit rate is increased around 10 Gbps by using high quality lasers.
- Introduce the optical amplifier in 1989 gave a major boost to fiber transmission capacity.
- GaAlAs was first introduced but successful & widely used devices are Erbium Doped FiberAmplifier(EDFA) ->1500nmandPrascodymiumDopedFiber Amplifier(PDFA)->1300nm.
- The use of WDM offers a further boost in fiber transmission capacity.
- The basis of WDM is to use multiple sources operating at slightly different wavelengths to transmit several independent information streams over the same fiber.Mid-1990’s, a combination of EDFAs & WDM was used to boost fiber capacity to even higher levels and to increase the transmission distance.

4. ELEMENTS OF AN OPTICAL FIBER TRANSMISSION LINK:

- The basic components in the optical fiber communication are light source, the light signal transmitter, the optical fiber & photo detecting receiver.
- The other elements include fiber and cable splices and connectors, regenerators, beam splitters and optical amplifiers.

- The information signal to be transmitted may be voice, video or computer data. The first step is to convert the information into a form compatible with the communications medium.

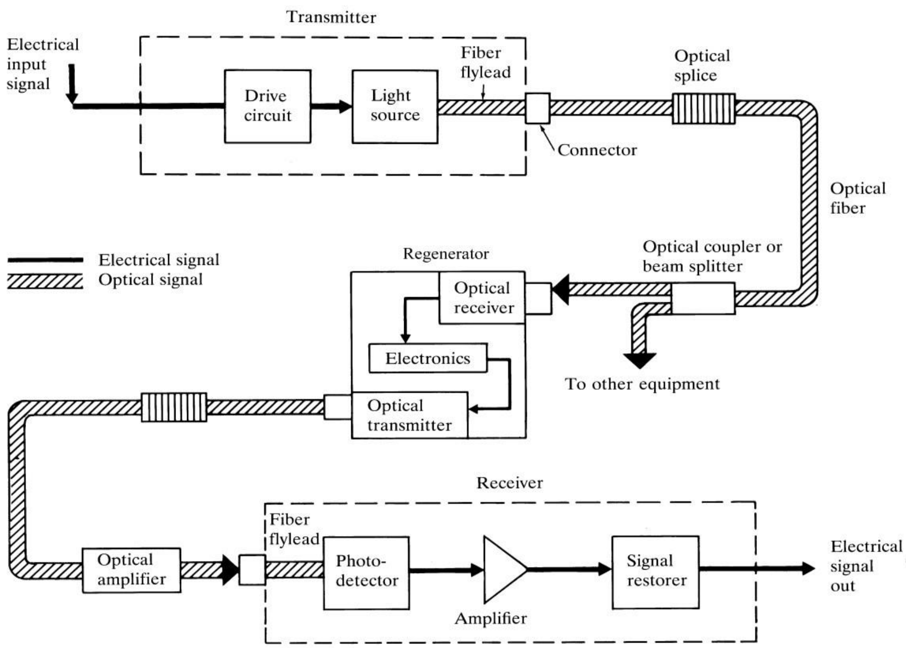


Figure: 1.1 Major elements of an Optical fiber transmission link

5. BASIC LAWS & DEFINITIONS:

5.1 Refractive Index (or) Index of Refraction:

The ratio of speed of light in free space to the speed of light in medium

$$n = c/v$$

n-> 1.00 for air, 1.50 for glass, 1.33 for water, 2.42 for diamond

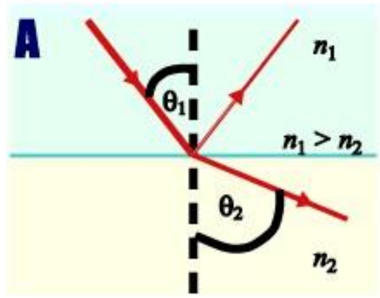


Figure:1.2Law of reflection

5.2 Angle of incidence(φ1):

- The angle at which light strikes a surface with respect to normal is called angle of incidence.
- The angle of incident light ray determines whether the ray will be reflected or refracted.

5.3 Angle of Reflection (φ2):

The angle at which light is reflected from a surface is called angle of reflection. The law of reflection is φ1= φ2.

5.4 Snells law:

It states that how the light ray reacts when it meets the interface of two media having different refractive indexes.

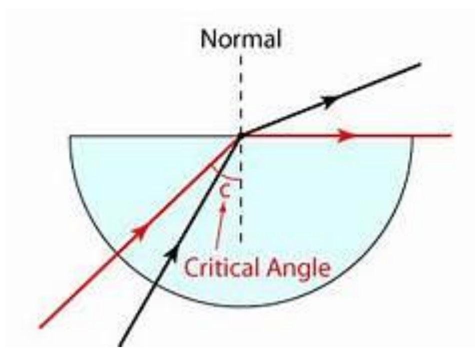
Snell's Law

$$\frac{\sin(i)}{\sin(r)} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

5.5

5.5 Critical angle:

The value of angle of incidence at which the angle of refraction is 90° is called critical angle.



5.6 Total Internal Reflection:

When the light ray strikes the interface at an angle greater than the critical angle, the light ray does not pass through the interface into the glass. When this occurs, the angle of reflection **φ2** is equal to angle of incidence **φ1**. This action is known as total internal reflection.

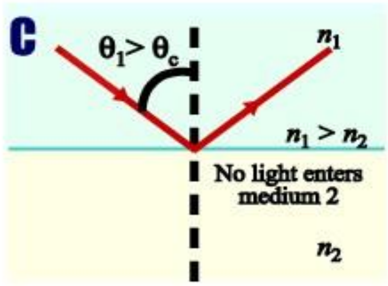


Figure:1.4 Total internal Reflection

Condition:

i.n1>n2 ii.φ1> φ2

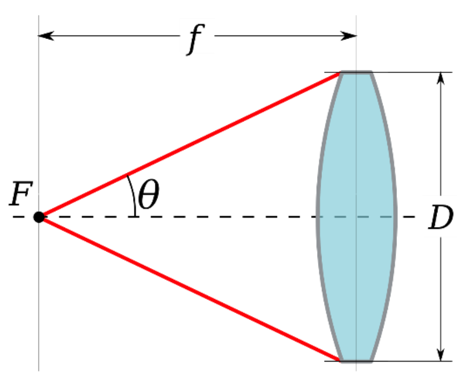
5.7 Numerical aperture:

It is used to describe the light gathering or light collecting ability of an optical fiber. It is referred as figure of merit commonly used to measure the magnitude of acceptance angle. The numerical aperture for light entering the glass fiber from an air medium is described mathematically as

NA=sinϴin

Where ϴin-> acceptance angle

Acceptance angle is the maximum angle to the fiber axis at which light may enter the fiber axis in order to be propagated.



6. RAY OPTICS:

There are 2 types of rays in fiber.

i.Meridional rays.

ii.Skew rays.

6.1 Meridional rays:

- These rays are confined to the meridian planes of fiber, which are the planes the contain the axis of symmetry of the fiber.
- It lies in a single plane, its path is easy to track as it travels along the fiber. It can be classified into

  i.Bound rays.

  ii.Unbound rays.

6.1.1 Bound rays:

That are trapped in the core and propagate along the fiber axis according to the laws of geometrical optics.

6.1.2 Unbound rays:

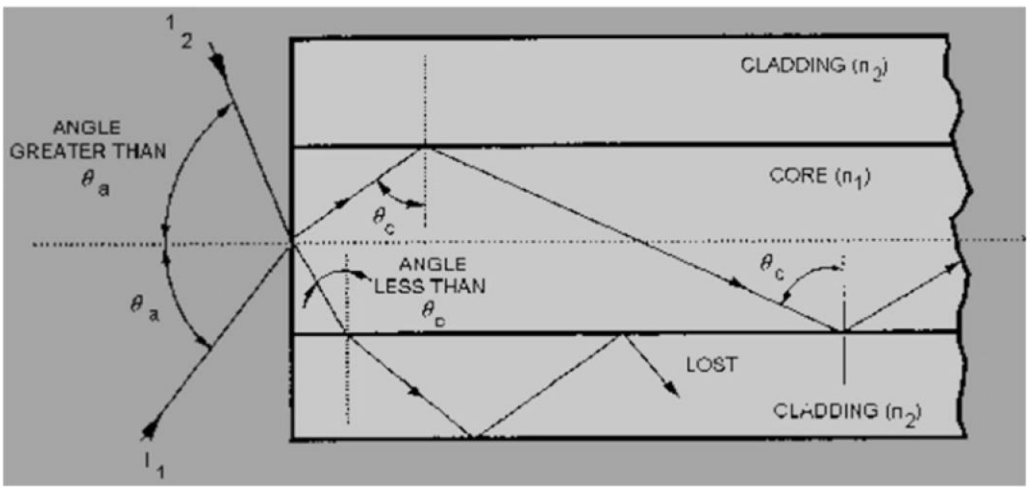
That are refracted out of the fiber core.

6.2 Skew rays:

- These rays are confined to single plane, but instead tend to follow a helical type path along the fiber.
- These rays are more difficult to track as they travel along the fiber, since do not lie in a single plane.
- A greater power loss arises when skew rays are included in analysis that are actually leaky rays. These leaky rays are only partially confined to the core of circular optical fiber and attenuate as light travels along the optical waveguide.

6.3 Meridional rays for Step index fiber:

- The light ray enters the fiber core from a medium of refractive index n at an angle Θo with respect to fiber axis and strikes the core cladding interface at an normal angle φ.
- If it strikes this interface at such an angle that it is totally internally reflected, then meridional ray allows a zigzag path along the fiber core.



Meridional ray optics representation of the propagation mechanism in an optical waveguide

From Snells law, the minimum angle φmin that supports total internal reflection for meridional ray is

$$\sin \varphi_{min} = n2/n1$$

□The rays striking the core-cladding interface at angles less then φmin will refract out of core and be lost in cladding. By applying Snell's law to the air-fiber face boundary, then the relationship is

7. MODES:

The number of paths for the light rays in the fiber. The set of electromagnetic waves propagate inside any wave guide. There are two types of modes are.

i. **Single mode fiber:**

Only one signal can propagate inside along the optical fiber parallel to core axis.

ii. **Multimode fiber:**

The light takes many paths through the core. The number of paths possible for multimode fiber cable depends on frequency of light signal, refractive index of core and cladding and core diameter.

Index profile:

It is a graphical representation of value of refractive index of core diameter.

According to index profile we can divide the configuration into 3 types of modes.

i. Single mode step index fiber. ii. Multimode step index fiber.

iii. Multimode graded index fiber.

Step index:

Refractive index of core is uniform throughout & undergoes a abrupt change at cladding is called step-index fiber.

Graded index:

The core of refractive index is made to vary as a function of radial distance from the center of fiber.

Advantages of cladding:

- Used to reduce the scattering loss.
- It protects the core from absorbing surface.
- It adds mechanical strength to the fiber.

Fiber structure:

- Step index fiber

  Graded index Fiber

Difference between Step index Fiber and Graded index Fiber

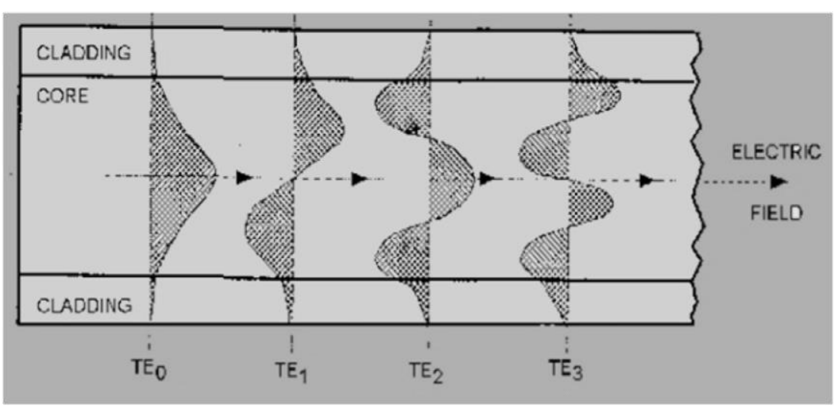
STEP INDEX	GRADED INDEX
Refractive index of core is uniform	Not uniform & is made to vary as a function of radial distance from the center of fiber
Light rays are meridional	Light rays are skew rays
No distortion for single mode fiber &signal distortion in multimode fiber	Distortion is less because of self focusing effect & light rays reach the fiber at the same time due to helical path or light propagation
Attenuation : Single mode fiber: less effect Multimode fiber: more effect	Less attenuation
Numerical Aperture: Single mode fiber: less efficiency Multimode fiber: high efficiency	Less efficiency
Bandwidth single mode fiber-> ghz	Theoretically infinite bandwidth

8. MODE THEORY OF CIRCULAR WAVE GUIDE:

- In optical fiber, the core cladding boundary conditions lead to coupling between electric & magnetic field components.
- This gives rise to hybrid modes, which makes optical waveguide analysis more complex than metallic waveguide analysis.
- The hybrid modes are HE or EH modes depending on whether the transverse electric or magnetic field is larger for that mode. The lower order modes are HE_{11} and TE_{01}.
- Fibers usually are constructed so that the difference in the core & cladding refractive index is very small, then only four field components exists(n1-n2<<1).
- These 4 field components are called linearly polarized modes & labeled as LP_{jm} , where j & m are integers designating mode solutions.
- Each LP_{0m} mode is derived from HE_{1m} mode and each LP_{1m} mode comes from TE_{0m} , TM_{0m} and HE_{0m} modes. Thus the fundamental LP_{01} mode corresponds to HE_{11} mode.

8.1 Overview of Modes:

1. Guided modes- waves should be propagated inside the core.
2. Radiated modes- unbounded rays.
3. Leaky Modes- more amount of power in cladding region.



Electric field Distributions for the lower-order guided modes

The order of a mode is equal to number of field zeros across the guide.

- The order of mode is also related to the angle that the ray congruence corresponding to this mode makes with the plane of waveguide or axis of fiber.
- The plot shows that electric field of guided modes are not completely confined to the central dielectric slab i.e., they do not go to zero at core – cladding interface & extends into the cladding.
- The field vary harmonically in core region of refractive index n1 and decay exponentially outside of this region of refractive index n2.
- In lower- order modes, the fields are tightly concentrated near the center of slab or axis of an optical fiber, with little penetration into cladding region.
- In higher-order modes, the fields are distributed more towards the edge of guide and penetrate further into the cladding region.
- Due to this penetration, radiated modes are propagated in cladding region.
- In the leaky modes the fields are confined partially in the fiber core & attenuated as they propagate along the fiber length due to radiation and tunnel effect.

8.2 Tunnel effect:

The leaky modes are continuously radiating their power out of the core as they propagate along the fiber. This power radiation out of the wave guide results from quantum mechanical phenomenon known as tunnel effect.

SAMPLE QUESTIONS

PART-A

1. Define Acceptance angle.
2. Define mode field diameter.
3. Write the expression for refractive index in the graded index fiber.
4. What are the two type's rays in optical fibers? Explain.
5. Define refractive index.
6. Write the expression for V number and number of modes?
7. Draw the single fiber structure?
8. Difference between single mode and multimode fiber.
9. Difference between step index and graded index fiber.
10. State the two conditions for total internal reflection.
11. What are the connecting elements used in optical fiber &write its necessity.
12. Write the expression fir index difference.
13. What are the types of modes in optical fiber?
14. Difference between V number and Numerical aperture.
15. Define Critical angle.
16. State Snell's law.
17. Define Birefringence.
18. Define fiber beat length.
19. Write the advantages of optical fiber.
20. What is the fundamental parameter of single mode fiber?

21. Give the expression for the effective no. of modes guided by a curved multimode fiber.

22. Define normalized propagation constant.

23. Give the relationship between rays & modes of optical fiber.

24. Write the advantages & disadvantages of ray optic theory.

25. An optical fiber has the following data n1=1.53, n2=1.5. Calculate (i) Critical Angle.

(ii) Acceptance angle. (iii) NA.

26. Calculate V number and the number of modes present in the GI fiber with n1=1.5 n2=1.4 and with the core radius of 50µm operating at 1500 nm.

27. The SM fiber has the beat length of 8 cm at 1300nm.Find the Birefringence.

28. The SM Fiber operating at the wavelength of 1300nm with n1=1.505 & n2=1.502. Find the NA&core radius.

29. A SI fiber has the normalized frequency of 26.6 at 1300nm wavelength. If the core radius is

25 µm. Find NA &mode Volume.

30. A GI fiber has the core with parabolic refractive index profile which has the diameter 50µm

& NA=0.2. Estimate the number of guided modes propagating at a wavelength of 1 µm.

31. A typical relative refractive index difference for an optical fiber is 1%. Estimate NA.When n1=1.47.

32. Define weakly guiding fibers.

33. Give the expression for the no. of modes in a multimode GI fiber.

PART-B

1. Explain the types of modes in optical fiber.

2. Differentiate step index and graded index fiber with suitable diagram.

3. A multimode step index fiber with core diameter of 80μm and a relative index of 1.5%is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48, estimatethe normalized frequency for the fiber and the number of guided modes.
4. Discuss the propagation of modes in single-mode fiber.
5. Discuss the structure of graded index fiber.
6. Discuss the signal distortion in single mode fibers.
7. Briefly explain the evolution of fiber optic system.
8. Explain the mode theory of circular waveguides.