UNIT I INTRODUCTION TO OPTICAL FIBERS

1.1 Evolution of fiber optic system:

In 1966 Charles K. Kao and George Hockham proposed optical fibers at STC Laboratories (STL), Harlow, when they showed that the losses of 1000 db/km in existing glass (compared to 5-10 db/km in coaxial cable) was due to contaminants, which could potentially be removed.

Optical fiber was successfully developed in 1970 by Corning Glass Works, with attenuation low enough for communication purposes (about 20dB/km), and at the same time GaAs semiconductor lasers were developed that were compact and therefore suitable for transmitting light through fiber optic cables for long distances.

After a period of research starting from 1975, the first commercial fiber-optic communications system was developed, which operated at a wavelength around 0.8 µm and used GaAs semiconductor lasers. This first-generation system operated at a bit rate of 45 Mbps with repeater spacing of up to 10 km. Soon on 22 April, 1977, General Telephone and Electronics sent the first live telephone traffic through fiber optics at a 6 Mbps throughput in Long Beach, California.

The second generation of fiber-optic communication was developed for commercial use in the early 1980s, operated at 1.3 µm, and used InGaAsP semiconductor lasers. Although these systems were initially limited by dispersion, in 1981 the single-mode fiber was revealed to greatly improve system performance. By 1987, these systems were operating at bit rates of up to 1.7 Gb/s with repeater spacing up to 50 km.

The first transatlantic telephone cable to use optical fiber was TAT-8, based on Desurvire optimized laser amplification technology. It went into operation in 1988.

Third-generation fiber-optic systems operated at 1.55 µm and had losses of about 0.2 dB/km. They achieved this despite earlier difficulties with pulse-spreading at that wavelength using conventional InGaAsP semiconductor lasers. Scientists overcame this difficulty by using dispersion-shifted fibers designed to have minimal dispersion at 1.55 µm or by limiting the laser spectrum to a single longitudinal mode. These developments eventually allowed third-generation systems to operate commercially at 2.5 Gbit/s with repeater spacing in excess of 100 km.

The fourth generation of fiber-optic communication systems used optical amplification to reduce the need for repeaters and wavelength-division multiplexing to increase data capacity. These two improvements caused a revolution that resulted in the doubling of system capacity every 6 months starting in 1992 until a bit rate of 10 Tb/s was reached by 2001. Recently, bit-rates of up to 14 Tbit/s have been reached over a single 160 km line using optical amplifiers.

The focus of development for the fifth generation of fiber-optic communications is on extending the wavelength range over which a WDM system can operate. The conventional wavelength window, known as the C band, covers the wavelength range 1.53-1.57 µm, and the new *dry fiber* has a low-loss window promising an extension of that range to 1.30-1.65 µm. Other developments include the concept of "optical solitons, " pulses that preserve their shape by counteracting the effects of dispersion with the nonlinear effects of the fiber by using pulses of a specific shape.

In the late 1990s through 2000, industry promoters, and research companies such as KMI and RHK predicted vast increases in demand for communications bandwidth due to increased use of the Internet, and commercialization of various bandwidth-intensive consumer services, such as video on demand. Internet protocol data traffic was increasing exponentially, at a faster rate than integrated circuit complexity had increased under Moore's Law. From the bust of the dot-com bubble through 2006, however, the main trend in the industry has been consolidation of firms and offshoring of manufacturing to reduce costs. Recently, companies such as Verizon and AT&T have taken advantage of fiber-optic communications to deliver a variety of high-throughput data and broadband services to consumers' homes.

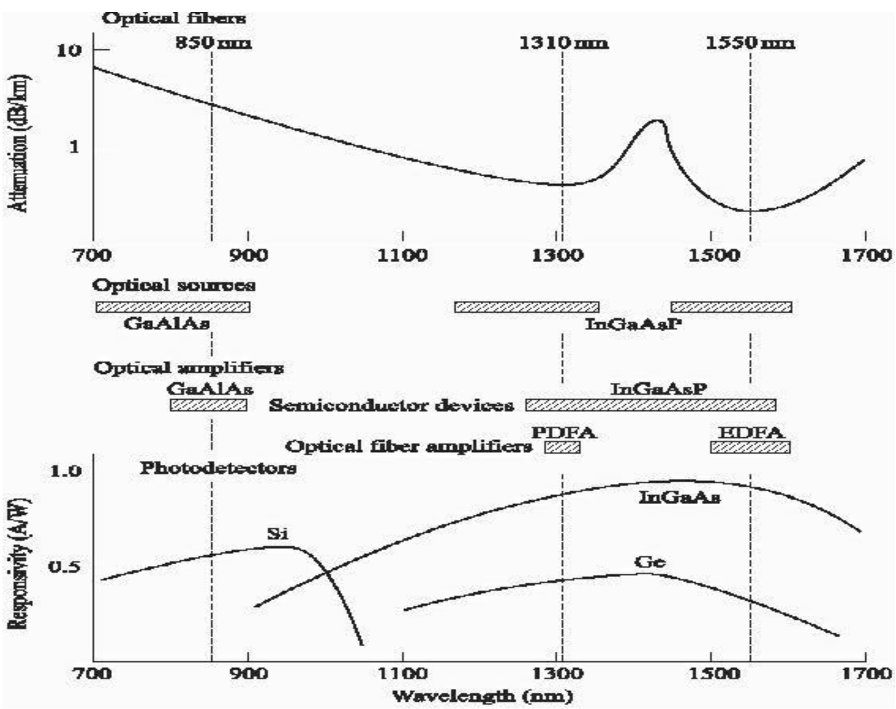


Fig. : Operating ranges of components

1.2 Element of an Optical Fiber Transmission link:

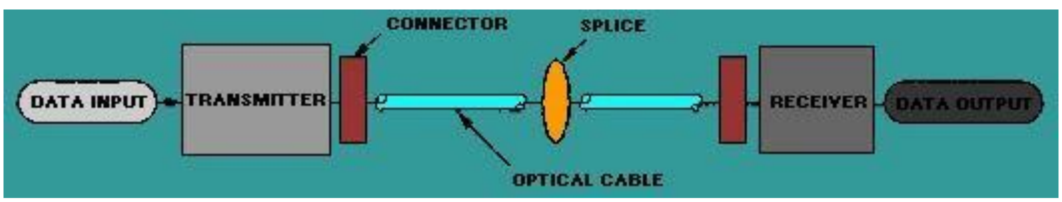
A fiber optic data link sends input data through fiber optic components and provides this data as output information. It has the following three **basic functions**:

- To convert an electrical input signal to an optical signal
- To send the optical signal over an optical fiber
- To convert the optical signal back to an electrical signal

A fiber optic data link consists of three parts - **transmitter**, **optical fiber**, and **receiver**. Figure 1-1 is an illustration of a fiber optic data-link connection. The transmitter, optical fiber, and receiver perform the basic functions of the fiber optic data link. Each part of the data link is responsible for the successful transfer of the data signal.

A fiber optic data link needs a transmitter that can effectively convert an electrical input signal to an optical signal and launch the data-containing light down the optical fiber. A fiber optic data link also needs a receiver that can effectively transform this optical signal back into its original form. This means that the electrical signal provided as data output should exactly match the electrical signal provided as data input.

Figure 1-1. - Parts of a fiber optic data link.



The transmitter converts the input signal to an optical signal suitable for transmission. The transmitter consists of two parts, an interface circuit and a source drive circuit. The transmitter's drive circuit converts the electrical signals to an optical signal. It does this by varying the current flow through the light source. The two types of optical sources are light-emitting diodes (LEDs) and laser diodes.

The optical source launches the optical signal into the fiber. The optical signal will become progressively weakened and distorted because of scattering, absorption, and dispersion mechanisms in the fiber waveguides.

The receiver converts the optical signal exiting the fiber back into an electrical signal. The receiver consists of two parts, the optical detector and the signal-conditioning circuits. An optical detector detects the optical signal. The signal-conditioning circuit conditions the detector output so that the receiver output matches the original input to the transmitter. The receiver should amplify and process the optical signal without introducing noise or signal distortion. Noise is any disturbance that obscures or reduces the quality of the signal. Noise effects and limitations of the signal-conditioning circuits cause the distortion of the receiver's electrical output signal.

An optical detector can be either a semiconductor positive-intrinsic-negative (*PIN*) diode or an avalanche photodiode (APD).

A *PIN* diode changes its electrical conductivity according to the intensity and wavelength of light. The *PIN* diode consists of an intrinsic region between p-type and n-type semiconductor material. A fiber optic data link also includes passive components other than an optical fiber. Figure 1-1 does not show the optical connections used to complete the construction of the fiber optic data link. Passive components used to make fiber connections affect the performance of the data link. These components can also prevent the link from operating. Fiber optic components used to make the optical connections include optical splices, connectors, and couplers.

Proof of link performance is an integral part of the design, fabrication, and installation of any fiber optic system. Various measurement techniques are used to test individual parts of a data link. Each data link part is tested to be sure the link is operating properly.

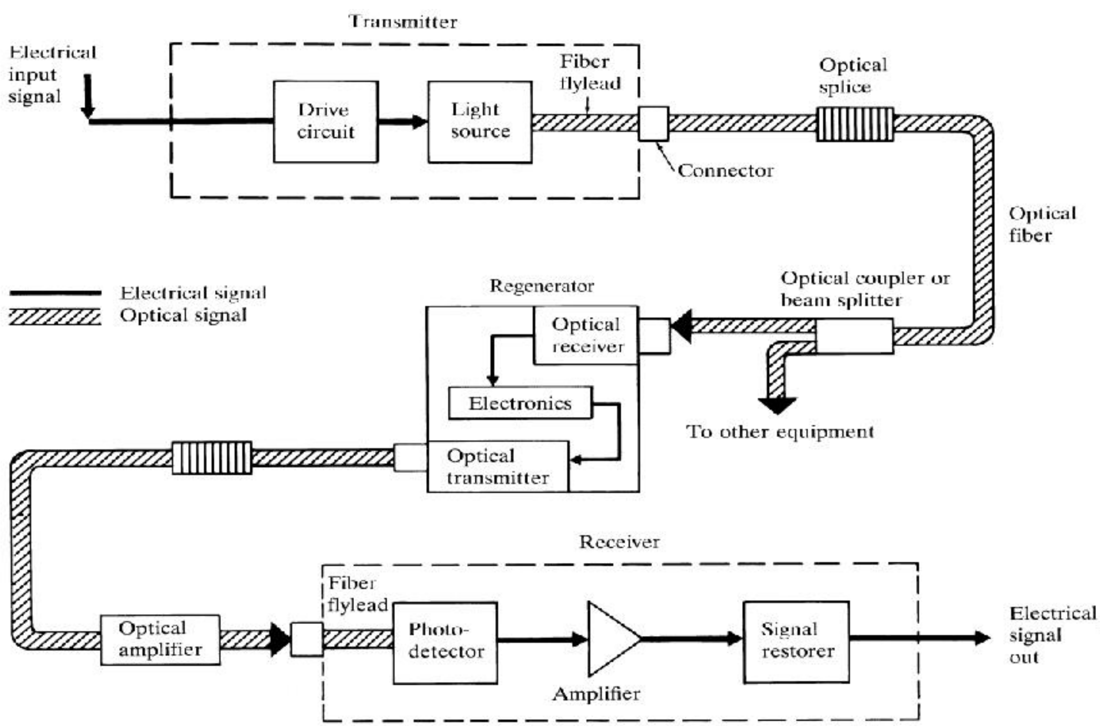


Fig. :Major elements of an optical fiber link

1.3 Propagation of light:

The exact nature of light is not fully understood, although people have been studying the subject for many centuries. In the 1700s and before, experiments seemed to indicate that light was composed of particles. In the early 1800s, a physicist Thomas Young showed that light exhibited wave characteristics.

Further experiments by other physicists culminated in James Clerk (pronounced Clark) Maxwell collecting the four fundamental equations that completely describe the behavior of the electromagnetic fields. James Maxwell deduced that light was simply a component of the electromagnetic spectrum. This seems to firmly establish that light is a wave. Yet, in the early 1900s, the interaction of light with semiconductor materials, called the **photoelectric effect**, could not be explained with electromagnetic-wave theory.

The advent of quantum physics successfully explained the photoelectric effect in terms of fundamental particles of energy called **quanta**. Quanta are known as **photons** when referring to light energy.

Today, when studying light that consists of many photons, as in propagation, that light behaves as a continuum - an electromagnetic wave. On the other hand, when studying the interaction of light with semiconductors, as in sources and detectors, the quantum physics approach is taken. The wave versus particle dilemma can be addressed in a more formal way, but that is beyond the scope of this text. It suffices to say that much has been reconciled between the two using quantum physics. In this manual, we use both the electromagnetic wave and photon concepts, each in the places where it best matches the phenomenon we are studying.

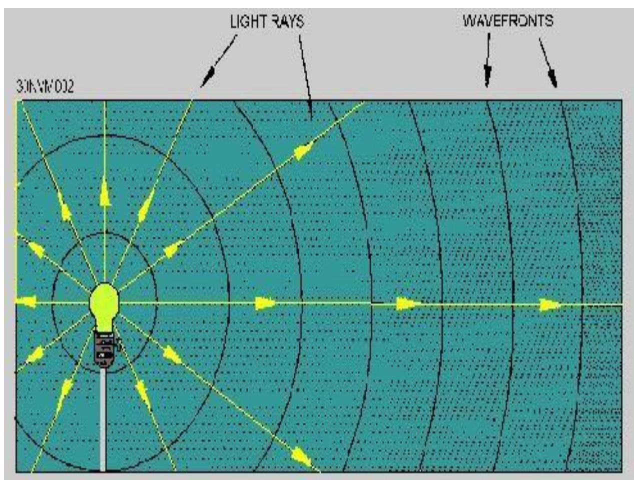
The electromagnetic energy of light is a form of electromagnetic radiation.

Light and similar forms of radiation are made up of moving electric and magnetic forces. A simple example of motion similar to these radiation waves can be made by dropping a pebble into a pool of water. In this example, the water is not actually being moved by the outward motion of the wave, but rather by the up-and-down motion of the water. The up-and-down motion is transverse, or at right angles, to the outward motion of the waves. This type of wave motion is called **transverse-wave motion**. The transverse waves spread out in expanding circles until they reach the edge of the pool, in much the same manner as the transverse waves of light spread from the sun. However, the waves in the pool are very slow and clumsy in comparison with light, which travels approximately 186,000 miles per second.

Light radiates from its source in all directions until it is absorbed or diverted by some substance (fig. 1-2). The lines drawn from the light source (a light bulb in this instance) to any point on one of the transverse waves indicate the direction that the wavefronts are moving. These lines, are called **light rays**.

Although single rays of light typically do not exist, light rays shown in illustrations are a convenient method used to show the direction in which light is traveling at any point. A ray of light can be illustrated as a straight line.

Figure 1-2. - Light rays and wavefronts from a nearby light source.



1.4 Properties of light:

When light waves, which travel in straight lines, encounter any substance, they are either reflected, absorbed, transmitted, or refracted. This is illustrated in figure 2-2. Those substances that transmit almost all the light waves falling upon them are said to be **transparent**. A transparent substance is one through which you can see clearly.

Clear glass is transparent because it transmits light rays without diffusing them (view A of figure 1-3). There is no substance known that is perfectly transparent, but many substances are nearly so. Substances through which some light rays can pass, but through which objects cannot be seen clearly because the rays are diffused, are called **translucent** (view B of figure 1-3). The frosted glass of a light bulb and a piece of oiled paper are examples of translucent materials. Those substances that are unable to transmit any light rays are called **opaque** (view C of figure 2-3). Opaque substances either reflect or absorb all the light rays that fall upon them.

All substances that are not light sources are visible only because they reflect all or some part of the light reaching them from some luminous source.

Examples of luminous sources include the sun, a gas flame, and an electric light filament, because they are sources of light energy. If light is neither transmitted nor reflected, it is absorbed or taken up by the medium. When light strikes a substance, some absorption and some reflection always take place. No substance completely transmits, reflects, or absorbs all the light rays that reach its surface.

Figure 1-2. - Light waves reflected, absorbed, and transmitted.

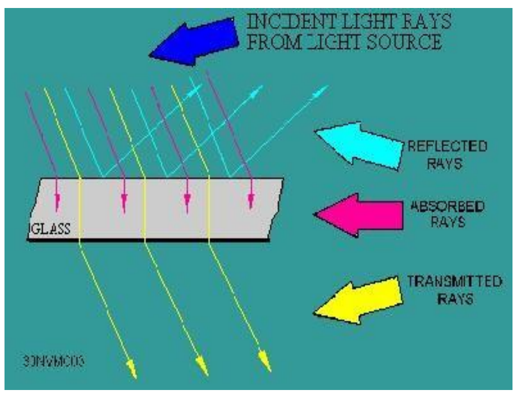
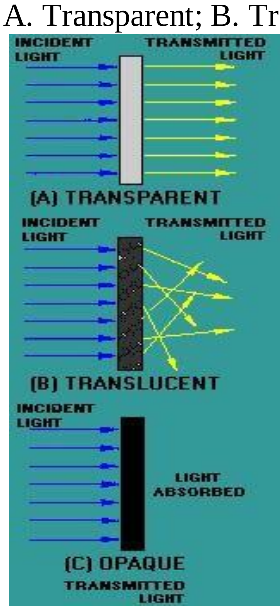


Figure 1-3. - Substances: A. Transparent; B. Translucent; and C. Opaque.

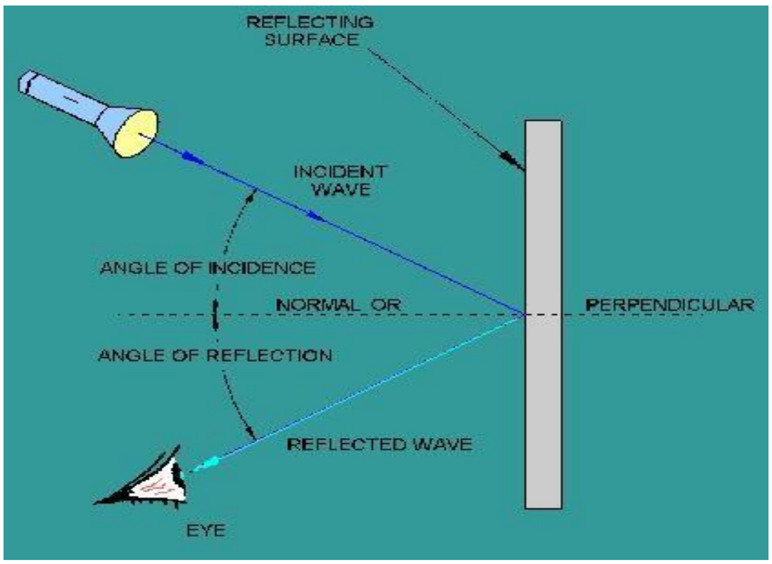


1.5 REFLECTION OF LIGHT

Reflected waves are simply those waves that are neither transmitted nor absorbed, but are reflected from the surface of the medium they encounter. When a wave approaches a reflecting surface, such as a mirror, the wave that strikes the surface is called the **incident** wave, and the one that bounces back is called the **reflected** wave (refer to figure 2-4). An imaginary line perpendicular to the point at which the incident wave strikes the reflecting surface is called the **normal**, or the perpendicular. The angle between the incident wave and the normal is called the **angle of incidence**.

The angle between the reflected wave and the normal is called the **angle of reflection**.

Figure 2-4. - Reflection of a wave.



If the surface of the medium contacted by the incident wave is smooth and polished, each reflected wave will be reflected back at the same angle as the incident wave. The path of the wave reflected from the surface forms an angle equal to the one formed by its path in reaching the medium.

This conforms to the **law of reflection** which states: The angle of incidence is equal to the angle of reflection.

The amount of incident-wave energy that is reflected from a surface depends on the nature of the surface and the angle at which the wave strikes the surface. The amount of wave energy reflected increases as the angle of incidence increases. The reflection of energy is the greatest when the wave is nearly parallel to the reflecting surface. When the incidence wave is perpendicular to the surface, more of the energy is transmitted into the substance and reflection of energy is at its least. At any incident angle, a mirror reflects almost all of the wave energy, while a dull, black surface reflects very little.

Light waves obey the law of reflection. Light travels in a straight line through a substance of uniform density. For example, you can see the straight path of light rays admitted through a narrow slit into a darkened room. The straight path of the beam is made visible by illuminated dust particles suspended in the air. If the light is made to fall onto the surface of a mirror or other reflecting surface, however, the direction of the beam changes sharply.

The light can be reflected in almost any direction, depending on the angle with which the mirror is held.

1.6 REFRACTION OF LIGHT

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**. As in the discussion of reflection, the wave striking the boundary

(surface) is called the **incident wave**, and the imaginary line perpendicular to the boundary is called the **normal**. The angle between the incident wave and the normal is called the **angle of incidence**. As the wave passes through the boundary, it is bent either toward or away from the normal. The angle between the normal and the path of the wave through the second medium is the **angle of refraction**.

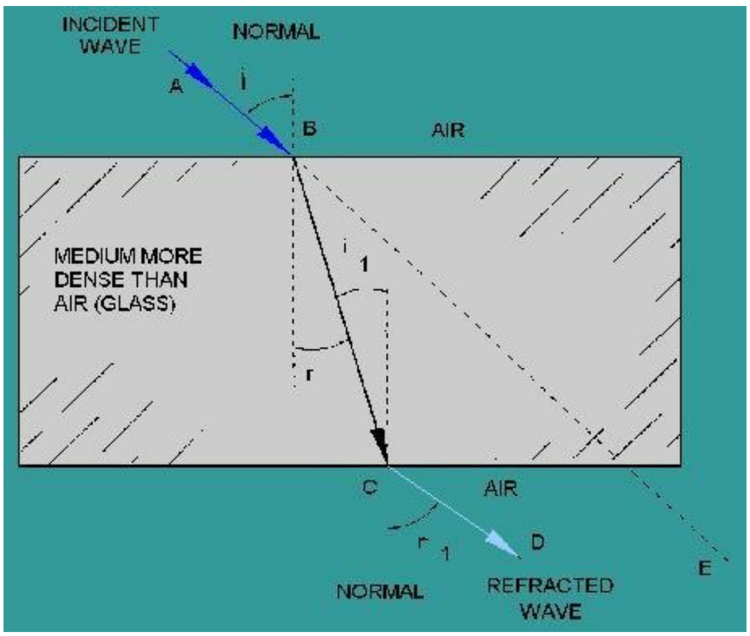
A light wave passing through a block of glass is shown in figure 2-5. The wave moves from point A to point B at a constant speed. This is the incident wave. As the wave penetrates the glass boundary at point B, the velocity of the wave is slowed down. This causes the wave to bend toward the normal. The wave then takes the path from point B to point C through the glass and becomes both the refracted wave from the top surface and the incident wave to the lower surface. As the wave passes from the glass to the air (the second boundary), it is again refracted, this time away from the normal, and takes the path from point C to point D. After passing through the last boundary, the velocity increases to the original velocity of the wave. As illustrated, refracted waves can bend toward or away from the normal.

This bending depends on the velocity of the wave through different mediums. The broken line between points B and E is the path that the wave would travel if the two mediums (air and glass) had the same density.

Another interesting condition can be shown using figure 2-5. If the wave passes from a less dense to a more dense medium, it is bent toward the normal, and the angle of refraction (r) is less than the angle of incidence (i). Likewise, if the wave passes from a more dense to a less dense medium, it is bent away from the normal, and the angle of refraction (r_1) is greater than the angle of incidence (i_1).

An example of refraction is the apparent bending of a spoon when it is immersed in a cup of water. The bending seems to take place at the surface of the water, or exactly at the point where there is a change of density.

Figure 2-5. - Refraction of a wave.



Obviously, the spoon does not bend from the pressure of the water. The light forming the image of the spoon is bent as it passes from the water (a medium of high density) to the air (a medium of comparatively low density).

Without refraction, light waves would pass in straight lines through transparent substances without any change of direction. Figure 2-5 shows that rays striking the glass at any angle other than perpendicular are refracted. However, perpendicular rays, which enter the glass normal to the surface, continue through the glass and into the air in a straight line - no refraction takes place.

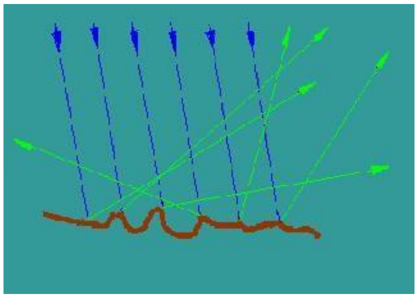
1.7 DIFFUSION OF LIGHT

When light is reflected from a mirror, the angle of reflection equals the angle of incidence. When light is reflected from a piece of plain white paper; however, the reflected beam is scattered, or **diffused**, as shown in figure 2-6. Because the surface of the paper is not smooth, the reflected light is broken up into many light beams that are reflected in all directions.

1.8 ABSORPTION OF LIGHT

If the surface upon which the light beam falls is perfectly black, there is no reflection; that is, the light is totally absorbed. No matter what kind of surface light falls upon, some of the light is absorbed.

Figure 2-6. - Diffusion of light.



1.9 TRANSMISSION OF LIGHT THROUGH OPTICAL FIBERS

The transmission of light along optical fibers depends not only on the nature of light, but also on the structure of the optical fiber. Two methods are used to describe how light is transmitted along the optical fiber. The first method, **ray theory**, uses the concepts of light reflection and refraction. The second method, **mode theory**, treats light as electromagnetic waves. You must first understand the basic optical properties of the materials used to make optical fibers. These properties affect how light is transmitted through the fiber.

1.9.1 Ray Optics:

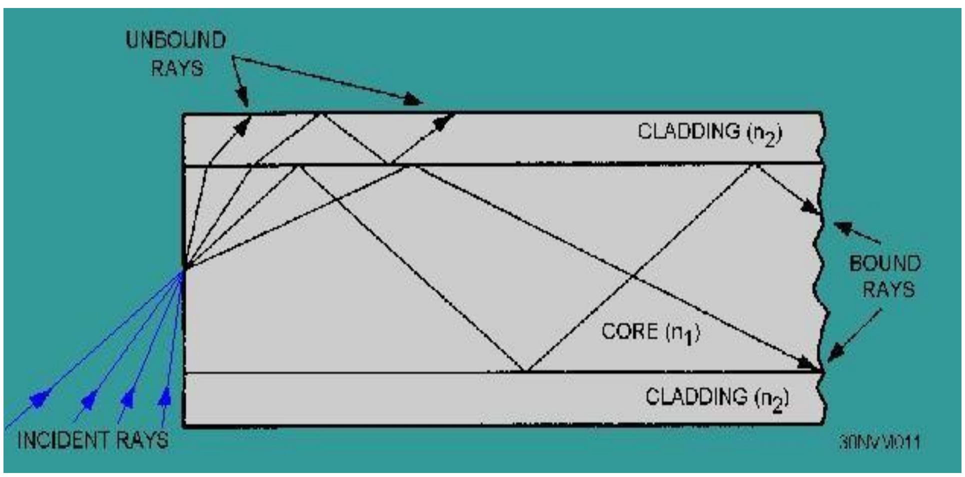
Two types of rays can propagate along an optical fiber. The first type is called meridional rays. **Meridional rays** are rays that pass through the axis of the optical fiber. Meridional rays are used to illustrate the basic transmission properties of optical fibers.

The second type is called skew rays. **Skew rays** are rays that travel through an optical fiber without passing through its axis.

1.9.2 MERIDIONAL RAYS. - Meridional rays can be classified as bound or unbound rays. Bound rays remain in the core and propagate along the axis of the fiber. **Bound** rays propagate through the fiber by total internal reflection. **Unbound** rays are refracted out of the fiber core. Figure 2-10 shows a possible path taken by bound and unbound rays in a step-index fiber. The core of the step-index fiber has an index of refraction n_1. The cladding of a step-index has an index of refraction n_2, that is lower than n_1. Figure 2-10 assumes the core-cladding interface is perfect. However, imperfections at the core-cladding interface will cause part of the bound rays to be refracted out of the core into the cladding. The light rays refracted into the cladding will eventually escape from the fiber. In general, meridional rays follow the laws of reflection and refraction.

It is known that bound rays propagate in fibers due to total internal reflection, but how do these light rays enter the fiber? Rays that enter the fiber must intersect the core-cladding interface at an angle greater than the critical angle (Θ$_c$). Only those rays that enter the fiber and strike the interface at these angles will propagate along the fiber.

Figure 2-10. - Bound and unbound rays in a step-index fiber.



How a light ray is launched into a fiber is shown in figure 2-11. The incident ray I_1 enters the fiber at the angle Θ$_a$. I_1 is refracted upon entering the fiber and is transmitted to the core-cladding interface. The ray then strikes the core-cladding interface at the critical angle (Θ $_c$). I_1 is totally reflected back into the core and continues to propagate along the fiber. The incident ray I_2 enters the fiber at an angle greater than Θ$_a$. Again, I_2 is refracted upon entering the fiber and is transmitted to the core-cladding interface. I_2 strikes the core-cladding interface at an angle less than the critical angle (Θ$_c$). I_2 is refracted into the cladding and is eventually lost. The light ray incident on the fiber core must be within the **acceptance cone** defined by the angle Θ$_a$ shown in figure 2-12.

Angle Θ$_a$ is defined as the acceptance angle. The **acceptance angle** (Θ$_a$) is the maximum angle to the axis of the fiber that light entering the fiber is propagated. The value of the angle of acceptance (Θ$_a$) depends on fiber properties and transmission conditions.

Figure 2-12 illustrates the relationship between the acceptance angle and the refractive indices. The index of refraction of the fiber core is n_1. The index of refraction of the fiber cladding is n_2. The index of refraction of the surrounding medium is n_0. By using Snell's law and basic trigonometric relationships, the NA of the fiber is given by:

$$NA = n_0 \times \sin\Theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}}$$

Since the medium next to the fiber at the launching point is normally air, n_0 is equal to 1.00. The NA is then simply equal to sin Θ$_a$.

Figure 2-11. - How a light ray enters an optical fiber.

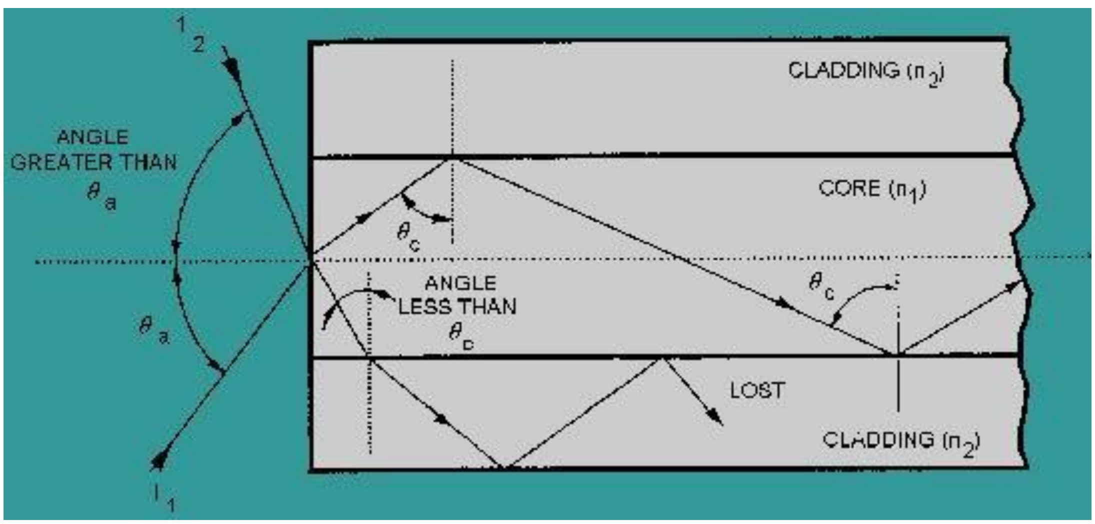
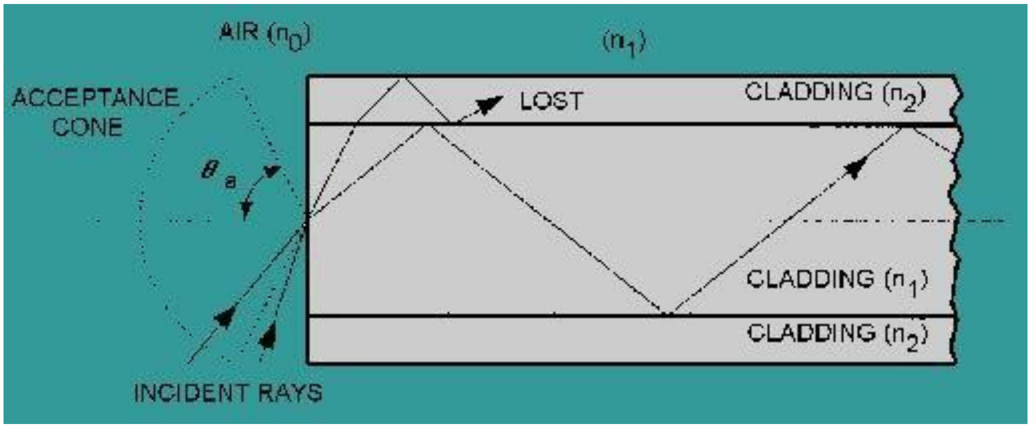


Figure 2-12. - Fiber acceptance angle.



The NA is a convenient way to measure the light-gathering ability of an optical fiber. It is used to measure source-to-fiber power-coupling efficiencies. A high NA indicates a high source-to-fiber coupling efficiency.

Source-to-fiber coupling efficiency is described in chapter 6. Typical values of NA range from 0.20 to 0.29 for glass fibers. Plastic fibers generally have a higher NA. An NA for plastic fibers can be higher than 0.50.

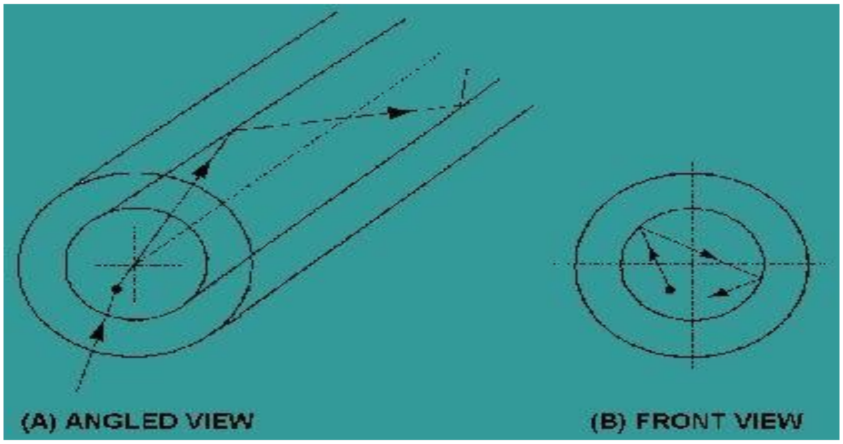
In addition, the NA is commonly used to specify multimode fibers.

However, for small core diameters, such as in single mode fibers, the ray theory breaks down. 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. Optical fibers can support only a specific number of guided modes. In small core fibers, the number of modes supported is one or only a few modes. Mode theory is used to describe the types of plane waves able to propagate along an optical fiber.

1.9.3 SKEW RAYS. - A possible path of propagation of skew rays is shown in figure 2-13. Figure 2-13, view A, provides an angled view and view B provides a front view. Skew rays propagate without passing through the center axis of the fiber.

The acceptance angle for skew rays is larger than the acceptance angle of meridional rays. This condition explains why skew rays outnumber meridional rays. Skew rays are often used in the calculation of light acceptance in an optical fiber. The addition of skew rays increases the amount of light capacity of a fiber. In large NA fibers, the increase may be significant.

Figure 2-13. - Skew ray propagation: A. Angled view; B. Front view.



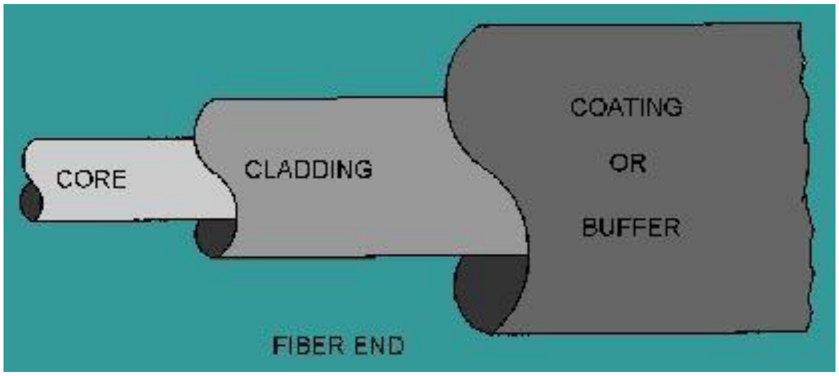
The addition of skew rays also increases the amount of loss in a fiber. Skew rays tend to propagate near the edge of the fiber core. A large portion of the number of skew rays that are trapped in the fiber core are considered to be **leaky rays**. Leaky rays are predicted to be totally reflected at the core-cladding boundary. However, these rays are partially refracted because of the curved nature of the fiber boundary. Mode theory is also used to describe this type of leaky ray loss.

1.10 Optical Fiber Modes and Configurations:

1.10.1 Basic structure of an optical fiber:

The basic structure of an optical fiber consists of three parts; the **core**, the **cladding**, and the **coating** or **buffer**. The basic structure of an optical fiber is shown in figure 2-9. 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. 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.

Figure 2-9. - Basic structure of an optical fiber.



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

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.

1.11 OPTICAL FIBER TYPES

Optical fibers are characterized by their structure and by their properties of transmission. Basically, optical fibers are classified into two types. The first type is single mode fibers. The second type is multimode fibers. As each name implies, optical fibers are classified by the number of modes that propagate along the fiber. As previously explained, the structure of the fiber can permit or restrict modes from propagating in a fiber. The basic structural difference is the core size. Single mode fibers are manufactured with the same materials as multimode fibers. Single mode fibers are also manufactured by following the same fabrication process as multimode fibers.

1.11.1 Single Mode Fibers

The core size of single mode fibers is small. The core size (diameter) is typically around 8 to 10 micrometers (μm). A fiber core of this size allows only the fundamental or lowest order mode to propagate around a 1300 nanometer (nm) wavelength. Single mode fibers propagate only one mode, because the core size approaches the operational wavelength (λ). The value of the normalized frequency parameter (V) relates core size with mode propagation.

In single mode fibers, V is less than or equal to 2.405. When V ≤ 2.405, single mode fibers propagate the fundamental mode down the fiber core, while high-order modes are lost in the cladding. For low V values (≤1.0), most of the power is propagated in the cladding material. Power transmitted by the cladding is easily lost at fiber bends. The value of V should remain near the 2.405 level.

Single mode fibers have a lower signal loss and a higher information capacity (bandwidth) than multimode fibers. Single mode fibers are capable of transferring higher amounts of data due to low fiber dispersion. Basically, dispersion is the spreading of light as light propagates along a fiber. Dispersion mechanisms in single mode fibers are discussed in more detail later in this chapter. Signal loss depends on the operational wavelength (λ). In single mode fibers, the wavelength can increase or decrease the losses caused by fiber bending. Single mode fibers operating at wavelengths larger than the cutoff wavelength lose more power at fiber bends. They lose power because light radiates into the cladding, which is lost at fiber bends. In general, single mode fibers are considered to be low-loss fibers, which increase system bandwidth and length.

1.11.2 Multimode Fibers

As their name implies, multimode fibers propagate more than one mode. Multimode fibers can propagate over 100 modes. The number of modes propagated depends on the core size and numerical aperture (NA). As the core size and

NA increase, the number of modes increases. Typical values of fiber core size and NA are 50 to 100 μm and 0.20 to 0.29, respectively.

A large core size and a higher NA have several advantages. Light is launched into a multimode fiber with more ease. The higher NA and the larger core size make it easier to make fiber connections. During fiber splicing, core-to-core alignment becomes less critical. Another advantage is that multimode fibers permit the use of light-emitting diodes (LEDs). Single mode fibers typically must use laser diodes. LEDs are cheaper, less complex, and last longer. LEDs are preferred for most applications.

Multimode fibers also have some disadvantages. As the number of modes increases, the effect of modal dispersion increases. Modal dispersion (intermodal dispersion) means that modes arrive at the fiber end at slightly different times. This time difference causes the light pulse to spread. Modal dispersion affects system bandwidth. Fiber manufacturers adjust the core diameter, NA, and index profile properties of multimode fibers to maximize system bandwidth.

1.12 OPTICAL FIBERS

Chapter 2 classified optical fibers as either single mode or multimode fibers. Fibers are classified according to the number of modes that they can propagate. Single mode fibers can propagate only the fundamental mode. Multimode fibers can propagate hundreds of modes. However, the classification of an optical fiber depends on more than the number of modes that a fiber can propagate.

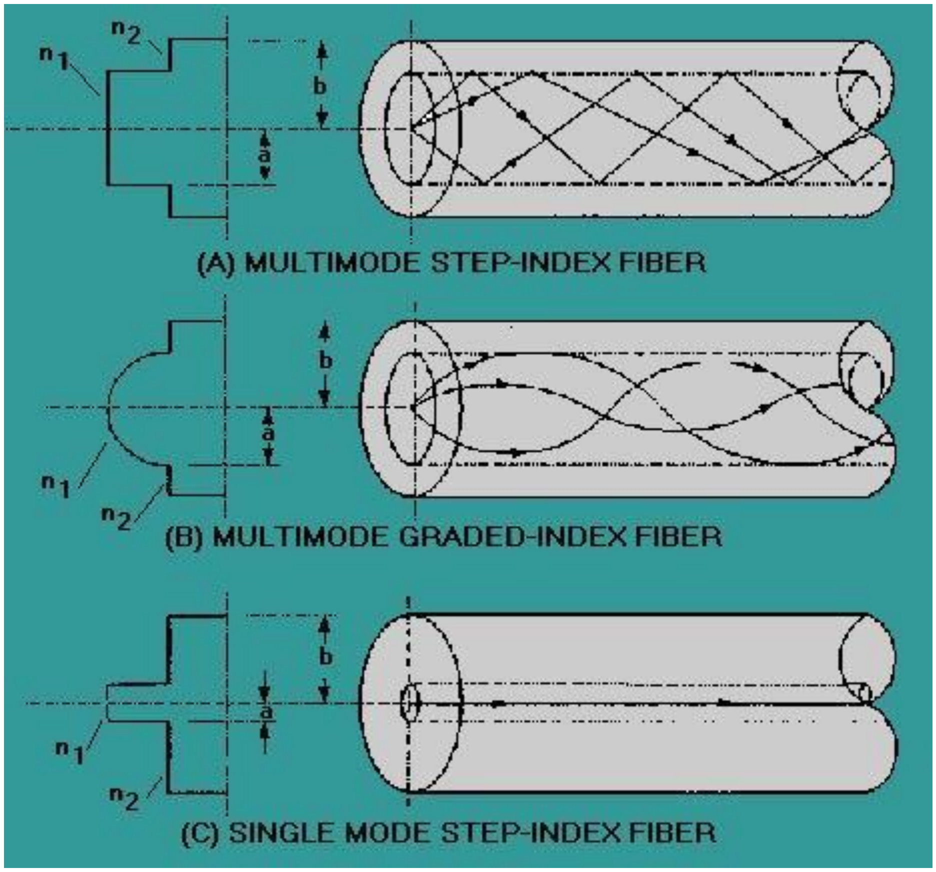
An optical fiber's refractive index profile and core size further distinguish single mode and multimode fibers. The **refractive index profile** describes the value of refractive index as a function of radial distance at any fiber diameter. Fiber refractive index profiles classify single mode and multimode fibers as follows:

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

In a **step-index** fiber, the refractive index of the core is uniform and undergoes an abrupt change at the core-cladding boundary. Step-index fibers obtain their name from this abrupt change called the step change in refractive index. In **graded-index** fibers, the refractive index of the core varies gradually as a function of radial distance from the fiber center.

Single mode and multimode fibers can have a step-index or graded-index refractive index profile. The performance of multimode graded-index fibers is usually superior to multimode step-index fibers. However, each type of multimode fiber can improve system design and operation depending on the intended application. Performance advantages for single mode graded-index fibers compared to single mode step-index fibers are relatively small. Therefore, single mode fiber production is almost exclusively step-index. Figure 3-1 shows the refractive index profile for a multimode step-index fiber and a multimode graded-index fiber. Figure 3-1 also shows the refractive index profile for a single mode step-index fiber. Since light propagates differently in each fiber type, figure 3-1 shows the propagation of light along each fiber.

Figure 3-1. - The refractive index profiles and light propagation in multimode step-index, multimode graded-index, and single mode step-index fibers.



A small change in core size and material composition affects fiber transmission properties, such as attenuation and dispersion.

When selecting an optical fiber, the system designer decides which fiber core size and material composition is appropriate.

Standard core sizes for multimode step-index fibers are 50 μm and 100 μm. Standard core sizes for multimode graded-index fibers are 50 μm, 62.5 μm, 85 μm, and 100 μm. Standard core sizes for single mode fibers are between 8 μm and 10 μm. In most cases, the material used in the preparation of optical fibers is high-quality glass (SiO_2).

This glass contains very low amounts of impurities, such as water or elements other than silica and oxygen. Using high-quality glass produces fibers with low losses. Small amounts of some elements other than silica and oxygen are added to the glass material to change its index of refraction. These elements are called material dopants. Silica doped with various materials forms the refractive index profile of the fiber core and material dopants are discussed in more detail later in this chapter. Glass is not the only material used in fabrication of optical fibers. Plastics are also used for core and cladding materials in some applications.

A particular optical fiber design can improve fiber optic system performance.

Each single mode or multimode, step-index or graded-index, glass or plastic, or large or small core fiber has an intended application. The system designer must choose an appropriate fiber design that optimizes system performance in his application.

1.13 MULTIMODE STEP-INDEX FIBERS

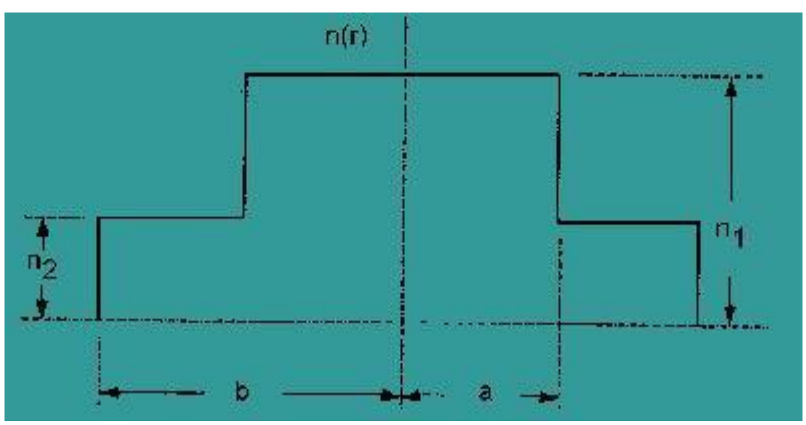
A multimode step-index fiber has a core of radius (a) and a constant refractive index n_1. A cladding of slightly lower refractive index n_2 surrounds the core. Figure 3-2 shows the refractive index profile n(r) for this type of fiber. n(r) is equal to n_1 at radial distances r < a (core). n(r) is equal to n_2 at radial distances r ≥ a (cladding). Notice the step decrease in the value of refractive index at the core-cladding interface.

This step decrease occurs at a radius equal to distance (a). The difference in the core and cladding refractive index is the parameter Δ:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

Δ is the **relative refractive index difference.**

Figure 3-2. - The refractive index profile for multimode step-index fibers.



The ability of the fiber to accept optical energy from a light source is related to Δ. Δ also relates to the numerical aperture by

$$NA \simeq n_1\sqrt{2\Delta}.$$

The number of modes that multimode step-index fibers propagate depends on Δ and core radius (a) of the fiber. The number of propagating modes also depends on the wavelength (λ) of the transmitted light.

In a typical multimode step-index fiber, there are hundreds of propagating modes.

Most modes in multimode step-index fibers propagate far from cutoff.

Modes that are cut off cease to be bound to the core of the fiber. Modes that are farther away from the cutoff wavelength concentrate most of their light energy into the fiber core. Modes that propagate close to cutoff have a greater percentage of their light energy propagate in the cladding. Since most modes propagate far from cutoff, the majority of light propagates in the fiber core.

Therefore, in multimode step-index fibers, cladding properties, such as cladding diameter, have limited affect on mode (light) propagation.

Multimode step-index fibers have relatively large core diameters and large numerical apertures. A large core size and a large numerical aperture make it easier to couple light from a light-emitting diode (LED) into the fiber. Multimode step-index fiber core size is typically 50 μm or 100 μm.

Unfortunately, multimode step-index fibers have limited bandwidth capabilities.

Dispersion, mainly modal dispersion, limits the bandwidth or information-carrying capacity of the fiber. System designers consider each factor when selecting an appropriate fiber for each particular application.

Multimode step-index fiber selection depends on system application and design. Short-haul, limited bandwidth, low-cost applications typically use multimode step-index fibers.

1.14 MULTIMODE GRADED-INDEX FIBERS

A multimode graded-index fiber has a core of radius (a). Unlike step-index fibers, the value of the refractive index of the core (n_1) varies according to the radial distance (r). The value of n_1 decreases as the distance (r) from the center of the fiber increases.

The value of n_1 decreases until it approaches the value of the refractive index of the cladding (n_2). The value of n_1 must be higher than the value of n_2 to allow for proper mode propagation. Like the step-index fiber, the value of n_2 is constant and has a slightly lower value than the maximum value of n_1. The relative refractive index difference (Δ) is determined using the maximum value of n_1 and the value of n_2.

Figure 3-3 shows a possible refractive index profile n(r) for a multimode graded-index fiber. Notice the parabolic refractive index profile of the core. The **profile parameter**

(α) determines the shape of the core's profile. As the value of &agr; increases, the shape of the core's profile changes from a triangular shape to step as shown in figure 3-4. Most multimode graded-index fibers have a parabolic refractive index profile. Multimode fibers with near parabolic graded-index profiles provide the best performance. Unless otherwise specified, when discussing multimode graded-index fibers, assume that the core's refractive index profile is parabolic (α=2).

Light propagates in multimode graded-index fibers according to refraction and total internal reflection. The gradual decrease in the core's refractive index from the center of the fiber causes the light rays to be refracted many times. The light rays become refracted or curved, which increases the angle of incidence at the next point of refraction. Total internal reflection occurs when the angle of incidence becomes larger than the critical angle of incidence. Figure 3-5 shows the process of refraction and total internal reflection of light in multimode graded-index fibers. Figure 3-5 also illustrates the boundaries of different values of core refractive index by dotted lines. Light rays may be reflected to the axis of the fiber before reaching the core-cladding interface.

Figure 3-3. - The refractive index profile for multimode graded-index fibers.

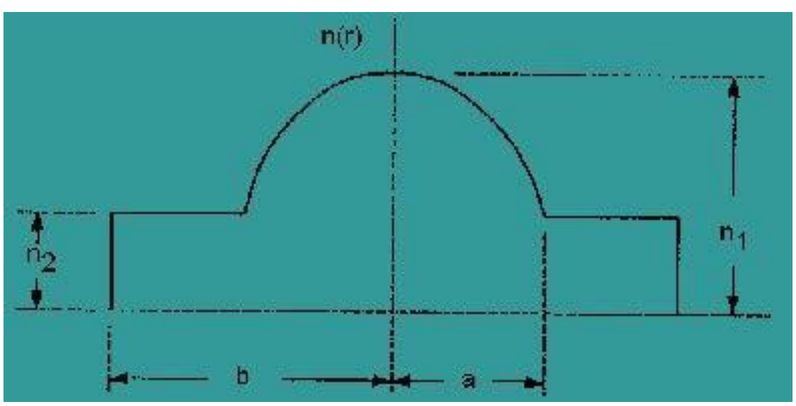


Figure 3-4. - The refractive index profiles for different values of &agr;.

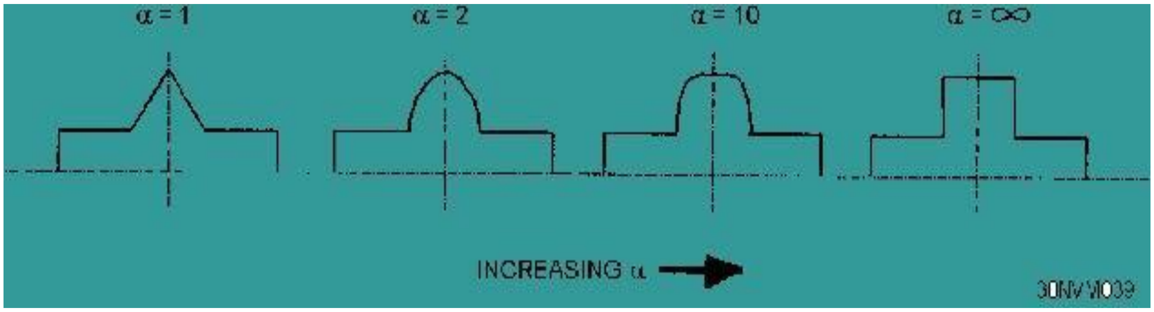
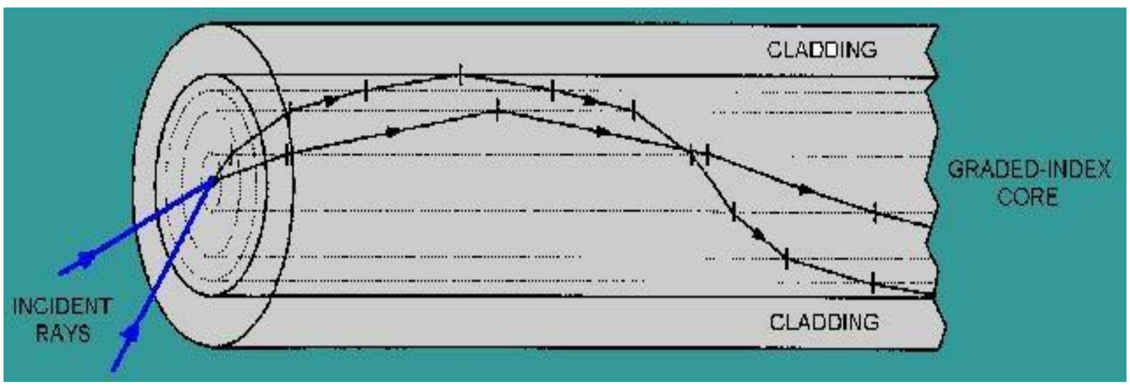


Figure 3-5. - Refractive index grading and light propagation in multimode graded-index fibers.



The NA of a multimode graded-index fiber is at its maximum value at the fiber axis. This NA is the **axial numerical aperture [NA(0)]. NA(0) is approximately equal to**

$n_1\sqrt{2\Delta}$.

However, the NA for graded-index fibers varies as a function of the radial distance (r). NA varies because of the refractive index grading in the fiber's core. The NA decreases from the maximum, NA(0), to zero at distances greater than the core-cladding boundary distance (r>a). The NA, relative refractive index difference (Δ), profile parameter (α), and normalized frequency (V) determine the number of propagating modes in multimode graded-index fibers. A multimode graded-index fiber with the same normalized frequency as a multimode step-index fiber will have approximately one-half as many propagating modes. However, multimode graded-index fibers typically have over one-hundred propagating modes.

Multimode graded-index fibers accept less light than multimode step-index fibers with the same core Δ. However, graded-index fibers usually outperform the step-index fibers. The core's parabolic refractive index profile causes multimode graded-index fibers to have less modal dispersion.

Figure 3-5 shows possible paths that light may take when propagating in multimode graded-index fibers. Light rays that travel farther from the fiber's axis travel a longer distance. Light rays that travel farther from the center travel in core material with an average lower refractive index.

In chapter 2, you learned that light travels faster in a material with a lower refractive index. Therefore, those light rays that travel the longer distance in the lower refractive index parts of the core travel at a greater average velocity. This means that the rays that travel farther from the fiber's axis will arrive at each point along the fiber at nearly the same time as the rays that travel close to the fiber's axis. The decrease in time difference between light rays reduces modal dispersion and increases multimode graded-index fiber bandwidth. The increased bandwidth allows the use of multimode graded-index fibers in most applications.

Most present day applications that use multimode fiber use graded-index fibers. The basic design parameters are the fiber's core and cladding size and Δ. Standard multimode graded-index fiber core and cladding sizes are 50/125 μm, 62.5/125 μm, 85/125 μm, and 100/140 μm. Each fiber design has a specific Δ that improves fiber performance. Typical values of Δ are around 0.01 to 0.02. Although no single multimode graded-index fiber design is appropriate for all applications, the 62.5/125 μm fiber with a Δ of 0.02 offers the best overall performance.

A multimode graded-index fiber's source-to-fiber coupling efficiency and insensitivity to microbending and macrobending losses are its most distinguishing characteristics. The fiber core size and Δ affect the amount of power coupled into the core and loss caused by microbending and macrobending. Coupled power increases with both core diameter and Δ, while bending losses increase directly with core diameter and inversely with Δ. However, while these values favor high Δs, a smaller Δ improves fiber bandwidth.

In most applications, a multimode graded-index fiber with a core and cladding size of 62.5/125 μm offers the best combination of the following properties:

- Relatively high source-to-fiber coupling efficiency
- Low loss
- Low sensitivity to microbending and macrobending
- High bandwidth
- Expansion capability

For example, local area network (LAN) and shipboard applications use multimode graded-index fibers with a core and cladding size of 62.5/125 μm. In LAN-type environments, macrobend and microbend losses are hard to predict. Cable tension, bends, and local tie-downs increase macrobend and microbend losses. In shipboard applications, a ship's cable-way may place physical restrictions, such as tight bends, on the fiber during cable plant installation. The good microbend and macrobend performance of 62.5/125 μm fiber permits installation of a rugged and robust cable plant. 62.5/125 μm multimode graded-index fibers allow for uncomplicated growth because of high fiber bandwidth capabilities for the expected short cable runs on board ships.

1.15 SINGLE MODE STEP-INDEX FIBERS

There are two basic types of single mode step-index fibers: matched clad and depressed clad. **Matched cladding** means that the fiber cladding consists of a single homogeneous layer of dielectric material. **Depressed cladding** means that the fiber cladding consists of two regions: the inner and outer cladding regions.

Matched-clad and depressed-clad single mode step-index fibers have unique refractive index profiles.

A matched-clad single mode step-index fiber has a core of radius (a) and a constant refractive index n_1. A cladding of slightly lower refractive index surrounds the core. The cladding has a refractive index n_2. Figure 3-6 shows the refractive index profile n(r) for the matched-clad single mode fiber. Figure 3-6. - Matched-clad refractive index profile.

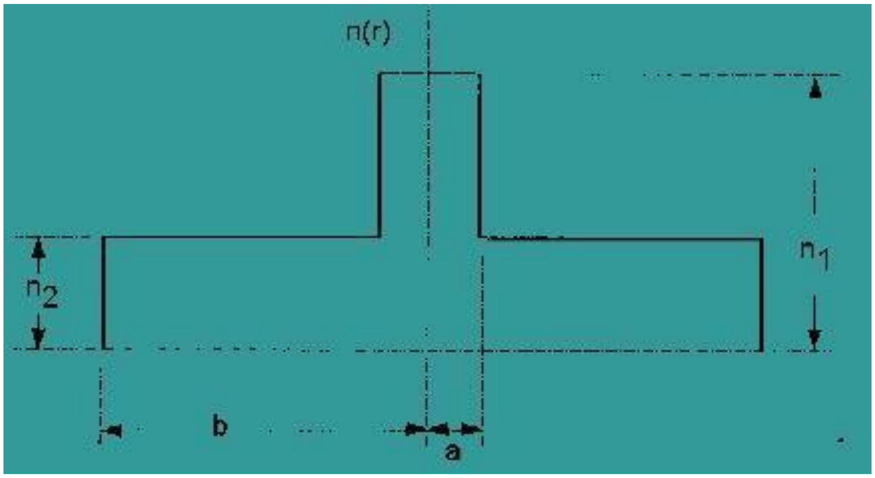


Figure 3-7 shows the refractive index profile n(r) for the depressed-clad single mode fiber. A depressed-clad single mode step-index fiber has a core of radius (a) with a constant refractive index n_1. A cladding, made of two regions, surrounds the core.

An inner cladding region surrounds the core of the fiber and has a refractive index of n_2. The inner cladding refractive index n_2 is lower than the core's refractive index n_1.

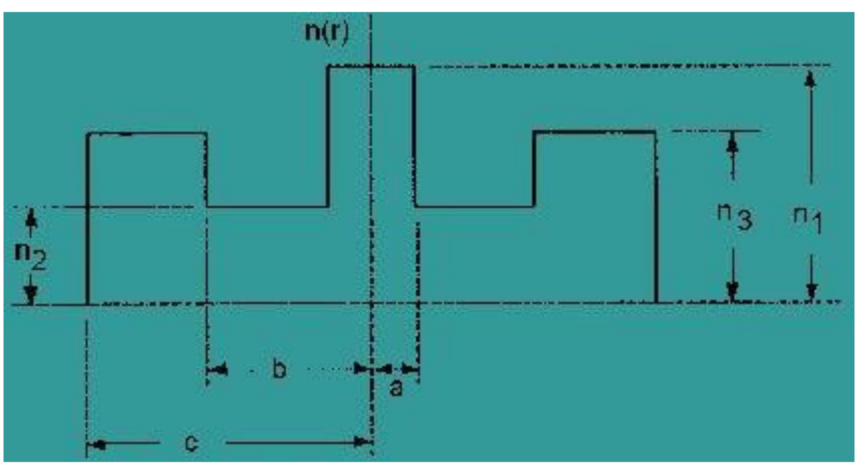
An outer cladding region surrounds the inner cladding region and has a higher refractive index n_3 than the inner cladding region. However, the outer cladding refractive index n_3 is lower than the core's refractive index n_1.

Single mode step-index fibers propagate only one mode, called the fundamental mode. Single mode operation occurs when the value of the fiber's normalized frequency is between 0 and 2.405 (0 ≤ V < 2.405). The value of V should remain near the 2.405 level. When the value of V is less than 1, single mode fibers carry a majority of the light power in the cladding material. The portion of light transmitted by the cladding material easily radiates out of the fiber. For example, light radiates out of the cladding material at fiber bends and splices.

Single mode fiber cutoff wavelength is the smallest operating wavelength when single mode fibers propagate only the fundamental mode. At this wavelength, the 2nd-order mode becomes lossy and radiates out of the fiber core. As the operating wavelength becomes longer than the cutoff wavelength, the fundamental mode becomes increasingly lossy.

The higher the operating wavelength is above the cutoff wavelength, the more power is transmitted through the fiber cladding. As the fundamental mode extends into the cladding material, it becomes increasingly sensitive to bending loss.

Figure 3-7. - Depressed-clad refractive index profile.



Single mode fiber designs include claddings of sufficient thickness with low absorption and scattering properties to reduce attenuation of the fundamental mode. To increase performance and reduce losses caused by fiber bending and splicing, fiber manu facturers adjust the value of V. To adjust the value of V, they vary the core and cladding sizes and relative refractive index difference (Δ).

A single mode step-index fiber has low attenuation and high bandwidth properties. Present applications for single mode fibers include long-haul, high-speed telecommunication systems. Future applications include single mode fibers for sensor systems. However, the current state of single mode technology makes installation of single mode systems expensive and difficult. Short cable runs, low to moderate bandwidth requirements, and high component cost make installation of single mode fiber shipboard systems impractical at this time.

1.16 SINGLE MODE GRADED-INDEX FIBERS

There are several types of single mode graded-index fibers. These fibers are not standard fibers and are typically only used in specialty applications.

1.16.1 Mode Theory :

The mode theory, along with the ray theory, is used to describe the propagation of light along an optical fiber. The mode theory is used to describe the properties of light that ray theory is unable to explain. The mode theory uses electromagnetic wave behavior to describe the propagation of light along a fiber. A set of guided electromagnetic waves is called the **modes** of the fiber.

1.16.2 **PLANE WAVES**. - The mode theory suggests that a light wave can be represented as a plane wave. A **plane wave** is described by its direction, amplitude, and wavelength of propagation. A plane wave is a wave whose surfaces of constant phase are infinite parallel planes normal to the direction of propagation.

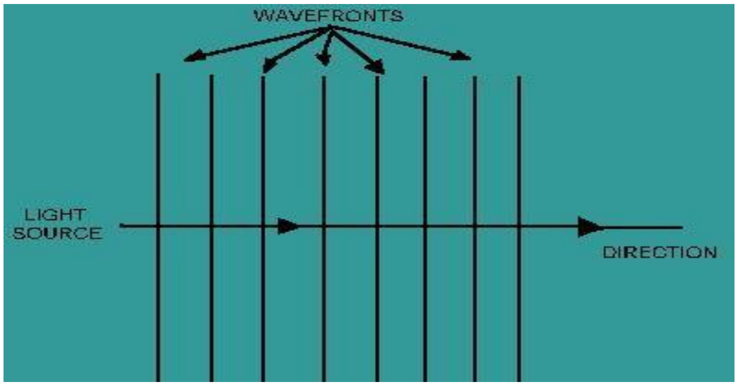
The planes having the same phase are called the wavefronts. The wavelength (λ) of the plane wave is given by:

$$\text{wavelength } (\lambda) = \frac{c}{fn}$$

where *c* is the speed of light in a vacuum, *f* is the frequency of the light, and n is the index of refraction of the plane-wave medium.

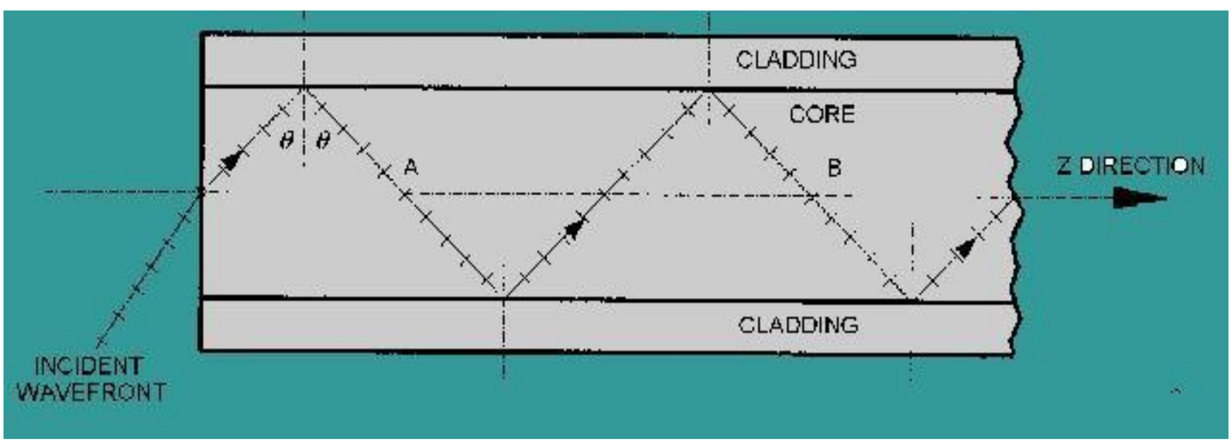
Figure 2-14 shows the direction and wavefronts of plane-wave propagation. Plane waves, or wavefronts, propagate along the fiber similar to light rays. However, not all wavefronts incident on the fiber at angles less than or equal to the critical angle of light acceptance propagate along the fiber. Wavefronts may undergo a change in phase that prevents the successful transfer of light along the fiber.

Figure 2-14. - Plane-wave propagation.



Wavefronts are required to remain in phase for light to be transmitted along the fiber. Consider the wavefront incident on the core of an optical fiber as shown in figure 2-15. Only those wavefronts incident on the fiber at angles less than or equal to the critical angle may propagate along the fiber. The wavefront undergoes a gradual phase change as it travels down the fiber. Phase changes also occur when the wavefront is reflected. The wavefront must remain in phase after the wavefront transverses the fiber twice and is reflected twice. The distance transversed is shown between point A and point B on figure 2-15. The reflected waves at point A and point B are in phase if the total amount of phase collected is an integer multiple of 2π radian. If propagating wavefronts are not in phase, they eventually disappear. Wavefronts disappear because of **destructive interference**. The wavefronts that are in phase interfere with the wavefronts that are out of phase. This interference is the reason why only a finite number of modes can propagate along the fiber.

Figure 2-15. - Wavefront propagation along an optical fiber.



The plane waves repeat as they travel along the fiber axis. The direction the plane waves travel is assumed to be the z direction as shown in figure 2-15. The plane waves repeat at a distance equal to λ/sinΘ. Plane waves also repeat at a periodic frequency β = 2π sin Θ/λ. The quantity β is defined as the **propagation constant** along the fiber axis. As the wavelength (λ) changes, the value of the propagation constant must also change.

For a given mode, a change in wavelength can prevent the mode from propagating along the fiber. The mode is no longer bound to the fiber. The mode is said to be cut off. Modes that are bound at one wavelength may not exist at longer wavelengths. The wavelength at which a mode ceases to be bound is called the **cutoff wavelength** for that mode. However, an optical fiber is always able to propagate at least one mode. This mode is referred to as the fundamental mode of the fiber. The fundamental mode can never be cut off.

The wavelength that prevents the next higher mode from propagating is called the cutoff wavelength of the fiber. An optical fiber that operates above the cutoff wavelength (at a longer wavelength) is called a single mode fiber. An optical fiber that operates below the cutoff wavelength is called a multimode fiber. Single mode and multimode optical fibers are discussed later in this chapter.

In a fiber, the propagation constant of a plane wave is a function of the wave's wavelength and mode. The change in the propagation constant for different waves is called **dispersion**. The change in the propagation constant for different wavelengths is called **chromatic dispersion**. The change in propagation constant for different modes is called **modal dispersion**.

These dispersions cause the light pulse to spread as it goes down the fiber (fig. 2-16). Some dispersion occurs in all types of fibers. Dispersion is discussed later in this chapter.

Figure 2-16. - The spreading of a light pulse.

1.17 MODES. - A set of guided electromagnetic waves is called the **modes** of an optical fiber.

Maxwell's equations describe electromagnetic waves or modes as having two components. The two components are the electric field, E(x, y, z), and the magnetic field, H(x, y, z). The electric field, E, and the magnetic field, H, are at right angles to each other. Modes traveling in an optical fiber are said to be transverse. The transverse modes, shown in figure 2-17, propagate along the axis of the fiber. The mode field patterns shown in figure 2-17 are said to be transverse electric (TE). In TE modes, the electric field is perpendicular to the direction of propagation.

The magnetic field is in the direction of propagation. Another type of transverse mode is the transverse magnetic (TM) mode. TM modes are opposite to TE modes. In TM modes, the magnetic field is perpendicular to the direction of propagation. The electric field is in the direction of propagation. Figure 2-17 shows only TE modes.

The TE mode field patterns shown in figure 2-17 indicate the **order** of each mode. The order of each mode is indicated by the number of field maxima within the core of the fiber. For example, TE_0 has one field maxima. The electric field is a maximum at the center of the waveguide and decays toward the core-cladding boundary. TE_0 is considered the fundamental mode or the lowest order standing wave. As the number of field maxima increases, the order of the mode is higher. Generally, modes with more than a few (5-10) field maxima are referred to as high-order modes.

The order of the mode is also determined by the angle the wavefront makes with the axis of the fiber. Figure 2-18 illustrates light rays as they travel down the fiber. These light rays indicate the direction of the wavefronts. High-order modes cross the axis of the fiber at steeper angles. Low-order and high-order modes are shown in figure 2-18.

Figure 2-17. - Transverse electric (TE) mode field patterns.

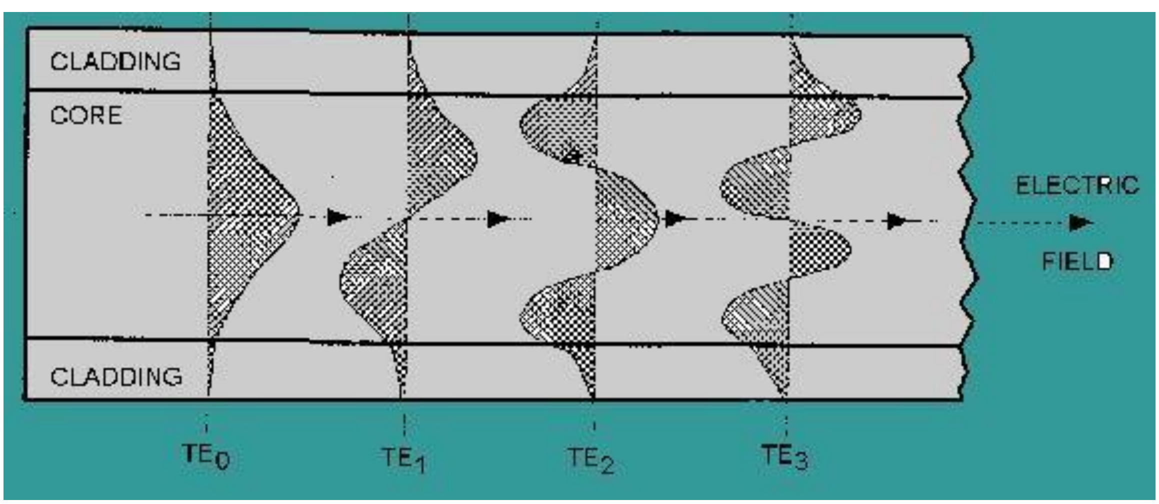
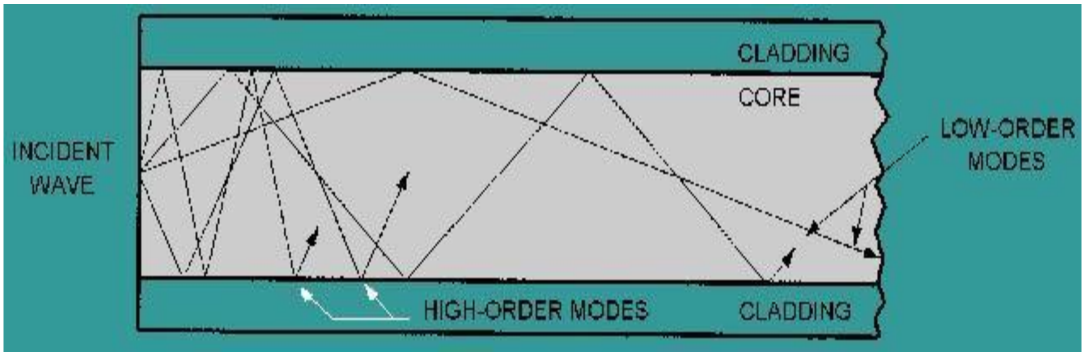


Figure 2-18. - Low-order and high-order modes.



Before we progress, let us refer back to figure 2-17.

Notice that the modes are not confined to the core of the fiber. The modes extend partially into the cladding material. Low-order modes penetrate the cladding only slightly. In low-order modes, the electric and magnetic fields are concentrated near the center of the fiber. However, high-order modes penetrate further into the cladding material. In high-order modes, the electrical and magnetic fields are distributed more toward the outer edges of the fiber.

This penetration of low-order and high-order modes into the cladding region indicates that some portion is refracted out of the core. The refracted modes may become trapped in the cladding due to the dimension of the cladding region. The modes trapped in the cladding region are called **cladding modes**. As the core and the cladding modes travel along the fiber, mode coupling occurs. **Mode coupling** is the exchange of power between two modes. Mode coupling to the cladding results in the loss of power from the core modes.

In addition to bound and refracted modes, there are leaky modes.

Leaky modes are similar to leaky rays. **Leaky modes** lose power as they propagate along the fiber. For a mode to remain within the core, the mode must meet certain boundary conditions. A mode remains bound if the propagation constant β meets the following boundary condition:

$$\frac{2\pi n_2}{\lambda} < \beta < \frac{2\pi n_1}{\lambda}$$

where n_1 and n_2 are the index of refraction for the core and the cladding, respectively. When the propagation constant becomes smaller than 2πn_2/λ, power leaks out of the core and into the cladding. Generally, modes leaked into the cladding are lost in a few centimeters. However, leaky modes can carry a large amount of power in short fibers.

1.18 NORMALIZED FREQUENCY. - Electromagnetic waves bound to an optical fiber are described by the fiber's normalized frequency.

The **normalized frequency** determines how many modes a fiber can support. Normalized frequency is a dimensionless quantity.

Normalized frequency is also related to the fiber's cutoff wavelength. Normalized frequency (V) is defined as:

$$V = \frac{2\pi a}{\lambda}(n_1^2 - n_2^2)^{\frac{1}{2}}$$

where n_1 is the core index of refraction, n_2 is the cladding index of refraction, *a* is the core diameter, and λ is the wavelength of light in air.

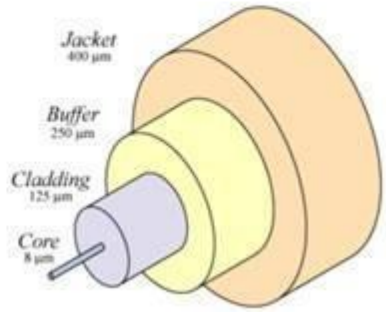
The number of modes that can exist in a fiber is a function of V. As the value of V increases, the number of modes supported by the fiber increases. Optical fibers, single mode and multimode, can support a different number of modes.

Single Mode Fiber (Single Mode Fiber Optic Cable):

When the fiber core is so small that only light ray at 0° incident angle can stably pass through the length of fiber without much loss, this kind of fiber is called single mode fiber. The basic requirement for single mode fiber is that the core be small enough to restrict transmission to a singe mode. This lowest-order mode can propagate in all fibers with smaller cores (as long as light can physically enter the fiber).

The most common type of single mode fiber has a core diameter of 8 to 10 µm and is designed for use in the near infrared (the most common are 1310nm and 1550nm). Please note that the mode structure depends on the wavelength of the light used, so that this fiber actually supports a small number of additional modes at visible wavelengths. Multi mode fiber, by comparison, is manufactured with core diameters as small as 50um and as large as hundreds of microns.

The following picture shows the fiber structure of a single mode fiber.



What Are the Conditions for Single Mode Transmission?

To calculate the number of modes $\mathbf{N_m}$ in a step-index fiber, $\mathbf{N_m}$ can be simplified as:

$$Nm = 0.5\left(\frac{\pi D}{\lambda}\right)^2 (n_f^2 - n_c^2)$$

Where

D is core diameter of the fiber
λ is the operating wavelength
$\mathbf{n_f}$ is refractive index of the fiber core
$\mathbf{n_c}$ is refractive index of the fiber cladding

Reducing the core diameter sufficiently can limit transmission to a single mode. The following formula defines the maximum core diameter, **D**, which limits transmission to a single mode at a particular wavelength, **λ** :

$$D < \frac{2.4\lambda}{\pi\sqrt{n_f^2 - n_c^2}}$$

If the core is any larger, the fiber can carry two modes.

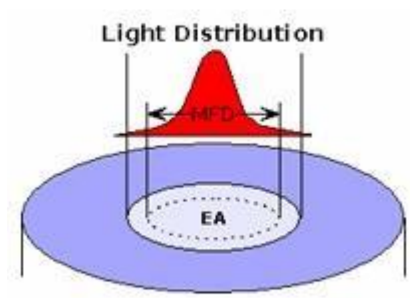
1.18.1 Mode Field Diameter (MFD)

he typical core diameter of communication single mode fibers is from 8~10um for operating wavelength 1.31um to 1.5um. Fiber with a core diameter less than about ten times the wavelength of the propagating light cannot be modeled using geometric optics as we did in the explanation of step-index multimode fiber. Instead, it must be analyzed as an electromagnetic structure, by solution of Maxwell's equations as reduced to the electromagnetic wave equation.

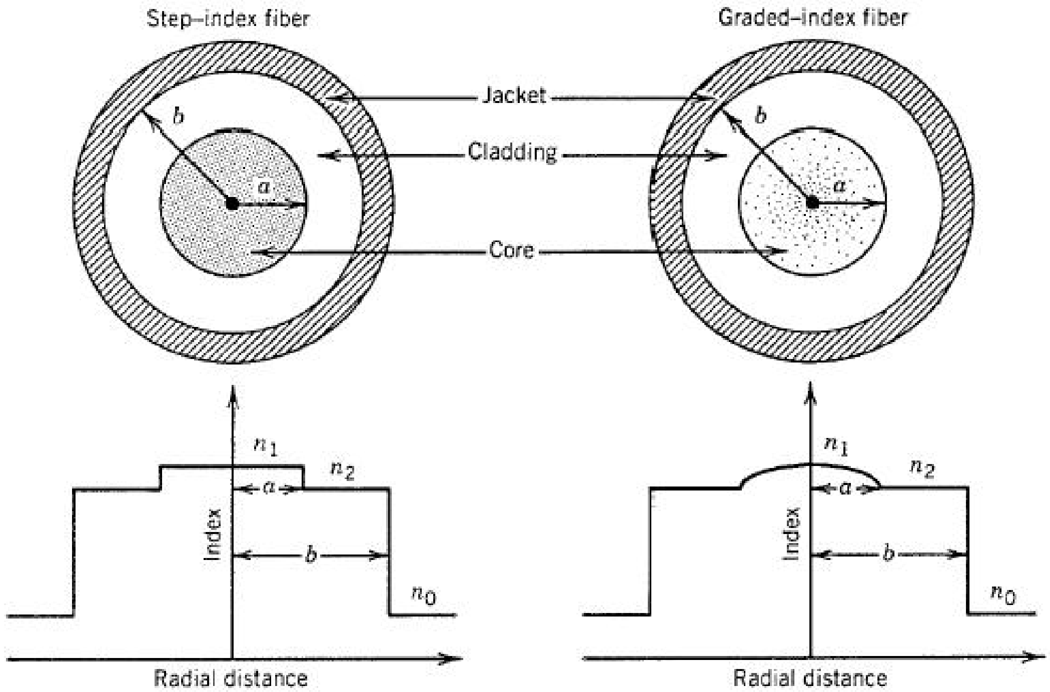
So even though the fiber cladding confines the light within the fiber core, some light does penetrate into the cladding, despite the fact that it nominally undergoes total internal reflection. This occurs both in single mode and multimode fibers, but this phenomenon is more significant in single mode fibers.

For a Gaussian power distribution (*lasers used in communications are Gaussian power distribution*) in a single mode optical fiber, the **mode field diameter** (**MFD**) is defined as the point at which the electric and magnetic field strengths are reduced to 1/e of their maximum values, *i.e.*, the diameter at which power is reduced to 1/e2 (0.135) of the peak power (*because the power is proportional to the square of the field strength*). For single mode fibers, the peak power is at the center of the core.

Mode field diameter is slightly larger than the core diameter, as shown in the following illustration.



SINGLE MODE FIBER:



Cross section and refractive-index profile for step-index and graded-index fibers.

properties of optical fibers can be gained by using a ray picture based on geometrical optics The geometrical-optics description, although approximate, is valid when the core radius a is much larger than the light wavelength λ. When the two become comparable, it is necessary to use the wave-propagation theory

Step-Index Fibers

Consider the geometry , where a ray making an angle θ_i with the fiber axis is incident at the core center. Because of refraction at the fiber–air interface, the ray bends toward the normal. The angle θ_r of the refracted ray

$$n_0 \sin\theta_i = n_1 \sin\theta_r,$$

where n_1 and n_0 are the refractive indices of the fiber core and air, respectively. The refracted ray hits the core–cladding interface and is refracted again. However, refraction is possible only for an angle of incidence ϕ such that $\sin\phi < n_2/n_1$. For angles larger than a *critical angle* ϕ_c,

$$\sin\phi_c = n_2/n_1,$$

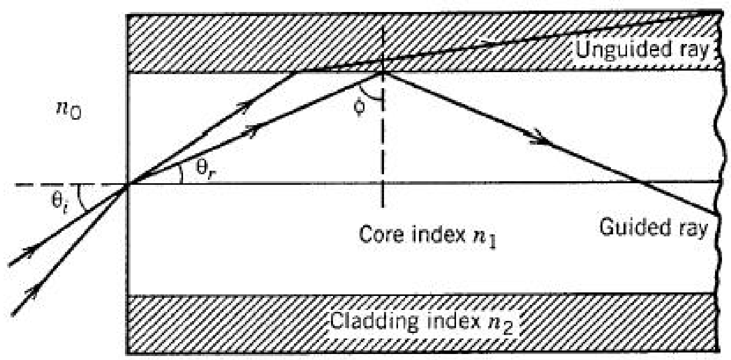


Figure 2.2: Light confinement through total internal reflection in step-index fibers. Rays for which $\phi < \phi_c$ are refracted out of the core.

One can use Eqs. (2.1.1) and (2.1.2) to find the maximum angle that the incident ray should make with the fiber axis to remain confined inside the core. Noting that $\theta_r = \pi/2 - \phi_c$ for such a ray and substituting it in Eq. (2.1.1), we obtain

$$n_0 \sin\theta_i = n_1 \cos\phi_c = (n_1^2 - n_2^2)^{1/2}. \tag{2.1.3}$$

In analogy with lenses, $n_0 \sin\theta_i$ is known as the *numerical aperture* (NA) of the fiber. It represents the light-gathering capacity of an optical fiber. For $n_1 \simeq n_2$ the NA can be approximated by

$$\text{NA} = n_1(2\Delta)^{1/2}, \qquad \Delta = (n_1 - n_2)/n_1, \tag{2.1.4}$$

where Δ is the fractional index change at the core–cladding interface. Clearly, Δ should be made as large as possible in order to couple maximum light into the fiber. However, such fibers are not useful for the purpose of optical communications because of a phenomenon known as multipath dispersion or *modal dispersion* (the concept of fiber modes is introduced in Section 2.2).

Multipath dispersion can be understood by referring to Fig. 2.2, where different rays travel along paths of different lengths. As a result, these rays disperse in time at the output end of the fiber even if they were coincident at the input end and traveled at the same speed inside the fiber. A short pulse (called an *impulse*) would broaden considerably as a result of different path lengths. One can estimate the extent of pulse broadening simply by considering the shortest and longest ray paths. The shortest path occurs for $\theta_i = 0$ and is just equal to the fiber length L. The longest path occurs for θ_i given by Eq. (2.1.3) and has a length $L/\sin\phi_c$. By taking the velocity of propagation $v = c/n_1$, the time delay is given by

$$\Delta T = \frac{n_1}{c}\left(\frac{L}{\sin\phi_c} - L\right) = \frac{L}{c}\frac{n_1^2}{n_2}\Delta. \tag{2.1.5}$$

The time delay between the two rays taking the shortest and longest paths is a measure of broadening experienced by an impulse launched at the fiber input.

We can relate ΔT to the information-carrying capacity of the fiber measured through the bit rate B. Although a precise relation between B and ΔT depends on many details, such as the pulse shape, it is clear intuitively that ΔT should be less than the allocated bit slot ($T_B = 1/B$). Thus, an order-of-magnitude estimate of the bit rate is obtained from the condition $B\Delta T < 1$. I

$$BL < \frac{n_2}{n_1^2}\frac{c}{\Delta}.$$

This condition provides a rough estimate of a fundamental limitation of step-index fibers. As an illustration, consider an unclad glass fiber with $n_1 = 1.5$ and $n_2 = 1$. The bit rate–distance product of such a fiber is limited to quite small values since $BL < 0.4$ (Mb/s)-km. Considerable improvement occurs for cladded fibers with a small index step. Most fibers for communication applications are designed with $\Delta < 0.01$. As an example, $BL < 100$ (Mb/s)-km for $\Delta = 2 \times 10^{-3}$. Such fibers can communicate data at a bit rate of 10 Mb/s over distances up to 10 km and may be suitable for some local-area networks.

Two remarks are in order concerning the validity (First, it is obtained by considering only rays that pass through the fiber axis after each total internal reflection. Such rays are called *meridional rays*. In general, the fiber also supports *skew rays*, which travel at angles oblique to the fiber axis. Skew rays scatter out of the core at bends and irregularities and are not expected to contribute significantly to Eq. (Second, even the oblique meridional rays suffer higher losses than paraxial meridional rays because of scattering. Equation (provides a conservative estimate since all rays are treated equally. The effect of intermodal dispersion can be considerably reduced by using graded-index fibers, which are discussed in the next subsection. It can be eliminated entirely by using the single-mode fibers

Graded-Index Fibers

The refractive index of the core in graded-index fibers is not constant but decreases gradually from its maximum value n_1 at the core center to its minimum value n_2 at the core–cladding interface. Most graded-index fibers are designed to have a nearly quadratic decrease and are analyzed by using α-profile, given by

$$n(\rho) = \begin{cases} n_1[1 - \Delta(\rho/a)^\alpha]; & \rho < a, \\ n_1(1 - \Delta) = n_2 \ ; & \rho \geq a, \end{cases}$$

where a is the core radius. The parameter α determines the index profile. A step-index profile is approached in the limit of large α. A *parabolic-index fiber* corresponds to $\alpha = 2$.

It is easy to understand qualitatively why intermodal or multipath dispersion is reduced for graded-index fibers. Figure shows schematically paths for three different rays. Similar to the case of step-index fibers, the path is longer for more oblique rays. However, the ray velocity changes along the path because of variations in the refractive index. More specifically, the ray propagating along the fiber axis takes the shortest path but travels most slowly as the index is largest along this path. Oblique rays have a large part of their path in a medium of lower refractive index, where they travel faster. It is therefore possible for all rays to arrive together at the fiber output by a suitable choice of the refractive-index profile.

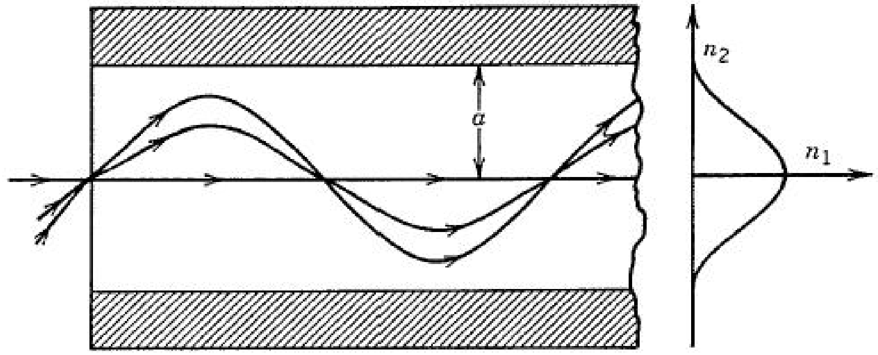


Figure 2.3: Ray trajectories in a graded-index fiber.

Geometrical optics can be used to show that a parabolic-index profile leads to nondispersive pulse propagation within the *paraxial approximation*. The trajectory of a paraxial ray is obtained by solving [22]

$$\frac{d^2\rho}{dz^2} = \frac{1}{n}\frac{dn}{d\rho}, \tag{2.1.8}$$

where ρ is the radial distance of the ray from the axis. By using Eq. (2.1.7) for $\rho < a$ with $\alpha = 2$, Eq. (2.1.8) reduces to an equation of harmonic oscillator and has the general solution

$$\rho = \rho_0 \cos(pz) + (\rho_0'/p)\sin(pz), \tag{2.1.9}$$

where $p = (2\Delta/a^2)^{1/2}$ and ρ_0 and ρ_0' are the position and the direction of the input ray, respectively. Equation (2.1.9) shows that all rays recover their initial positions and directions at distances $z = 2m\pi/p$, where m is an integer (see Fig. 2.3). Such a complete restoration of the input implies that a parabolic-index fiber does not exhibit intermodal dispersion.

The conclusion above holds only within the paraxial and the geometrical-optics approximations, both of which must be relaxed for practical fibers. Intermodal dispersion in graded-index fibers has been studied extensively by using wave-propagation techniques [13]–[15]. The quantity $\Delta T/L$, where ΔT is the maximum multipath delay in a fiber of length L, is found to vary considerably with α. Figure 2.4 shows this variation for $n_1 = 1.5$ and $\Delta = 0.01$. The minimum dispersion occurs for $\alpha = 2(1-\Delta)$ and depends on Δ as [23]

$$\Delta T/L = n_1\Delta^2/8c. \tag{2.1.10}$$

The limiting bit rate–distance product is obtained by using the criterion $\Delta T < 1/B$ and is given by

$$BL < 8c/n_1\Delta^2. \tag{2.1.11}$$

The right scale in Fig. 2.4 shows the BL product as a function of α. Graded-index fibers with a suitably optimized index profile can communicate data at a bit rate of 100 Mb/s over distances up to 100 km. The BL product of such fibers is improved by nearly three orders of magnitude over that of step-index fibers. Indeed, the first generation

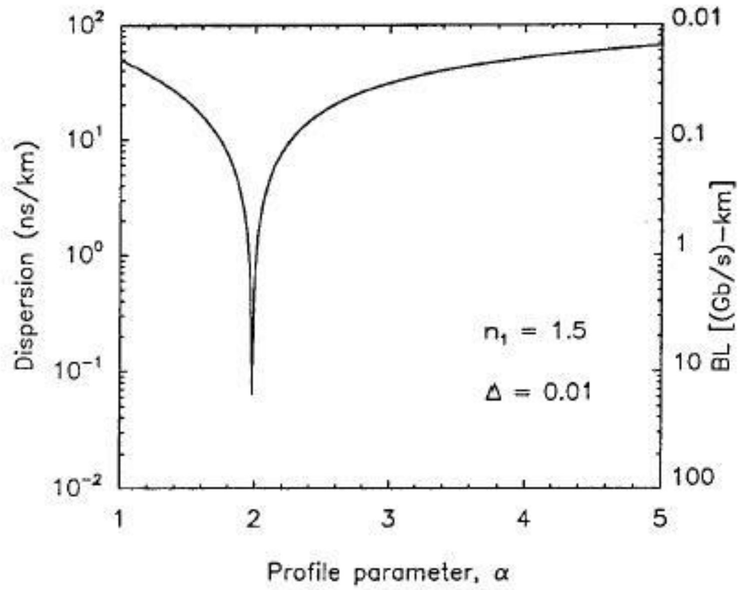


Figure 2.4: Variation of intermodal dispersion $\Delta T/L$ with the profile parameter α for a graded-index fiber. The scale on the right shows the corresponding bit rate–distance product.

of lightwave systems used graded-index fibers. Further improvement is possible only by using single-mode fibers whose core radius is comparable to the light wavelength. Geometrical optics cannot be used for such fibers.

Although graded-index fibers are rarely used for long-haul links, the use of graded-index *plastic* optical fibers for data-link applications has attracted considerable attention during the 1990s [24]–[29]. Such fibers have a relatively large core, resulting in a high numerical aperture and high coupling efficiency but they exhibit high losses (typically exceeding 50 dB/km). The *BL* product of plastic fibers, however, exceeds 2 (Gb/s)-km because of a graded-index profile [24]. As a result, they can be used to transmit data at bit rates $>$1 Gb/s over short distances of 1 km or less. In a 1996 demonstration, a 10-Gb/s signal was transmitted over 0.5 km with a bit-error rate of less than 10^{-11} [26]. Graded-index plastic optical fibers provide an ideal solution for transferring data among computers and are becoming increasingly important for Ethernet applications requiring bit rates in excess of 1 Gb/s.

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UNIT II
SIGNAL DEGRADATION OPTICAL FIBERS

2.1 ATTENUATION :

Attenuation in an optical fiber is caused by absorption, scattering, and bending losses. **Attenuation** is the loss of optical power as light travels along the fiber. Signal attenuation is defined as the ratio of optical input power (P_i) to the optical output power (P_o). Optical input power is the power injected into the fiber from an optical source. Optical output power is the power received at the fiber end or optical detector. The following equation defines signal attenuation as a unit of length:

$$\text{attenuation} = \left(\frac{10}{L}\right)\log_{10}\left(\frac{P_i}{P_o}\right)$$

Signal attenuation is a log relationship. Length (L) is expressed in kilometers. Therefore, the unit of attenuation is decibels/kilometer (dB/km). As previously stated, attenuation is caused by absorption, scattering, and bending losses. Each mechanism of loss is influenced by fiber-material properties and fiber structure. However, loss is also present at fiber connections. Fiber connector, splice, and coupler losses are discussed in chapter 4. The present discussion remains relative to optical fiber attenuation properties.

2.2 ABSORPTION. - Absorption is a major cause of signal loss in an optical fiber. **Absorption** is defined as the portion of attenuation resulting from the conversion of optical power into another energy form, such as heat. Absorption in optical fibers is explained by three factors:

- Imperfections in the atomic structure of the fiber material
- The intrinsic or basic fiber-material properties
- The extrinsic (presence of impurities) fiber-material properties

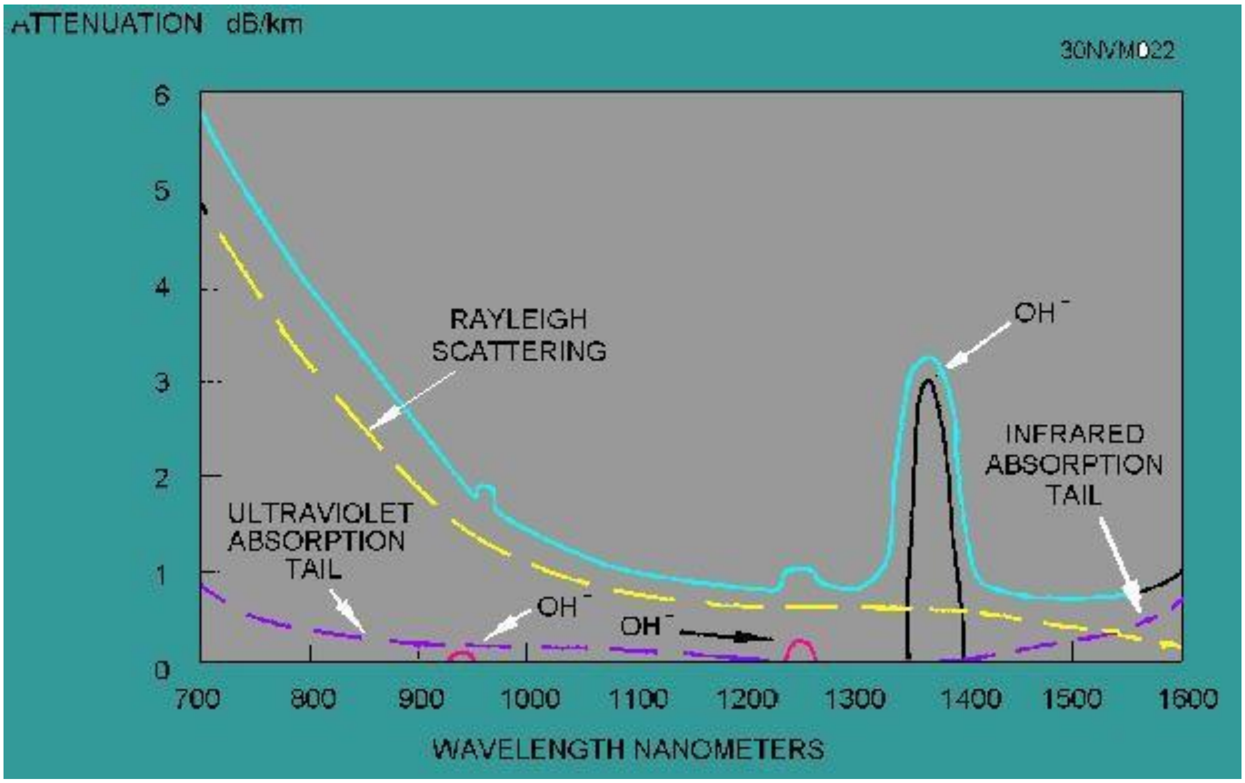
Imperfections in the atomic structure induce absorption by the presence of missing molecules or oxygen defects. Absorption is also induced by the diffusion of hydrogen molecules into the glass fiber. Since intrinsic and extrinsic material properties are the main cause of absorption, they are discussed further.

Intrinsic Absorption. - Intrinsic absorption is caused by basic fiber-material properties. If an optical fiber were absolutely pure, with no imperfections or impurities, then all absorption would be intrinsic. Intrinsic absorption sets the minimal level of absorption.

In fiber optics, silica (pure glass) fibers are used predominately. Silica fibers are used because of their low intrinsic material absorption at the wavelengths of operation.

In silica glass, the wavelengths of operation range from 700 nanometers (nm) to 1600 nm. Figure 2-21 shows the level of attenuation at the wavelengths of operation. This wavelength of operation is between two intrinsic absorption regions. The first region is the **ultraviolet** region (below 400-nm wavelength). The second region is the **infrared** region (above 2000-nm wavelength).

Figure 2-21. - Fiber losses.



Intrinsic absorption in the ultraviolet region is caused by electronic absorption bands. Basically, absorption occurs when a light particle (photon) interacts with an electron and excites it to a higher energy level. The tail of the ultraviolet absorption band is shown in figure 2-21.

The main cause of **intrinsic absorption** in the infrared region is the characteristic vibration frequency of atomic bonds. In silica glass, absorption is caused by the vibration of silicon-oxygen (Si-O) bonds. The interaction between the vibrating bond and the electromagnetic field of the optical signal causes intrinsic absorption. Light energy is transferred from the electromagnetic field to the bond. The tail of the infrared absorption band is shown in figure 2-21.

Extrinsic Absorption. - Extrinsic absorption is caused by impurities introduced into the fiber material. Trace metal impurities, such as iron, nickel, and chromium, are introduced into the fiber during fabrication. **Extrinsic absorption** is caused by the electronic transition of these metal ions from one energy level to another.

Extrinsic absorption also occurs when hydroxyl ions (OH^-) are introduced into the fiber. Water in silica glass forms a silicon-hydroxyl (Si-OH) bond. This bond has a fundamental absorption at 2700 nm. However, the harmonics or overtones of the fundamental absorption occur in the region of operation. These harmonics increase extrinsic absorption at 1383 nm, 1250 nm, and 950 nm. Figure 2-21 shows the presence of the three OH^- harmonics. The level of the OH^- harmonic absorption is also indicated.

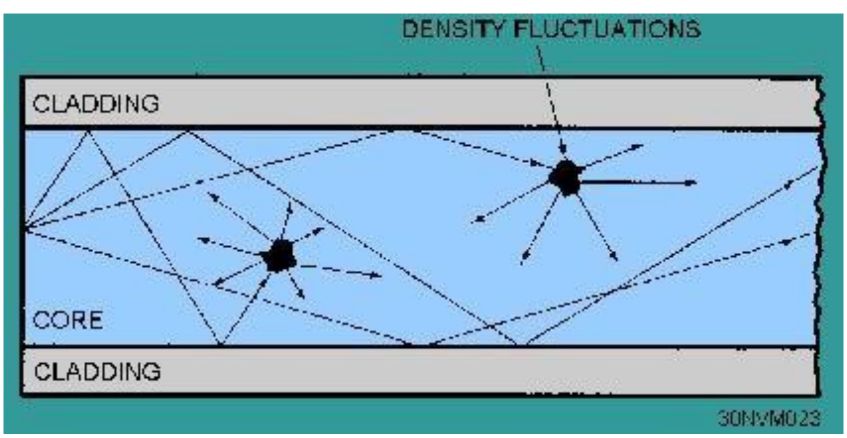
These absorption peaks define three regions or windows of preferred operation. The first window is centered at **850** nm. The second window is centered at **1300** nm. The third window is centered at **1550** nm. Fiber optic systems operate at wavelengths defined by one of these windows.

The amount of water (OH^-) impurities present in a fiber should be less than a few parts per billion. Fiber attenuation caused by extrinsic absorption is affected by the level of impurities (OH^-) present in the fiber. If the amount of impurities in a fiber is reduced, then fiber attenuation is reduced.

2.3 SCATTERING. - Basically, scattering losses are caused by the interaction of light with density fluctuations within a fiber. Density changes are produced when optical fibers are manufactured.

During manufacturing, regions of higher and lower molecular density areas, relative to the average density of the fiber, are created. Light traveling through the fiber interacts with the density areas as shown in figure 2-22. Light is then partially scattered in all directions.

Figure 2-22. - Light scattering.



In commercial fibers operating between 700-nm and 1600-nm wavelength, the main source of loss is called Rayleigh scattering. Rayleigh scattering is the main loss mechanism between the ultraviolet and infrared regions as shown in figure 2-21. **Rayleigh scattering** occurs when the size of the density fluctuation (fiber defect) is less than one-tenth of the operating wavelength of light. Loss caused by Rayleigh scattering is proportional to the fourth power of the wavelength (1/λ^{4}). As the wavelength increases, the loss caused by Rayleigh scattering decreases.

If the size of the defect is greater than one-tenth of the wavelength of light, the scattering mechanism is called **Mie scattering**. Mie scattering, caused by these large defects in the fiber core, scatters light out of the fiber core. However, in commercial fibers, the effects of Mie scattering are insignificant. Optical fibers are manufactured with very few large defects.

2.4 BENDING LOSS. - Bending the fiber also causes attenuation. Bending loss is classified according to the bend radius of curvature: microbend loss or macrobend loss.

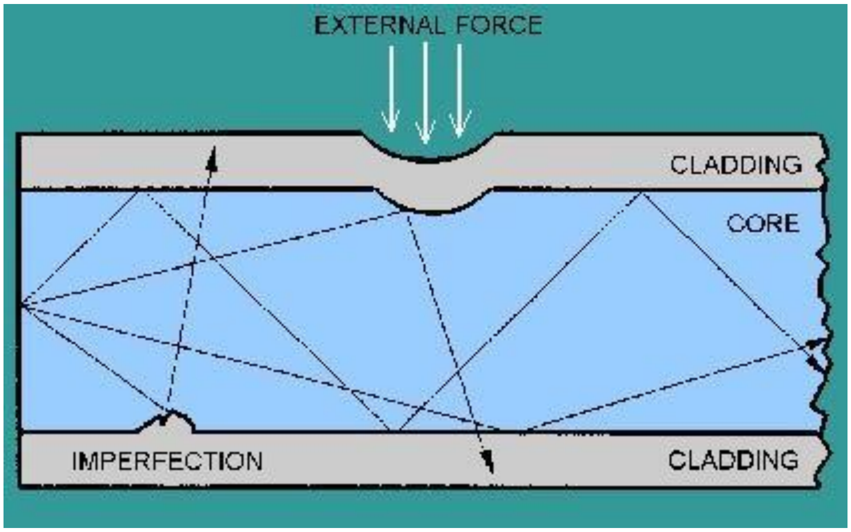
Microbends are small microscopic bends of the fiber axis that occur mainly when a fiber is cabled. **Macrobends** are bends having a large radius of curvature relative to the fiber diameter. Microbend and macrobend losses are very important loss mechanisms. Fiber loss caused by microbending can still occur even if the fiber is cabled correctly. During installation, if fibers are bent too sharply, macrobend losses will occur.

Microbend losses are caused by small discontinuities or imperfections in the fiber. Uneven coating applications and improper cabling procedures increase microbend loss. External forces are also a source of microbends. An external force deforms the cabled jacket surrounding the fiber but causes only a small bend in the fiber. Microbends change the path that propagating modes take, as shown in figure 2-23. **Microbend loss** increases attenuation because low-order modes become coupled with high-order modes that are naturally lossy.

Macrobend losses are observed when a fiber bend's radius of curvature is large compared to the fiber diameter.

These bends become a great source of loss when the radius of curvature is less than several centimeters. Light propagating at the inner side of the bend travels a shorter distance than that on the outer side. To maintain the phase of the light wave, the mode phase velocity must increase. When the fiber bend is less than some critical radius, the mode phase velocity must increase to a speed greater than the speed of light. However, it is impossible to exceed the speed of light. This condition causes some of the light within the fiber to be converted to high-order modes. These high-order modes are then lost or radiated out of the fiber.

Figure 2-23. - Microbend loss.



Fiber sensitivity to bending losses can be reduced. If the refractive index of the core is increased, then fiber sensitivity decreases. Sensitivity also decreases as the diameter of the overall fiber increases. However, increases in the fiber core diameter increase fiber sensitivity. Fibers with larger core size propagate more modes. These additional modes tend to be more lossy.

2.5 SIGNAL DISTORTION IN OPTICAL WAVE GUIDES:

2.5.1 DISPERSION

There are two different types of dispersion in optical fibers.

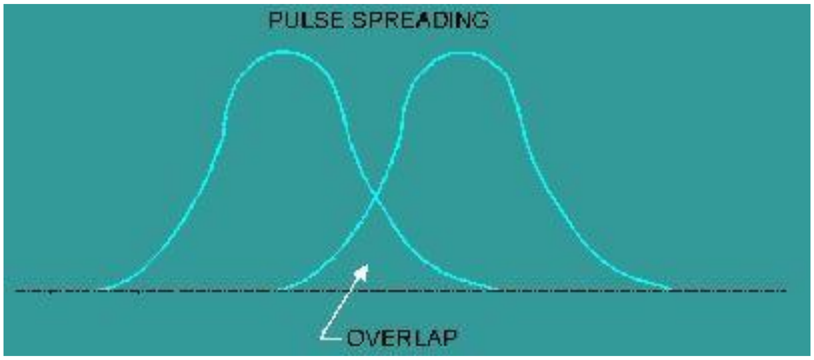
The types are intramodal and intermodal dispersion. Intramodal, or chromatic, dispersion occurs in all types of fibers. Intermodal, or modal, dispersion occurs only in multimode fibers. Each type of dispersion mechanism leads to pulse spreading. As a pulse spreads, energy is overlapped. This condition is shown in figure 2-24. The spreading of the optical pulse as it travels along the fiber limits the information capacity of the fiber.

Intramodal Dispersion

Intramodal, or chromatic, dispersion depends primarily on fiber materials. There are two types of intramodal dispersion. The first type is material dispersion. The second type is waveguide dispersion.

Intramodal dispersion occurs because different colors of light travel through different materials and different waveguide structures at different speeds.

Figure 2-24. - Pulse overlap.



Material dispersion occurs because the spreading of a light pulse is dependent on the wavelengths' interaction with the refractive index of the fiber core. Different wavelengths travel at different speeds in the fiber material. Different wavelengths of a light pulse that enter a fiber at one time exit the fiber at different times. Material dispersion is a function of the source spectral width. The spectral width specifies the range of wavelengths that can propagate in the fiber. Material dispersion is less at longer wavelengths.

Waveguide dispersion occurs because the mode propagation constant (β) is a function of the size of the fiber's core relative to the wavelength of operation. Waveguide dispersion also occurs because light propagates differently in the core than in the cladding.

In multimode fibers, waveguide dispersion and material dispersion are basically separate properties. Multimode waveguide dispersion is generally small compared to material dispersion. Waveguide dispersion is usually neglected.

However, in single mode fibers, material and waveguide dispersion are interrelated.

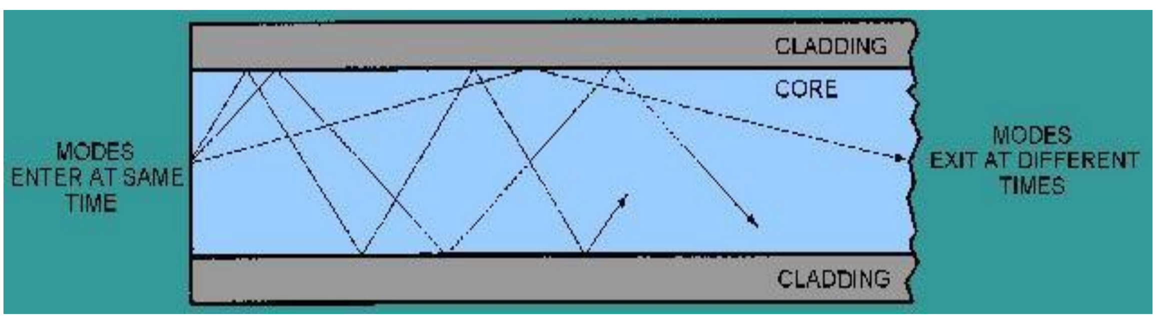
The total dispersion present in single mode fibers may be minimized by trading material and waveguide properties depending on the wavelength of operation.

Intermodal Dispersion

Intermodal or modal dispersion causes the input light pulse to spread. The input light pulse is made up of a group of modes. As the modes propagate along the fiber, light energy distributed among the modes is delayed by different amounts. The pulse spreads because each mode propagates along the fiber at different speeds. Since modes travel in different directions, some modes travel longer distances. **Modal dispersion** occurs because each mode travels a different distance over the same time span, as shown in figure 2-25. The modes of a light pulse that enter the fiber at one time exit the fiber a different times. This condition causes the light pulse to spread. As the length of the fiber increases, modal dispersion increases.

Modal dispersion is the dominant source of dispersion in multimode fibers. Modal dispersion does not exist in single mode fibers. Single mode fibers propagate only the fundamental mode. Therefore, single mode fibers exhibit the lowest amount of total dispersion. Single mode fibers also exhibit the highest possible bandwidth.

Figure 2-25. - Distance traveled by each mode over the same time span.



2.5.2 Information Capacity Determination:

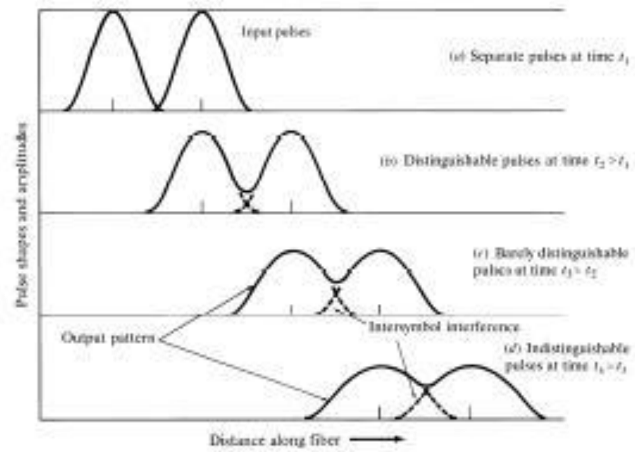
A light pulse will broaden as it travels along the fiber. The pulse broadening will eventually cause neighboring pulses to overlap. After a certain amount of overlap, neighboring pulses will not be distinguishable. Thus, this dispersive mechanism limits the information capacity of a fiber.

One measure of the information capacity of an optical waveguide is called the *bandwidth-distance product.* This value is usually given as x Hz km.

For example, you are given a fiber with an bandwidth-distance product of 250 MHz km and you need to use a five kilometer length. The useable bandwidth over this link is then (ignoring other issues)

$$BW = \frac{250MHz \cdot km}{5km} = 50\,MHz$$

Fig. 3-10: Pulse broadening and attenuation



2.5.3 Group Delay

Let us presume a linear system where an optical source launches light power into a fiber where all the modes carry equal power. The spectral components will be assumed to travel independently. Each component will undergo a time delay called the *group delay* per unit length in the direction of travel.

$$Velocity_{group} = V_g = \frac{c}{n(\lambda)}$$

$$\frac{\text{time delay}}{\text{length}}\,\frac{\text{sec}}{m} = \frac{\tau_g}{L} = \frac{1}{Velocity_{group}\,\frac{m}{s}} = \frac{1}{V_g}$$

$$\tau_g = \frac{L}{V_g}$$

From chapter 2, the author showed that the phase velocity travels dow the fiber as

$$V_p = \frac{\omega}{\beta}$$

The group velocity is then

$$V_g = \frac{d\omega}{d\beta} \qquad where\ \omega = 2\pi v = \frac{2\pi c}{\lambda}$$

$$= \frac{d\left(\frac{2\pi c}{\lambda}\right)}{d\beta} = \frac{d(kc)}{d\beta} = c\frac{dk}{d\beta} \qquad and\ V_g = 2\pi c\frac{d(\lambda)^{-1}}{d\beta}$$

By use of the chain rule, we have

$$V_g = (-)\frac{2\pi c}{\lambda^2}\frac{d\lambda}{d\beta} \qquad \Rightarrow \frac{1}{V_g} = (-)\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}$$

Since the index of refraction depends on the wavelength and the velocity of light in a medium depends on the index of refraction, then the group velocity depends on the wavelength of the light.

$$\beta = k \cdot n(\lambda) \quad = \frac{2\pi}{\lambda}n(\lambda)$$

Under this chromatic dispersion each spectral component will undergo a different time delay and the pulse will spread with transmission distance.

$$\frac{\tau_g}{L} = \frac{1}{V_g} \quad = (-)\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda} \qquad \Rightarrow \tau_g = (-)\frac{L\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}$$

$$\tau_g = (-)\frac{L\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}$$

Plug the group time delay τg into the time spread equation yields

$$\delta\tau = \frac{d}{d\lambda}\left[(-)\frac{L\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}\right]\delta\lambda \quad = (-)\frac{L}{2\pi c}\left[2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right]\delta\lambda$$

The text (appendix F) now defines a new term $\beta 2$ called the *group velocity dispersion* (GVD).

$$\beta_2 = \frac{d^2\beta}{d\omega^2}$$

Similar to acceleration, $\beta 2$ indicates how rapidly the index of refraction is changing per unit wavelength.

For “not to wide” spectral widths, the total delay difference is

$$\delta\tau = \frac{d\tau_g}{d\lambda}\delta\lambda$$

The total time spread δτ is the time delay per unit wavelength times the wavelength spread δλ of the source light.

The dispersion coefficient D defines the pulse spread as a function of wavelength.

$$D = \frac{1}{L}\frac{d\tau_g}{d\lambda} = (-)\frac{1}{2\pi c}\left[2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right]$$

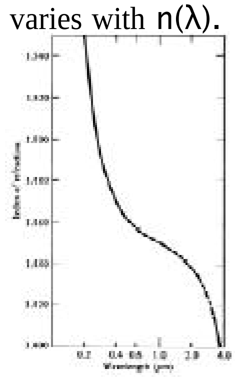
The units of the dispersion coefficient may be typically listed as A dimensionless coefficient for the group velocity dispersion can be defined as

$$D = \underbrace{c\omega\frac{d^2k}{d\omega^2}}_{\text{Lui, Photonic Devices}} = \underbrace{-\frac{2\pi c^2}{\lambda}\beta_2}_{\text{Keiser text}}$$

2.5.4 Material Dispersion:

Material dispersion occurs because the index of refraction varies as a function of the optical wavelength.

Or alternately, we can say that β varies with n(λ).



Material dispersion is an intramodal effect and of particular importance for single-mode and LED systems.

Let the variation in the index of refraction be n(λ). The propagation constant is now

$$\beta = \frac{2\pi n(\lambda)}{\lambda} = k\,n(\lambda)$$

The group delay due to material dispersion is then

$$\frac{\tau_{material}}{L} = \frac{1}{V_g} = (-)\frac{\lambda^2}{2\pi c}\left[\frac{d\beta}{d\lambda}\right] = (-)\frac{\lambda^2}{2\pi c}\left\{\frac{\partial}{\partial\lambda}\left[\frac{2\pi n(\lambda)}{\lambda}\right]\right\}$$

$$= (-)\frac{\lambda^2}{2\pi c}\left\{2\pi\left[\frac{-n(\lambda)}{\lambda^2} + \frac{1}{\lambda}\frac{dn}{d\lambda}\right]\right\} = \frac{1}{c}\left[n(\lambda) - \lambda\frac{dn}{d\lambda}\right]$$

The total dispersion of a length L is then

$$\tau_{mat} = \frac{L}{c}\left[n(\lambda) - \lambda dn(\lambda)\right]$$

In terms of rms, the pulse spread σmat is

$$\sigma_{mat} \approx \left|\frac{d\tau_{mat}}{d\lambda}\right|\sigma_\lambda \quad = \sigma_\lambda L\left|D_{mat}(\lambda)\right|$$

2.5.5 Waveguide Dispersion:

Waveguide dispersion occurs because a single-mode fiber confines only about 80% of the optical power to the core of the fiber. Waveguide dispersion is another intramodal effect. It occurs within one mode and each mode in a many mode system will have its own waveguide dispersion. In terms of the modal propagation constant, β varies a/λ. The optical fiber radial dimension (radius a) relative to the light wavelength λ is now the important parameter.

The group delay in terms of the normalized propagation constant b is (review chapter 2 and equation 2-48)

$$b = 1 - \left(\frac{ua}{V}\right)^2 \quad = \frac{\frac{\beta^2}{k^2} - n_2^2}{n_1^2 - n_2^2}$$

The derivation moves forward by assuming the weakly guided condition where Δ << 1.

$$b \approx \frac{\frac{\beta}{k} - n_2}{n_1 - n_2}$$

Solving for β

$$\frac{\beta}{k} = n_2 + b(n_1 - n_2)$$

Using the relation $n_2 = n_1 (1 - \Delta) \quad \Rightarrow n_1 = \frac{n_2}{1-\Delta}$

$$n_1 - n_2 = \frac{n_2}{1-\Delta} - n_2 \quad = \frac{n_2 - n_2(1-\Delta)}{1-\Delta} \quad = n_2 \frac{\Delta}{1-\Delta}$$

Plug this result into the last equation for β

$$\frac{\beta}{k} = n_2 + b n_2 \frac{\Delta}{1-\Delta}$$

$$\beta = k n_2 + k n_2 b \frac{\Delta}{1-\Delta}$$

Since $\Delta << 1$, we have

$$\beta \approx k n_2 + k n_2 b \frac{\Delta}{1} \quad = k n_2 + k n_2 b \Delta \quad = k n_2 (b\Delta + 1)$$

$$\tau_{wg} = \frac{L}{c}\left(n_2 + n_2 \Delta \frac{dVb}{dV} \right)$$

The first term in the equation is a constant. It is the time delay for a light pulse traveling in a waveguide where n2 = a constant.

The second term above is the group delay arising from waveguide dispersion.

The author then shows the V factor in terms of Bessel functions.

$$\frac{d(Vb)}{dV} = b\left[1 - \frac{2J_\nu^2(ua)}{J_{\nu+1}(ua)J_{\nu-1}(ua)} \right]$$

Main message on waveguide dispersion:

The group delay is different for every guided mode.

For small radius waveguides, waveguide dispersion can be significant.

For large radius waveguides (multimode), waveguide dispersion is very small and can be neglected.

2.5.6 Signal Distortion in Single-Mode Fibers:

For single-mode fibers, material τmat and waveguide τwg dispersion can be nearly equal. Examine by looking at the pulse spread σwg occurring over a distribution of wavelengths $\sigma\lambda$. This pulse spreading can be found by taking the derivative of the group delay with respect to wavelength λ.

$$\frac{d\tau_{wg}}{d\lambda} = \frac{d\tau_{wg}}{dV}\frac{dV}{d\lambda} \quad = \frac{d\tau_{wg}}{dV}(-)\frac{V}{\lambda}$$

$$V = \frac{2\pi a}{\lambda}(NA) \qquad \Rightarrow dV = (-)\frac{2\pi a}{\lambda^2}(NA)d\lambda$$

$$\frac{dV}{d\lambda} = (-)\frac{2\pi a}{\lambda^2}(NA) \quad = (-)\frac{V}{\lambda}$$

$$\frac{d\tau_{wg}}{d\lambda} = \frac{d\tau_{wg}}{dV}(-)\frac{V}{\lambda}$$

$$\tau_{wg} = \frac{L}{c}\left(n_2 + n_2 \Delta \frac{dVb}{dV} \right)$$

$$\frac{d\tau_{wg}}{dV} = \frac{L}{c}\frac{d}{dV}\left(n_2 + n_2\Delta\frac{dVb}{dV}\right) \quad = \frac{L}{c}\left(n_2\Delta\frac{d^2Vb}{dV^2}\right)$$

Thus

$$\frac{d\tau_{wg}}{d\lambda} = \frac{L}{c}\left(n_2\Delta\frac{d^2Vb}{dV^2}\right)\left(-\frac{V}{\lambda}\right)$$

The total waveguide dispersion over a finite wavelength spread is

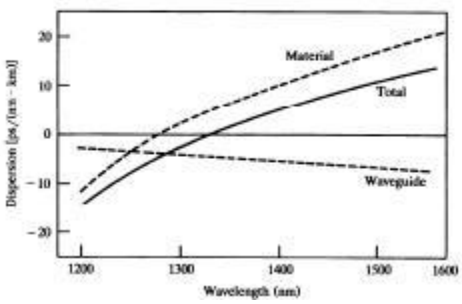
$$\sigma_{wg} = \frac{L}{c}\left(n_2\Delta\frac{d^2Vb}{dV^2}\right)\left(-\frac{V}{\lambda}\right)\sigma_\lambda \quad = \frac{-LVn_2\Delta\sigma_\lambda}{c\lambda}\frac{d^2Vb}{dV^2}$$

$$\sigma_{wg} = \frac{-LVn_2\Delta\sigma_\lambda}{c\lambda}\frac{d^2Vb}{dV^2}$$

The behavior of the dispersion by wavelength is

At longer wavelengths $\lambda \rightarrow \tau_{mat} > \tau_{wg}$

At shorter wavelengths $\lambda \rightarrow \tau_{mat} < \tau_{wg}$

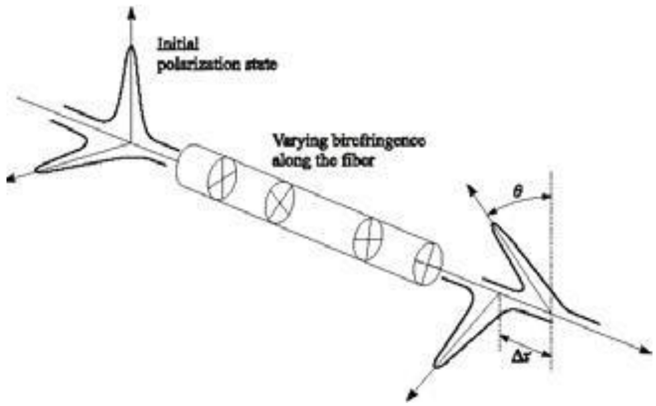


2.5.7 Polarization-Mode Dispersion:

The effects of fiber birefringence on the polarization sates of an optical signal are another source of pulse broadening. Birefringence can result from intrinsic factors such as geometric irregularities of the fiber core or internal stress on it. Bending, twisting, or pinching of the fiber can also lead to birefringence. A fundamental property of an optical signal is its polarization state. If the polarization state varies as the light travels down the fiber, and the fiber is birefringent, then there will be pulse broadening.

The time of arrival differences between two orthogonal polarizations is given by

$$\tau_{pol} = \left|\frac{L}{v_{gx}} - \frac{L}{v_{gy}}\right|$$



Temperature and movement are big factors in birefringence in the fiber. Thus Polarization-Mode dispersion (PMD) varies randomly along a fiber, particularly in aerial cables.

2.5.8 Intermodal Distortion:

The final factor giving rise to signal degradation is intermodal distortion. Each mode has a different value for the group delay as can be seen from ray tracing. Different path length = different arrival time.

$\delta T_{intermodal} = T_{max} - T_{min}$

Each mode has a different value for the group delay as can be seen from ray tracing. Different path length = different arrival time.

$$\delta T_{intermodal} = T_{max} - T_{min} = \frac{n_1 (L_{max} - L_{min})}{c} = \frac{n_1 \Delta L}{c}$$

2.6 Design Optimization of Single-Mode Fibers:

Telecommunication happens mostly over single-mode fibers. So we should take a brief look at the distortion in such fibers. This section looks at design-optimization characteristics, cutoff wavelength, dispersion, mode-field diameter and bending loss.

2.6.1 Refractive-Index Profiles

In the design of single-mode fibers, dispersion (rather than attenuation) is a major distinguishing feature. For silica fibers the least attenuation occurs around 1550 nm. The least dispersion occurs around 1300 nm. There are several approaches to either minimize the attenuation at 1300 nm or to minimize the dispersion at 1550 nm.

See figure 3-22

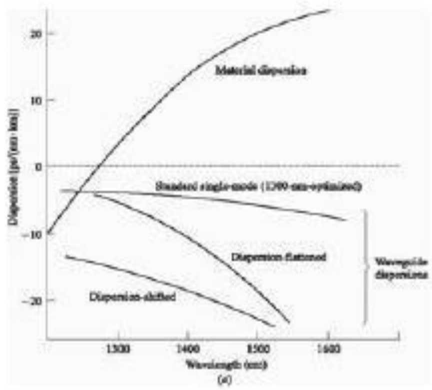
1300 nm optimized fiber

Dispersion shifted (towards 1550 nm)

Dispersion flattened (broad range suitable for WDM)

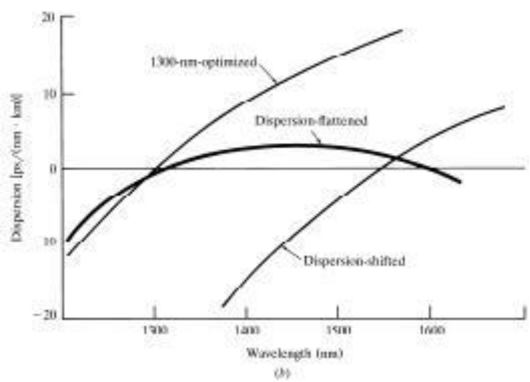
Large effective core area (good for optical amplifier use)

Figure 3-24



Both material and waveguide dispersion.

Figure 3-24



Total dispersion.

2.6.2 Cutoff Wavelength

The cutoff wavelength of the first higher-order mode LP11 (where only the HE11 and LP01 will propagate) is given by

$$\lambda_{cutoff} = \frac{2\pi a}{V}\sqrt{n_1^2 - n_2^2}$$

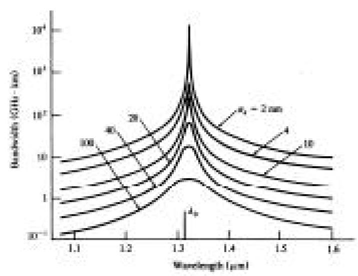
Where V = 2.405 for step-index fibers.

A practical method is the test standards listed on page 127, so that comparison of an actual fiber to desired specification can be tested. Trial and error is still the rule with analysis only somewhat guiding the search for appropriate fibers.

2.6.3 Dispersion Calculations

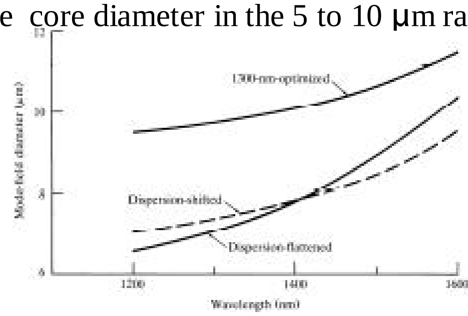
Limiting the spectral width σλ and choosing a minimum dispersion wavelength is the most effective way to have a high-bandwidth channel in a single-mode fiber.

The Electronics Industry Alliance (EIA) has set a number of methods and standards to assure performance requirements.



2.6.4 Mode-Field Diameter

The selection of core size versus wavelength determines how much of the light energy travels in the cladding. The figure shows that the typical odern single-mode fiber should have core diameter in the 5 to 10 μm range.



2.6.5 Bending Loss

Macrobending and microbending losses are most evident in the 1550 nm region. he lower the cutoff wavelength relative to the operating wavelength, he more susceptible single-mode fibers are to bending losses.
The bending losses are primarily a function of the mode-field diameter.
The smaller the mode-field diameter, the smaller the bending loss. By specifying bend-radius limitations, the macrobending losses can be largely avoided.

UNIT III
FIBER OPTICAL SOURCES AND COUPLING

3.1 INTRODUCTION TO OPTICAL SOURCES AND FIBER OPTIC TRANSMITTERS

A fiber optic data link has three basic functions.

One function is that a fiber optic data link must convert an electrical signal to an optical signal permitting the transfer of data along an optical fiber.

The fiber optic device responsible for that signal conversion is a fiber optic transmitter.

A **fiber optic transmitter** is a hybrid device.

It converts electrical signals into optical signals and launches the optical signals into an optical fiber. A fiber optic transmitter consists of an interface circuit, a source drive circuit, and an optical source. The interface circuit accepts the incoming electrical signal and processes it to make it compatible with the source drive circuit. The source drive circuit intensity modulates the optical source by varying the current through the source.

An **optical source** converts electrical energy (current) into optical energy (light). Light emitted by an optical source is launched, or coupled, into an optical fiber for transmission. Fiber optic data link performance depends on the amount of optical power (light) launched into the optical fiber. This chapter attempts to provide an understanding of light-generating mechanisms within the main types of optical sources used in fiber optics.

3.2 OPTICAL SOURCE PROPERTIES

The development of efficient semiconductor optical sources, along with low-loss optical fibers, led to substantial improvements in fiber optic communications. Semiconductor optical sources have the physical characteristics and performance properties necessary for successful implementations of fiber optic systems. It is desirable that optical sources:

- Be compatible in size to low-loss optical fibers by having a small light-emitting area capable of launching light into fiber
- Launch sufficient optical power into the optical fiber to overcome fiber attenuation and connection losses allowing for signal detection at the receiver
- Emit light at wavelengths that minimize optical fiber loss and dispersion.
- Optical sources should have a narrow spectral width to minimize dispersion

- Allow for direct modulation of optical output power

Maintain stable operation in changing environmental conditions (such as temperature) Cost less and be more reliable than electrical devices, permitting fiber optic communication systems to compete with conventional systems Semiconductor optical sources suitable for fiber optic systems range from inexpensive light-emitting diodes (LEDs) to more expensive semiconductor lasers. Semiconductor LEDs and laser diodes (LDs) are the principal light sources used in fiber optics.

3.3 SEMICONDUCTOR LIGHT-EMITTING DIODES AND LASER DIODES

Semiconductor LEDs emit **incoherent light**.

Spontaneous emission of light in semiconductor LEDs produces light waves that lack a fixed-phase relationship. Light waves that lack a fixed-phase relationship are referred to as **incoherent light**. Spontaneous emission of light is discussed in more detail later in this chapter. The use of LEDs in single mode systems is severely limited because they emit unfocused incoherent light. Even LEDs developed for single mode systems are unable to launch sufficient optical power into single mode fibers for many applications. LEDs are the preferred optical source for multimode systems because they can launch sufficient power at a lower cost than semiconductor LDs.

Semiconductor LDs emit **coherent light**.

LDs produce light waves with a fixed-phase relationship (both spatial and temporal) between points on the electromagnetic wave. Light waves having a fixed-phase relationship are referred to as coherent light. Stimulated emission of light is discussed later in this chapter. Since semiconductor LDs emit more focused light than LEDs, they are able to launch optical power into both single mode and multimode optical fibers. However, LDs are usually used only in single mode fiber systems because they require more complex driver circuitry and cost more than LEDs.

Optical power produced by optical sources can range from microwatts (μW) for LEDs to tens of milliwatts (mW) for semiconductor LDs. However, it is not possible to effectively couple all the available optical power into the optical fiber for transmission.

The amount of optical power coupled into the fiber is the relevant optical power. It depends on the following factors:

- The angles over which the light is emitted
- The size of the source's light-emitting area relative to the fiber core size

- The alignment of the source and fiber
- The coupling characteristics of the fiber (such as the NA and the refractive index profile)

Typically, semiconductor lasers emit light spread out over an angle of 10 to 15 degrees. Semiconductor LEDs emit light spread out at even larger angles. Coupling losses of several decibels can easily occur when coupling light from an optical source to a fiber, especially with LEDs.

Source-to-fiber coupling efficiency is a measure of the relevant optical power. The coupling efficiency depends on the type of fiber that is attached to the optical source. Coupling efficiency also depends on the coupling technique.

Source-to-fiber coupling involves centering a flat fiber-end face over the emitting region of the light source. If the fiber end face is directly placed over the source emitting region, it is referred to as **butt coupling**. If the source's output light pattern is larger than the fiber's acceptance pattern, source-to-fiber coupling efficiency may be improved by placing a small lens between the source and fiber. Lensing schemes improve coupling efficiency when coupling both LEDs and LDs to optical fibers.

3.4 SEMICONDUCTOR MATERIAL AND DEVICE OPERATING PRINCIPLES

Understanding optical emission in semiconductor lasers and LEDs requires knowledge of semiconductor material and device properties. Providing a complete description of semiconductor properties is beyond the scope of this introductory manual. In this chapter we only discuss the general properties of semiconductor LEDs and LDs.

Semiconductor sources are diodes, with all of the characteristics typical of diodes. However, their construction includes a special layer, called the active layer, which emits photons (light particles) when a current passes through the layer. The particular properties of the semiconductor are determined by the materials used and the layering of the materials within the semiconductor. **Silicon (Si)** and **gallium arsenide (GaAs)** are the two most common semiconductor materials used in electronic and electro-optic devices. In some cases other elements, such as aluminum (Al), indium (In) and phosphorus (P), are added to the base semiconductor material to modify the semiconductor properties. These elements are called dopants.

Current flowing through a semiconductor optical source causes it to produce light. An in-depth description of either of the two processes by which this occurs is beyond the scope of this module. However, we discuss elementary descriptions in the following paragraphs.

LEDs generally produce light through **spontaneous emission** when a current is passed through them. Spontaneous emission is the random generation of photons within the active layer of the LED. The emitted photons move in random directions. Only a certain percentage of the photons exit the semiconductor and are coupled into the fiber. Many of the photons are absorbed by the LED materials and the energy dissipated as heat.

This process causes the light output from an LED to be incoherent, have a broad spectral width, and have a wide output pattern.

Laser diodes are much more complex than LEDs. Laser is an acronym for light amplification by the stimulated emission of radiation. Laser diodes produce light through stimulated emission when a current is passed through them. **Stimulated emission** describes how light is produced in any type of laser. In the laser diode, photons, initially produced by spontaneous emission interact with the laser material to produce additional photons. This process occurs within the active area of the diode called the laser cavity. The process does not affect the original photon. The stimulated photon has many of the same properties (wavelength, direction, phase) as the original photon.

As with the LED, not all of the photons produced are emitted from the laser diode. Some of the photons are absorbed and the energy dissipated as heat. The emission process and the physical characteristics of the diode cause the light output to be coherent, have a narrow spectral width, and have a narrow output pattern.

It is important to note that in both LED and laser diodes all of the electrical energy is not converted into optical energy. A substantial portion is converted to heat. Different LED and laser diode structures convert differing amounts of electrical energy into optical energy.

3.5 LIGHT-EMITTING DIODES

A **light-emitting diode** (LED) is a semiconductor device that emits incoherent light, through spontaneous emission, when a current is passed through it. Typically LEDs for the 850-nm region are fabricated using GaAs and AlGaAs. LEDs for the 1300-nm and 1550-nm regions are fabricated using InGaAsP and InP.

The basic LED types used for fiber optic communication systems are the surface-emitting LED (SLED), the edge-emitting LED (ELED), and the superluminescent diode (SLD). LED performance differences help link designers decide which device is appropriate for the intended application. For short-distance (0 to 3 km), low-data-rate fiber optic systems, SLEDs and ELEDs are the preferred optical source. Typically, SLEDs operate efficiently for bit rates up to 250 megabits per second (Mb/s). Because SLEDs emit light over a wide area (wide far-field angle), they are almost exclusively used in multimode systems.

For medium-distance, medium-data-rate systems, ELEDs are preferred.

ELEDs may be modulated at rates up to 400 Mb/s. ELEDs may be used for both single mode and multimode fiber systems. Both SLDs and ELEDs are used in long-distance, high-data-rate systems. SLDs are ELED-based diodes designed to operate in the superluminescence mode. A further discussion on superluminescence is provided later in this chapter. SLDs may be modulated at bit rates of over 400 Mb/s.

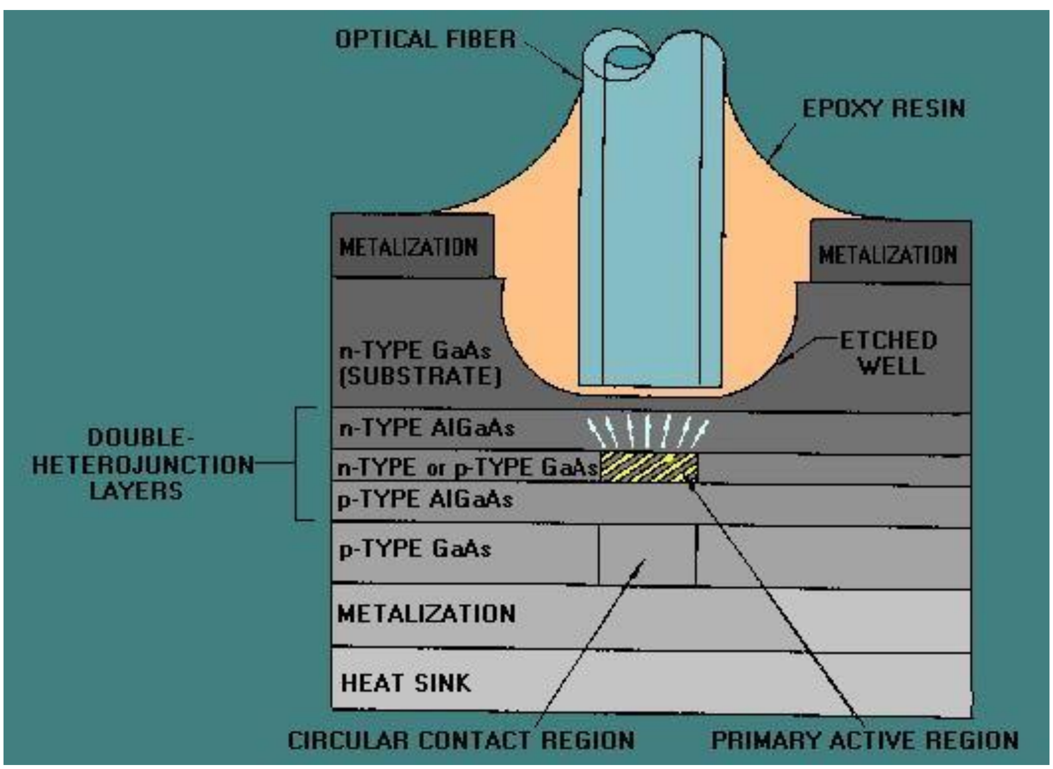
3.5.1 Surface-Emitting LEDs

he surface-emitting LED (shown in figure 6-1) is also known as the Burrus LED in honor of C. A. Burrus, its developer. In SLEDs, the size of the primary active region is limited to a small circular area of 20 μm to 50 μm in diameter. The active region is the portion of the LED where photons are emitted. The primary active region is below the surface of the semiconductor substrate perpendicular to the axis of the fiber.

A **well** is etched into the substrate to allow direct coupling of the emitted light to the optical fiber. The etched well allows the optical fiber to come into close contact with the emitting surface.

In addition, the epoxy resin that binds the optical fiber to the SLED reduces the refractive index mismatch, increasing coupling efficiency.

Figure 6-1. - Example of the SLED structure.



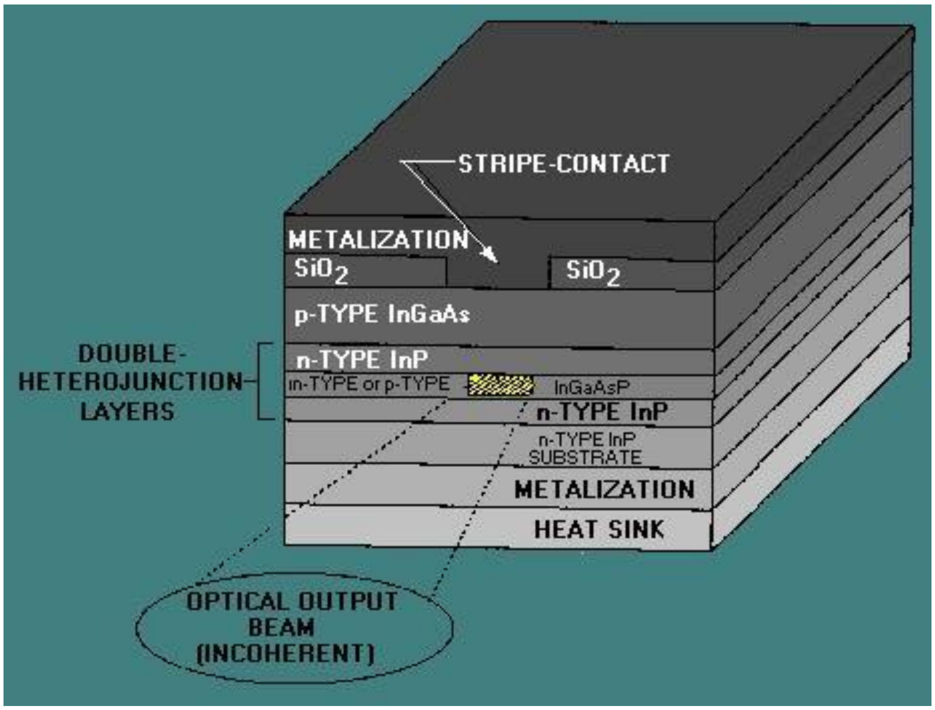
3.5.2 Edge-Emitting LEDs

The demand for optical sources for longer distance, higher bandwidth systems operating at longer wavelengths led to the development of edge-emitting

LEDs. Figure 6-2 shows a typical ELED structure. It shows the different layers of semiconductor material used in the ELED. The primary active region of the ELED is a narrow stripe, which lies below the surface of the semiconductor substrate. The semiconductor substrate is cut or polished so that the stripe runs between the front and back of the device.

The polished or cut surfaces at each end of the stripe are called facets.

Figure 6-2. - Example of the ELED structure.



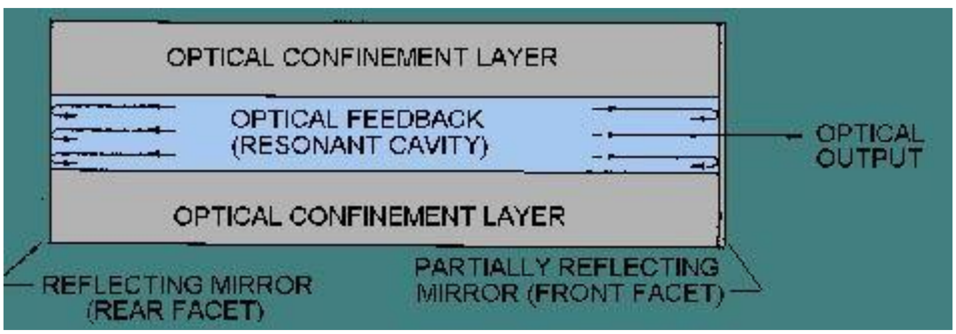
In an ELED the rear facet is highly reflective and the front facet is antireflection-coated. The rear facet reflects the light propagating toward the rear end-face back toward the front facet. By coating the front facet with antireflection material, the front facet reduces optical feedback and allows light emission. ELEDs emit light only through the front facet. ELEDs emit light in a narrow emission angle allowing for better source-to-fiber coupling. They couple more power into small NA fibers than SLEDs. ELEDs can couple enough power into single mode fibers for some applications. ELEDs emit power over a narrower spectral range than SLEDs. However, ELEDs typically are more sensitive to temperature fluctuations than SLEDs.

3.6 LASER DIODES

A **laser** is a device that produces optical radiation by the process of stimulated emission. It is necessary to contain photons produced by stimulated emission within the laser active region.

Figure 6-3 shows an optical cavity formed to contain the emitted photons by placing one reflecting mirror at each end of an amplifying medium. One mirror is made partially reflecting so that some radiation can escape from the cavity for coupling to an optical fiber.

Figure 6-3. - Optical cavity for producing lasing.

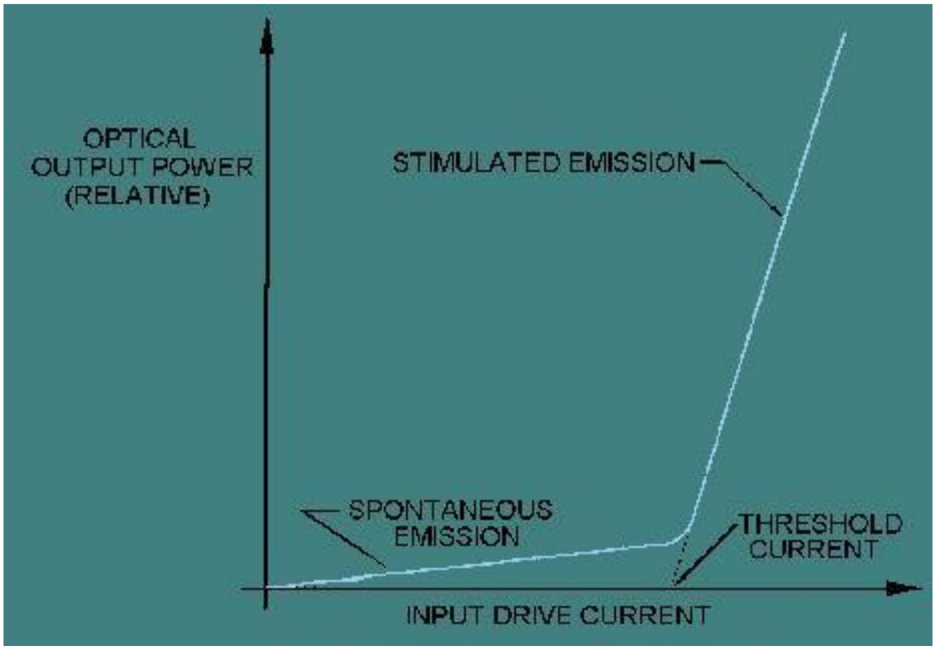


Only a portion of the optical radiation is amplified. For a particular laser structure, there are only certain wavelengths that will be amplified by that laser. Amplification occurs when selected wavelengths, also called laser modes, reflect back and forth through the cavity. For lasing to occur, the optical gain of the selected modes must exceed the optical loss during one round-trip through the cavity. This process is referred to as optical feedback.

The **lasing threshold** is the lowest drive current level at which the output of the laser results primarily from stimulated emission rather than spontaneous emission. Figure 6-4 illustrates the transition from spontaneous emission to stimulated emission by plotting the relative optical output power and input drive current of a semiconductor laser diode. The lowest current at which stimulated emission exceeds spontaneous emission is the **threshold current**.

Before the threshold current is reached, the optical output power increases only slightly with small increases in drive current. However, after the threshold current is reached, the optical output power increases significantly with small changes in drive currents.

Figure 6-4. - The optical output power as a function of input drive current of a semiconductor laser diode.



Many types of materials including gas, liquid, and semiconductors can form the lasing medium. However, in this chapter we only discuss semiconductor laser diodes. Semiconductor laser diodes are the primary lasers used in fiber optics. A laser diode emits light that is highly monochromatic and very directional.

This means that the LD's output has a narrow spectral width and small output beam angle.

A semiconductor LD's geometry is similar to an ELED with light-guiding regions surrounding the active region. Optical feedback is established by making the front facet partially reflective. This chapter provides no diagram detailing LD structures because they are similar to ELEDs in design. The rear facet is typically coated with a reflective layer so that all of the light striking the facet is reflected back into the active region. The front facet is typically left uncoated so that most of the light is emitted. By increasing the drive current, the diode becomes a laser.

t currents below the threshold current, LDs function as ELEDs.

To optimize Frequency response, laser diodes are often biased above this laser threshold. As a result, in an LD fiber optic system, light is modulated between a high power level and a lower power level, but never shut off. LDs typically can be modulated at frequencies up to over 2 gigahertz (GHz). Some lasers are capable of being modulated at frequencies over 20 GHz.

There are several important differences between LDs and LEDs. One is that LEDs usually lack reflective facets and in some cases are designed to suppress reflections back into the active region. Another is that lasers tend to operate at higher drive currents to produce light. A higher driver current results in more complicated drive circuits and more heat dissipation in the device.

LDs are also much more temperature sensitive than either SLEDs or ELEDs. Increases in the laser temperature significantly reduce laser output power. Increases in laser temperature beyond certain limits result in the loss of lasing. When lasers are used in many applications, the temperature of the laser must be controlled. Typically, electronic coolers, called **thermo-electric (TE) coolers**, are used to cool LDs in system application

3.7 SUPERLUMINESCENT DIODES

Superluminescence occurs when the spontaneous emissions of an ELED experience gain due to higher injected currents and reflections from facets. Superluminescent diodes (SLDs) are differentiated from both conventional LEDs and LDs. Although the output is not fully coherent,

SLDs emit light that consists of amplified spontaneous emissions. The spectral width and beam angle of SLDs are narrower than that of conventional LEDs and wider than that of LDs.

An SLD is, in essence, a combination of a laser and an ELED. SLDs are similar in geometry to lasers but have no built-in optical feedback mechanism required by laser diodes for stimulated emission to achieve lasing. SLDs have structural features similar to those of ELEDs that suppress the lasing action by reducing the reflectivity of the facets. SLDs are essentially highly optimized ELEDs.

While SLDs operate like ELEDs at low current levels, their output power increases superlinearly and the spectral width narrows at high currents.

Optical gain resulting from the higher injection currents causes the superlinear power increase and narrowing of the spectral width.

The advantages of SLDs over conventional LEDs include higher coupled power, narrower spectral width, and greater bandwidths. The disadvantages include nonlinear power-current characteristics, higher temperature sensitivity, and lower reliability.

3.8 OPTICAL AMPLIFIER:

An **optical amplifier** is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal. An optical amplifier may be thought of as a laser without an optical cavity, or one in which feedback from the cavity is suppressed. Stimulated emission in the amplifier's gain medium causes amplification of incoming light. Optical amplifiers are important in optical communication and laser physics.

3.8.1 Erbium-doped fiber amplifiers:

Erbium-doped fiber amplifiers are the by far most important fiber amplifiers in the context of long-range optical fiber communications; they can efficiently amplify light in the 1.5-μm wavelength region, where telecom fibers have their loss minimum.

Setup and Operation Principle

A typical setup of a simple erbium-doped fiber amplifier (EDFA) is shown in Figure 1. Its core is the erbium-doped optical fiber, which is typically a single-mode fiber. In the shown case, the *active fiber* is "pumped" with light from two laser diodes (bidirectional pumping), although unidirectional pumping in the forward or backward direction (co-directional and counter-directional pumping) is also very common. The pump light, which most often has a wavelength around 980 nm and sometimes around 1450 nm, excites the erbium ions (Er^{3+}) into the $^4I_{13/2}$ state (in the case of 980-nm pumping via $^4I_{11/2}$), from where they can amplify light in the 1.5-μm wavelength region via stimulated emission back to the ground-state manifold $^4I_{15/2}$. (See also Figure 1 in the article on erbium-doped gain media.)

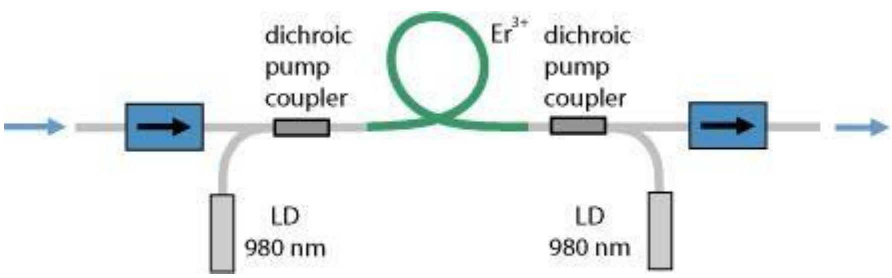


Figure 1: Schematic setup of a simple erbium-doped fiber amplifier. Two laser diodes (LDs) provide the pump power for the erbium-doped fiber. The pump light is injected via dichroic fiber couplers. Pig-tailed optical isolators reduce the sensitivity of the device to back-reflections.

The setup shown also contains two "pig-tailed" (fiber-coupled) optical isolators. The isolator at the input prevents light originating from amplified spontaneous emission from disturbing any previous stages, whereas that at the output suppresses lasing (or possibly even destruction) if output light is reflected back to the amplifier. Without isolators, fiber amplifiers can be sensitive to back-reflections.

Apart from optical isolators, various other components can be contained in a commercial fiber amplifier. For example, there can be fiber couplers and photodetectors for monitoring optical power levels, pump laser diodes with control electronics and gain-flattening filters. For particularly compact packages, various passive optical components can be combined into a photonic integrated circuit (*planar lightwave circuit*).

Very high signal gains, as used, e.g., for the amplification of ultrashort pulses to high energies, are usually realized with amplifier chains, consisting of several amplifier stages with additional optical elements (e.g. isolators, filters, or modulators) in between.

Gain Spectrum

The shape of the erbium gain spectrum depends both on the host glass and on the excitation level, because the erbium ions have a quasi-three-level transition. Figure 2 shows data for a common type of glass, which is some variant of silica with additional dopants e.g. to avoid clustering of erbium ions.

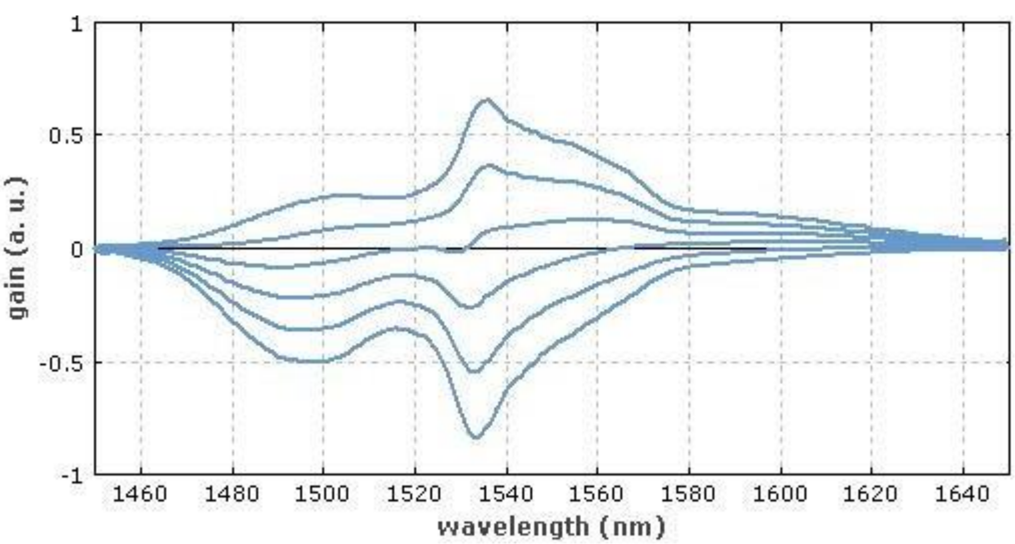


Figure 2: Gain and absorption (negative gain) of erbium (Er^{3+}) ions in a phosphate glass for excitation levels from 0 to 100% in steps of 20%.

Strong three-level behavior (with transparency reached only for > 50% excitation) occurs at 1535 nm. In that spectral region, the unpumped fiber exhibits substantial losses, but the high emission cross section allows for a high gain for strong excitation. At longer wavelengths (e.g. 1580 nm), a lower excitation level is required for obtaining gain, but the maximum gain is smaller.

The maximum gain typically occurs in the wavelength region around 1530–1560 nm, with the 1530-nm peak being most pronounced for high excitation levels. The local excitation level depends on the emission and absorption cross sections and on the pump and signal intensity (apart from that of ASE light). The average excitation level over the whole fiber length depends on the pump and signal powers, but also on the fiber length and the erbium concentration. Such parameters are used to optimize EDFAs for a particular wavelength region, such as the telecom C or L band.

A good flatness of the gain in a wide wavelength region (→ *gain equalization*), as required e.g. for wavelength division multiplexing (see below), can be obtained by using optimized glass hosts (e.g. telluride or fluoride fibers, or some combination of amplifier sections with different glasses) or by combination with appropriate optical filters, such as long-period fiber Bragg gratings.

Erbium-doped Amplifiers in Telecom Systems

EDFAs can serve various functions in systems for optical fiber communications; the most important applications are the following:

- The power of a data transmitter may be boosted with a high-power EDFA before entering a long fiber span, or a device with large losses, such as a fiber-optic splitter. Such splitters are widely used e.g. in cable-TV systems, where a single transmitter is used to deliver signals into many fibers.
- A fiber amplifier may also be used in front of a data receiver, if the arriving signal is weak. Despite the introduction of amplifier noise, this can improve the signal-to-noise ratio and thus the possible data transmission rate, since the amplifier noise may be weaker than the input noise of the receiver. It is more common, however, to use avalanche photodiodes, which have some built-in signal amplification.
- In-line EDFAs are used between long spans of passive transmission fiber. Using multiple amplifiers in a long fiber-optic link has the advantage that large transmission losses can be compensated without (a) letting the optical power drop to too low levels, which would spoil the signal-to-noise ratio, and (b) without transmitting excessive optical powers at other locations, which would cause detrimental nonlinear effects due to the unavoidable fiber nonlinearities. Many of these in-line EDFAs are operated even under difficult conditions, e.g. on the ocean floor, where maintenance would be hardly possible.
- Although data transmitters are normally not based on erbium-doped devices, EDFAs are often part of equipment for testing transmission hardware. They are also used in the context of optical signal processing.

These functions can be realized in the telecom C and L bands. Other types of fiber amplifiers, e.g. based on praseodymium, have been considered for other bands, but none can compete with erbium-based devices in terms of gain and gain efficiency.

A particular attraction of EDFAs is their large gain bandwidth, which is typically tens of nanometers and thus actually more than enough to amplify data channels with the highest data rates without introducing any effects of gain narrowing. A single EDFA may be used for simultaneously amplifying many data channels at different wavelengths within the gain region; this technique is called *wavelength division multiplexing*. Before such fiber amplifiers were available, there was no practical method for amplifying all channels e.g. between long fiber spans of a fiber-optic link: one had to separate all data channels, detect and amplify them electronically, optically resubmit and again combine them. The introduction of fiber amplifiers thus brought an enormous reduction in the complexity, along with a corresponding increase in reliability. Very long lifetimes are possible by using redundant down-rated pump diodes.

The only competitors to erbium-doped fiber amplifiers in the 1.5-μm region are Raman amplifiers, which profit from the development of higher power pump lasers. Raman amplification can also be done in the transmission fiber. Nevertheless, EDFAs remain very dominant.

3.8.2 Stimulated Raman Scattering fiber amplifier:

The nonlinear response of a transparent optical medium to the optical intensity of light propagating through the medium is very fast, but not instantaneous. In particular, a non-instantaneous response is caused by vibrations of the crystal (or glass) lattice. When these vibrations are associated with optical phonons, the effect is called *Raman scattering*, whereas acoustical phonons are associated with Brillouin scattering. When e.g. two laser beams with different wavelengths (and normally with the same polarization direction) propagate together through a Raman-active medium, the longer wavelength beam can experience optical amplification at the expense of the shorter wavelength beam. In addition, lattice vibrations are excited, leading to a temperature rise. The Raman gain for the longer wavelength beam can be exploited in Raman amplifiers and Raman lasers.

When the intensity of the generated wave (called the *Stokes wave*) becomes sufficiently high, that wave may again act as the pump for a further Raman process. Particularly in some Raman lasers, it is possible to observe several Stokes orders (*cascaded Raman lasers*).

Apart from the mentioned stimulated Raman scattering effect, which can be described with classical physics, there is also *spontaneous* Raman scattering, caused by quantum effects.

Raman scattering can also occur within the broad spectrum of, e.g., an ultrashort optical pulse, effectively shifting the spectral envelope of the pulse towards longer wavelengths (*Raman self-frequency shift*, also called *soliton self-frequency shift*).

Some typical Raman-active media are

- certain gases, e.g. hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2), used in, e.g., high pressure cells for Raman shifters
- solid-state media such as glass fibers or certain crystals, e.g. barium nitride = $Ba(NO_3)_2$ or various tungstates such as $KGd(WO_4)_2$ = KGW and $KY(WO_4)_2$ = KYW

The Raman effect occurs together with the Kerr effect, which results from the (nearly) instantaneous response of the electrons.

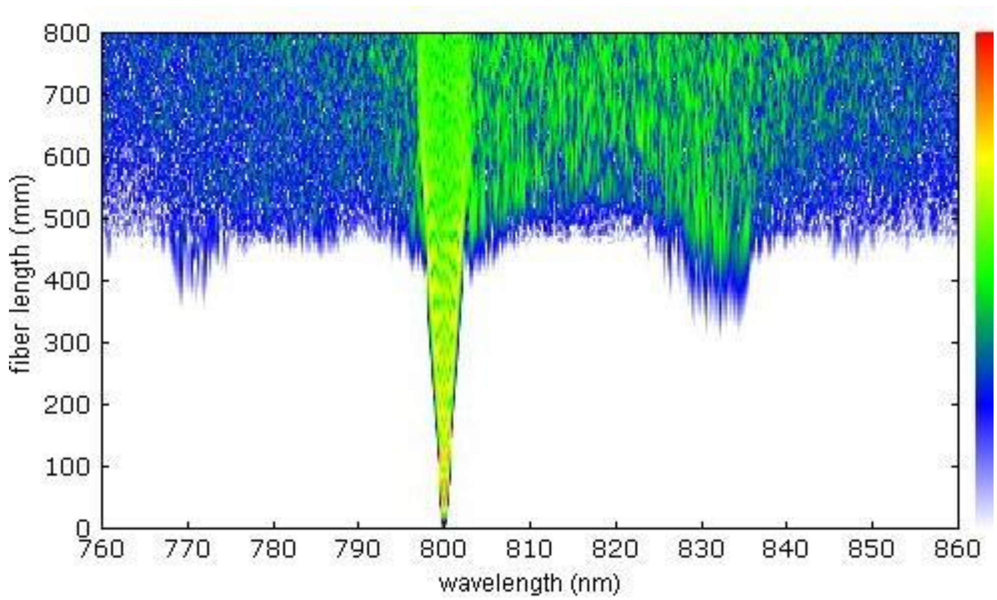


Figure 1: Evolution of the optical spectrum of a 20-ps pulse with an initial peak power of 18 kW in an optical fiber, shown with a logarithmic color scale for the power spectral density. The spectrum is first broadened mainly due to self-phase modulation, but after ~ 300 mm of fiber, some Raman-shifted light is observed, which is then further amplified.

In optical fiber devices such as fiber amplifiers for intense pulses, Raman scattering can be detrimental: it can transfer much of the pulse energy into a wavelength range where laser amplification does not occur. This effect can limit the peak power achievable with such devices. Even in continuous-wave high-power fiber lasers and amplifiers, Raman scattering can be a problem. There are, however, various kinds of solutions to such problems, including chirped-pulse amplification and the use of special fiber designs which suppress Raman scattering by attenuating the Raman-shifted wavelength component.

In bulk media, such as certain nonlinear crystal materials, unwanted stimulated Raman scattering can occur even via non-collinear phase matching, if the pump intensity is rather high and the beam width is large enough. This can occur e.g. in optical parametric generators operated with intense pump pulses.

Raman scattering is also used in spectroscopy. In particular, it allows one to investigate the vibrational modes of materials.

Brillouin Scattering:

Brillouin scattering is an effect caused by the $\chi^{(3)}$ nonlinearity of a medium, specifically by that part of the nonlinearity which is related to acoustic phonons [1]. An incident photon can be converted into a scattered photon of slightly lower energy, usually propagating in the backward direction, and a phonon. The coupling of optical fields and acoustic waves occurs via electrostriction. The effect can occur spontaneously even at low optical powers, then reflecting the thermally generated phonon field. For higher optical powers, there can be a stimulated effect, where the optical fields substantially contribute to the phonon population. Above a certain threshold power of a light beam in a medium, stimulated Brillouin scattering can reflect most of the power of an incident beam. This process involves a strong nonlinear optical gain for the back-reflected wave: an originally weak counterpropagating wave at the suitable optical frequency can be strongly amplified. Here, the two counter-propagating waves generate a traveling refractive index grating; the higher the reflected power, the stronger the index grating and the higher the effective reflectivity.

The frequency of the reflected beam is slightly lower than that of the incident beam; the frequency difference ν_B corresponds to the frequency of emitted phonons. This so-called *Brillouin frequency shift* is set by a phase-matching requirement. For pure backward Brillouin scattering, the Brillouin shift can be calculated from the refractive index n, the acoustic velocity v_a, and the vacuum wavelength λ:

$$\nu_B = \frac{2 n \upsilon_a}{\lambda}$$

(For Brillouin scattering in fibers, the effective refractive index must be used.)

The Brillouin frequency shift depends on the material composition and to some extent the temperature and pressure of the medium. Such dependencies are exploited for fiber-optic sensors.

Another important application of stimulated Brillouin scattering is *optical phase conjugation*. There are for example phase-conjugate mirrors for high-power Q-switched lasers which make it possible that the thermal distortions occurring in forward and backward direction in the laser crystal compensate each other.

3.8.3 Stimulated Brillouin Scattering in Optical Fibers:

Stimulated Brillouin scattering (SBS) is frequently encountered when narrow- band optical signals (e.g. from a single-frequency laser) are amplified in a fiber amplifier, or just propagated through a passive fiber. While the material nonlinearity of e.g. silica is actually not very high, the typically small effective mode area and long propagation length strongly favor nonlinear effects. For silica fibers, the Brillouin frequency shift is of the order of 10−20 GHz, and the Brillouin gain has an intrinsic bandwidth of typically 50−100 MHz, which is determined by the strong acoustic absorption (short phonon lifetime). However, the Brillouin gain spectrum may be strongly "smeared out" by various effects, such as transverse variations of the acoustic phase velocity [12, 17] or longitudinal temperature variations [9, 11]. Accordingly, the peak gain may be strongly reduced, leading to a substantially higher SBS threshold.

The Brillouin threshold of optical fibers for narrow-band continuous-wave light typically corresponds to a Brillouin gain of the order of 90 dB. (With additional laser gain in an active fiber, the threshold can be lower.) For trains of ultrashort pulses, the SBS threshold is determined not by a peak power, but rather by a power spectral density, as explained in a Spotlight article.

SBS introduces the most stringent power limit for the amplification and the passive propagation of narrow-band optical signals in fibers. In order to raise the Brillouin threshold, it is possible to increase the bandwidth of the light beyond the Brillouin gain bandwidth, reduce the fiber length, concatenate fibers with slightly different Brillouin shift, or (in high-power active fiber devices) exploit the longitudinally varying temperature [19]. There are also attempts to reduce the overlap of guided optical and acoustic waves, or to introduce significant propagation losses for the acoustic wave. To some extent, SBS problems can be reduced via basic amplifier design modifications, concerning e.g. the doping concentration, effective mode area and pump propagation direction.

On the other hand, the Brillouin gain can be used for operating a *Brillouin fiber laser* [3, 8, 16]. Such devices are often made as fiber ring lasers. Due to low resonator loss, they can have a relatively low pump threshold and a very small linewidth.

The temperature dependence of the Brillouin shift can be used for temperature and pressure sensing (→ *fiber-optic sensors*).

UNIT IV

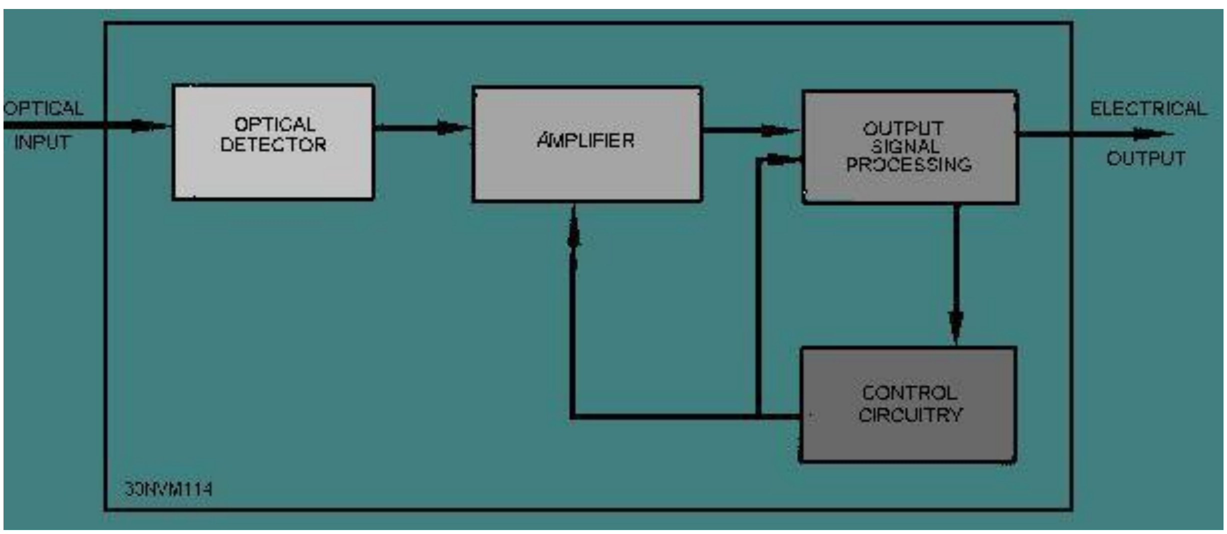
FIBER OPTICAL RECEIVERS

4.1 INTRODUCTION TO OPTICAL DETECTORS AND FIBER OPTIC RECEIVERS :

A fiber optic transmitter is an electro-optic device capable of accepting electrical signals, converting them into optical signals, and launching the optical signals into an optical fiber. The optical signals propagating in the fiber become weakened and distorted because of scattering, absorption, and dispersion. The fiber optic device responsible for converting the weakened and distorted optical signal back to an electrical signal is a fiber optic receiver.

A **fiber optic receiver** is an electro-optic device that accepts optical signals from an optical fiber and converts them into electrical signals. A typical fiber optic receiver consists of an optical detector, a low-noise amplifier, and other circuitry used to produce the output electrical signal (see figure 7-1). The optical detector converts the incoming optical signal into an electrical signal. The amplifier then amplifies the electrical signal to a level suitable for further signal processing. The type of other circuitry contained within the receiver depends on what type of modulation is used and the receiver electrical output requirements.

Figure 7-1. - Block diagram of a typical fiber optic receiver.



Receiver spectral response, sensitivity, Frequency response, and dynamic range are key receiver performance parameters that can affect overall system operation. The choice of optical detector materials and structures determines the spectral response. Silicon (Si), gallium arsenide (GaAs), and gallium aluminum arsenide (GaAlAs) are typical detector materials used for receiver operation in the 850-nm wavelength region. germanium (Ge), indium phosphide (InP), and indium gallium arsenide (InGaAs) are examples of detector materials used for receiver operation in the 1300-nm and 1550-nm wavelength regions.

The **receiver sensitivity** is the minimum amount of optical power required to achieve a specific receiver performance.

For digital transmission at a given data rate and coding, this performance is described by a maximum bit-error rate (BER). In analog systems, for a given modulation and bandwidth, it is described by a minimum signal-to-noise ratio (SNR). **Dynamic range** refers to the range of optical power levels over which the receiver operates within the specified values. It usually is described by the ratio of the maximum input power to the sensitivity. Before discussing receiver sensitivity, bandwidth, dynamic range, and Frequency response in more detail, we discuss the main types of optical detectors used in fiber optics.

4.2 OPTICAL DETECTORS

A **transducer** is a device that converts input energy of one form into output energy of another. An **optical detector** is a transducer that converts an optical signal into an electrical signal. It does this by generating an electrical current proportional to the intensity of incident optical radiation. The relationship between the input optical radiation and the output electrical current is given by the detector responsivity. Responsivity is discussed later in this chapter.

OPTICAL DETECTOR PROPERTIES

Fiber optic communications systems require that optical detectors meet specific performance and compatibility requirements. Many of the requirements are similar to those of an optical source. Fiber optic systems require that optical detectors:

- Be compatible in size to low-loss optical fibers to allow for efficient coupling and easy packaging.
- Have a high sensitivity at the operating wavelength of the optical source.
- Have a sufficiently short response time (sufficiently wide bandwidth) to handle the system's data rate.
- Contribute low amounts of noise to the system.
- Maintain stable operation in changing environmental conditions, such as temperature.

Optical detectors that meet many of these requirements and are suitable for fiber optic systems are semiconductor photodiodes. The principal optical detectors used in fiber optic systems include semiconductor positive-intrinsic-negative (PIN) photodiodes and avalanche photodiodes (APDs).

4.3 SEMICONDUCTOR PHOTODIODES

Semiconductor photodiodes generate a current when they absorb photons (light). The amount of current generated depends on the following factors:

- The wavelengths of the incident light and the responsivity of the photodiode at those wavelengths
- The size of the photodiode active area relative to the fiber core size
- The alignment of the fiber and the photodiode

The optical fiber is coupled to semiconductor photodiodes similarly to the way optical sources are coupled to optical fibers. Fiber-to-photodiode coupling involves centering the flat fiber-end face over the photodiode active area. This is normally done directly by butt coupling the fiber up to the photodiode surface. As long as the photodiode active area is larger than that of the fiber core, fiber-to-detector coupling losses are very low. In some cases a lens may be used to couple the fiber end-face to the detector. However, this is not typically done

SEMICONDUCTOR MATERIAL AND DEVICE PROPERTIES

The mechanism by which optical detectors convert optical power into electrical current requires knowledge of semiconductor material and device properties. As stated in chapter 6, providing a complete description of these properties is beyond the scope of this manual. In this chapter we only discuss the general properties of semiconductor PINs and APDs.

Semiconductor detectors are designed so that optical energy (photons) incident on the detector active area produces a current. This current is called a **photocurrent**. The particular properties of the semiconductor are determined by the materials used and the layering of the materials within the device. Silicon (Si), gallium arsenide (GaAs), germanium (Ge), and indium phosphide (InP) are the most common semiconductor materials used in optical detectors. In some cases aluminum (Al) and indium (In) are used as dopants in the base semiconductor material.

Responsivity

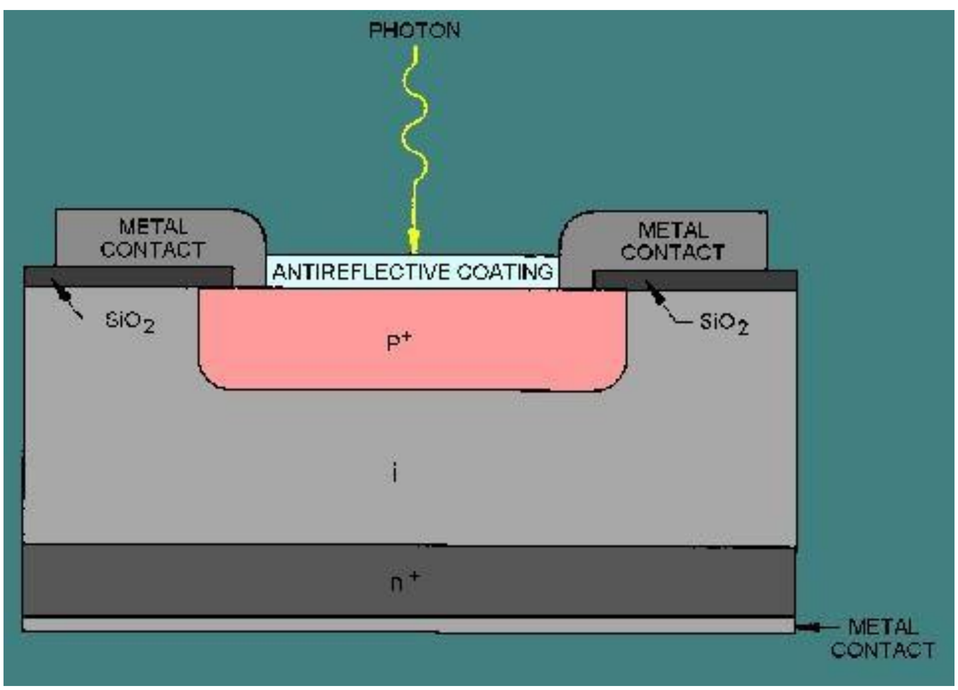
Responsivity is the ratio of the optical detector's output photocurrent in amperes to the incident optical power in watts. The responsivity of a detector is a function of the wavelength of the incident light and the efficiency of the device in responding to that wavelength. For a particular material, only photons of certain wavelengths will generate a photocurrent when they are absorbed. Additionally, the detector material absorbs some wavelengths better than others. These two properties cause the wavelength dependence in the detector responsivity. Responsivity is a useful parameter for characterizing detector performance because it relates the photocurrent generated to the incident optical power.

4.4 PIN PHOTODIODES

A **PIN photodiode** is a semiconductor positive-negative (p-n) structure with an intrinsic region sandwiched between the other two regions (see figure 7-2). It is normally operated by applying a reverse-bias voltage. The magnitude of the reverse-bias voltage depends on the photodiode application, but typically is less than a few volts. When no light is incident on the photodiode, a current is still produced. This current is called the **dark current**.

The dark current is the leakage current that flows when a reverse bias is applied and no light is incident on the photodiode. Dark current is dependent on temperature. While dark current may initially be low, it will increase as the device temperature increases.

Figure 7-2. - The basic structure of a PIN photodiode.

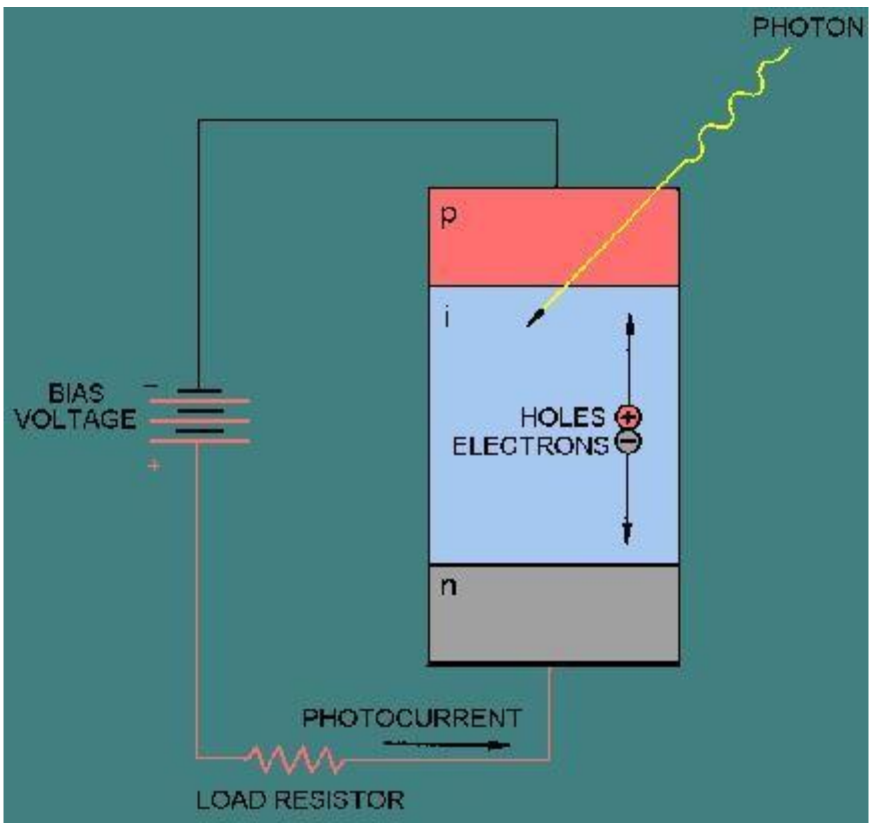


Response Time

There are several factors that influence the response time of a photodiode and its output circuitry (see figure 7-3).

The most important of these are the thickness of the detector active area and the detector RC time constant. The detector thickness is related to the amount of time required for the electrons generated to flow out of the detector active area. This time is referred to as the electron **transit time**. The thicker the detector active area, the longer the transit time will be.

Figure 7-3. - A schematic representation of a photodiode.



The **capacitance (C)** of the photodiode and the **resistance (R)** of the load form the RC time constant. The capacitance of the photodetector must be kept small to prevent the RC time constant from limiting the response time. The photodiode capacitance consists mainly of the junction capacitance and any capacitance relating to packaging. The **RC time constant** is given by $t_{RC} = RC$.

Trade-offs between fast transit times and low capacitance are necessary for high-speed response. However, any change in photodiode parameters to optimize the transit time and capacitance can also affect responsivity, dark current, and coupling efficiency. A fast transit time requires a thin detector active area, while low capacitance and high responsivity require a thick active region.

The diameter of the detector active area can also be minimized. This reduces the detector dark current and minimizes junction capacitance. However, a minimum limit on this active area exists to provide for efficient fiber-to-detector coupling.

Linearity

Reverse-biased photodetectors are highly linear devices. Detector **linearity** means that the output electrical current (photocurrent) of the photodiode is linearly proportional to the input optical power. Reverse-biased photodetectors remain linear over an extended range (6 decades or more) of photocurrent before saturation occurs. Output saturation occurs at input optical power levels typically greater than 1 milliwatt (mW). Because fiber optic communications systems operate at low optical power levels, detector saturation is generally not a problem.

4.4 AVALANCHE PHOTODIODES

An **avalanche photodiode (APD)** is a photodiode that internally amplifies the photocurrent by an avalanche process.

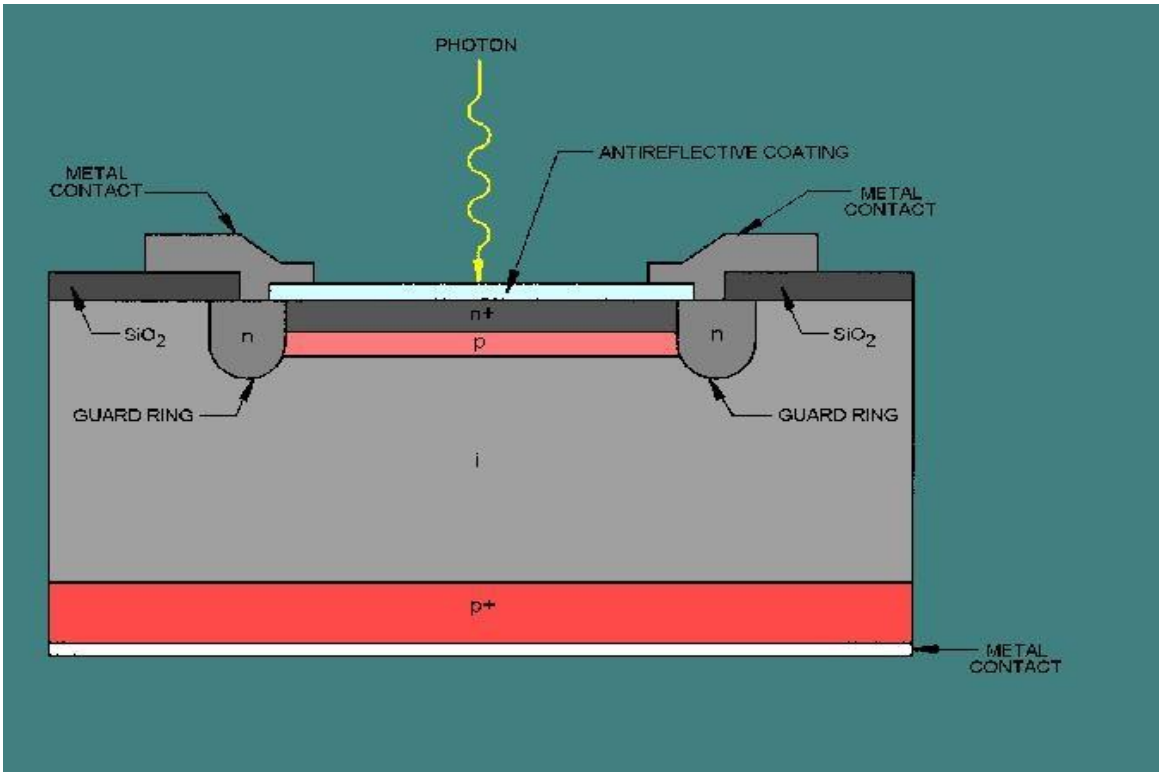
Figure 7-4 shows an example APD structure. In APDs, a large reverse-bias voltage, typically over 100 volts, is applied across the active region. This voltage causes the electrons initially generated by the incident photons to accelerate as they move through the APD active region.

As these electrons collide with other electrons in the semiconductor material, they cause a fraction of them to become part of the photocurrent. This process is known as **avalanche multiplication**. Avalanche multiplication continues to occur until the electrons move out of the active area of the APD.

The gain of the APD can be changed by changing the reverse-bias voltage. A larger reverse-bias voltage results in a larger gain. However, a larger reverse-bias voltage also results in increased noise levels. Excess noise resulting from the avalanche multiplication process places a limit on the useful gain of the APD. The avalanche process introduces excess noise because every photogenerated carrier does not undergo the same multiplication.

The noise properties of an APD are affected by the materials that the APD is made of. Typical semiconductor materials used in the construction of low-noise APDs include silicon (Si), indium gallium arsenide (InGaAs), and germanium (Ge).

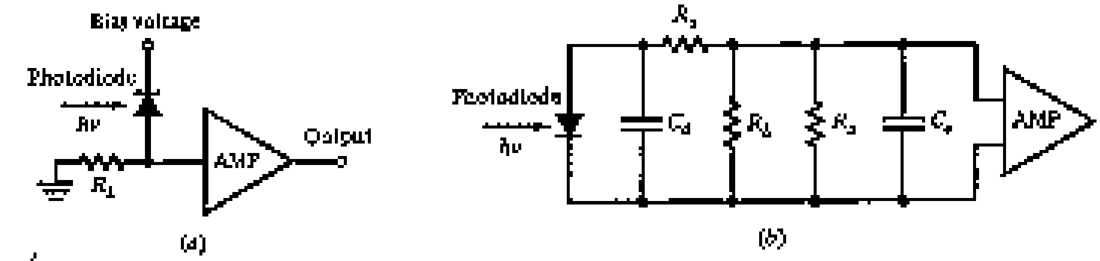
Figure 7-4. - The basic structure of an APD.



Trade-offs are made in APD design to optimize responsivity and gain, dark current, response time, and linearity. This chapter does not attempt to discuss trade-offs in APD design in more detail. Many aspects of the discussion provided on responsivity, dark current, and response time provided in the PIN photodiodes section also relate to APDs. The response time of an APD and its output circuitry depends on the same factors as PIN photodiodes. The only additional factor affecting the response time of an APD is the additional time required to complete the process of avalanche multiplication. To learn more about APD design trade-offs and performance parameters, refer to the reference material listed in appendix 2.

4.5 PHOTODETECTOR NOISE & S/N:

- Detection of weak optical signal requires that the photodetector and its following amplification circuitry be optimized for a desired signal-to-noise ratio.
- It is the noise current which determines the minimum optical power level that can be detected. This minimum detectable optical power defines the **sensitivity** of photodetector. That is the optical power that generates a photocurrent with the amplitude equal to that of the total noise current (*S/N=1*)



$$\frac{S}{N} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power} + \text{amplifier noise power}}$$

Signal Calculation:

Consider the modulated optical power signal *P(t)* falls on the photodetector with the form of

$$P(t) = P_0[1 + ms(t)]$$

Where *s(t)* is message electrical signal and *m* is modulation index. Therefore the primary photocurrent is (for pin photodiode *M=1*):

$$i_{ph} = \frac{\eta q}{h\nu} MP(t) = I_P[\text{DC value}] + i_p(t)[\text{AC current}]$$

The root mean square signal current is then

$$\langle i_s^2 \rangle = \langle i_p^2 \rangle M^2 = \sigma_s^2$$

$$\langle i_p^2 \rangle = \sigma_p^2 = \frac{m^2 I_P^2}{2} \quad \text{for sinusoidal signal}$$

Noise Sources in Photodetecors :

- The principal noises associated with photodetectors are :

1- Quantum (Shot) noise: arises from statistical nature of the production and collection of photo-generated electrons upon optical illumination. It has been shown that the statistics follow a Poisson process.

2- Dark current noise: is the current that continues to flow through the bias circuit in the absence of the light. This is the combination of bulk dark current, which is due to thermally generated e and h in the *pn* junction, and the surface dark current, due to surface defects, bias voltage an surface area.

- In order to calculate the total noise presented in photodetector, we should sum up the root mean square of each noise current by assuming that those are uncorrelated.
- Total photodetector noise current=quantum noise current +bulk dark current noise + surface current noise

Noise calculation :

Quantum noise current (lower limit on the sensitivity):

$$\langle i_Q^2 \rangle = \sigma_Q^2 = 2qI_P BM^2 F(M)$$

B: Bandwidth, *F(M)* is the noise figure and generally is

$$F(M) \approx M^x \quad 0 \le x \le 1.0$$

Bulk dark current noise:

$$\langle i_{DB}^2 \rangle = \sigma_{DB}^2 = 2qI_D BM^2 F(M)$$

Surface dark current noise

$$\langle i_{DS}^2 \rangle = \sigma_{DS}^2 = 2qI_L B$$

The total rms photodetector noise current is:

$$\langle i_N^2 \rangle = \sigma_N^2 = \langle i_Q^2 \rangle + \langle i_{DB}^2 \rangle + \langle i_{DS}^2 \rangle$$
$$= 2q(I_P + I_D)BM^2 F(M) + 2qI_L B$$

The thermal noise of amplifier connected to the photodetector is:

$$\langle i_T^2 \rangle = \sigma_T^2 = \frac{4k_B TB}{R_L}$$

4.6 S/N CALCULATION:

Having obtained the signal and total noise, the signal-to-noise-ratio can be written as:

$$\frac{S}{N}=\frac{\langle i_P{}^2\rangle M^2}{2q(I_P+I_D)BM^2F(M)+2qI_LB+4k_BTB/R_L}$$

Since the noise figure *F(M)* increases with M, there always exists an optimum value of *M* that maximizes the S/N. For sinusoidally modulated signal with *m=1* and $F(M)\approx M^x$:

$$M_{\text{opt}}^{x+2}=\frac{2qI_L+4k_BT/R_L}{xq(I_P+I_D)}$$

4.7 PHOTODETECTOR RESPONSE TIME:

- The response time of a photodetector with its output circuit depends mainly on the following three factors:

1- The transit time of the photocarriers in the depletion region. The transit time t_d depends on the carrier drift velocity v_d and the depletion layer width *w*, and is given by:

$$t_d=\frac{w}{v_d}$$

2- Diffusion time of photocarriers outside depletion region.

3- *RC* time constant of the circuit. The circuit after the photodetector acts like *RC* low pass filter with a passband given by:

$$B=\frac{1}{2\pi R_TC_T}$$

$$R_T=R_s\,||\,R_L \text{ and } C_T=C_a+C_d$$

UNIT V

DIGITAL TRANSMISSION SYSTEM

POINT-TO-POINT LINKS SYSTEM CONSIDERATIONS:

- In this section we develop a simple point-to-point digital transmission link design considering :
  - Link power budget calculations and
  - Link rise time calculations

A link should satisfy both these budgets

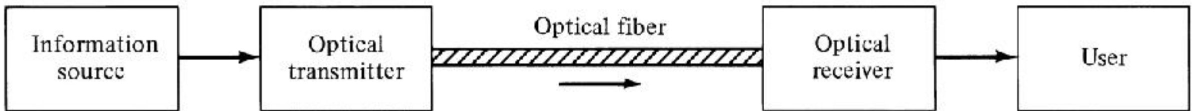


Fig. : Simple point-to-point link

System Requirements

1. Transmission Distance
2. Data Rate for a given BER

Selecting the Fiber

Bit rate and distance are the major factors

Other factors to consider: attenuation (depends on?) and distance-bandwidth product (depends on?) cost of the connectors, splicing etc.

Then decide

- Multimode or single mode
- Step or graded index fiber

Selecting the Optical Source:

- Emission wavelength
- Spectral line width (FWHM) and number of modes
- Output power
- Stability
- Emission pattern
- Effective radiating area

Selecting the detector:

- Type of detector

- **APD**: High sensitivity but complex, high bias voltage (40V or more) and expensive

- **PIN:** Simpler, thermally stable, low bias voltage (5V or less) and less expensive

- Responsivity (that depends on the avalanche gain & quantum efficiency)
- Operating wavelength and spectral selectivity
- Speed (capacitance) and photosensitive area
- Sensitivity (depends on noise and gain)

Design Considerations:

- Link Power Budget
  - There is enough power margin in the system to meet the given BER
- Rise Time Budget
  - Each element of the link is fast enough to meet the given bit rate

These two budgets give necessary conditions for satisfactory operation

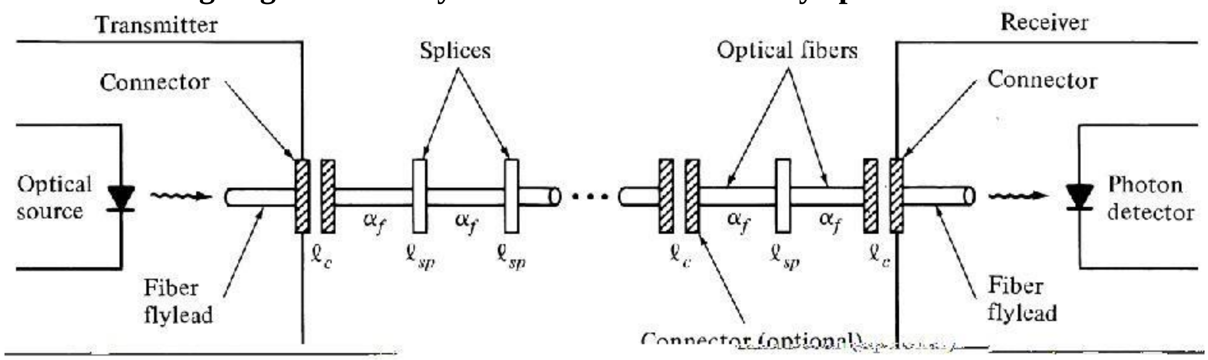


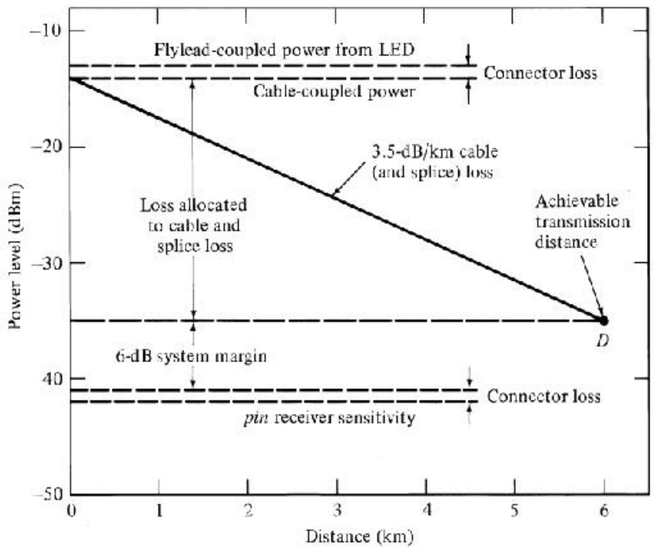
Fig. : Optical power-loss model

$$P_T = P_s - P_R = m l_c + n l_{sp} + \alpha_f L + \text{System Margin}$$

P_T: Total loss; P_s : Source power; P_R: Rx sensitivity

m connectors; n splices

Fig. : Example link-loss budget



Rise Time Budget:

- Total rise time depends on:
  - Transmitter rise time (t_{tx})
  - Group Velocity Dispersion (t_{GVD})
  - Modal dispersion rise time (t_{mod})
  - Receiver rise time (t_{rx})

$$t_{sys} = \left[\sum_{i=1}^{n} t_i^2 \right]^{1/2}$$

Total rise time of a digital link should not exceed 70% for a NRZ bit period, and 35% of a RZ bit period

$t_{rx} = 350/B_{rx}$ ns; where

B_{rx} is receiver bandwidth in MHz

Similarly

$$t_{tx} = 350 / B_{tx}$$

Assuming both transmitter and receiver as first order low pass filters

Modal Dispersion Rise Time:

Bandwidth $B_M(L)$ due to modal dispersion of a link length L is empirically given by, $B_M(L) = B_0 / L^q$

B_0 is the BW per km (MHz-km product) and q ~0.5-1 is the modal equilibrium factor

$$t_{mod} = 0.44 / B_M = 440 L^q / B_0 \text{ (ns)}$$

Group Velocity Dispersion:

$$t_{GVD} = |D| L\sigma_\lambda$$

Where,

D is the dispersion parameter (ns/km/nm) given by eq. (3.57)

σ_λ is the half power spectral width of the source (nm)

L is the distance in km

$$t_{sys} = \left[t_{tx}^2 + t_{rx}^2 + D^2 \sigma_\lambda^2 L^2 + \frac{440^2 L^{2q}}{B_0^2} \right]^{1/2}$$

Link Noise:

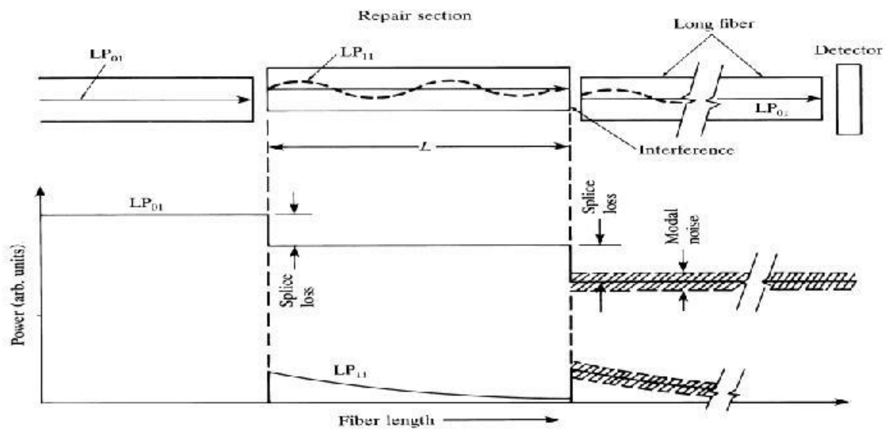
Modal Noise: When a laser is coupled to a multi mode fiber (MMF) modal noise exists. To avoid this,

- Use LED with MMF
- Use a laser with large number of modes
- Use a MMF with large NA
- Use single mode fiber with laser

Mode Partition Noise:

- This is the dominant noise in single mode fiber coupled with multimode laser
- Mode partition noise is associated with intensity fluctuations in the longitudinal modes of a laser diode
- Each longitudinal mode has different λ
- The SNR due to MPN can not be improved by increasing the signal power

Modal noise at a connection of a SMF

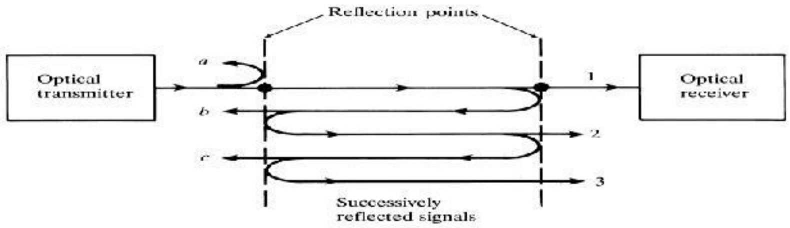


Interferometric Noise :

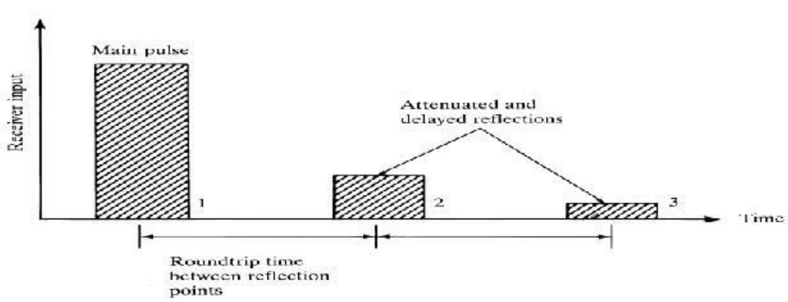
due to multiple reflections

- Increases RIN
- Laser instability
- Increases with signal power
- Can be decreased by

having angled, low back reflection connectorsand isolators



(a)



(b)

Optical Amplifiers:

- Why is there a requirement for optical amplifiers?

  => Light signal over long distances become attenuated.

=> Regeneration of the light signal is necessary especially over distances of perhaps several thousand kilometers.

=> The overhead of photodetection to electrical conversions and back to light via a lsaer diode. Contributes to high cost and speed.

Optical Amplifiers: EDFA, Raman, Laser amplifier.

Erbium Doped Fibre Amplifier:

- Fibre amplifier
- Core region is doped with Er^{3+} ions.
- Another rare earth ion dopant that is used is the neodymium (Nd^{3+})
- Host fibre is glass based. ($SiO_3 - GeO_2$) with other glass forming oxides (Al_2O_3)
- Important factor: It is possible to have relatively high concentrations of erbium in the core (up to 1000 ppm).

Erbium Doped Fibre Amplifier

- Refer to energy diagram.
- Erbium ions are optically pumped, typically by a 980 nm laser diode. Er^{3+} is raised to E_3.
- The erbium ions decay rapidly to E_2. They experience an atomically long lifetime here (10 ms).
- Decays from E_3 to E_3 and from E_3 to E_2 are very rapid.
- Therefore there is an accumulation of erbium ions at E_2 sitting 0.80 eV above ground.
- This accumulation of erbium ions lead to a population inversion between E_2 and E_1.
- Photons at 1550 nm have an energy of 0.80eV ($E_2 - E_1$).

- This triggers stimulated emission of erbium ions from
- Erbium ions left at E1 will absorb the incoming 1550 nm photons and rise to E2.
- Stimulated emission must exceed light absorption to achieve light amplification.
- Therefore there must be more erbium ions at E2 then at E1.

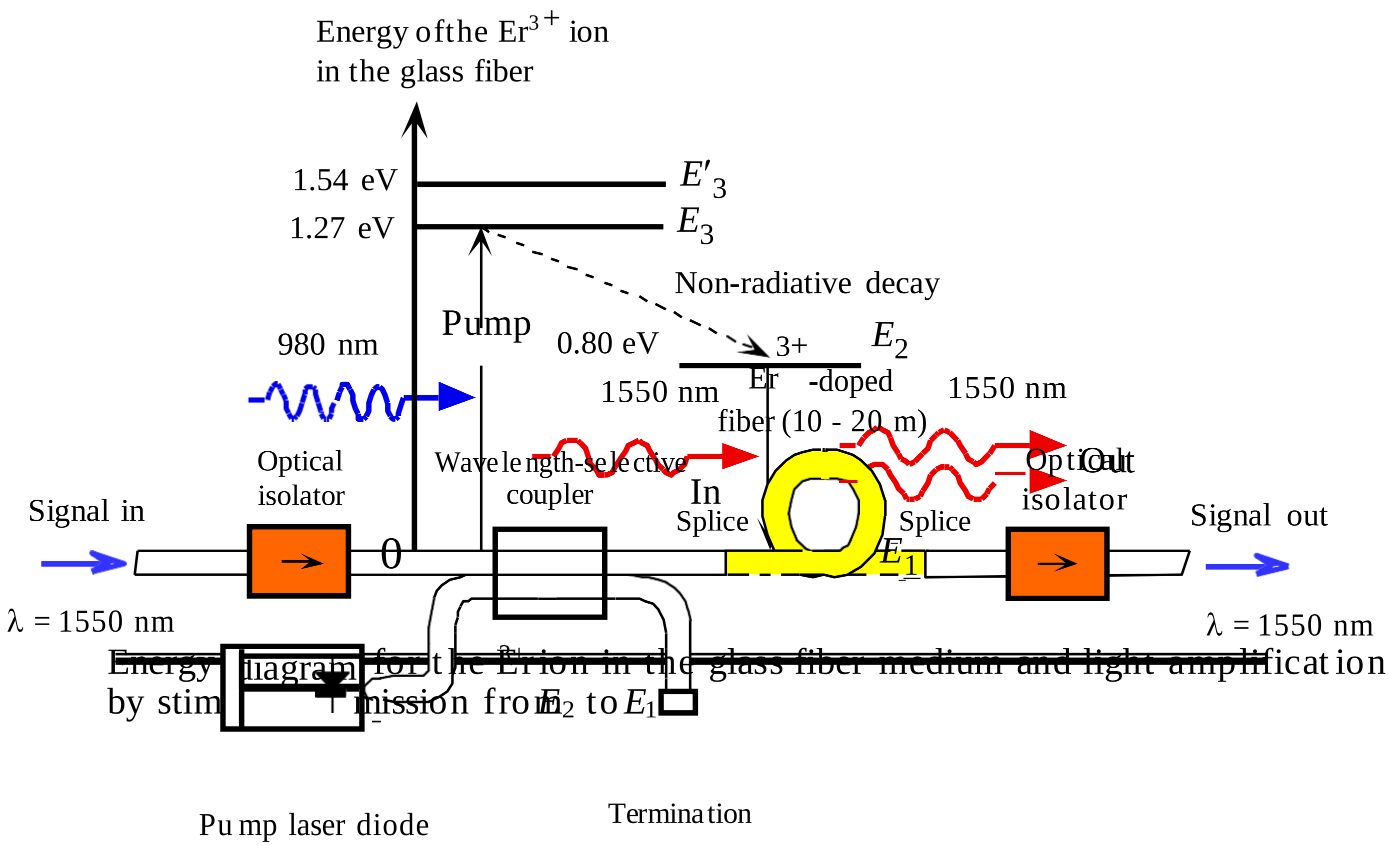
- Assume N2 and N1 are the number if erbium ions at E2 and E1.
- The difference between stimulated emission (E2 toE1) and absorption (E1 to E2) rate controls the optical gain.

$$G_{op} = K(N_2 - N_1)$$

where K is a constant that depends on pumping intensity

Considerations:

- Spontaneous decay of erbium ions from E2 to E1 will generate noise in the amplified light signal.
- If the EDFA is not pumped then it presents itself as an attenuator. 1550 nm photons will be absorbed by ions which will rise from E1 to E2.
- The range of stimulated transistions from E2 to E1 correspond to a wavelength range of 1525 to 1565 nm that can be amplified.
- This delivers an optical bandwidth of 40 nm.
- This permits usage with a WDM.
- Problem => Gain is not uniform across bandwidth.
- Techniques must be implemented to flatten the response.



Energy diagram for the Er ion in the glass fiber medium and light amplification by stim... mission from E_2 to E_1

Factors controlling the degree of gain uniformity:

1. Concentrations of the active ion (erbium).
2. Optical gain flattening filter.
3. Additional (second) pump laser at each end of the fibre.

One pump beam propagates with signal beam while the other propagates against it. Ensures that population inversion and gain remains constant along the fiber.

Physical Components of EDFA:

1. Biconical fused fibre couplers.
2. One or two (if high output required) laser pumps.
3. Polarization-insensitive optical isolators front and back. Allows only 1550 nm signals to pass. Pump radiation should not enter main fibre as well as optical feedback from reflections.
4. Optical filter for gain flattening.
5. Phgotodetector system to monitor pump power or EDFA output power.

Idea behind SONET:
Synchronous **O**ptical **NET**work

- Designed for ***optical*** transport (high bitrate)
- **Direct** mapping of lower levels into higher ones
- Carry all PDH types in **one** universal hierarchy
  - ITU version = **S**ynchronous **D**igital **H**ierarchy
  - different terminology but interoperable
- Overhead doesn’t increase with rate
- OAM designed-in from beginning

Standardization
The original Bellcore proposal:

- hierarchy of signals, all multiple of basic rate (50.688)
- basic rate about 50 Mbps to carry DS3 payload
- bit-oriented mux
- mechanisms to carry DS1, DS2, DS3

Many other proposals were merged into 1987 draft document (rate 49.920)

In summer of 1986 CCITT express interest in cooperation

- needed a rate of about 150 Mbps to carry E4
- wanted byte oriented mux

Initial compromise attempt

- byte mux
- US wanted 13 rows * 180 columns
- CEPT wanted 9 rows * 270 columns

Compromise!

- US would use basic rate of 51.84 Mbps, 9 rows * 90 columns
- CEPT would use three times that rate - 155.52 Mbps, 9 rows * 270 columns

SONET/SDH architecture:
Layers:
SONET was designed with definite layering concepts

Physical layer – optical fiber (linear or ring)

- when exceed fiber reach – regenerators
- regenerators are not mere amplifiers,
- regenerators use their own overhead
- fiber between regenerators called section (regenerator section)

Line layer – link between SONET muxes (Add/Drop Multiplexers)

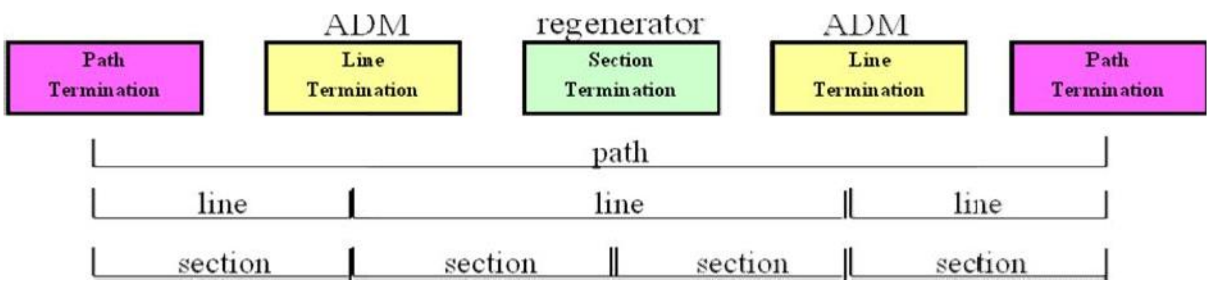
- input and output at this level are Virtual Tributaries (VCs)
- actually 2 layers
    - lower order VC (for low bitrate payloads)

- higher order VC (for high bitrate payloads)

Path layer – end-to-end path of client data (tributaries)

- client data (payload) may be
  - PDH
  - ATM
  - packet data

SONET architecture:



SONET (SDH) has at 3 layers:

- path – end-to-end data connection, muxes tributary signals path section
  - there are STS paths + Virtual Tributary (VT) paths
- line – protected multiplexed SONET payload multiplex section
- section – physical link between adjacent elements regenerator section

Each layer has its own overhead to support needed functionality

SDH terminology

A SONET signal is called a **S**ynchronous **T**ransport **S**ignal

The basic STS is STS-1, all others are multiples of it - STS-N

The (optical) physical layer signal corresponding to an STS-N is an OC-N

SONET	**Optical**		**rate**
STS-1	OC-1		51.84M

STS-3	OC-3		155.52M
STS-12	OC-12		622.080M
STS-48	OC-48		2488.32M
STS-192	OC-192		9953.28M

RATES AND FRAME STRUCTURE:

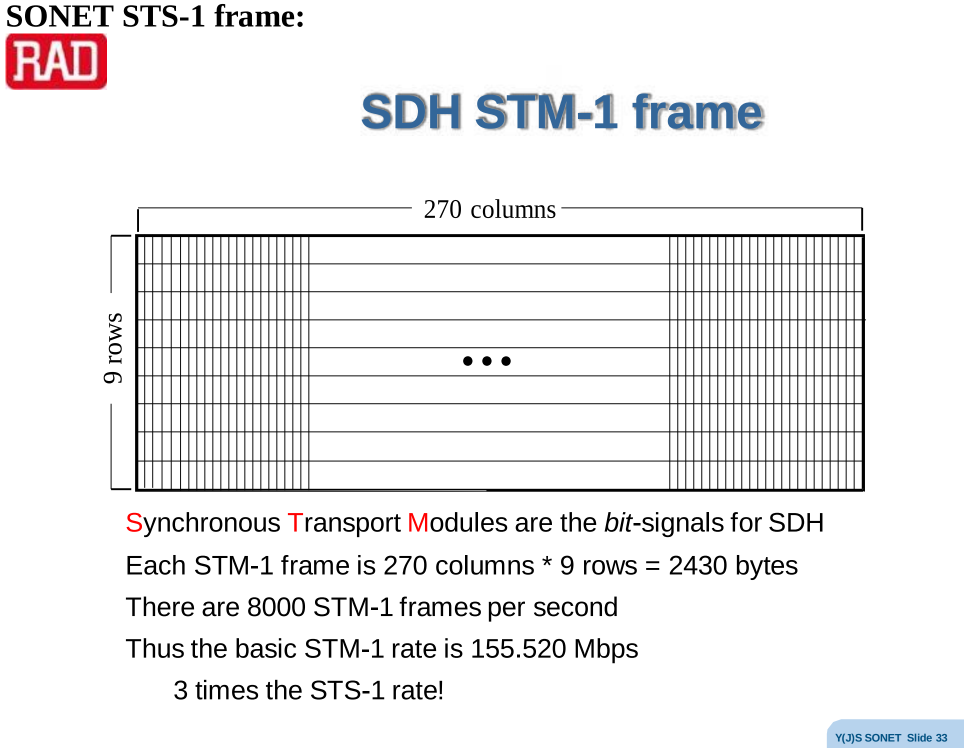
SONET / SDH frames:

Synchronous Transfer Signals are *bit*-signals (**OC** are optical)

Like all TDM signals, there are framing bits at the beginning of the frame

However, it is convenient to draw SONET/SDH signals as rectangles

SONET STS-1 frame:



STS-N has 90N columns   STM-M corresponds to STS-N with N = 3M

SDH rates increase by factors of 4 each time

STS/STM signals can carry PDH tributaries, for example:

- STS-1 can carry 1 T3 or 28 T1s or 1 E3 or 21 E1s
- STM-1 can carry 3 E3s or 63 E1s or 3 T3s or 84 T1s

SONET/SDH tributaries

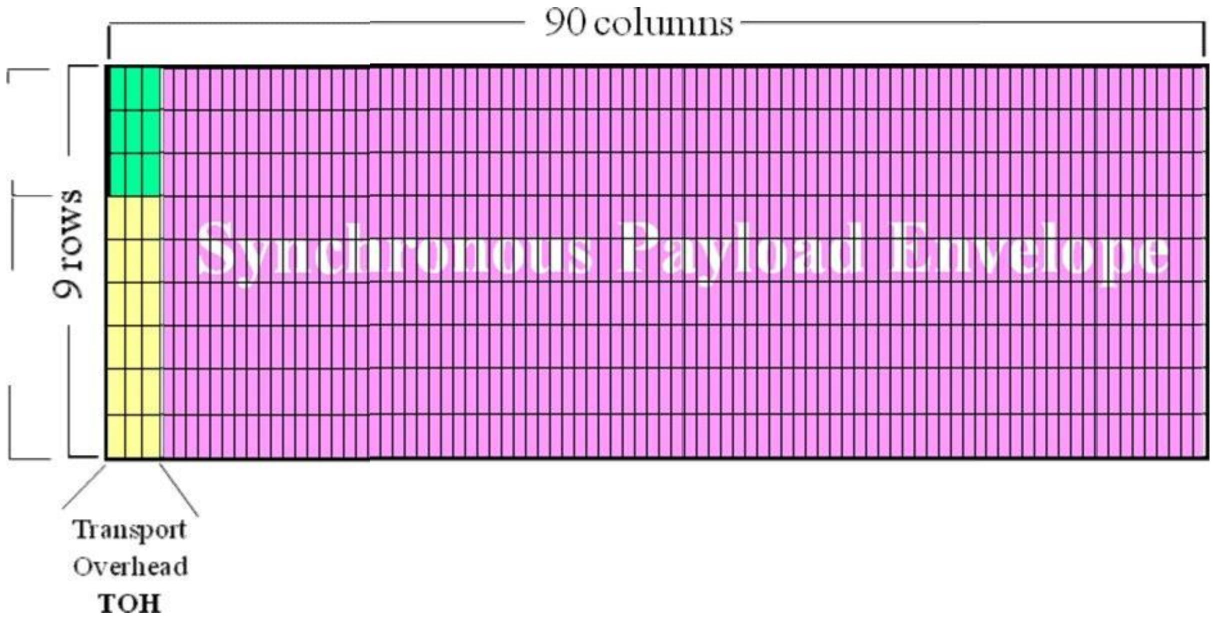
SONET	SDH	T1	T3	E1	E3	E4
STS-1		28	1	21	1	
STS-3	STM-1	84	3	63	3	1
STS-12	STM-4	336	12	252	12	4
STS-48	STM-16	1344	48	1008	48	16
STS-192	STM-64	5376	192	4032	192	64

E3 and T3 are carried as Higher Order Paths (HOPs)

E1 and T1 are carried as Lower Order Paths (LOPs)

(the numbers are for **direct** mapping)

STS-1 frame structure:



Section overhead is 3 rows * 3 columns = 9 bytes = 576 kbps

framing, performance monitoring, management

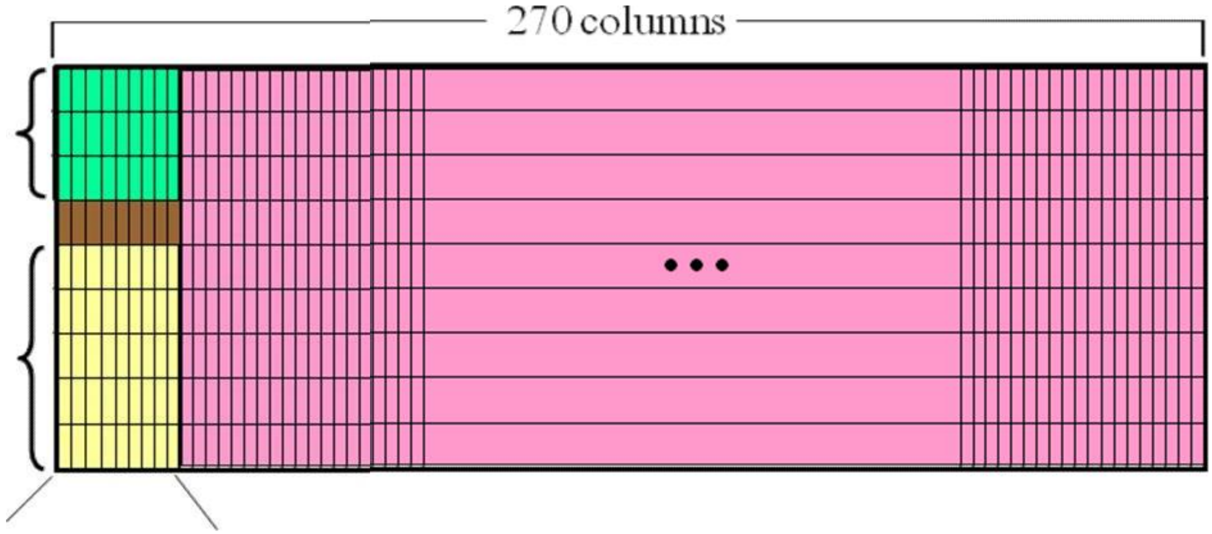
Line overhead is 6 rows * 3 columns = 18 bytes = 1152 kbps

protection switching, line maintenance, mux/concat, SPE pointer

SPE is 9 rows * 87 columns = 783 bytes = 50.112 Mbps

Similarly, STM-1 has 9 (different) columns of section+line overhead

STM-1 frame structure:



STM-1 has 9 (different) columns of transport overhead !

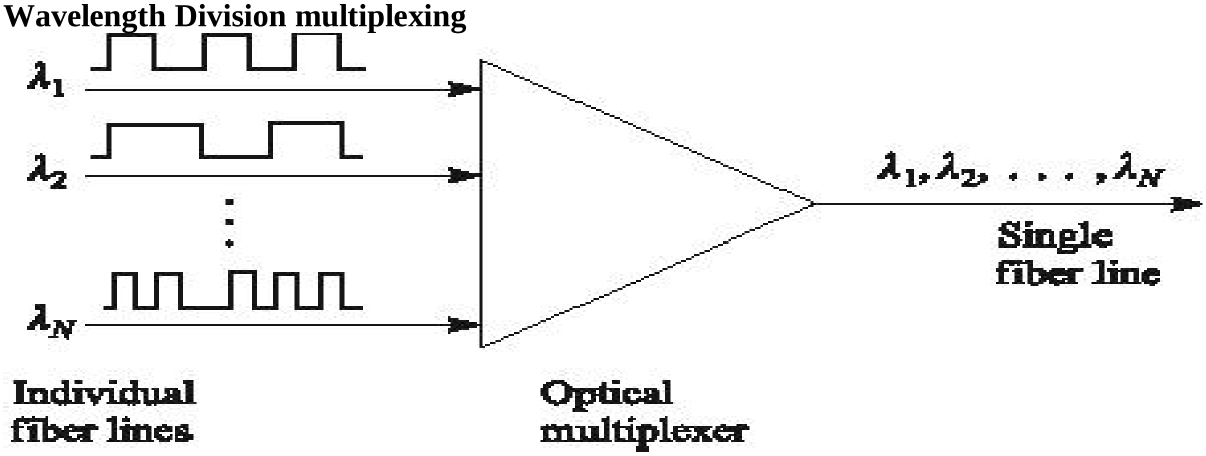
RS overhead is 3 rows * 9 columns

Pointer overhead is 1 row * 9 columns

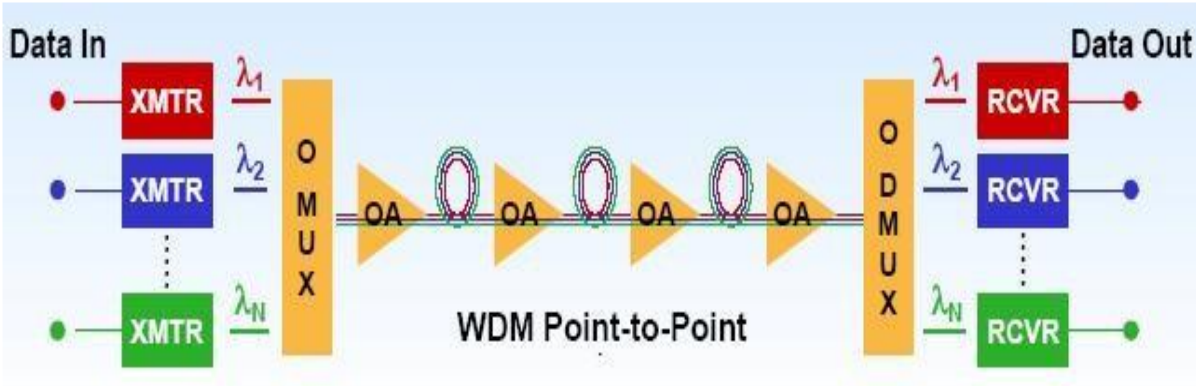
MS overhead is 5 rows * 9 columns

SPE is 9 rows * 261 columns

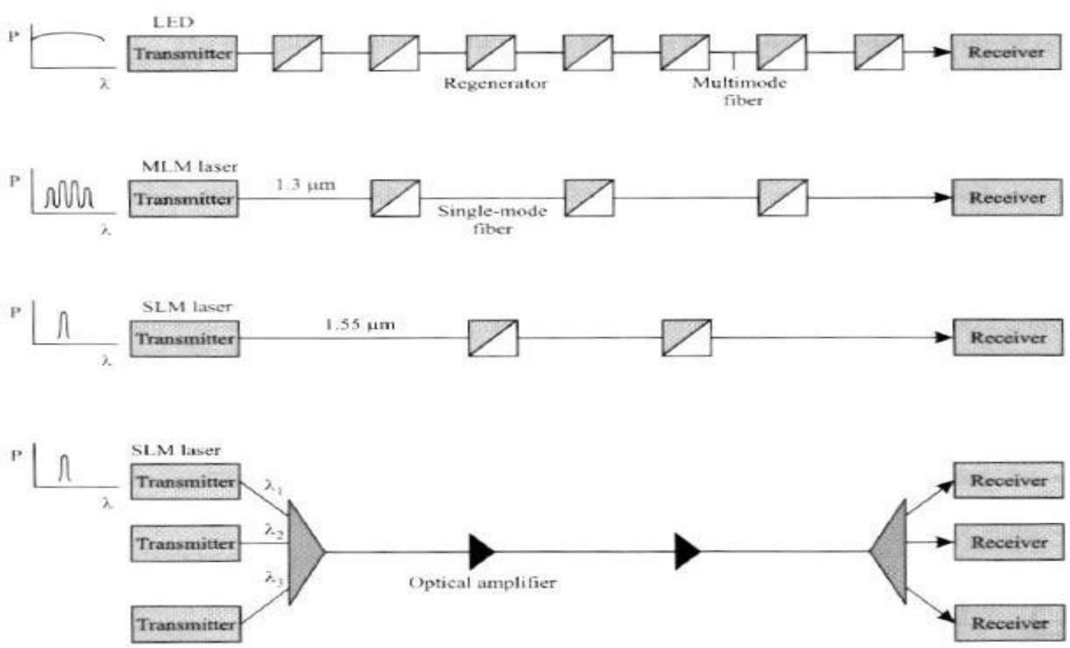
Wavelength Division multiplexing



Each wavelength is like a separate channel (fiber)



- Passive/active devices are needed to combine, distribute, isolate and amplify optical power at different wavelengths
- Capacity upgrade of existing fiber networks (without adding fibers)
- Transparency: Each optical channel can carry any transmission format (different asynchronous bit rates, analog or digital)
- Scalability– Buy and install equipment for additional demand as needed
- Wavelength routing and switching: Wavelength is used as another dimension to time and space



Key components for WDM

Passive Optical Components

- Wavelength Selective Splitters
- Wavelength Selective Couplers

Active Optical Components

- Tunable Optical Filter
- Tunable Source
- Optical amplifier
- Add-drop Multiplexer and De-multiplexer

Soliton Systems:

The use of SRS amplifiers only helps in reducing one of the problems of long haul transmission, namely the loss of the signal. The second problem, pulse broadening brought on by dispersion, still remains even with the use of SRS or SBS based amplifiers. Indeed, the fundamental limitation of the fiberoptic communication systems arises from dispersion.

Dispersion can be compensated if it is possible to keep the pulse from expanding or broadening. But, the dispersion in the fiber can only be reduced, not eliminated. However, along with pulse broadening if we can introduce pulse compression, the two counteracting effects, broadening and compression, will ensure that the pulses do not spread in time.

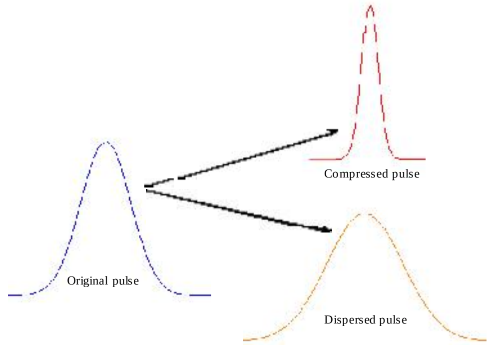


Figure 23 Original pulse, a compressed pulse and a dispersed pulse are shown.

It can be easily seen from Figure 23 that by having pulse a compressed pulse and a dispersed pulse, the pulse can traverse un-dispersed. Pulses that are not dispersed are referred to as solitons or solitary pulses. These pulses must have a certain definite shape and will require a minimum strength. The energy in the pulse introduces intensity induced refractive index change in the material of the fiber. Index changes from intensity variations are a manifestation of the non-linearity of the material. Intensity induced changes leads to pulse compression because such changes are equivalent to self-phase modulation. Phase modulation and frequency modulation increase the frequency content in the pulse. Using the Fourier property of duality (expansion in the frequency domain causes a compression in the frequency domain and vice versa), the pulse must now be narrower. This narrowing of the pulse will be sufficient to compensate for the dispersion in the fiber, keeping the pulse from spreading.

Fiberoptic communication systems based on solitons use SRS or other amplifiers to keep the signal energy back to the minimum value required to produce the nonlinearities needed. Thus, the system shown in Figure 22 where the input pulse is of a specific shape, will provide a fiberoptic communication system that mitigates the twin problems of attenuation and dispersion.