Fiber Optics

Introduction

An optical fiber is a flexible, transparent cable made by drawing glass (silica) or plastic to a cylindrical wire of diameter slightly thicker than that of a human hair.

Fibers are used instead of metal wires because signals travel along them with less loss

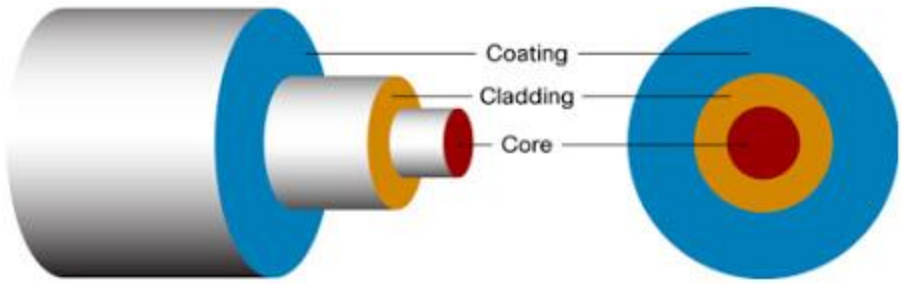
Fibers are immune to electromagnetic interference, a problem from which metal wires suffer.

Fibers are also used for illumination and imaging, and are often wrapped in bundles so they may be used to carry light into, or images out of confined spaces.

Specially designed fibers are also used for a variety of other applications, some of them being fiber optic sensors and fiber lasers.

Components of an optical fiber

A typical optical fiber comprises three main co-axial sections: Core, Cladding and outer Jacket/protective buffer coating.



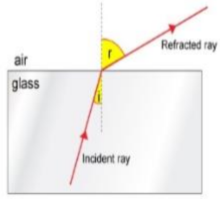
<u>Core</u>: The innermost cylindrical region which carries light. It is the denser medium and is made up glass/ plastic.

<u>Cladding</u>: The middle layer, which serves to confine the light to core. It is the rarer medium as its refractive index is slightly less than that of core.

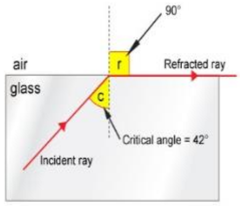
<u>Outer jacket/ Protective buffer coating:</u> The outermost layer which protects the fiber from physical damage and environmental effects.

Principle of optical fiber: Optical fibers work on the principle of total internal reflection.

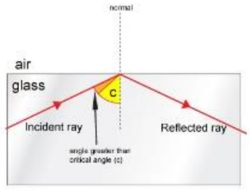
➢ When light travels from denser to rarer medium, it refracts away from the normal.



➢ At a particular angle of incidence, Called critical angle, the refracted ray traces the boundary such that angle of refraction becomes 90^0.



➢ When the angle of incidence of the light ray is greater than the critical angle then no refraction takes place. Instead, all the light is reflected back into the denser material . This Phenomenon is called **total internal reflection**.



So for total internal reflection to occur

❖ The light must travel from a denser medium to a rarer medium.
❖ Angle of incidence should be greater than the critical angle.

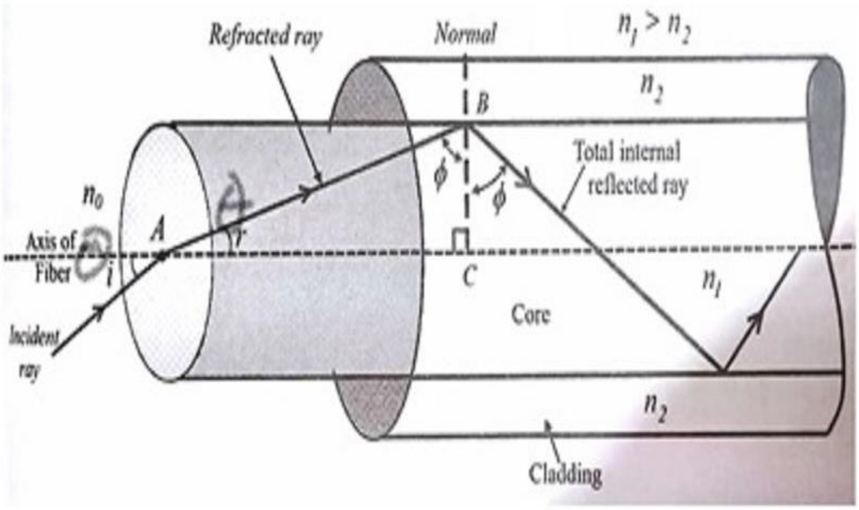
Acceptance angle and Numerical aperture

The maximum possible launching angle with the axis of the fiber up to which a light ray accepted into the core of the fiber is called ***acceptance angle***. By rotating the acceptance angle about the core axis, a cone will be appeared and is called **acceptance cone**. The light rays that enter the fiber beyond acceptance cone refracts into cladding.

The sine of the acceptance angle is called **numerical aperture**. So it is a measure of light collecting capacity of given optical fiber.

Expression for Numerical aperture and Acceptance angle:

Consider an ***optical fiber*** which consists of a core with refractive index n_1 and a cladding with refractive index n_2 such that ($n_1 > n_2$). The refractive index of the launching medium is n_0. Let us consider a light ray enters the fiber making an angle $\boldsymbol{\theta}_i$ with its axis. AB is the refracted ray that makes an angle $\boldsymbol{\theta}_r$ with the axis and strikes core-cladding interface at an angle $\boldsymbol{\phi}$, which is greater than critical angle $\boldsymbol{\phi}_c$. Thus, it undergoes total internal reflection at the interface.



It is clear from the figure that as the value of angle θ_i increases, θ_r will also increase and ϕ will decrease.For light propagation through the fiber, it is compulsory that the value of angle ϕ should not be less than critical angle ϕ_c. Thus we may increase the incident angle θ_i up to a certain value that is acceptance angle θ_{max}.

Now, by applying Snell's law at the launching end

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0} \quad \text{or} \quad \sin\theta_i = \frac{n_1}{n_0}\sin\theta_r \tag{1}$$

But in right angled triangle ABC, $\sin\theta_r = \sin(90^\circ - \emptyset) = \cos\emptyset$

$$\therefore \quad \sin\theta_i = \frac{n_1}{n_0}\cos\emptyset \tag{2}$$

When $\phi = \phi_c$ then $\theta_i = \theta_{max}$

$$\text{Thus,} \quad \sin\theta_{max} = \frac{n_1}{n_0}\cos\emptyset_c \tag{3}$$

Now, applying Snell`s law at core-cladding interface,

$$\frac{\sin \emptyset_c}{\sin 90^\circ} = \frac{n_2}{n_1} \qquad \text{or} \qquad \sin \emptyset_c = \frac{n_2}{n_1}$$

or $$\sqrt{(1 - cos^2 \emptyset_c)} = \frac{n_2}{n_1}$$

or $$1 - cos^2 \emptyset_c = \frac{{n_2}^2}{{n_1}^2}$$

$\therefore$ $$\cos \emptyset_c = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_1} \qquad (4)$$

Hence, $$\sin \theta_{max} = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0} \qquad (5)$$

Therefore acceptance angle

$$\theta_{max} = \sin^{-1} \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0}$$

For air $n_0 = 1$

$$\boxed{\theta_{max} = \sin^{-1} \sqrt{{n_1}^2 - {n_2}^2}} \qquad (6)$$

Fractional refractive index change or relative refractive index

Fractional refractive index change or relative refractive index is the ratio of difference between the refractive index of core and cladding to the refractive index of core. It is denoted by Δ. *i.e.*

$$\Delta = \frac{(n_1 - n_2)}{n_1} \tag{7}$$

Δ is always positive and generally of the order of 1/100.

Numerical aperture

It is a very important parameter, which is a measure of amount of light that can be accepted by the fibre. It is defined as the sine of the acceptance angle, *i.e.*,

$$NA = \sin\theta_{max} = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0} \tag{8}$$

For air $n_0 = 1$

$$\therefore \qquad NA = \sin\theta_{max} = \sqrt{{n_1}^2 - {n_2}^2} \tag{9}$$

Now, $${n_1}^2 - {n_2}^2 = (n_1 + n_2)(n_1 - n_2) = \frac{(n_1 + n_2)}{2}\frac{(n_1 - n_2)}{n_1} 2n_1$$

We can take approximately $\frac{(n_1 + n_2)}{2} \approx n_1$ and since $\Delta = \frac{(n_1 - n_2)}{n_1}$

$$\therefore \qquad {n_1}^2 - {n_2}^2 = 2n_1^2\Delta$$

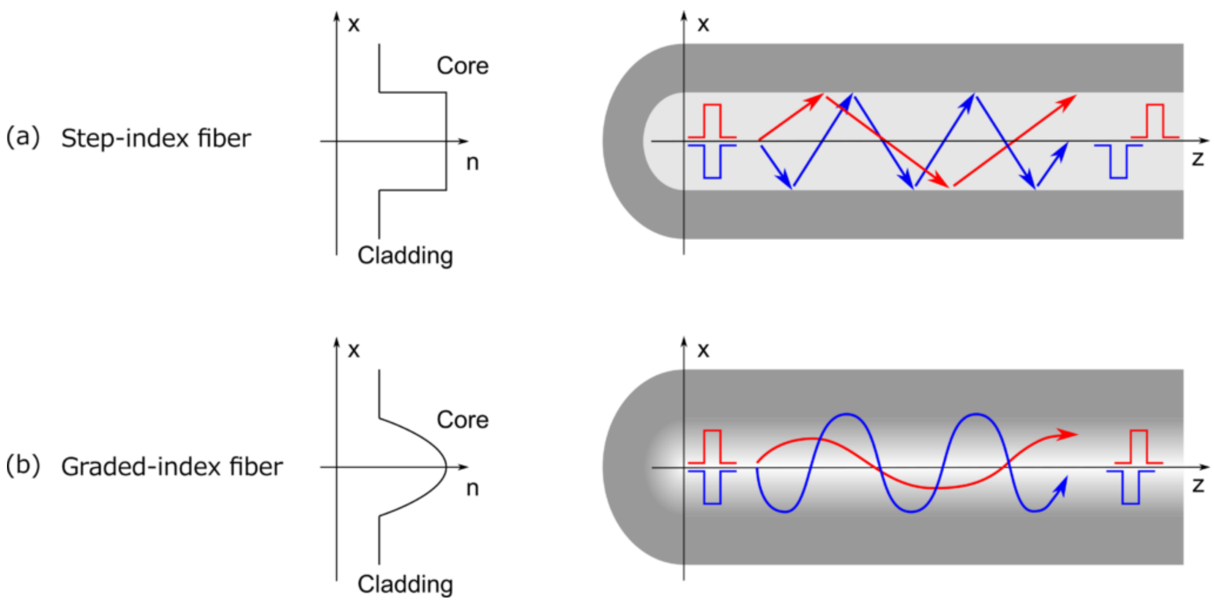
Or

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

The values of NA typically range from about 0.1 to 0.5.

Step index fiber

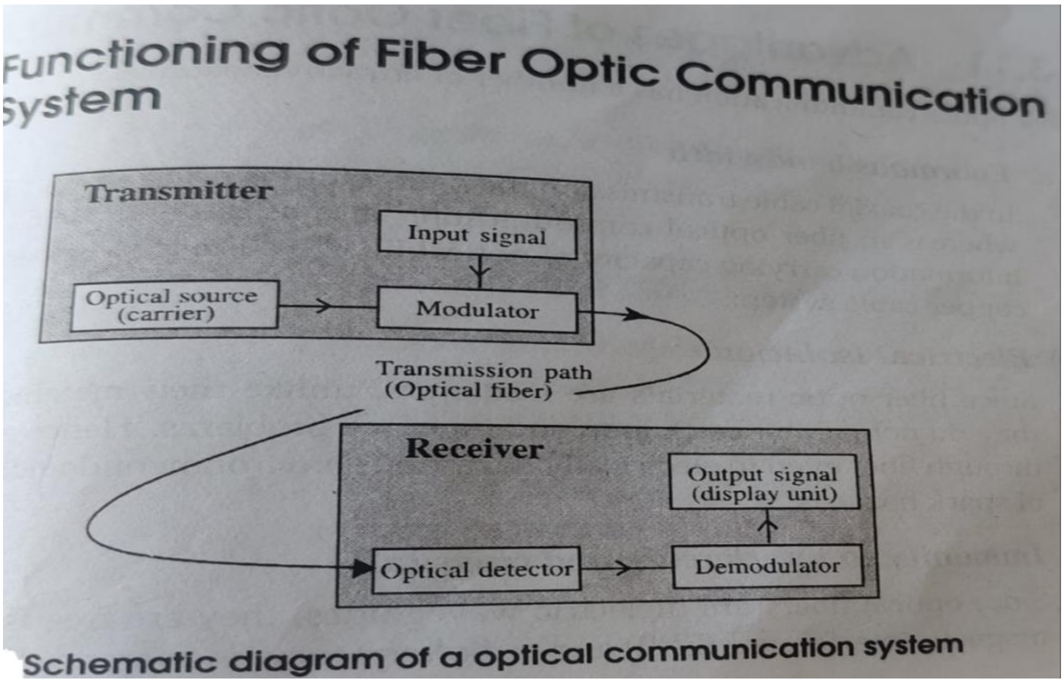
1. Step index fiber is a fiber in which the core is with uniform refractive index and there is a sharp decrease in the index of refraction at the cladding.
2. Step index fiber is found in two types, that is mono mode fiber and multimode fiber.
3. Index profiles are in the shape of step.
4. The light rays propagate in *zig–zag* manner inside the core.
5. Signal distortion is more in case of high-angle rays in multimode step index fiber. In single mode step index fiber, there is no distortion.
6. This fiber has lower bandwidth.
7. The diameter of the core is between 50-200µm in the case of multimode fiber and 10µm in the case of single mode fiber.
8. Attenuation of light rays is more in multimode step index fibers but for single mode step index fibers, it is very less.
9. Less expensive.
10. NA of multimode step index fiber is more whereas in single mode step index fibers, it is very less.
11. Pulse broadening and inter modal dispersion are present.



Graded index fiber

1. Graded index fiber is a type of fiber where the refractive index of the core is maximum at the center and decreases towards core-cladding interface.
2. Graded index fiber is of only one type, that is, multimode fiber.
3. Index profiles is in the shape of a parabolic curve (for α=2).
4. The light rays propagate in the form of skew rays or helical rays. They will not cross the fiber axis.
5. Signal distortion is very low even though the rays travel with different speeds inside the fiber.
6. This fiber has higher bandwidth.
7. The diameter of the core is about 50µm in the case of multimode fiber.
8. Attenuation of light rays is less in graded index fibers.
9. Highly expensive.
10. NA of graded index fibers is less.
11. No pulse broadening and inter modal dispersion.

Block diagram of Optical fiber communication system



Applications of Optical Fiber

Optical fibers find applications in various fields. Some of them are

- **Medical**
  Used as light guides, imaging tools and also as lasers for surgeries.
- **Defence /Government**
  Used as hydrophones for seismic waves and SONAR , as wiring in aircraft, submarines and other vehicles and also for field networking.
- **Telecommunications**
  Fiber is used for transmission of information from transmitter to receiver.
- **Networking**
  Used to connect users and servers in a variety of network settings and help to increase the speed and accuracy of data transmission.
- **Industrial/Commercial**
  Used as sensory devices to make temperature, pressure and other measurements and as wiring in automobiles and in industrial settings.
- **Broadcast/CATV**
  Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet and other applications.