Unit 2
Chapter 4
Optical Fiber Transmission Media

1. Define an optical fiber transmission system or an optical fiber and Contrast the advantages and disadvantages of fiber optic cables compared metallic transmission lines.

Optical fiber: An optical fiber is a dielectric waveguide for guiding the electromagnetic waves at optical frequencies. They allow propagation of light waves in a way, which is very similar to metallic waveguides that allow propagation of microwaves through them.

ADVANTAGES OF OPTICAL FIBER CABLES: Communications using glass or plastic optical fiber cables has several overwhelming advantages over conventional metallic transmission media for both telecommunication and computer networking applications. The advantages of using optical fibers include the following:

1. **Wider bandwidth and greater information capacity:** Optical fibers have greater information capacity than metallic cables because of the inherently wider bandwidths available with optical frequencies. Optical fibers are available with bandwidths up to several thousand gigahertz. The primary electrical constants (resistance, inductance, and capacitance) in metallic cables cause them to act like low-pass filters, which limit their transmission frequencies, bandwidth, bit rate, and information-carrying capacity. Modern optical fiber communications systems are capable of transmitting several gigabits per second over hundreds of miles, allowing literally millions of individual voice and data channels to be combined and propagated over one optical fiber cable.
2. **Immunity to crosstalk:** Optical fiber cables are immune to crosstalk because glass and plastic fibers are nonconductors of electrical current. Therefore, fiber cables are not surrounded by a changing magnetic field, which is the primary cause of crosstalk between metallic conductors located physically close to each other.
3. **Immunity to static interference:** Because optical fiber cables are nonconductors of electrical current, they are immune to static noise due to electromagnetic interference (EMI) caused by lightning, electric motors, relays, fluorescent lights, and other electrical noise sources (most of which are man-made). For the same reason, fiber cables do not radiate electromagnetic energy.
4. **Environmental immunity:** Optical fiber cables are more resistant to environmental extremes (including weather variations) than metallic cables. Optical cables also operate over a wider temperature range and are less affected by corrosive liquids and gases.
5. **Safety and convenience:** Optical fiber cables are safer and easier to install and maintain than metallic cables. Because glass and plastic fibers are nonconductors, there are no electrical currents or voltages associated with them. Optical fibers can be used around volatile liquids and gasses without worrying about their causing explosions or fires. Optical fibers are also smaller and much more lightweight and compact than metallic cables. Consequently, they are more flexible, are easier to work with, require less storage space, are cheaper to transport, and are easier to install and maintain.
6. **Lower transmission loss:** Optical fibers have considerably less signal loss than their metallic counterparts. Optical fibers are currently being manufactured with as little as a few tenths of a dB loss per kilometer. Consequently, optical regenerators and amplifiers can be spaced considerably farther apart than with metallic transmission lines.
7. **Security:** Optical fiber cables are more secure than metallic cables. It is virtually impossible to tap into a fiber cable without the user's knowledge, and optical cables cannot be detected with metal detectors unless they are reinforced with steel for strength.
8. **Durability and reliability:** Optical fiber cables last longer and are more reliable than metallic facilities because fiber cables have a higher tolerance to changes in environmental conditions and are immune to corrosive materials.

9. **Economics:** The cost of optical fiber cables is approximately the same as metallic cables. Fiber cables have less loss and require fewer repeaters, which equates to lower installation and overall system costs and improved reliability.

DISADVANTAGES OF OPTICAL FIBER CABLES: Although the advantages of optical fiber cables far exceed the disadvantages, it is import ant to know the limitations of the fiber. The disadvantages of optical fibers include the following:

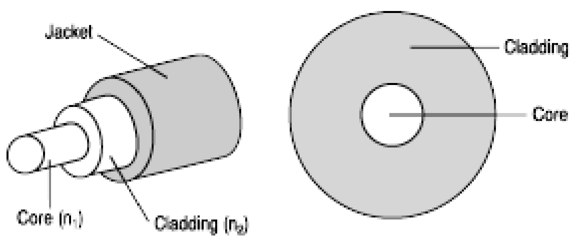
1. **Interfacing costs:** Optical fiber cable systems are virtually useless by themselves. To be practical and useful, they must be connected to standard electronic facilities, which often require expensive interfaces.
2. **Strength:** Optical fibers by themselves have a significantly lower tensile strength than coaxial cable. This can be improved by coating the fiber with standard Kevlar and a protective jacket of PVC. In addition, glass fiber is much more fragile than copper wire, making fiber less attractive where hardware portability is required.
3. **Remote electrical power:** Occasionally, it is necessary to provide electrical power to remote interface or regenerating equipment. This cannot be accomplished with the optic al cable, so additional metallic cables must he included in the cable assembly.
4. **Losses through bending:** Optical fiber cables are more susceptible to losses introduced by bending the cable. Electromagnetic waves propagate through an optical cable by either refraction or reflection. Therefore, bending the cable causes irregularities in the cab le dimensions, resulting in a loss of signal power. Optical fibers are also more prone to manufacturing defects as even the most minor defect can cause excessive loss of signal power.
5. **Specialized tools, equipment and training:** Optical fiber cables require special tools to splice and repair cables and special test equipment to make routine measurements. Not only is repairing fiber cables difficult and expensive, but technicians working on optical cables also require special skills and training. In addition, sometimes it is difficult to locate faults in optical cables because there is no electrical continuity.

2. Briefly describe the construction of an optical fiber.

The basic structure of an optical fiber is as shown below. It consists of three parts:

1. **<u>Core</u>:** The core is a cylindrical rod of dielectric material. Dielectric material conducts no electricity. Light propagates mainly along the core of the fiber. The core is generally made of glass. The core is described as having a radius of ‘a’ and an index of refraction n_1.

2. **<u>Cladding</u>:** The core is surrounded by a layer of material called the cladding. Even though light will propagate along the fiber core without the layer of cladding material, the cladding does perform some necessary functions.



The cladding layer is made of a dielectric material with an index of refraction n_2. The index of refraction of the cladding material is less than that of the core material. The cladding is generally made of glass or plastic. The cladding performs the following functions:

- Reduces loss of light from the core into the surrounding air
- Reduces scattering loss at the surface of the core
- Protects the fiber from absorbing surface contaminants
- Adds mechanical strength

2. **Sheath or Coating or Buffer:** For extra protection, the cladding is enclosed in an additional layer called the coating or buffer. The coating or buffer is a layer of material used to protect an optical fiber from physical damage. The material used for a buffer is a type of plastic.

The buffer is elastic in nature and prevents abrasions. The buffer also prevents the optical fiber from scattering losses caused by microbends. Microbends occur when an optical fiber is placed on a rough and distorted surface.

3. Explain the following:

Refractive index: A fundamental optical parameter of a material is the refractive index. It is defined as the ratio of the speed of light in a vacuum to that in matter and is given by,

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

Typical values of 'n' are 1.00 for air, 1.33 for water, 1.5 for glass, and 2.42 for diamond.

Reflection of light:

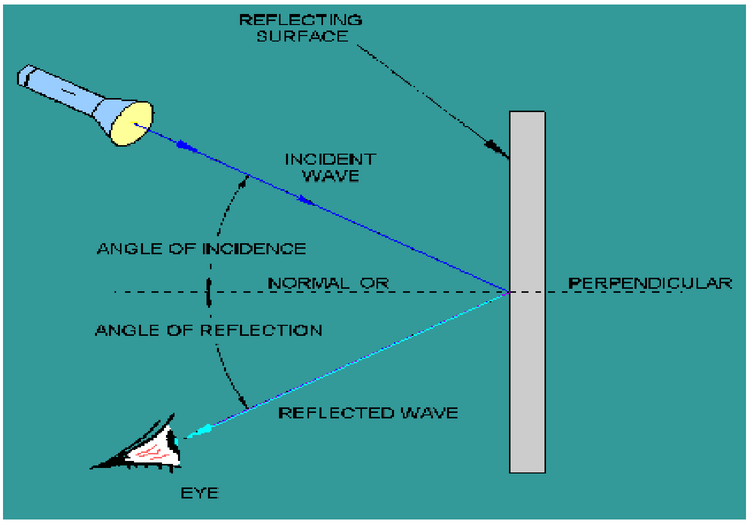


Figure: Reflection of a wave.

The angle between the reflected wave and the normal is called the angle of reflection**.** The angle of incidence is equal to the angle of reflection and is known as **law of reflection**

Refraction of light:

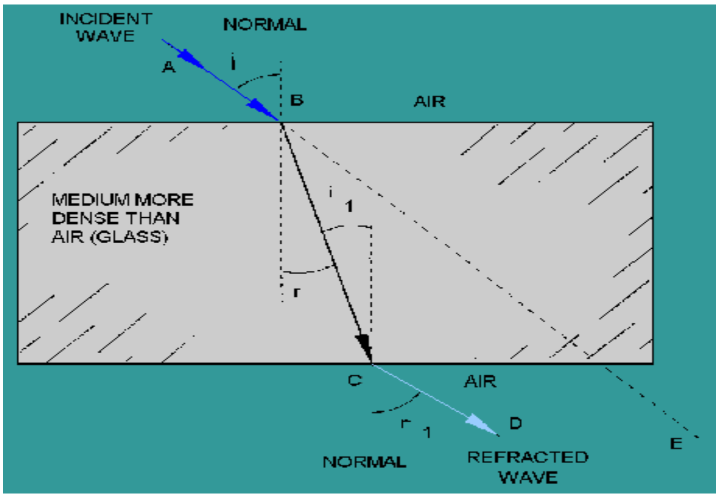


Figure: Refraction of a wave.

When a light wave passes from one medium into a medium having a different velocity of propagation (the speed waves can travel through a medium), a change in the direction of the wave will occur. This change of direction as the wave enters the second medium is called **refraction**.

The angle between the normal and the path of the wave through the second medium is the **angle of refraction**.

Snell's Law & Total Internal Reflection:

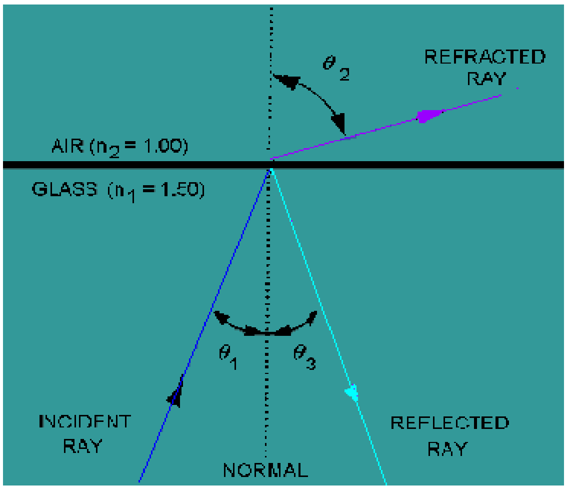


Figure: Light reflection and refraction at a glass-air boundary.

Snell's law of refraction is used to describe the relationship between the incident and the refracted rays at the boundary. **Snell's Law** is given by:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

As the angle of incidence (θ_1) becomes larger, the angle of refraction (θ_2) approaches 90^0. At this point, no refraction is possible. The light ray is totally reflected back into the glass medium. No light escapes into the air. This condition is called **total internal reflection**.

The angle at which total internal reflection occurs is called the **critical angle of incidence**. The critical angle of incidence (θ_c) is shown in figure below. At any angle of incidence (θ_1) greater than the critical angle, light is totally reflected back into the glass medium. The critical angle of incidence is determined by using Snell's Law.

The critical angle is given by: $\sin\theta_c = \frac{n_2}{n_1}$

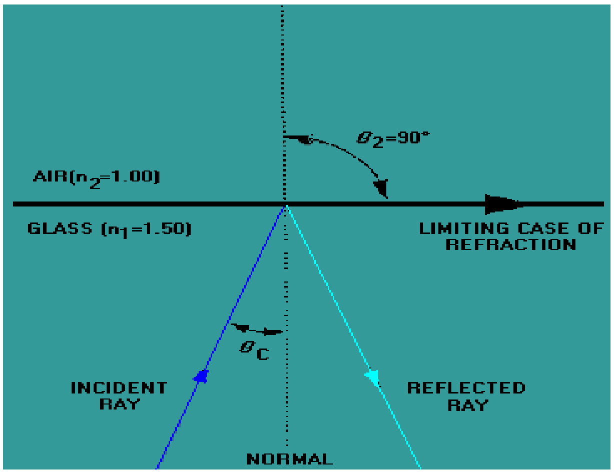


Figure: Critical angle of incidence.

The condition of total internal reflection is an ideal situation.

However, in reality, there is always some light energy that penetrates the boundary. This situation is explained by the mode theory, or the electromagnetic wave theory, of light.

4. Compare different types of fibers.

Fiber refractive index profiles classify single mode and multimode fibers as follows:

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

Single-mode step-index fiber

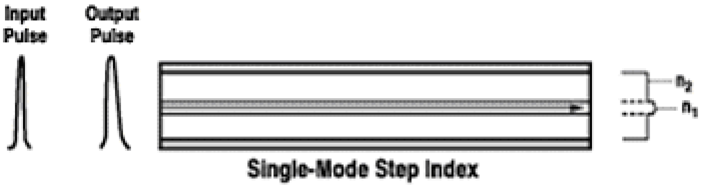


Figure: The refractive index profiles and light propagation in single mode step-index fiber.

Advantages

1. There is minimum dispersion. Because all rays propagating down the fiber take approximately the same path, they take approximately the same amount of time to travel down the cable. Consequently, a pulse of light entering the cable can be reproduced at the receiving end very accurately.
2. Because of the high accuracy in reproducing transmitted pulses at the receive end, larger bandwidths and higher information transmission rates are possible with SMSI fibers than with the other types of fibers.

Disadvantages
1. Because the central core is very small, it is difficult to couple light into and out of this type of fiber. The source-to-fiber aperture is smallest of all the fiber types.
2. Again, because of the small central core, a highly directive light source such as a laser is required to couple light into a SMSI fiber.
3. SMSI fibers are expensive and difficult to manufacture.

Multimode step-index fiber

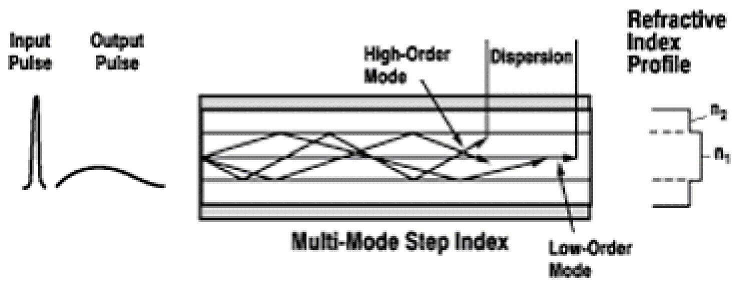


Figure: The refractive index profiles and light propagation in multimode step-index fiber.

Advantages
1. MMSI fibers are inexpensive and simple to manufacture.
2. It is easy to couple light into and out of MMSI fibers; they have a relatively large source-to-fiber aperture.

Disadvantages
1. Light rays take many different paths down the fiber, which results in large differences in their propagation times. Because of this, rays traveling down this type of fiber have a tendency to spread out. Consequently, a pulse of light propagating down a MMSI fiber is distorted more than with other types of fibers.
2. The bandwidth and rate of information transfer possible with this type of cable are less than the other types.

Multimode graded-index fiber

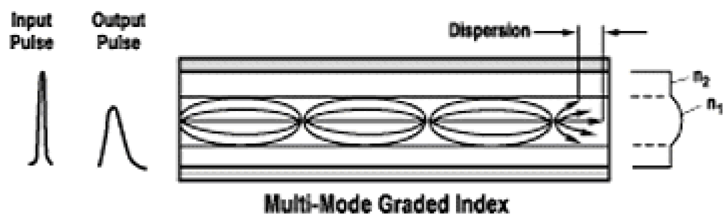
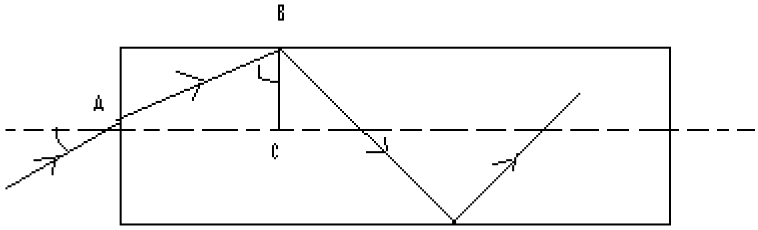


Figure: The refractive index profiles and light propagation in multimode graded-index fiber.

Essentially, there are no outstanding advantages or disadvantages of this type of fiber. MMGI fibers are easier to couple light into and out of than SMSI fibers but more difficult than MMSI fibers. Distortion due to multiple propagation paths is greater in SMSI fibers but less than in MMSI fibers. GI fibers are easier to manufacture than SMSI fibers but more difficult than MMSI fibers. MMGI fibers are considered as an intermediate fibers compared to other fiber types.

5. Explain propagation of light through a fiber and define numerical aperture, acceptance angle, and acceptance cone

Transmission of light through fiber optic cable is based on the principle of total internal reflection, which states that all the light striking the boundary between two media (at an angle greater than the critical angle) will be totally reflected.



Let n_0 be the R.I of medium from which light is launched into the fiber. Let a light ray enter the fiber at angle θ_i to the axis of the fiber. The ray refracts at an angle θ_r and strikes the core-clad interface at angle ϕ. If ϕ is greater than ϕ_c, the ray undergoes total internal reflection at the interface, since $n_1 > n_2$. As long as angle ϕ is greater than ϕ_c, the light will stay within the fiber.
[let us compute the incident angle θ_i for which $\phi \geq \phi_c$ such that light rebounds within the fiber]

Applying snell's law to the launching face of the fiber, we have

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0} \qquad \text{----------------(1)}$$

If θ_i is increased beyond a limit, ϕ will drop below the critical angle ϕ_c and the ray escapes from the sidewalls of the fiber. The largest value of θ_i occurs when $\phi = \phi_c$.

From Δ^{le} ABC, it is seen that $\sin\theta_r = \sin(90-\phi) = \cos\phi$

$$\therefore \sin\theta_i = \frac{n_1}{n_0}\cos\phi \qquad \text{-----------------(2)}$$

when $\phi = \phi_c$, $\sin[\theta_i(\max)] = \frac{n_1}{n_0}\cos\phi_c$ -----------------(3)

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

$$\sin\phi[\theta_i(\max)] = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \qquad \text{-----------------(4)}$$

Quite often the incident ray is launched from air medium, for which n_0=1 and let $\theta_i(\max) = \theta_0$.

$$\therefore \sin\theta_0 = \sqrt{n_1^2 - n_2^2}$$

(Or) $\theta_0 = \sin^{-1}\sqrt{n_1^2 - n_2^2}$ ---------------- (5)

The angle θ_0 is called the acceptance angle of the fiber. It is defined as the maximum angle that a light ray can have relative to the axis of the fiber.

Rotating the acceptance angle around the fiber axis describes the acceptance cone of the fiber input. It is defined as the area in front of the fiber face that determines the angle of light waves that will be accepted into the fiber.

Acceptance angle: The half angle of acceptance cone is called acceptance cone.

Numerical aperture: it is the figure of merit that is used to describe the light gathering or light collecting ability of an optical fiber. It is defined as "the sine of acceptance angle".

$$\therefore N.A = \theta_0 = \sin^{-1}\sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta}$$

The value of N.A depends on R.Is of core and cladding materials. The larger the magnitude of N.A, the greater the amount of light accepted by the fiber from the external light source.

6. Describe the various transmission losses associated with optical fibers

Transmission losses in optical fiber cables arc one of the most important characteristics of the fibers. Losses in the fiber result in a reduction in the light power, thus reducing the system bandwidth, information transmission rate, efficiency, and overall system capacity. The predominant losses in optic al fiber cables are the following:

1. Absorption loss
2. Material or Rayleigh scattering losses
3. Chromatic or wavelength dispersion
4. Radiation losses
5. Modal dispersion
6. Coupling losses

Absorption Losses

Absorption loss in optical fibers is analogous to power dissipation in copper cables; impurities in the fiber absorb the light and convert it to heat. The ultrapure glass used to manufacture optical fibers is approximately 99.9999% pure. Still, absorption losses between I dB/km and 1000 dB/km are typical. Essentially, there are three factors that contribute to the absorption losses in optical fibers: ultraviolet absorption, infrared absorption, and ion resonance absorption.

Ultraviolet absorption: Ultraviolet absorption is caused by valence electrons in the silica material from which fibers are manufactured. Light ionizes the valence electrons into conduction. The ionization is equivalent to a loss in the total light field and, consequently, contributes to the transmission losses of the fiber.

Infrared absorption: Infrared absorption is a result of photons of light that are absorbed by the atoms of the glass core molecules. The absorbed photons are converted to random mechanical vibrations typical of heating.

Ion resonance absorption: Ion resonance absorption is caused by OH^- ions in the material. The source of the $0H^-$ ions is water molecules that have been trapped in the glass during the manufacturing process. Iron, copper, and chromium molecules also cause ion absorption.

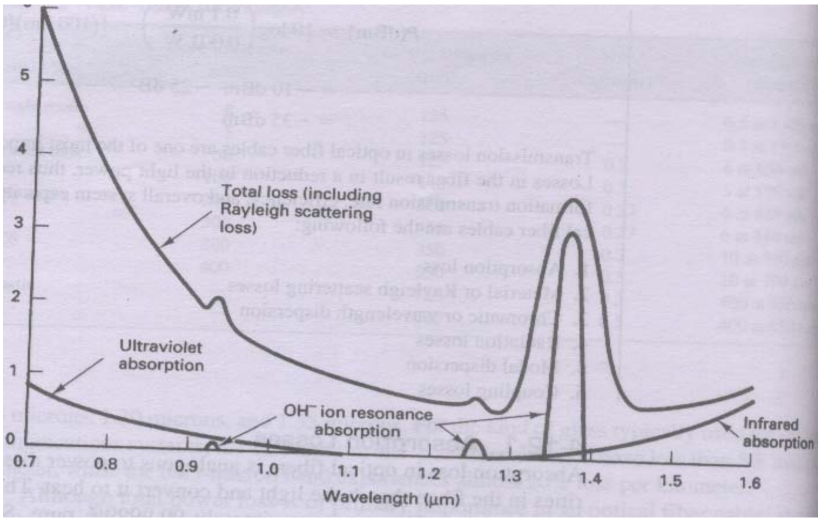


Figure: Typical losses in optical fiber cables due to ultraviolet, infrared, and ion resonance absorption.

Material or Rayleigh Scattering Losses: During manufacturing, glass is drawn into long fibers of very small diameter. During this process, the glass is in a plastic state (not liquid and not solid). The tension applied to the glass causes the cooling glass to develop permanent submicroscopic irregularities. When light rays propagating down a fiber strike one of these impurities, they are diffracted. Diffraction causes the light to disperse, or spread out, in many directions. Some of the diffracted light continues down the fiber, and some of it escapes through the cladding. The light rays that escape represent a loss in light power. This is called Rayleigh scattering loss.

Chromatic Distortion or Wavelength Dispersion: Light-emitting diodes (LEDs) emit light containing many wavelengths. Each wavelength within the composite light signal travels at a different velocity when propagating through glass. Consequently, light rays that are simultaneously emitted from an LED and gated down an optical fiber do not arrive at the far end of the fiber at the same time, results in an impairment called chromatic distortion (sometimes called wavelength dispersion). Chromatic distortion can be eliminated by using a monochromatic light source as an injection laser diode (ILD). Chromatic distortion occurs only in fibers with a mode of transmission

Radiation Losses: Radiation losses are caused predominantly by small bends and kinks in the fiber. Essentially, there are two types of bends: microbends and constant-radius bends. Micro bending occurs as a result of differences in the thermal contraction rates between the core and the cladding material. A microbend is a miniature bend or geometric imperfection along the axis of the fiber and represents a discontinuity in the fiber where Rayleigh scattering can occur. Microbending losses generally contribute less than 20% of the total attenuation in a fiber. Constant-radius bends are caused by excessive pressure and tension and generally occur when fibers are bent during handling or installation.

Modal Dispersion: Modal dispersion (sometimes called pulse spreading) is caused by the difference in the propagation times of light rays that take different paths down a fiber. Obviously, modal dispersion can occur only in multimode fibers. It can be reduced considerably by using graded- index fibers and almost entirely eliminated by using single-mode step-index fibers.

Modal dispersion can cause a pulse of light energy to spread out in time as it propagates down a fiber. If the pulse spreading is sufficiently severe, one pulse may interfere with another. In multimode step-index fibers, a light ray propagating straight down the axis of the fiber takes the least amount of time to travel the length of the fiber. A light ray that strikes the core/cladding interface at the critical angle will undergo the largest number of internal reflections and, consequently, take the longest time to travel the length of the cable.

For multimode propagation, dispersion is often expressed as a bandwidth length product (BLP) or bandwidth distance product (BDP). BLP indicates what signal frequencies can be propagated through a given distance of fiber cable and is expressed mathematically as the product of distance and bandwidth (sometimes called line width). Bandwidth length products are often expressed in MHz/km units. As the length of an optical cable increases, the bandwidth (and thus the bit rate) decreases in proportion.

7. Describe various types of coupling losses associated with optical fibers.

Coupling losses are caused by imperfect physical connections. In fiber cables coupling losses can occur at any of the following three types of optical junctions: light source-to-fiber connections, fiber-to-fiber connections, and fiber-to-photodetector connections. Junction losses are most often caused by one of the following alignment problems: lateral misalignment, gap misalignment, angular misalignment, and imperfect surface finishes.

Lateral displacement: Lateral displacement (misalignment) is shown in of figure above and is the lateral or axial displacement between two pieces of adjoining fiber cables. The amount of loss can be from a couple tenths of a decibel to several decibels. This loss is generally negligible if the fiber axes are aligned to within 5% of the smaller fiber's diameter.

Gap displacement (misalignment): Gap displacement (misalignment) is sometimes called end separation. When splices are made in optical fibers, the fibers should actually touch. The farther apart the fibers are, the greater the loss of light. If two fibers are joined with a connector, the ends should not touch because the two ends rubbing against each other in the connector could cause damage to either or both fibers.

Angular displacement (misalignment): Angular displacement (misalignment) is sometimes called angular displacement. If the angular displacement is less than 2 degrees, the loss will typically be less than 0.5 dB.

Imperfect surface finish: The ends of the two adjoining fibers should be highly polished and fit together squarely. If the fiber ends are less than 3 degrees off from perpendicular, the losses will typically be less than 0.5 dB.

8. Describe two primary types of light sources used with optical fibers.

An optical source is the most important component of an optical fiber transmitter. It converts electrical energy (current) into optical energy (light).

There are two types of light emitting junction diodes that can be used as the optical source of the Transmitter. These are the light emitting diode (LED) and the laser diode (LD). LED's are simpler and generate incoherent, lower power, light. LD's are more complex and generate coherent, higher power light. Figure below illustrates the optical power output, P, from each of these devices as a function of the electrical current input, I, from the modulation circuitry. As the figure indicates the LED has a relatively linear P-I characteristic while the LD has a strong non-linearity or threshold effect. The LD may also be prone to kinks where the power actually decreases with increasing bandwidth.

With minor exceptions, LDs have advantages over LED's in the following ways.

- They can be modulated at very high speeds.
- They produce greater optical power.
- They have higher coupling efficiency to the fiber optic cable.

LED's have advantages over LD's because they have

- higher reliability
- better linearity
- lower cost

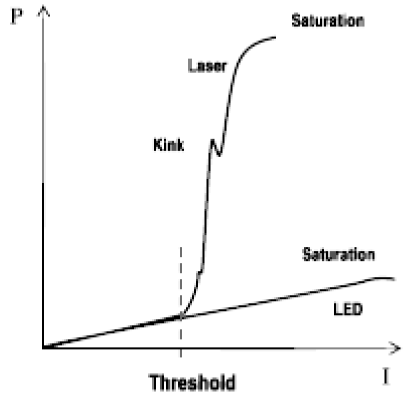


Figure: LED and laser diodes: P-I characteristics

Both the LED and LD generate an optical beam with such dimensions that it can be coupled into a fiber optic cable. However, the LD produces an output beam with much less spatial width than an LED. This gives it greater coupling efficiency. Each can be modulated with a digital electrical signal. For very high-speed data rates the link architect is generally driven to a Transmitter having a LD. When cost is a major issue the link architect is generally driven to a Transmitter having an LED.

A key difference in the optical output of an LED and a LD is the wavelength spread over which the optical power is distributed. The spectral width, s_l, is the 3 dB optical power width (measured in nm or microns). The spectral width impacts the effective transmitted signal bandwidth. A larger spectral width takes up a larger portion of the fiber optic cable link bandwidth. Figure below illustrates the spectral width of the two devices. The optical power generated by each device is the area under the curve. The spectral width is the half-power spread. A LD will always have a smaller spectral width than a LED. The specific value of the spectral width depends on the details of the diode structure and the semiconductor material. However, typical values for a LED are around 40 nm for operation at 850 nm and 80 nm at 1310 nm. Typical values for a LD are 1 nm for operation at 850 nm and 3 nm at 1310 nm.

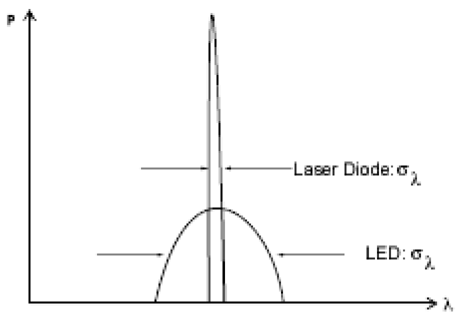


Figure: LED and laser spectral widths

Once a Transmitter is selected on the basis of being either an LED or a LD, additional concerns should be considered in reviewing the specifications of the candidates. These concerns include packaging, environmental sensitivity of device characteristics, heat sinking and reliability.

With either an LED or LD the Transmitter package must have a transparent window to transmit light into the fiber optic cable. It may be packaged with either a fiber optic cable pigtail or with a transparent plastic or glass window. Some vendors supply the Transmitter with a package having a small hemispherical lens to help focus the light into the fiber optic cable.

Packaging must also address the thermal coupling for the LED or LD. A complete Transmitter module may consume over 1W- significant power consumption in a small package. Attention has to be paid to the heat sinking capabilities. Plastic packages can be used for lower speed and lower reliability applications. However, for high speed and high reliability look for the Transmitter to be in a metal package with built-in fins for heat sinking.