

## Chapter 18: Fiber Optic and Laser Technology

### Chapter 18 Objectives

*At the conclusion of this chapter, the reader will be able to:*

- Describe the construction of fiber optic cable.
- Describe the propagation modes in fiber.
- Utilize fiber specifications (such as numerical aperture) to evaluate fiber performance characteristics.
- Predict the dispersion and effective bandwidth of a multimode fiber.
- Describe the operation of LED and laser light sources, and their associated drive circuitry.
- Describe the operation of several light wave demodulation devices.
- Use electrical and optical test equipment to troubleshoot fiber optic systems.

Transmission lines are used to carry signal energy or information between two points. The traditional forms of these lines (such as twisted wire pairs or coaxial cables) are made of copper wire, and for carrying high-power radio frequency signals over a short distance, they are excellent performers. However, when we want to carry just information (such as a group of telephone conversations) over a long distance without using radio waves (sending it over the air), conventional transmission lines are not the best choice.

*Fiber optics* are transmission lines designed to convey *light* signals instead of radio signals. In a fiber optic system, a light wave acts as a carrier signal, and is modulated with information before it's sent down the cable. On the other end, the light wave is "demodulated" and the original information is recovered.

There are several advantages to doing it this way. First, modern fiber optic cables have much lower signal loss than copper transmission lines, which means that a signal can be carried much farther on an optical cable before it needs amplification. Second, because the frequency of a light wave is very high, much more bandwidth is available on a fiber optic cable than with a copper line. This means that fiber optics can carry much more information than copper. Also, fiber optic signals are very secure (it's hard to tamper with a fiber optic line), and since the signals in the cable are light instead of electricity, they are not affected by external sources of noise. Finally, fiber optic cables are much lighter than conventional transmission lines, and are completely safe for hazardous environments where an explosive atmosphere or nuclear radiation might be present.

There are disadvantages to fiber optics. First, they can be more difficult to work with than copper transmission lines. Special tools are needed to put connectors on fiber optic cable, and splicing can be a challenge. Second, it is nearly impossible to measure the performance of a fiber optic connection without specialized optical test equipment. For large companies, these problems are minor when compared with the benefits fiber provides.

### 18-1 Fiber Optic Construction and Operation

#### Parts of a Fiber Optic Cable

The construction of a fiber optic cable is quite straightforward, as shown in Figure 18-1. A fiber optic line consists of an *outer jacket*, an inner *cladding*, and a central *core*.

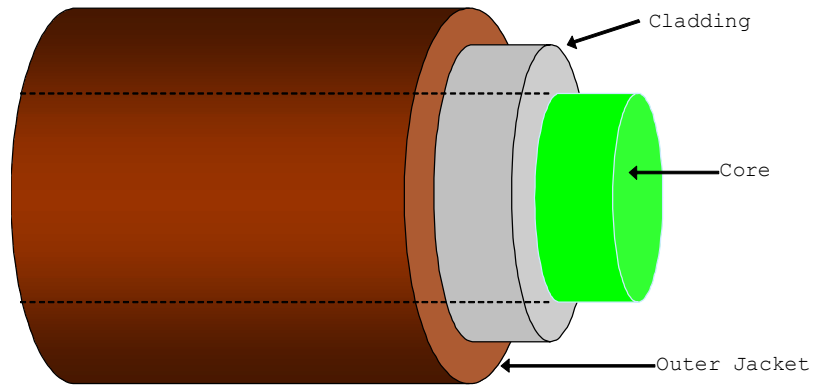


Figure 18-1: Fiber Optic Cable Construction

The *outer jacket* provides most of the mechanical strength of the cable. Its purpose is to protect the inner works from contamination by moisture and dirt. The outer jacket is usually made of a tough but flexible plastic. When greater strength is needed, strands of reinforcing fiber (such as kevlar) may also be included inside the outer jacket.

The *cladding* surrounds the inner *core*, and these two components function together to carry light wave down the fiber. The purpose of the core is to carry the light; it can be made of either transparent plastic or glass. The highest performance fibers use a glass core, which provides much lower loss and wider bandwidth than plastic. The function of the cladding is to help the core contain the light waves. Without the cladding, some of the light would escape the core on the way down the cable, resulting in signal loss. The combined optical characteristics of the core and cladding work together to keep light inside the fiber, as we'll soon see. Figure 18-2 shows the construction details of a modern single-mode fiber optic cable.

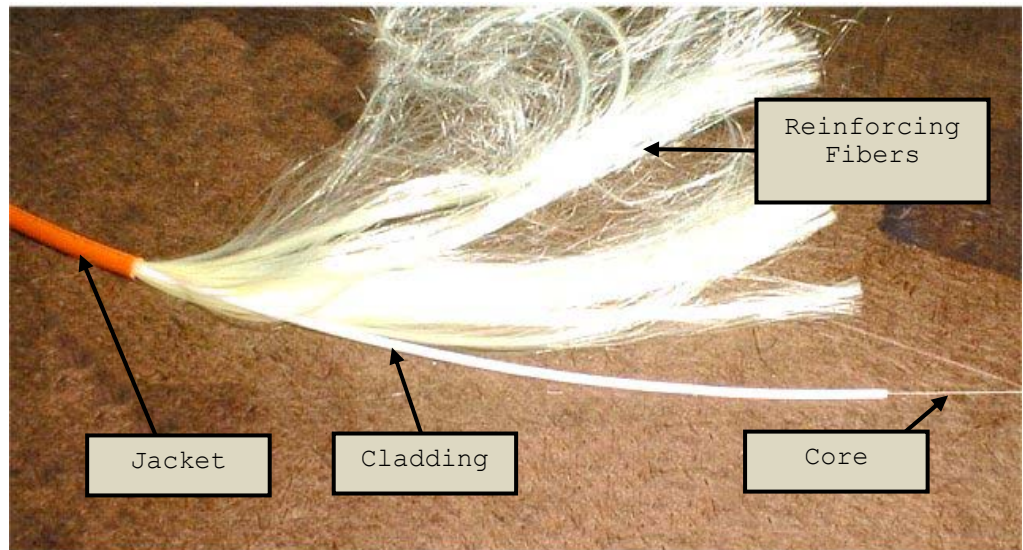


Figure 18-2: Single-Mode Fiber Optic Cable Construction

**Light Waves**

Light waves are electromagnetic energy, just like radio waves. The primary difference between light and radio waves is *frequency*. Light has a much shorter wavelength than the highest radio frequency, and therefore a much higher frequency. The light frequencies used in fiber optics are generally in the *infrared* region, which is invisible to the eye. Infrared light is used because the fiber optic core materials generally have the lowest signal loss at these frequencies. Figure 18-3 shows the relationship between radio waves and light waves.

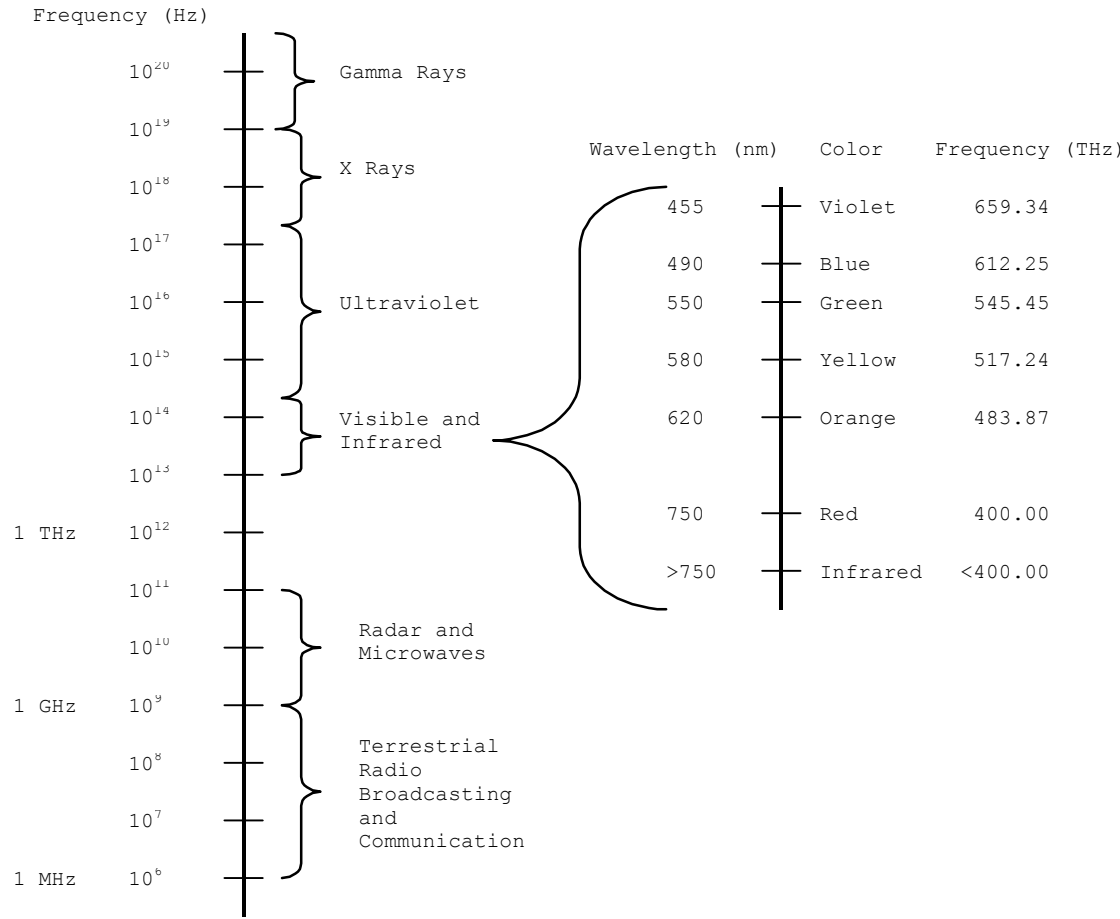


Figure 18-3: Radio and Light Waves

Figure 18-3 shows that light energy is *much* higher in frequency than radio waves. The lowest light frequency (in the infrared region, at 10 THz) is more than 100 times the highest useful microwave radio frequency (100 GHz). The wavelength of a light wave is calculated in exactly the same way as for a radio wave:

$$(18-1) \lambda = \frac{v}{f}$$

Where  $\lambda$  is the wavelength in meters,  $v$  is the speed of light ( $3 \times 10^8$  m/s), and  $f$  is the frequency of the wave.

## Example 18-1

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What is the frequency of infrared light with a wavelength of 800 nm?

*Solution*

Equation 18-1 (the same equation we've used throughout this book) is simply solved for frequency, yielding:

$$f = \frac{v}{\lambda} = \frac{3 \times 10^8 \text{ m/s}}{800 \times 10^{-9} \text{ m}} = \underline{\underline{3.75 \times 10^{14} \text{ Hz}}} = \underline{\underline{375 \text{ THz}}}$$

This frequency agrees with the the data of Figure 18-3. Notice that the visible light spectrum is but a narrow sliver of the available light frequencies!

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### How Light Waves Propagate

Light tends to move in a straight line unless something interferes with it, changing the direction of motion. There are three ways that a light wave can be made to alter its course. These are *reflection*, *diffraction*, and *refraction*, as shown in Figure 18-4.

### Reflection

Reflection is the most intuitive of the propagation modes; when an electromagnetic wave (light or a radio signal) strikes a conductive surface, it bounces off the surface. Good conductors of electricity make good reflectors; poor conductors make poor reflectors. *To make a good optical reflector requires a polished conductive surface.* You'll notice that there is no metal in the optical fiber of Figure 18-1. The reason for this is that fiber optics do not rely on reflection.

### Diffraction

You've observed *diffraction* many times. Suppose there is one room in your house with the light on, and the door to that room is partially open. The door causes a shadow, but the edges of the shadow are not perfectly sharp. This is caused by the diffraction of light at the edge of the door. It is explained by Huygen's principle, which states that each point on a (radio or light) wavefront can be considered to be a tiny point source of energy, or isotropic radiator. Huygen's principle says that electromagnetic energy doesn't "like" to be confined to a narrow edge (where one side has energy, and the other does not). Some of the wave energy diffuses over to the "dark" side, partially blurring the shadow. Diffraction is not normally a desirable property in a fiber optic system. Light wave signals that undergo diffraction become slightly blurred or distorted, which limits bandwidth (and also drastically reduces the received energy at the fiber optic receiver).

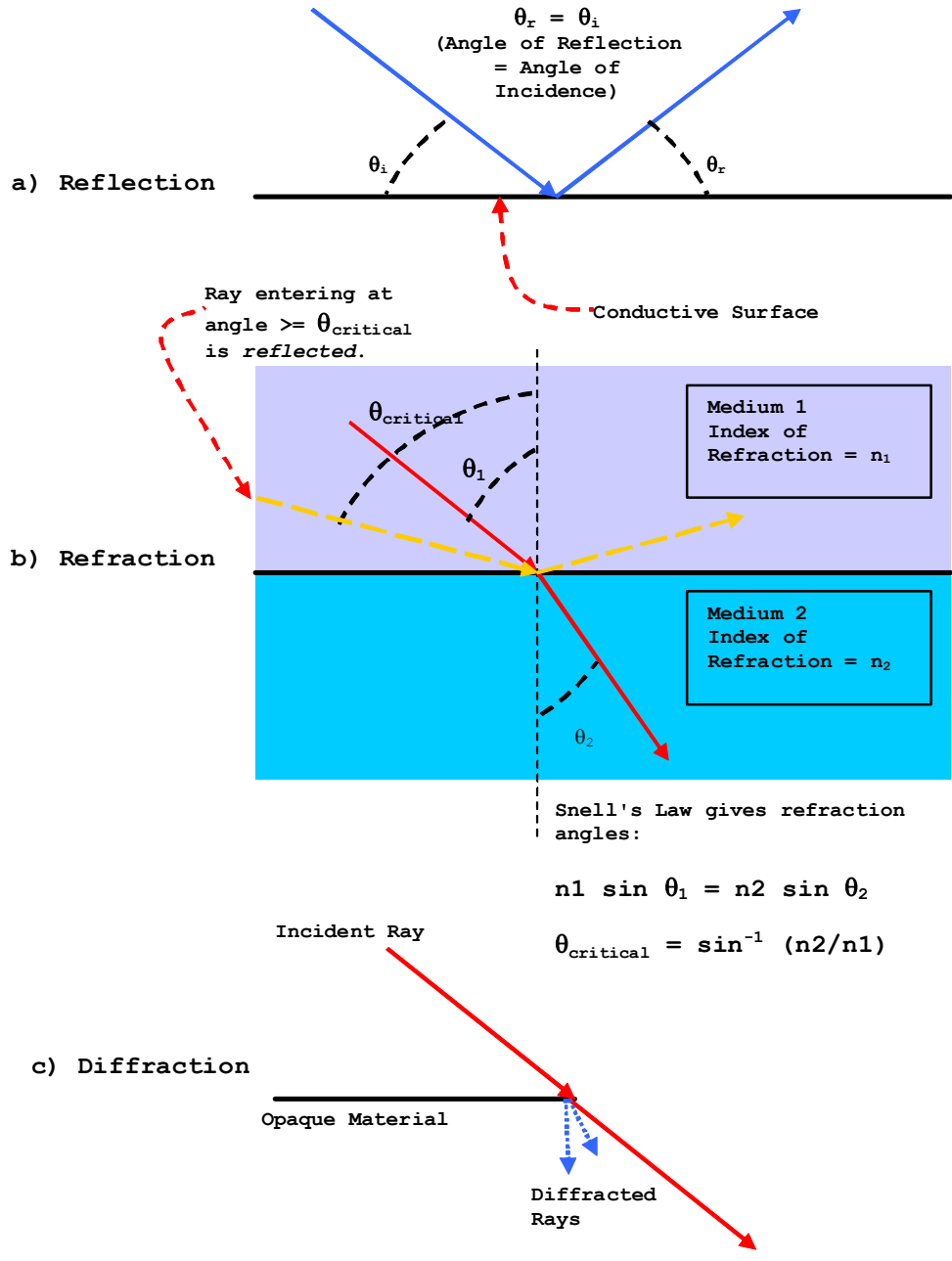


Figure 18-4: Reflection, Refraction, and Diffraction

**Refraction -  
The Mode of  
Fiber Optic  
Transmission**

Fiber optics rely on the mechanism of refraction for conducting light waves down the core. The basic need in all fiber optic cables is to keep all the light within the fiber core so that maximum signal will be transferred to the other end. We could accomplish this by surrounding the fiber optic core with a tube of shiny metal (such as polished foil). However, in doing this, we are now relying upon *reflection* of the light to keep it within the core. That is not a very efficient propagation mode, because good reflection requires a metal conductor "mirror" with very low electrical resistance. Our fiber would now be experiencing losses similar to the  $I^2R$  losses in a copper transmission line!

However, by using refraction, we can eliminate the need for a metal reflector and still keep most of the signal within the fiber. *Refraction is the bending of a light wave.* When a

wave travels from one material into another (such as from air into water), it is *bent* or *refracted*. The index of refraction for each material, and the original angle of the incoming wave (ray) determines the amount of bending and the new angle of travel in the second material. The *index of refraction* of a material is defined as the ratio of the speed of light in free space to the speed of light within the material. It is usually symbolized by the letter  $n$  in an equation:

$$(18-2) \quad n = \frac{c}{v}$$

where  $n$  is the index of refraction of the material,  $v$  is the velocity (speed) of light within the material, and  $c$  is the speed of light in free space ( $3 \times 10^8$  m/s). Figure 18-5 gives the indices of refraction for various materials.

Material	Index of Refraction
Vacuum (Free Space)	1.0
Air	1.0003
Water	1.33
Fused Quartz, $\text{SiO}_2$	1.46
Glass	1.5
Diamond	2.5

Figure 18-5: Indices of Refraction for Selected Materials

## Example 18-2

Calculate the velocity of propagation and wavelength of a ray of green light as it passes through diamond.

### Solution

The velocity of propagation can be calculated by rearranging equation 18-2 since we know that the index of refraction for diamond is 2.5 (from Figure 18-5):

$$v = \frac{c}{n} = \frac{3 \times 10^8 \text{ m/s}}{2.5} = \underline{1.2 \times 10^8 \text{ m/s}}$$

After calculating the velocity of the waves, the wavelength can be calculated. To find wavelength, we must also know the frequency of the light. The frequency can be calculated by solving equation 18-1 for *frequency*, and substituting the free-space values for the speed of light ( $c$ ) and wavelength ( $\lambda$ ):

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/s}}{550 \text{ nm}} = 5.4545 \times 10^{14} \text{ Hz}$$

The wavelength of the light within the material can now be calculated:

$$\lambda = \frac{v}{f} = \frac{1.2 \times 10^8 \text{ m/s}}{5.4545 \times 10^{14} \text{ Hz}} = \underline{220 \text{ nm}}$$

Note that the wavelength got *smaller* as the wave passed through the diamond, but the frequency remained constant. In fact, the two equations above can be combined into one simpler relationship:

$$(18-3) \quad \lambda = \frac{\lambda_{fs}}{n}$$

The above equation tells us that we can find the wavelength of a signal within a material with a refractive index of  $n$  by dividing its free-space wavelength ( $\lambda_{fs}$ ) by the refractive index of the material. Applying equation (18-3) gives:

$$\lambda = \frac{\lambda_{fs}}{n} = \frac{550nm}{2.5} = \underline{\underline{220nm}}$$

That is certainly much simpler, but what does this calculation mean? It simply reminds us that the wavelength of a signal depends on both its frequency and the material it happens to be passing through. Electromagnetic waves (both radio and light waves) always slow down when they enter any material except a perfect vacuum.

### Light Wave Propagation in Fiber

Figure 18-6 shows that *two* optical materials are used in a fiber optic cable, the *core* and the *cladding*. These two materials have slightly different indices of refraction. The cladding always has a slightly lower index of refraction than the core. Because of this, when light enters the fiber core at an appropriate angle, it is refracted back towards the center of the core when it tries to escape through the cladding. The light wave experiences *apparent* total internal reflection. We say *apparent*, because the wave is *bent* or *refracted*, not *reflected* at the junction of the core and cladding.

For the light rays to stay within the fiber of Figure 18-6, they must approach the wall of the cladding at an angle *at least* that equal to the *critical angle* for the core-cladding junction. This angle can be calculated using Snell's law; by substituting a value of 90 degrees for  $\Theta_2$ , we get the following relationship:

$$(18-4) \quad \Theta_{crit} = \sin^{-1} \frac{n_2}{n_1}$$

where  $\sin^{-1}$  is the *arcsine* or inverse sine function,  $n_1$  is the index of refraction for the core, and  $n_2$  is the index for the cladding material. Figure 18-7 shows what happens when the light rays approach the cladding of the fiber at various angles.

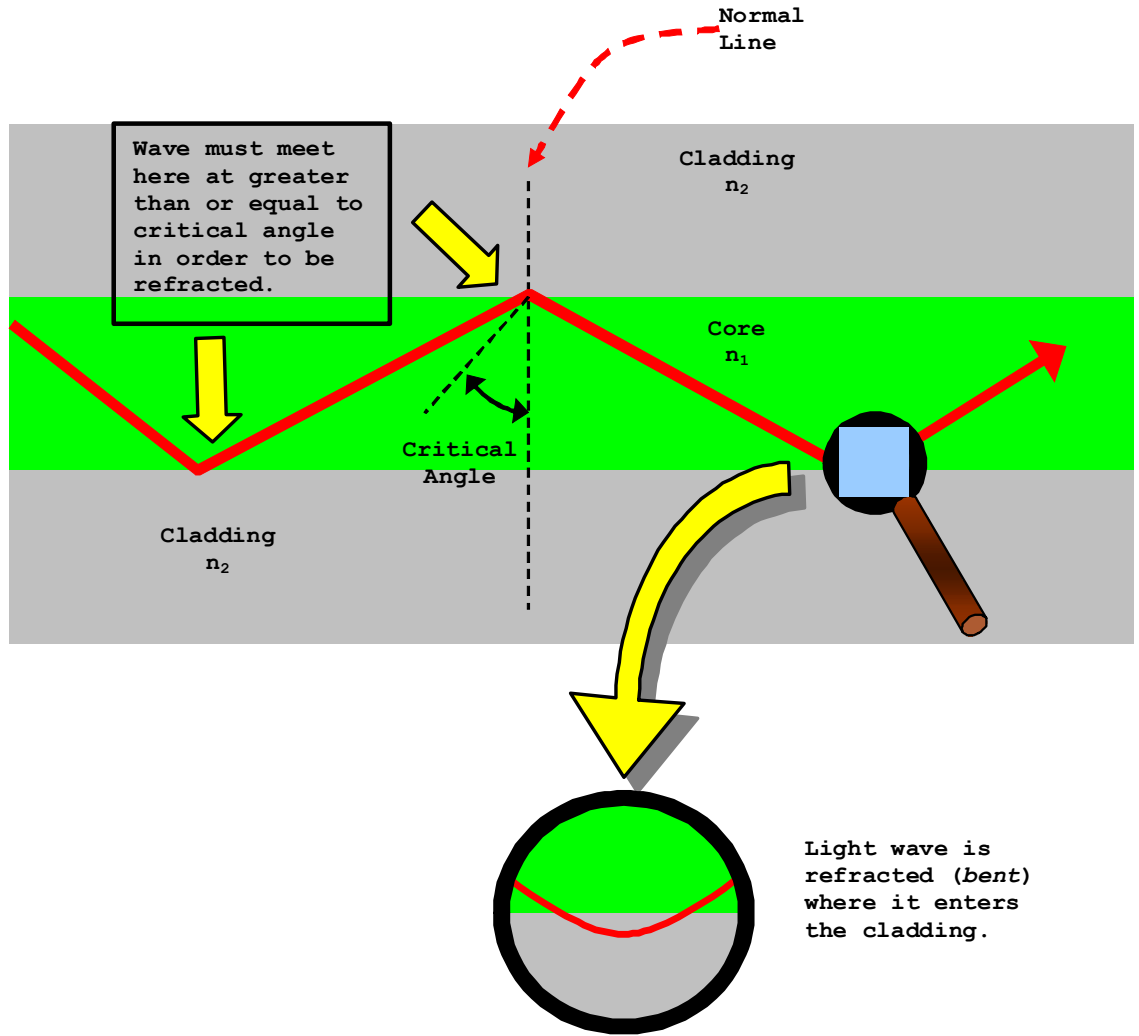


Figure 18-6: Fiber Optic Core and Cladding



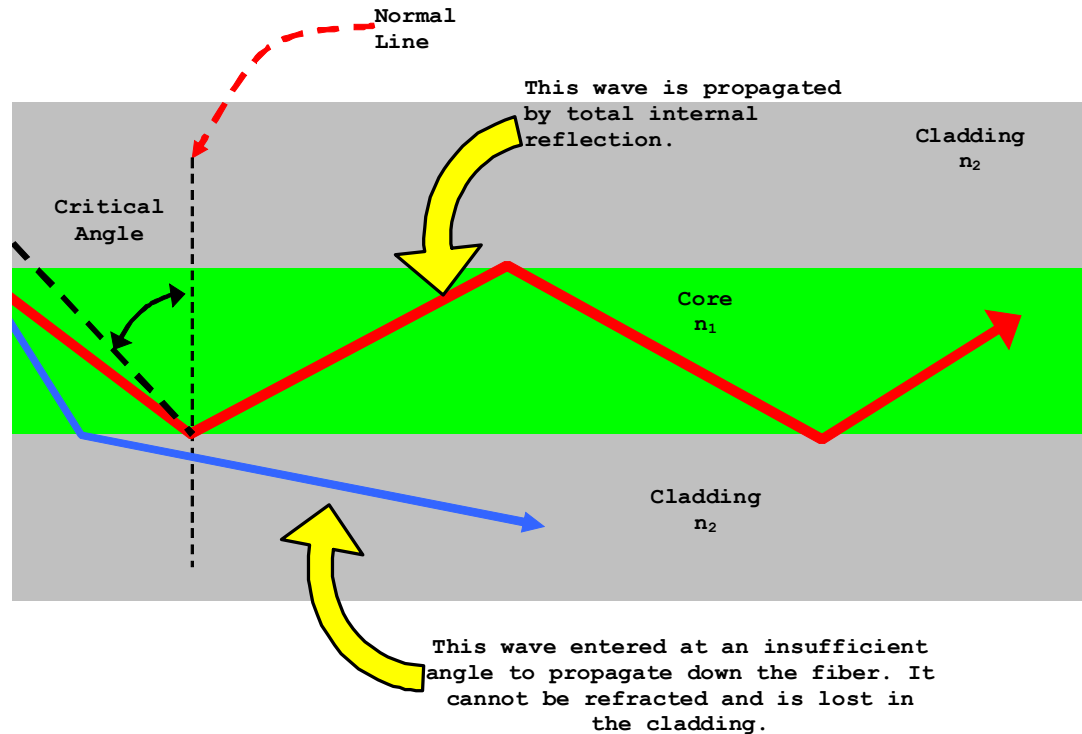


Figure 18-7: Not all Waves can be Refracted

In the figure, some of the light rays are escaping into the cladding instead of propagating down the core. This is because they are approaching the cladding at too narrow an angle to be refracted. These light rays will be lost; they will be absorbed and lost within the cladding rather than moving down the fiber core.

### Example 18-3

Suppose that the core material in Figure 18-7 is glass, and the cladding material is a plastic with a refractive index of 1.35. What is the critical angle within the fiber?

*Solution*

The refractive index of glass is 1.5, as given in Figure 18-5. Equation 18-4 calculates the critical angle:

$$\Theta_{crit} = \sin^{-1} \frac{n_2}{n_1} = \sin^{-1} \frac{1.35}{1.5} = \underline{\underline{64.2^\circ}}$$

Be careful when you perform this calculation. Your calculator must be set to deliver answers in *degrees*. The light rays in our fiber cable must angled at least 64.2 degrees from the normal line, or they simply won't propagate.

## Numerical Aperture and Acceptance Cone

By knowing the indices of refraction of the core and cladding materials, we can calculate two important properties of a fiber optic cable. These are the *numerical aperture* and *acceptance cone angle*.

The numerical aperture is a dimensionless number that tells us how well a fiber can collect light at its end (where a light source would be coupled). It is calculated as follows:

$$(18-5) \quad NA = \sqrt{n_1^2 - n_2^2}$$

where  $n_1$  is the index of refraction for the fiber core, and  $n_2$  is the index for the cladding material.

The greater the value for numerical aperture, the easier it is for light to get into the fiber. The maximum possible value for NA approaches a value of 1. It might sound like the highest possible NA would be desirable, but this is not always the case. A high value of numerical aperture allows many *propagation modes* to coexist within the fiber. This leads to pulse spreading or *dispersion*, which reduces the available bandwidth. We will study dispersion shortly.

Figure 18-8 shows the *acceptance cone* of a fiber. The acceptance cone is the total angular range of light rays that the fiber can accept and propagate. The calculated *acceptance cone angle* usually gives half of this range.

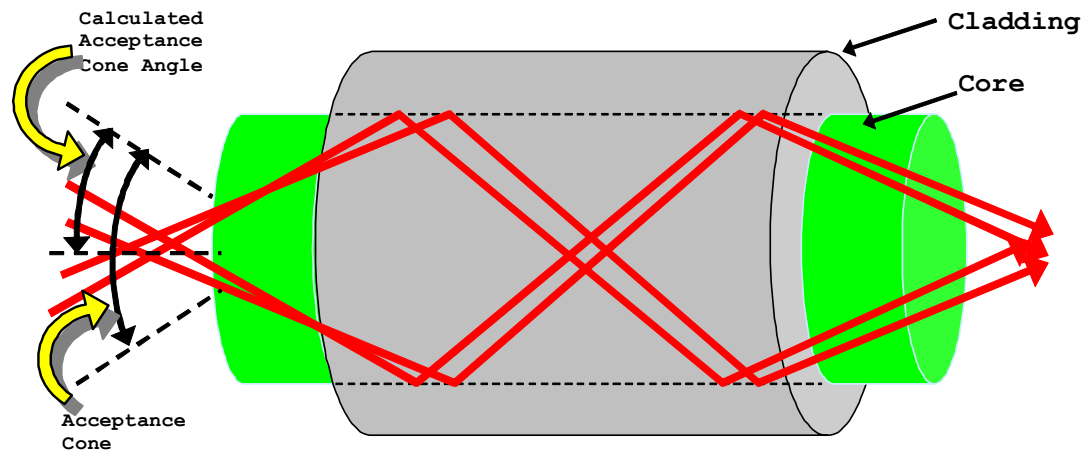


Figure 18-8: Acceptance Cone

The acceptance cone angle can be directly calculated from the numerical aperture:

$$(18-6) \quad \Theta_{accept} = \sin^{-1} NA$$

Where  $\Theta_{accept}$  is the acceptance cone angle (half of the range of the actual acceptance cone), and  $NA$  is the numerical aperture of the fiber.

## Example 18-4

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Calculate the numerical aperture (NA) and acceptance cone angle for a fiber with a glass core ( $n_1=1.5$ ) and a plastic cladding ( $n_2=1.35$ ).

*Solution*

The numerical aperture is calculated according to Equation 18-5:

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.5^2 - 1.35^2} = \underline{\underline{0.654}}$$

The acceptance cone can be directly calculated from this result using Equation 18-6:

$$\Theta_{\text{accept}} = \sin^{-1} NA = \sin^{-1} 0.654 = \underline{\underline{40.83^\circ}}$$

The total angular range over which the fiber can accept incoming light rays (at least when they're coupled from air to the fiber core) is *twice* the acceptance cone angle, or about 81.66 degrees.

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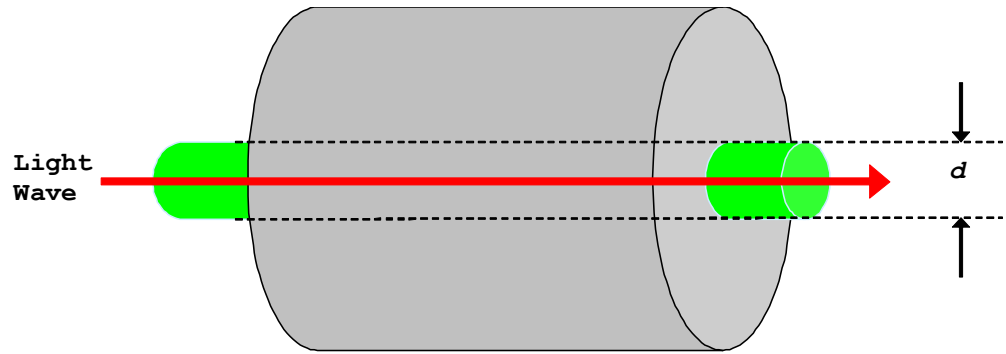
## Section Checkpoint

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- 18-1 List several advantages of fiber optics when compared to copper.
  - 18-2 List the three parts of a fiber optic cable, explaining the purpose of each one.
  - 18-3 What is the difference between light and radio wave energy?
  - 18-4 Why do most fiber optic systems use infrared light?
  - 18-5 What are the three ways that a light wave can change direction?
  - 18-6 What propagation mechanism keeps light waves inside a fiber optic core?
  - 18-7 Explain the meaning of the *index of refraction* for an optical material.
  - 18-8 Describe what happens to the wavelength of light as it passes from free space into a material such as glass.
  - 18-9 What is the significance of the *critical angle* for light wave propagation in fiber?
  - 18-10 What property of a fiber is described by its numerical aperture (NA)?
  - 18-11 How are the numerical aperture and acceptance cone angle related?
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## 18-2 Propagation Modes and Dispersion

Light waves can move down optical fibers in many different ways. A *propagation mode* is one particular type of light wave path in a fiber. In general, propagation can be classified as either *single-mode* or *multimode*. The design of the fiber controls the type of propagation that is possible. Figure 18-9 shows light wave movement in a single-mode fiber.



To support single-mode propagation, the fiber diameter  $d$  must be less than approximately 2 wavelengths of the light frequency to be propagated.  $d < 2\lambda$

Figure 18-9: Light Waves in a Single Mode Fiber

Single-mode propagation is the simplest possible: The light wave travels straight through (or very nearly so) the fiber from end to end. Because all the light rays arrive in step with each other in a single-mode fiber, very little distortion of the signal occurs. However, single-mode fiber must have a *very* small core diameter, usually less than 10  $\mu\text{m}$ . This small diameter is what restricts operation to a single mode; higher modes just won't fit! Because of the tiny core dimensions, it is more difficult to couple light efficiently into a single-mode fiber. The fiber of Figure 18-2 is a single mode unit.

**Multimode Propagation**

When the width of the fiber core is more than approximately two wavelengths of light, multiple propagation modes become available. These multiple propagation modes complicate the propagation picture, as shown in Figure 18-10.

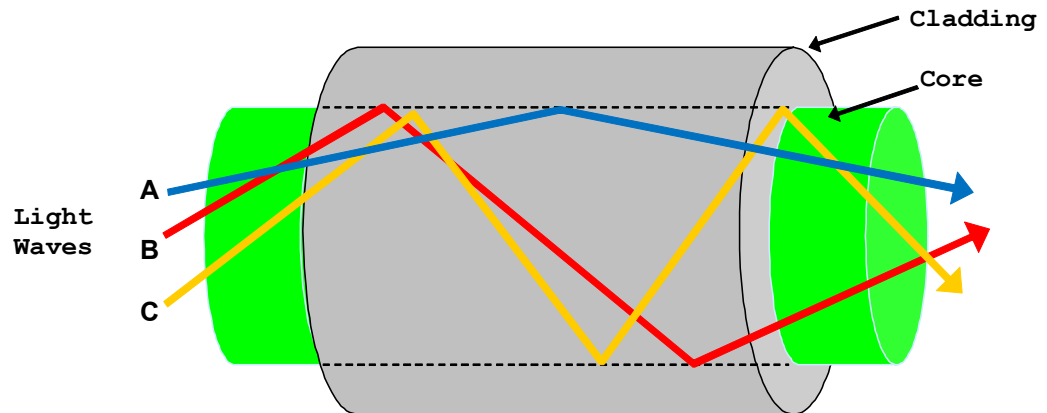


Figure 18-10: Multimode propagation

The problem with multimode propagation is that each of the light rays travels a slightly different distance as it moves through the fiber. In Figure 18-10, light ray A has the shortest path, and arrives first. Rays B and C are *higher-order modes*; they enter the fiber at steeper angles, and take longer to arrive, since they travel a much longer effective distance. All of the light waves do not arrive at the end at the same time! The distortion caused by this effect is called *modal dispersion*. Figure 18-11 shows what happens to the shape of a square pulse as it travels through a multimode fiber:

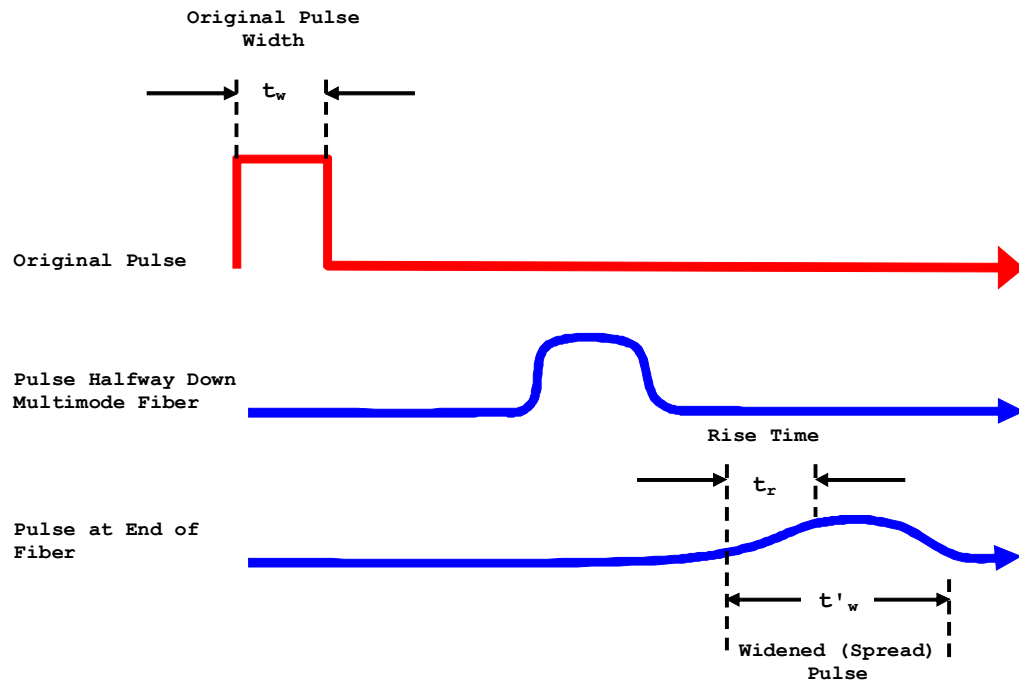


Figure 18-11: Pulse Effects in Multimode Propagation

Modal dispersion causes the edges of digital pulses to be rounded off. The longer the fiber, the worse the distortion becomes. In the figure, the nice square input pulse has already developed rounded edges halfway down the fiber. The dispersion only gets worse as the pulse makes its way to the receiving end. The timing differences between the various lightwave paths are magnified in proportion to the cable length. In this example, the pulse is hardly recognizable at the end; in fact, it appears to have a rise and fall shaped very much like it had passed through an RC low-pass filter circuit! *The widening effect on pulses is what limits the bandwidth of a multimode fiber.* In fact, we can estimate the bandwidth of such a fiber by using an equation from electronic fundamentals:

$$(18-7) \quad BW = \frac{0.35}{t_r}$$

where  $t_r$  is the rise time (10% to 90% electric field intensity) of the optical signal.

However, to use Equation 18-7, we need to know the rise time. For a multimode fiber, the rise time can be estimated as the difference in time between the arrival of the *first* photons of a light pulse, and the *last* photons of the same pulse. With trigonometry, we can derive the following relationship:

$$(18-8) \quad t_r \approx \Delta t \approx \frac{n_1 L}{c} \left( \frac{n_1}{n_2} - 1 \right)$$

where  $t_r$  is the effective rise time due to modal dispersion,  $n_1$  is the refractive index for the core,  $n_2$  is the cladding index,  $c$  is the speed of light, and  $L$  is the length of the fiber.

Equation 18-8 tells us two important things. First, it demonstrates that modal dispersion gets progressively worse as the length of a fiber,  $L$ , is increased. Second, it shows that the *ratio* of refractive indices for the core and cladding controls the amount of dispersion. The closer together the refractive indices, the less dispersion and the better the pulse shape will appear at the end of the fiber. However, equations 18-5 and 18-6 also tell us that as the refractive indices of the core and cladding get closer in value, the numerical aperture (NA) and acceptance cone of the fiber shrink, making it difficult to get light into the fiber.

## Example 18-5

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Compare the acceptance cone angle and dispersion-limited bandwidth for two different optical fibers. Both fibers are 1 km long. Fiber "A" has a core with a refractive index of 1.6 and cladding with an index of 1.3. Fiber "B" has core and cladding indices of 1.6 and 1.5, respectively.

*Solution*

Fiber A:

The numerical aperture must first be calculated according to Equation 18-5:

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.6^2 - 1.3^2} = 0.933$$

The acceptance cone can be directly calculated from this result using Equation 18-6:

$$\Theta_{accept} = \sin^{-1} NA = \sin^{-1} 0.933 = \underline{\underline{68.87^\circ}}$$

The amount of modal dispersion can be calculated with Equation 18-8:

$$t_r \approx \Delta t \approx \frac{n_1 L}{c} \left( \frac{n_1}{n_2} - 1 \right) = \frac{(1.6)(1000m)}{3 \times 10^8 m/s} \left( \frac{1.6}{1.3} - 1 \right) = 1.23 \mu s$$

Knowing this, we can now use equation 18-7 to estimate the bandwidth:

$$BW = \frac{0.35}{t_r} = \frac{0.35}{1.23 \mu s} = \underline{\underline{284.4 kHz}}$$

Fiber B:

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.6^2 - 1.5^2} = 0.557$$

The acceptance cone is:

$$\Theta_{accept} = \sin^{-1} NA = \sin^{-1} 0.557 = \underline{\underline{33.83^\circ}}$$

The amount of modal dispersion is:

$$t_r \approx \Delta t \approx \frac{n_1 L}{c} \left( \frac{n_1}{n_2} - 1 \right) = \frac{(1.6)(1000m)}{3 \times 10^8 m/s} \left( \frac{1.6}{1.5} - 1 \right) = 0.35 \mu s$$

The resulting bandwidth is:

$$BW = \frac{0.35}{t_r} = \frac{0.35}{0.35 \mu s} = \underline{\underline{984.4 kHz}}$$

What conclusion can be reached from this example? Fiber *B* certainly has a much better bandwidth. Fiber *B* produces less modal dispersion. However, its acceptance cone is not as wide as fiber *A*. Choosing the "best" combination of materials for these fiber optic cables is a trade-off. Improving bandwidth by limiting dispersion makes the acceptance cone smaller, which makes it harder to couple light into the fiber.

**Improving the Performance of Multimode Fibers**

The dispersion problem with multimode fibers arises because of the difference in time between the various possible light wave paths. *Graded-index fibers* are one solution to the dispersion problem. A graded-index fiber has a special core with a *graded* or *changing* index of refraction, as shown in Figure 18-12.

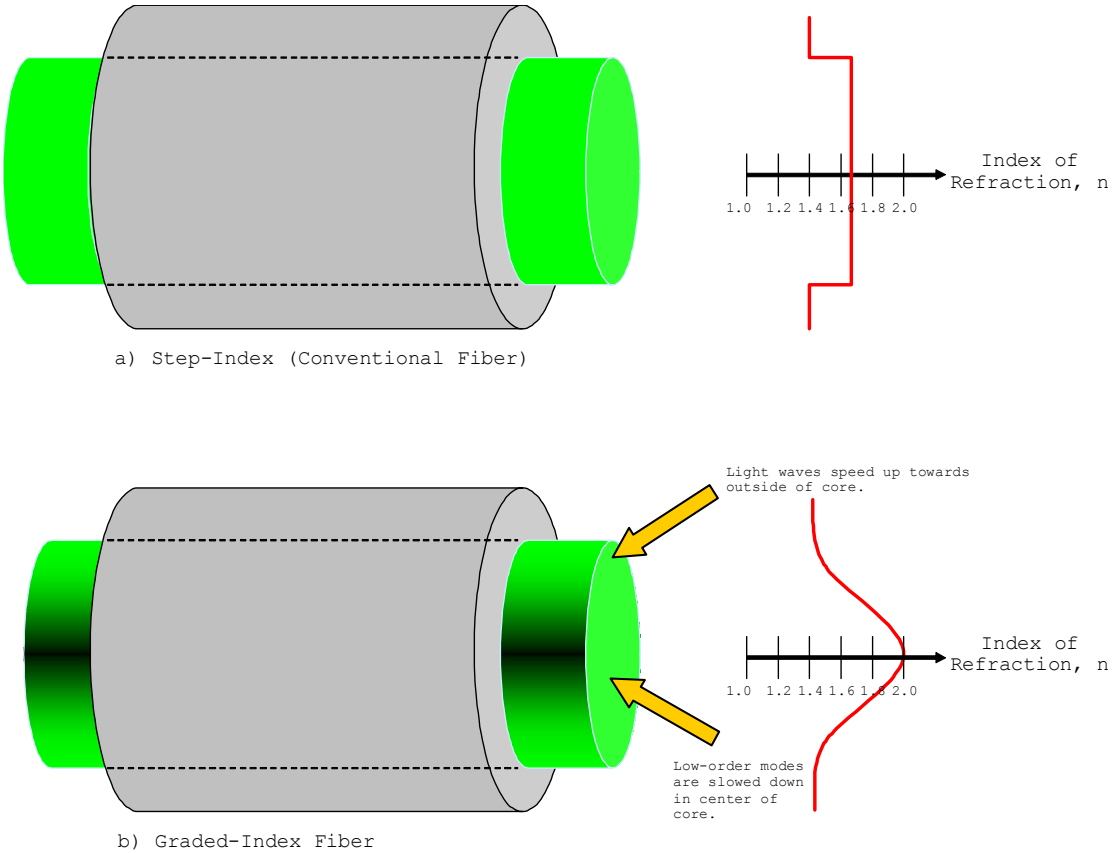


Figure 18-12: Step Index and Graded Index Fibers

The basic idea behind the graded-index fiber is as follows: In the higher order propagation modes, light waves travel back and forth between the walls of the core more than in low-order modes (those that travel approximately straight through the fiber). *Therefore, to equalize the time taken by each different mode, the lower-order modes must be slowed down in order for the waves from the high-order modes to "catch up."*

We know that the index of refraction of a material controls the velocity of wave propagation within it. In a step-index fiber, the velocity of propagation is constant throughout the core. In a graded-index fiber, the center of the core is designed with a higher index of refraction than the outer edges. Therefore, light waves slow down if they pass through the center, and speed up as they approach the edge.

The graphs to the right of the fibers in Figure 18-12 show the profile of refractive index for the fiber cores. The graded-index fiber generally uses a *parabolic* profile; you can see that the shape does look somewhat like a parabola.

*The main idea to remember is that graded index fibers control dispersion by slowing down waves near the center of the core in order to allow the higher-order waves to arrive at the same time.*

### Other Dispersion Modes

There are two other forms of optical distortion that can take place as a light wave passes down a fiber. These are *chromatic dispersion* (sometimes called *material dispersion*) and *waveguide dispersion*. While modal dispersion affects only multimode fibers, these two dispersion sources affect both single-mode and multimode fibers.

### Chromatic Dispersion

The index of refraction for most materials is not a constant. Instead, it depends slightly on the applied frequency (or wavelength). A prism separates white light into colors according to this principle, as shown in Figure 18-13.

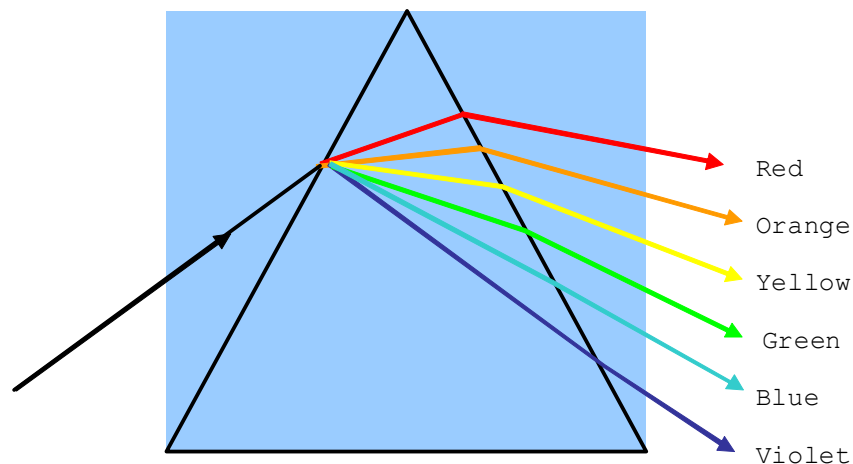


Figure 18-13: A Prism Separating Light Frequencies

A prism separates the colors of light because the refractive index of the prism material (glass or plastic) varies with frequency. Therefore, each color is refracted (bent) a different amount, and exits at a different angle.

*Chromatic dispersion will be present whenever the light source illuminating the fiber possesses more than one frequency of light.* No light source is perfect. For example, even though an LED may appear to emit only one color of light, it is actually radiating thousands of different wavelengths (all of which are close together in frequency). Because the velocity of propagation will be different for each of the light frequencies emitted by the LED (because the index of refraction depends on frequency), all of the light wave components will not reach the receiver at the same time, resulting in the same type of