Fundamentals of Optical Fiber Systems

Compiled by Mohammad Towhidul Islam, Lecturer, North South University, for the ETE 131 students of the Department of Computer Science and Engineering

Light plays a vital role in our daily lives. It is used in compact disc (CD) players, in which a laser reflecting off a CD transforms the returning signal into music. It is used in grocery store checkout lines, where laser beams read bar codes for prices. It is used by laser printers to record images on paper. It is used in digital cameras that capture our world and allow pictures to be displayed on the Internet. It is the basis of the technology that allows computers and telephones to be connected to one another over fiber-optic cables. And light is used in medicine, to produce images used in hospitals and in lasers that perform eye surgery.

BASIC FIBER OPTIC COMMUNICATION SYSTEM

Fiber optics is a medium for carrying information from one point to another in the form of light. Unlike the copper form of transmission, fiber optics is not electrical in nature. A basic fiber optic system consists of a transmitting device that converts an electrical signal into a light signal, an optical fiber cable that carries the light, and a receiver that accepts the light signal and converts it back into an electrical signal. The complexity of a fiber optic system can range from very simple (i.e., local area network) to extremely sophisticated and expensive (i.e., long-distance telephone or cable television trunking). For example, the system shown in Figure 1 could be built very inexpensively using a visible LED, plastic fiber, a silicon photodetector, and some simple electronic circuitry. The overall cost could be less than $20. On the other hand, a typical system used for long-distance, high-bandwidth telecommunication could cost tens or even hundreds of thousands of dollars.

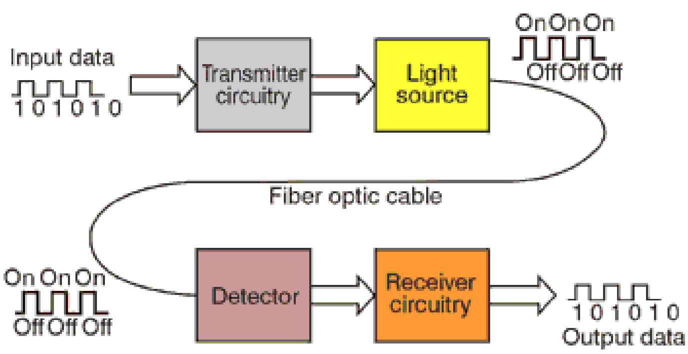


Figure 1: Basic fiber optic communication system

The basic question is, "How much information is to be sent and how far does it have to go?" With this in mind we will examine the various components that make up a fiber optic communication system and the considerations that must be taken into account in the design of such systems. Figure 2 shows the typical fiber optic cable.

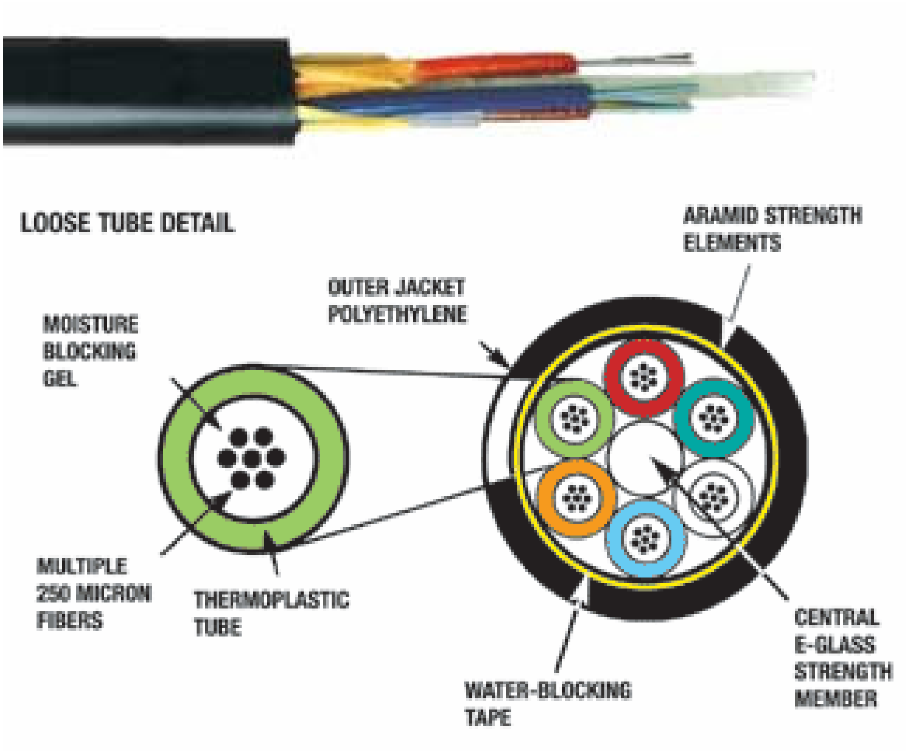


Figure 2: Typical Fiber Optic Cable

Advantage of Optical Fiber Communication:

- Enormous potential bandwidth: The optical carrier frequency has a far greater potential transmission BW than metallic cable systems.
- Small size and weight: Optical fiber has small diameters. Hence, even when such fibers are covered with protective coating they are far smaller and lighter than corresponding copper cables.
- Electrical Isolation: Optical fibers which are fabricated from glass or sometimes a plastic polymer are electrical insulators and unlike their metallic counterpart, they do not exhibit earth loop or interface problems. This property makes optical fiber transmission ideally suited for communication in electrically hazardous environments as fiber created no arcing or spark hazard at abrasion or short circuits.

- Signal security: The light from optical fiber does not radiate significantly and therefore they provide a high degree of signal security. This feature is attractive for military, banking and general data transmission i.e. computer networks application.
- Low transmission loss: The technological developments in optical fiber over last twenty years has resulted in optical cables which exhibits very low attenuation or transmission loss in comparison with best copper conductors.
- Potential low cost: The glass which provides the optical fiber transmission medium is made from sand. So, in comparison to copper conductors, optical fiber offers the potential for low cost line communication.

Disadvantage of Optical Fiber Communication:

- It requires a higher initial cost in installation
- Although the fiber cost is low, the connector and interfacing between the fiber optic costs a lot.
- Fiber optic requires specialized and sophisticated tools for maintenance and repairing.

Basic Law of Optics

At the heart of an optical communication system is the optical fiber that acts as the transmission channel carrying the light beam loaded with information? As mentioned earlier, the guidance of the light beam (through the optical fiber) takes place because of the phenomenon of total internal reflection (TIR), which we will now discuss. We first define the refractive index (*n*) of a medium:

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

where c ($\approx 3 \times 10^8$ m/s) is the speed of light in free space and v represents the velocity of light in that medium. For example, for light waves, $n = 1.5$ for glass and $n = 1.33$ for water.

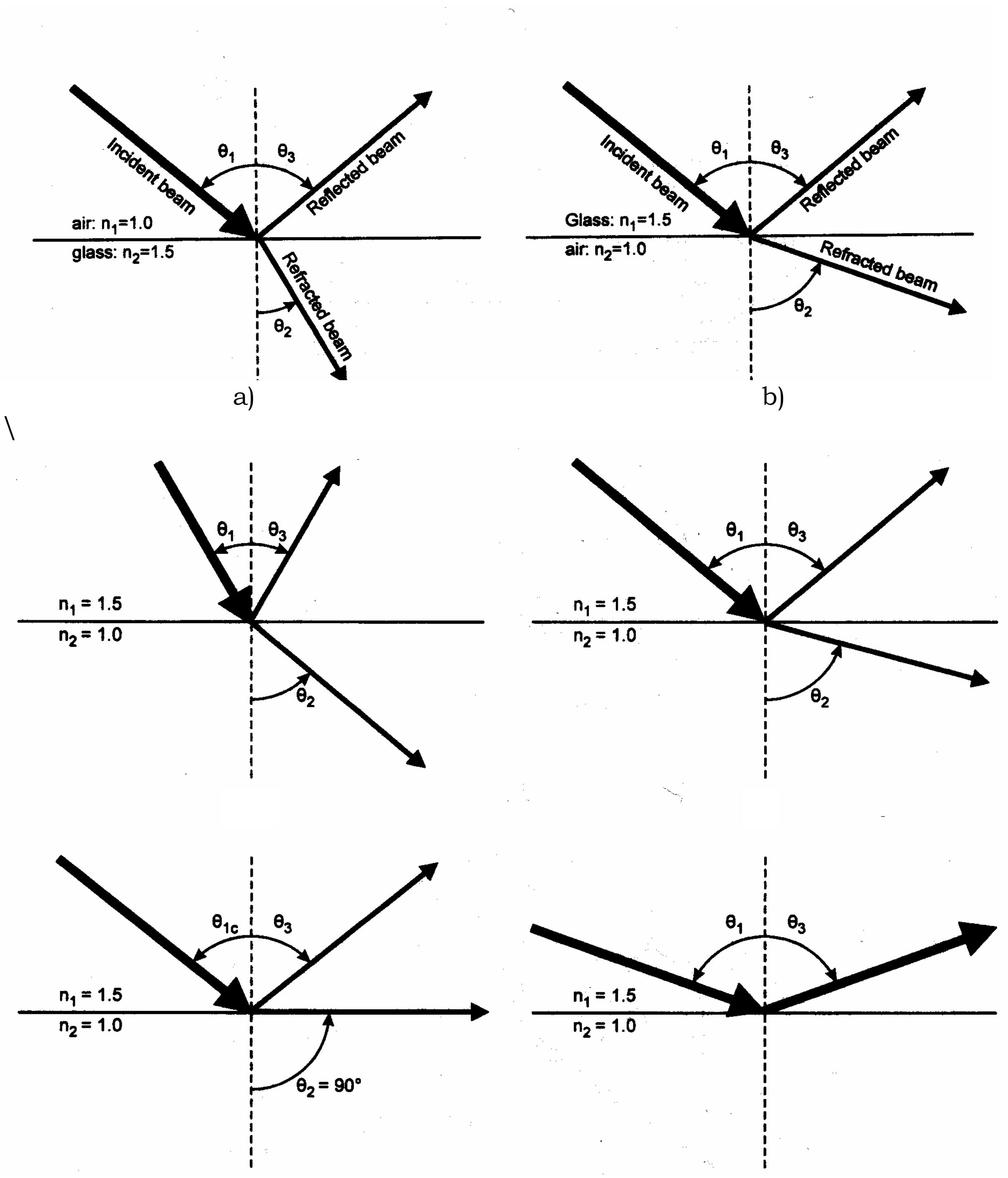


Figure 2: (a) *A ray of light incident on a denser medium* ($n_1 < n_2$)*. b)A ray incident on a rarer medium* ($n_1 > n_2$)*.* (c) *For* $n_2 < n_1$*, if the angle of incidence is greater than critical angle, it will undergo total internal reflection.*

As you know, when a ray of light is incident at the interface of two media (like air and glass), the ray undergoes partial reflection and partial refraction as shown in Figure 2a. The vertical dotted line represents the normal to the surface. The angles θ_1, θ_2, and θ_3 represent the angles that the incident ray, refracted ray, and reflected ray make with the normal. According to Snell's law and the law of reflection,

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad \text{and} \quad \theta_1 = \theta_3$$

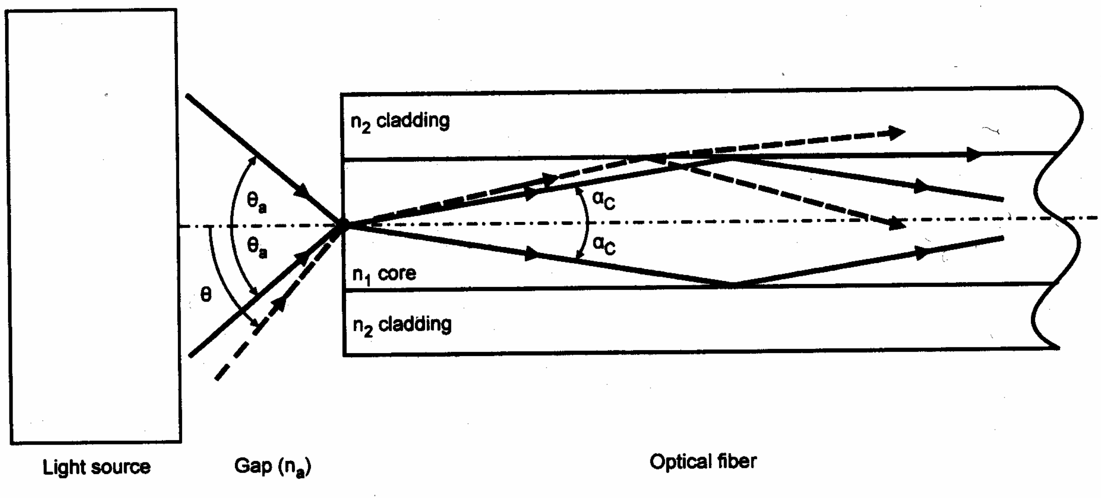
Further, the incident ray, reflected ray, and refracted ray lie in the same plane. In Figure 2a, since $n_2 > n_1$ we must have (from Snell's law) $\theta_2 < \theta_1$, i.e., the ray will bend toward the normal. On the other hand, if a ray is incident at the interface of a rarer medium ($n_2 < n_1$), the ray will bend away from the normal (see Figure 2b). The angle of incidence, for which the angle of refraction is 90°, is known as the critical angle and is denoted by θ_c. Thus, when

$$\theta_1 = \theta_c = \sin^{-1}(\frac{n_2}{n_1})$$

$\theta_2 = 90$. When the angle of incidence exceeds the critical angle (i.e., when $\theta_1 > \theta_c$), there is no refracted ray and we have total internal reflection (see Figure 2c).

Acceptance Angle:

Multimode optical fiber will only propagate light that enters the fiber within a certain cone, known as the acceptance cone of the fiber. The half-angle of this cone is called the acceptance angle, $\boldsymbol{\theta_{max}}$.



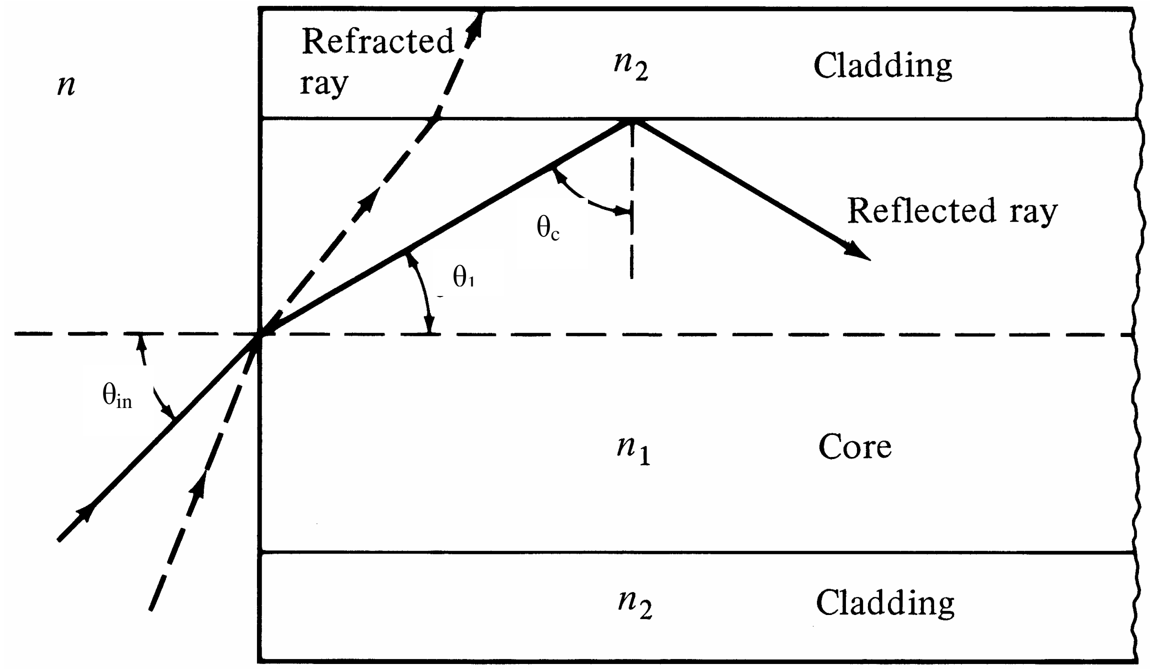


Figure 3

In the above figure it was shown that the light beam enters from air to the optical fiber, a less dense to the denser medium, with an external angle θ_{in}. This causes the light refracted towards the normal at an angle θ_1. To propagate the light beam down the optical fiber, the light beam at the core and cladding interface must taken an angle less than the critical angle θ_c.

Calculation of critical angle:

From Snells law we can write,

$$n\sin\theta_{in} = n_1\sin\theta_1 = n_1\sin(90-\theta_c) = n_1\cos\theta_c$$

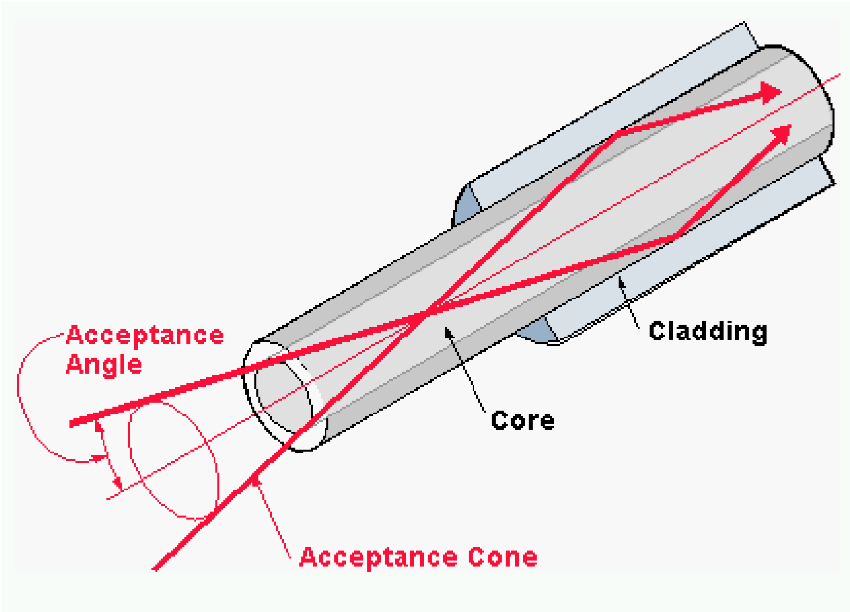
$$n\sin\theta_{in} = \frac{n_1\cos\theta_c}{n}$$

However, we may keep n as 1.

Therefore, $$\sin\theta_{in} = n_1\cos\theta_c = n_1\sqrt{1-\sin^2\theta_c} = n_1\sqrt{1-\left(\frac{n_2}{n_1}\right)^2} = n_1\frac{\sqrt{n_1^2-n_2^2}}{n_1}$$

$$\sin\theta_{in} = \sqrt{n_1^2-n_2^2}$$

θ_{in} is thus known as Acceptance angle or half of acceptance angel.



Numerical Aperture

Numerical Aperture is the measurement of the acceptance angle of an optical fiber, which is the maximum angle at which the core of the fiber will take in light that will be contained within the core. Taken from the fiber core axis (center of core), the measurement is the square root of the squared refractive index of the core minus the squared refractive index of the cladding.

$$NA = \sin \theta_{in}$$

Types of Optical Fiber

Optical fibers come in two main types. Single-mode fiber has a small core that forces the light waves to stay in the same path, or mode. This keeps the light signals going farther before they need to be beefed up, or amplified. Most long-distance, or long-haul, fiber optic telephone lines use single-mode fiber.

The second type, called multimode fiber, has a much larger core than single-mode fiber. This gives light waves more room to bounce around inside as they travel down the path. The extra movement eventually causes the pulses to smear, and lose information. That means multimode fiber signals can't travel as far before they need to be cleaned up and re-amplified. Multimode fibers can carry only a third or less the information-carrying capacity—or bandwidth—than single-mode fiber and they won't work for long distances.

Network engineers prefer multimode fiber for shorter-distance communication, such as in an office building or a local area network (LAN), because the technology is less expensive. However, with the growing demand for more bandwidth between computers and over the Internet, single-mode fiber is becoming more popular for smaller networks, too.

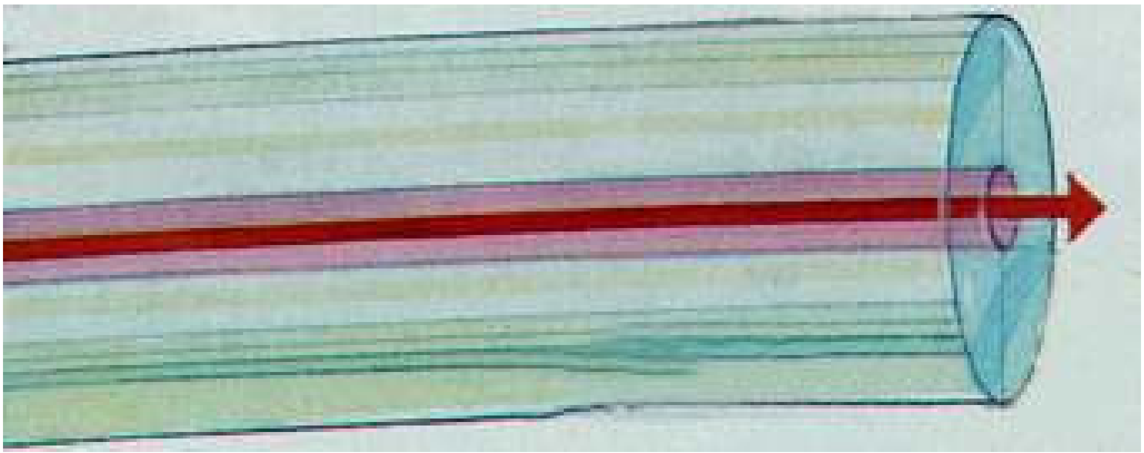
Therefore, we can categorize the fiber optic communication in two categories:

1. Step Index
    a. Single Mode
    b. Multimode
2. Guided Index

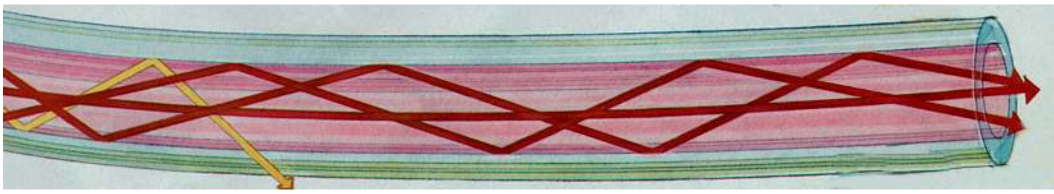
Step Index:

These types of fibers have sharp boundaries between the core and cladding, with clearly defined indices of refraction. The entire core uses single index of refraction.

Single Mode Step Index:
Single mode fiber has a core diameter of 8 to 9 microns, which only allows one light path or *mode.*

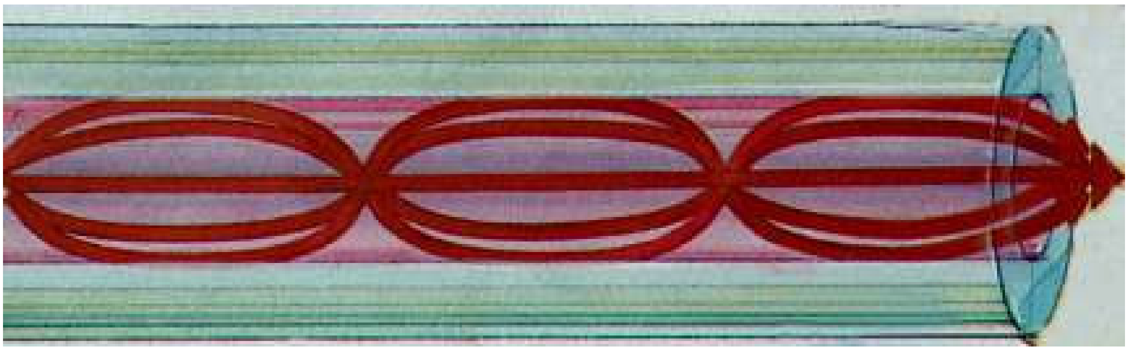


Multimode Step-Index Fiber:
Multimode fiber has a core diameter of 50 or 62.5 microns (sometimes even larger). It allows several light paths or *modes*. This causes *modal dispersion* – some modes take longer to pass through the fiber than others because they travel a longer distance



Multimode Graded-Index Fiber

Graded-index refers to the fact that the refractive index of the core gradually decreases farther from the center of the core. The increased refraction in the center of the core slows the speed of some light rays, allowing all the light rays to reach the receiving end at approximately the same time, reducing dispersion.



As the above figure shows, the light rays no longer follow straight lines; they follow a serpentine path being gradually bent back toward the center by the continuously declining refractive index. This reduces the arrival time disparity because all modes arrive at about the same time. The modes traveling in a straight line are in a higher refractive index, so they travel slower than the serpentine modes. These travel farther but move faster in the lower refractive index of the outer core region.

Attenuation

Attenuation and pulse dispersion represent the two most important characteristics of an optical fiber that determine the information-carrying capacity of a fiber optic communication system. The decrease in signal strength along a fiber optic waveguide caused by absorption and scattering is known as attenuation. Attenuation is usually expressed in dB/km.

Due to attenuation, the power output (P_{out}) at the end of 1km of optical fiber drops to some fraction (k) of the input power (P_{in}) i.e. $P_{out} = k.P_{in}$ (k less than 1).

Clearly, after 2km, $P_{out} = k^2.P_{in}$, and, after L km, $P_{out} = k^L.P_{in}$. Hence, the ratio of the power out of L km of optical fibre to the power in is given by taking the log of both sides and multiplying by 10 gives the power loss in dB as

$$
\begin{aligned}
Power\ loss(dB) &= 10\log_{10}\frac{P_{out}}{P_{in}} \\
&= 10\log_{10}k^{L} \\
&= L.10\log_{10}k. \\
&= \alpha.L
\end{aligned}
$$

where α (= 10 $\log_{10}$k)is the attenuation coefficient of the fiber in dB/km

Since attenuation is the loss, therefore, it is always expressed as

$$P_{out} = P_{in}10^{-\frac{\alpha L}{10}}$$

Dispersion

Dispersion, expressed in terms of the symbol Δt, is defined as pulse spreading in an optical fiber. As a pulse of light propagates through a fiber, elements such as numerical aperture, core diameter, refractive index profile, wavelength, and laser line width cause the pulse to broaden. This poses a limitation on the overall bandwidth of the fiber as demonstrated in Figure 4.

Figure 4 *Pulse broadening caused by dispersion*

Dispersion is generally divided into two categories: *modal dispersion* and *chromatic dispersion*. We will discuss only the modal dispersion.

Modal dispersion is defined as pulse spreading caused by the time delay between lower-order modes (modes or rays propagating straight through the fiber close to the optical axis) and higher-order modes (modes propagating at steeper angles). This is shown in Figure 5. Modal dispersion is problematic in multimode fiber, causing bandwidth limitation, but it is not a problem in single-mode fiber where only one mode is allowed to propagate.

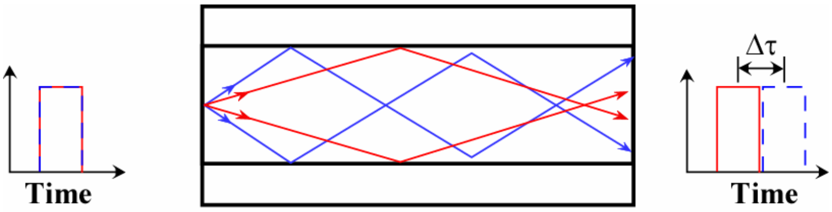
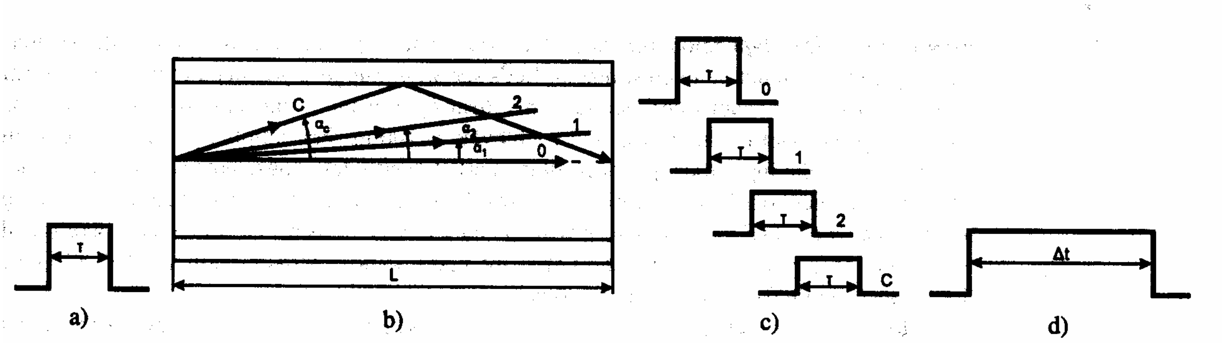
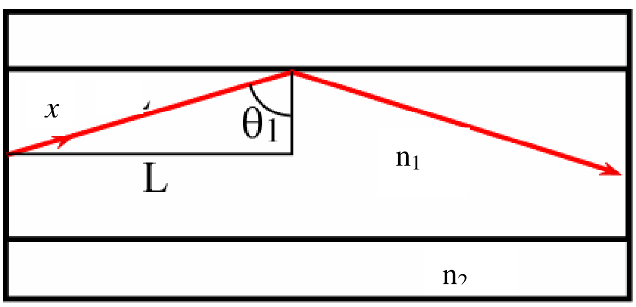


Figure 5: *Mode propagation in an optical fiber*

Intermodal Dispersion



\



Let the time takes for the zero order mode traveling along the central axis is given by:

$$t_0 = \frac{L}{v_g}$$

Where v_g is the velocity of the light inside the core and given by

$$v_g = \frac{c}{n_1}$$

Path length *x* depends on the propagation angle and is given by

$$x = \frac{L}{\sin\theta_1}$$

The time difference between the highest order mode and lowest order mode in step index multimode fiber is given by:

$$\Delta t_{SI} = t_1 - t_0 = \frac{Ln_1}{c}\left[\frac{n_1 - n_2}{n_2}\right]$$

Neglecting the difference between n_1 and n_2, the above equation can be expressed as:

$$\Delta t_{SI} = t_1 - t_0 = \frac{L(NA)^2}{2cn_2}$$

V Parameter:

The number of modes of multimode fiber cable depends on the wavelength of light, core diameter and material composition. This can be determined by the Normalized frequency parameter (V). The V is expressed as:

$$V = \frac{\pi d}{\lambda}\sqrt{n_1^{\,2} - n_2^{\,2}} = \frac{\pi d}{\lambda}(NA)$$

Where
d=fiber core diameter
λ=wavelength of light
NA=numerical aperture

For a single mode fiber, $V \le 2.405$ and for multimode fiber, $V \ge 20$. Mathematically, the number of modes for a step index, fiber is given by:

$$N_{SI} = \frac{V^2}{2}$$

For a graded index fiber, the number of mode is given by:

$$N_{GI} = \frac{V^2}{4}$$