CHAPTER

5

Properties of Optical Fibers

About This Chapter

Now that you have learned about the basic designs of optical fibers, the next step is to understand the properties of fibers important for light transmission. I have already touched upon many properties in Chapter 4; this chapter examines them more thoroughly.

The most important properties for communications are attenuation, light collection and propagation, fiber dispersion, and mechanical strength. Nonlinear effects can be important in some cases, particularly for sensing and high-performance systems. I will start with the property usually at the top of the list—attenuation.

Fiber Attenuation

The attenuation of an optical fiber measures the amount of light lost between input and output. Total attenuation is the sum of all losses. It is dominated by imperfect light coupling into the fiber and absorption and scattering within the fiber. Sometimes other effects can cause important losses, such as light leakage from fibers that suffer severe microbending. Attenuation limits how far a signal can travel through a fiber before it becomes too weak to detect.

Absorption and scattering are both cumulative, with their effects increasing with fiber length. In contrast, coupling losses occur only at the ends of the fiber. The longer the fiber, the more important are absorption and scattering losses, and the less important coupling losses. Conversely, attenuation and scattering may be much smaller than end losses for short fibers.

Loss during fiber transmission is the sum of scattering, absorption, and light-coupling losses.

To briefly review these losses, when you deliver an input power, P_0, to a fiber, a fraction of that light, ΔP, is lost. Thus only the power $P_0 - \Delta P$ gets into the fiber. This light then suffers absorption and scattering loss in the bulk of the fiber. As you learned in Chapter 2, these losses depend on length. If the light lost to absorption per unit length is α and the light lost to scattering per unit length is S, the fraction of light that remains is $(1 - \alpha - S)$. Outside the research laboratory, the quantity that matters is the attenuation per unit length, which is the sum of the absorption and scattering $(\alpha + S)$.

Recall that to calculate the power remaining after a distance D, you raise the fraction of light remaining after attenuation to the power D. This gives a formula for power at a distance D

$$P(D) = (P_0 - \Delta P)(1 - [\alpha + S])^D$$

That formula is more useful for looking at the process of light loss than for calculations. It reminds us that absorption and scattering combine to make attenuation. It also reminds us that attenuation acts only on light that gets into the fiber, because some light is lost on entry.

Now let's look at each of these components of loss.

Absorption

Absorption depends on wavelength and is cumulative with distance.

Every material absorbs some light energy. The amount of absorption depends on the wavelength and the material. A thin window of ordinary glass absorbs little visible light, so it looks transparent to the eye. The paper this book is printed on absorbs much more visible light, so it looks opaque. (You can read these words because the blank paper reflects more light than the ink, which absorbs most light striking it and reflects little.) The amount of absorption can vary greatly with wavelength. The clearest glass is quite opaque at an infrared wavelength of 10 μm. Air absorbs so strongly at short ultraviolet wavelengths that scientists call wavelengths shorter than about 0.2 μm the *vacuum ultraviolet* because only a vacuum transmits them.

Absorption depends very strongly on the composition of a substance. Some materials absorb light very strongly at wavelengths where others are quite transparent. For glass, this means that adding small amounts of certain impurities can dramatically increase absorption at wavelengths where glass is otherwise transparent. Removing such impurities is crucial for making the extremely transparent fibers used for communications. Typically, absorption is plotted as a function of wavelength. Some absorption peaks can look quite narrow because the material absorbs light in only a narrow range of wavelengths; others spread across a wider range.

Absorption is uniform. The same amount of the same material always absorbs the same fraction of light at the same wavelength. If you have three blocks of the same type of glass, each 1-centimeter thick, all three will absorb the same fraction of the light passing through them.

Absorption also is cumulative, so it depends on the total amount of material the light passes through. That means a material absorbs the same fraction of the light for each unit length. If the absorption is 1% per centimeter, it absorbs 1% of the light in the first centimeter, and 1% of the *remaining* light the next centimeter, and so on. If the only thing affecting light is absorption, the fraction of light absorbed per unit length is α, and the total length is D, the fraction of light remaining after a distance D is

$$(1 - \alpha)^D$$

In our example, this means that after passing through 1 m (100 cm) of glass, the fraction of light remaining would be

$$(1 - 0.01)^{100} = 0.366, \qquad \text{or } 36.6\%$$

Scattering

Atoms scatter a small fraction of passing light.

Atoms and other particles inevitably scatter some of the light that hits them. The light isn't absorbed, just sent in another direction in a process called *Rayleigh scattering*, after the British physicist Lord Rayleigh, as shown in Figure 5.1. However, the distinction between scattering and absorption doesn't matter much if you are trying to send light through a fiber, because the light is lost from the fiber in either case.

Like absorption, *scattering* is uniform and cumulative. The farther the light travels through a material, the more likely scattering is to occur. The relationship is the same as for light absorption, but the fraction of scattered light is written S.

$$\text{Remaining light} = (1 - S)^D$$

Scattering depends not on the specific type of material but on the size of the particles relative to the wavelength of light. The closer the wavelength is to the particle size, the more scattering. In fact, the amount of scattering increases quite rapidly as the wavelength λ decreases. For a transparent solid, the scattering loss in decibels per kilometer is given by

$$\text{Scattering} = A\lambda^{-4}$$

where A is a constant depending on the material. This means that dividing the wavelength by 2 multiplies scattering loss (in dB/km) by a factor of 16.

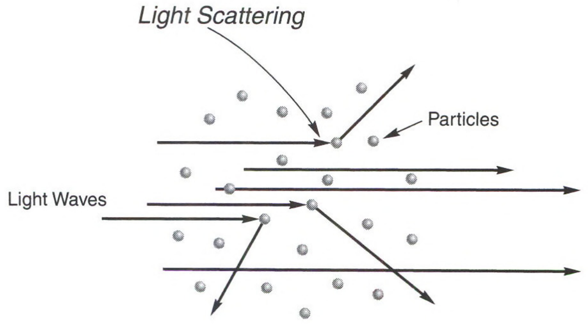


FIGURE 5.1
Rayleigh scattering of light.

Total Loss or Attenuation

Total attenuation, or loss, is the sum of scattering and attenuation; it is measured in decibels per kilometer.

Scattering and absorption combine to give total loss, or attenuation, which is the important number in communication systems. Figure 5.2 plots their contributions across the range of wavelengths used for communications. Attenuation normally is measured in decibels per kilometer for communication fibers. The plot shows small absorption peaks from traces of metal impurities remaining in the glass and other absorption arising from bonds that residual hydrogen atoms form with oxygen in the glass. (I picked this scale to emphasize the peaks, which look lower on other scales, and are smaller in many communications fibers.) The absorption at wavelengths longer than 1.6 μm comes from silicon-oxygen bonds in the glass; as the plot shows, the absorption increases rapidly at longer wavelengths. As a result, silica-based fibers are rarely used for communications at wavelengths longer than 1.62 μm.

Rayleigh scattering accounts for most attenuation at shorter wavelengths. As you can see in Figure 5.2, it increases sharply as wavelength decreases. The space between measured total attenuation and the theoretical scattering curve represents the absorption loss. The closer the two lines, the larger the fraction of total attenuation that arises from scattering. The rapid decrease in scattering at longer wavelengths makes loss lowest in the "valley" around 1.55 μm, where both Rayleigh scattering and infrared absorption are low. Except for the infrared absorption of silica, fiber loss would decrease even more at longer wavelengths.

Total attenuation is what matters for system performance.

The plot in Figure 5.2 compares theoretical scattering and the absorption of pure silica with attenuation measured across the spectrum. It is total attenuation that is important in fiber-optic communications, and that is what is generally measured. Absorption and scattering are hard to separate, and outside the laboratory there is little practical reason to bother. It's most useful to think of the power *(P)* at a distance D along the fiber as defined by

$$P(D) = (P_0 - \Delta P)(1 - A)^D$$

where A is attenuation per unit length, P_0 is initial power, and ΔP is the coupling loss, as before. In practice, it is simpler to make calculations if you first separate fiber attenuation from coupling losses by starting with the power that *enters* the fiber rather than the input power you *attempt* to couple into the fiber.

Calculating Attenuation in Decibels

Attenuation normally is calculated on the logarithmic decibel scale.

As we saw in Chapter 2, attenuation measures the ratio of output to input power: P_{out}/P_{in}. It normally is measured in decibels, as defined by the equation

$$\text{dB(attenuation)} = -10 \log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

Output power is less than input power, so the result would be a negative number if the equation didn't include a minus sign. You should remember that in some publications decibels are defined so that a negative number indicates loss.

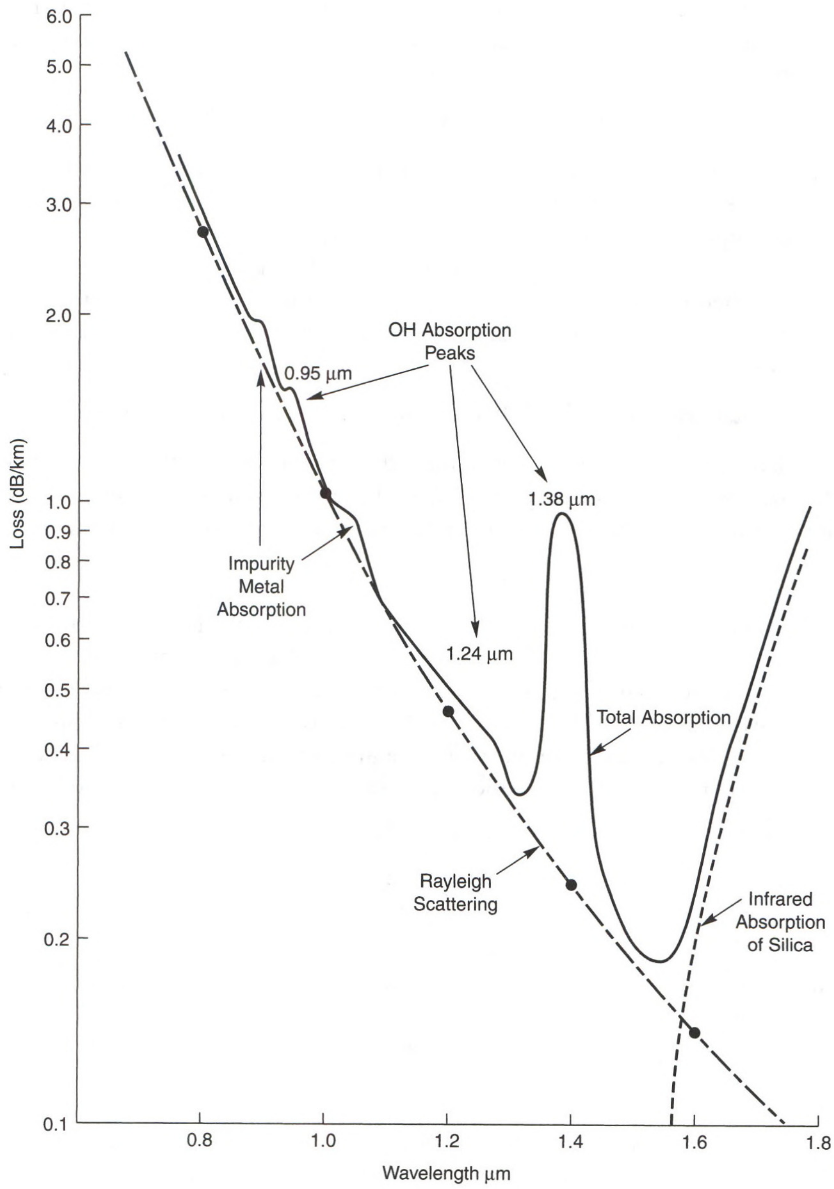


FIGURE 5.2
Total attenuation in a fiber is the sum of absorption and scattering losses.

The decibel scale simplifies calculations of power and attenuation.

Decibels may seem to be rather peculiar units, which appear to understate high attenuation. For example, a 3-dB loss leaves about half the original light, a 10-dB loss leaves 10%, and a 20-dB loss leaves 1%. The larger the number, the larger the apparent understatement. A 100-dB loss leaves only 10^{-10} of the original light, and a 1000-dB loss leaves 10^{-100}—a ratio smaller than one atom in the whole known universe. Appendix B translates some representative decibel measurements into ratios. You can also use the simple conversion

$$\text{Fraction of power remaining} = 10^{(-\text{dB}/10)}$$

Decibels are very convenient units for calculating signal power and attenuation. Suppose you want to calculate the effects of two successive attenuations. One blocks 80% of the input signal, and the second blocks 30%. To calculate total attenuation using fractions, you must convert both absorption figures to the fractions of power transmitted, then multiply them, and convert that number from the fraction of light transmitted to the fraction attenuated. If you use decibels, you merely add attenuations to get total loss.

$$\text{Total loss (dB)} = \text{loss (dB)}_1 + \text{loss (dB)}_2 + \text{loss (dB)}_3 + \cdots$$

The calculations are even simpler if you know the loss per unit length and want to know total loss of a longer (or shorter) piece of fiber. Instead of using the exponential formula mentioned previously, you simply multiply loss per unit length times the distance:

$$\text{Total loss} = \text{dB/km} \times \text{distance}$$

You can also measure power in decibels relative to some particular level. In fiber optics, the two most common decibel scales for power are decibels relative to 1 mW (*dBm*) and relative to 1 μW (*dB*μ). Powers above those levels have positive signs; those below have negative signs. Thus 10 mW is 10 dBm, and 0.1 mW is −10 dBm, or 100 dBμ.

If everything is in decibels, simple addition and subtraction suffice to calculate output power from input power and attenuation. You also can write the equation in other ways:

$$P_{\text{out}} = P_{\text{in}} - \text{loss (dB)}$$

$$\text{Loss (dB)} = P_{\text{in}} - P_{\text{out}}$$

$$P_{\text{in}} = P_{\text{out}} + \text{loss (dB)}$$

Note that it is vital to keep track of the plus and minus signs. In this case, we give loss in decibels a positive sign, as we did earlier. If you ever feel confused, you can do a simple truth test, by checking to see if the output power is less than the input. (The only way output can be more than input is if you have an optical amplifier or regenerator somewhere in the system.)

As an example of how the calculations work, consider a fiber system in which 3 dB is lost at the input end and that contains 6 km of fiber with loss of 0.5 dB/km. If the input power is 0 dBm (exactly 1 mW), the output is

$$P_{\text{out}} = 0 \text{ dBm} - 3 \text{ dB (input loss)} - (6 \text{ km} \times 0.5 \text{ dB/km}) = -6.0 \text{ dBm}$$

If you rewrite this as milliwatts, you have 0.25 mW.

Spectral Variation

As we saw before, fiber attenuation is the sum of absorption and scattering, both of which vary with wavelength. The spectral variation depends on the fiber composition. The attenuation curve in Figure 5.2 is fairly typical for single-mode communication fibers, except low-water types.

Attenuation varies with wavelength, depending on the material.

Most single-mode communication fibers are used at wavelengths between about 1280 and 1620 nm, where attenuation is generally below 0.5 dB/km except at the water peak where it may reach 1 dB/km. The traditional transmission bands in that region are at 1310 nm, and in the region from about 1530 to 1620 nm where erbium-doped fiber amplifiers are used. Fibers are available that have water content reduced to such low levels that the 1380-nm water peak almost vanishes, allowing them to be used across the entire 1280 to 1620-nm range.

Attenuation generally is higher in multimode fibers, with typical values about 2.5 dB/km at 850 nm, 0.8 dB/km at 1310 nm, and no more than 3 dB/km at the 1380 nm water peak. As can be seen from Figure 5.2, attenuation is not particularly low at 850 nm; the attraction of that wavelength is its match to the output of commercially available light sources.

Other materials are used in fibers to improve transmission at other wavelengths. Special grades of quartz are used for ultraviolet-transmitting fibers. Some plastics have relatively even transmission across the visible spectrum. *Fluoride* compounds are transparent at longer infrared wavelengths than silica glass. Chapter 6 will cover various materials in more detail.

Light Collection and Propagation

Several factors enter into how fibers collect light and propagate it. Most arise from the structure of fibers, described in Chapter 4. This section examines the impact of those considerations.

Core Size and Mode-Field Diameter

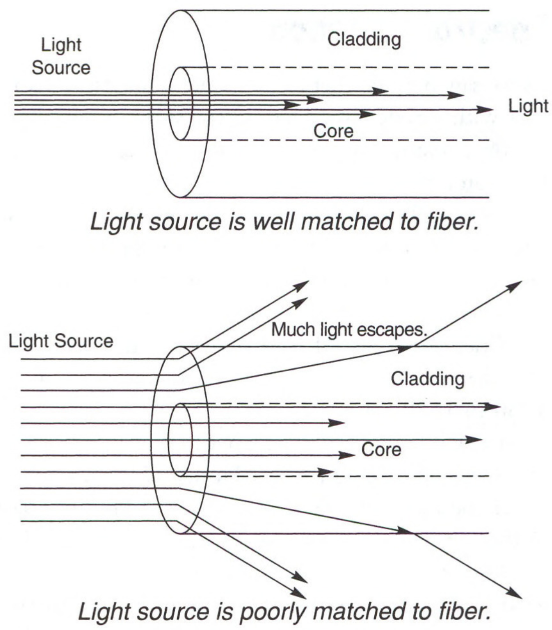
Core size is important in coupling light into a fiber. To collect light efficiently from a light source, the core should be at least as large as the source's emitting area. As shown in Figure 5.3, if the light source is larger than the core, much of its light goes into the cladding. Some of the light escapes quickly, whereas other light may be guided for a distance in the cladding, as if it were in a bare fiber. The larger the core size, the easier it is to align the fiber with the light source and the better the light coupling. Core size does not affect the acceptance angle, which is the range of angles over which a fiber collects light.

The larger the core diameter, the easier it is to align with a light source.

Core size is the physical dimension of the core, but light spreads through a slightly larger volume, including the inner edge of the cladding. This *mode-field diameter* or *effective area* is the critical dimension for light transfer between single-mode fibers. (The difference is not enough to matter in multimode fiber.)

Transferring light between fibers is the business of splices and connectors; details are covered in Chapter 13.

FIGURE 5.3
The match between light-source dimensions and core diameter helps determine light transfer.

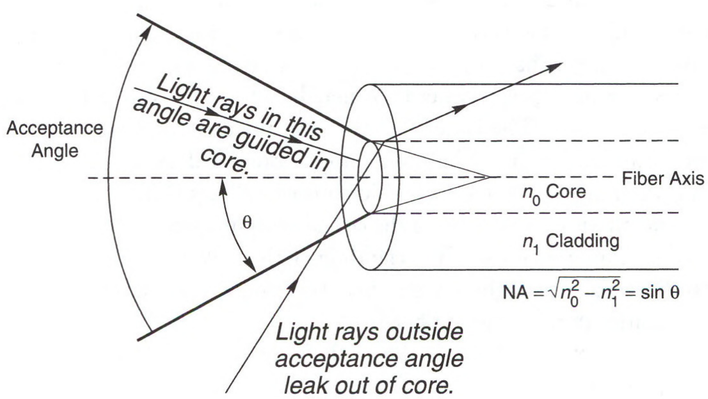


Numerical Aperture

Numerical aperture (NA) measures the fiber's acceptance angle.

A second factor in determining how much light a fiber collects is its acceptance angle, the range of angles over which a light ray can enter the fiber and be trapped in its core. The full-acceptance angle is the range of angles at which light is trapped; it extends both above and below the axis of the fiber. The half-acceptance angle is the angle measured from the fiber axis to the edge of the cone of light rays trapped in the core; it is shown in Figure 5.4.

FIGURE 5.4
Light rays have to fall within a fiber's acceptance angle, measured by NA, to be guided in the core.



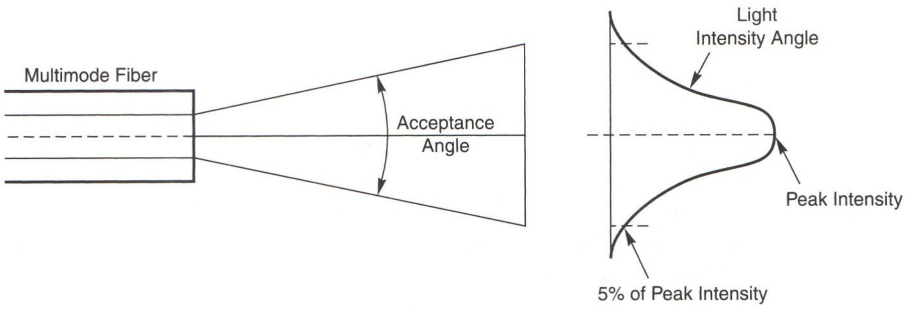


FIGURE 5.5
Intensity of light emerging from a multimode fiber falls to about 5% of peak value at the edge of its acceptance angle.

The standard measure of acceptance angle is the *numerical aperture*, NA, which is the sine of the half-acceptance angle, θ, for reasonably small angles. For a step-index fiber, it is defined as

$$\mathrm{NA} = \sqrt{(n_0^2 - n_1^2)} = \sin\theta$$

where n_0 is the core index and n_1 is the cladding index. A typical value for step-index single-mode fiber is around 0.14.

Numerical aperture is not calculated the same way in graded-index fibers; strictly speaking it varies across the core with the refractive index. However, you can measure numerical aperture by monitoring the divergence angle of light leaving a fiber core. As shown in Figure 5.5, the light emerging from a multimode fiber spreads over an angle equal to its acceptance angle. For practical measurements, care must be taken to eliminate modes guided in the cladding, and the *edge* of the beam is defined as the angle where intensity drops to 5% that in the center. NA can be calculated easily from the acceptance angle. Typical NA values are 0.20 for 50/125 graded-index fiber, and about 0.28 for 62.5/125 graded-index fiber.

Core diameter does not enter into the NA equation, but light rays must enter the core as well as fall within the acceptance angle to be guided in the core. Large core size and large NA do not have to go together, but in practice larger-core fibers tend to have larger core-cladding index differences and thus larger NAs. For example, step-index multimode fibers typically have NAs of at least 0.3, more than twice the value for single-mode step-index fibers.

The numerical aperture of single-mode fibers is defined by the same equation as for multimode fibers, but light does not spread out from them in the same way. (They carry only a single mode, and their cores are so small that another wave effect called *diffraction* controls how light spreads out from the end.) NA generally is not as important for single-mode fibers as it is for multimode fibers.

Cladding Modes and Leaky Modes

Light can be guided in cladding modes.

Light can enter the cladding either from a source at the end of the fiber or by escaping from the core when it hits the cladding boundary at an angle greater than the confinement angle. The resulting *cladding modes* can propagate in the cladding, guided by total internal reflection, if the material surrounding the core—air or a plastic coating—has a refractive index lower than that of the core. This phenomenon can introduce noise in communications fibers and crosstalk between fibers in an imaging bundle. To prevent this, manufacturers often coat fiber with a plastic that has a refractive index higher than that of the cladding, which prevents total internal reflection. (Light-absorbing materials generally have a high refractive index at wavelengths they absorb.) Fibers in rigid bundles may be separated by light-absorbing dark glass.

There is no sharp distinction between the highest-order modes guided in the core of a multimode fiber and the lowest-order modes that escape from the core. Modes in this hazy zone are called *leaky modes* because they are partly guided in the core, but escape into the cladding over longer distances. This makes them prone to leakage and loss.

Cladding and leaky modes must be removed to ensure accurate measurements. Devices called *mode strippers* surround a length of fiber with a high-index material that prevents total internal reflection at the outer edge of the cladding, removing these undesired modes. A long length of fiber with high attenuation in the cladding also can function as a mode stripper.

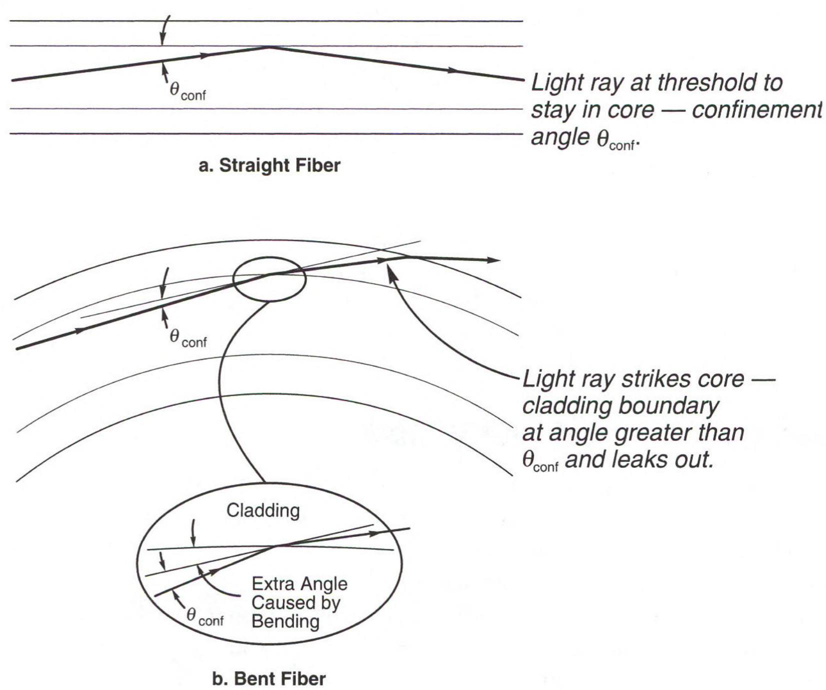
Bending Losses

Bends can cause excess fiber loss.

A variety of outside influences can change the physical characteristics of optical fibers, affecting how they guide light. Typically these effects are modest and must be enhanced or accumulated over long distances to make the kind of sensors described in Chapter 29. However, significant losses can arise if the fiber is bent so sharply that light strikes the core-cladding interface at a large enough angle that the light can leak out.

Bending loss is easiest to explain using the ray model of light in a multimode fiber. When the fiber is straight, light falls within its confinement angle. Bending the fiber changes the angle at which light hits the core-cladding boundary, as shown in Figure 5.6.

FIGURE 5.6
Light can leak out of a bent fiber.



If the bend is sharp enough, it hits the boundary at an angle outside the confinement angle θ_{conf}, and is refracted into the cladding where it can leak out.

Bend losses fall into two broad categories. *Macrobends* are single bends obvious to the eye, such as a fiber bent sharply where a cable ends at a connector. The case shown in Figure 5.6 is typical. *Microbends* are tiny kinks or ripples that can form along the length of fibers that become squeezed into too small a space. This can happen in a cable when the cabling material shrinks relative to the fiber, or the fiber stretches relative to the cable. Microbends are smaller, but they cause similar light leakage because they also affect the angle at which light hits the core-cladding boundary.

Dispersion

Dispersion is the spreading out of light pulses as they travel along a fiber. It occurs because the speed of light through a fiber depends on its wavelength and the propagation mode. The differences in speed are slight, but like attenuation, they accumulate with distance. The four main types of dispersion arise from multimode transmission, the dependence of refractive index on wavelength, variations in waveguide properties with wavelength, and transmission of two different polarizations of light through single-mode fiber.

The principal types of dispersion are modal, material, waveguide, and polarization.

Like attenuation, dispersion can limit the distance a signal can travel through an optical fiber, but it does so in a different way. Dispersion does not weaken a signal; it blurs it. If you send one pulse every nanosecond but the pulses spread to 10 ns at the end of the fiber, they blur together. The signal is present, but it's so blurred in time that it is unintelligible.

In its simplest sense, dispersion measures pulse spreading per unit distance in nanoseconds or picoseconds per kilometer. Total pulse spreading, Δt, is

$$\Delta t = \text{dispersion (ns/km)} \times \text{distance (km)}$$

This equation actually gives dispersion in two different forms. One is the unit or characteristic dispersion of the fiber, written as *dispersion* and measured per unit length (in units of time per kilometer). The other is the total pulse spreading in units of time over the entire length. As long as the same fiber is used throughout the cable, the total pulse spreading is simply the characteristic fiber dispersion times the fiber length. If different types of fibers are used, you need to calculate pulse spreading separately for each section, then add them.

The simple equation above holds for modal dispersion, which is the type most important for step-index multimode fibers, where modes travel at different speeds through the fiber. Graded-index fibers nominally equalize the speeds of all transmitted modes, but things don't work that perfectly in the real world. It's functionally impossible to achieve the ideal refractive-index profile needed to make all modes travel at exactly the same speed. That profile depends on wavelength, and fibers carry signals at a range of wavelengths. In practice, you have to rely on manufacturer specifications for the unit dispersion of graded-index fibers, typically specified in units of bandwidth (described below) rather than in time units.

Total pulse spreading is the square root of the sum of the squares of the pulse spreading from modal, chromatic, and polarization-mode dispersion.

Other types of dispersion also add to total pulse spreading. We'll get to them in a minute, but first let's look at how to calculate the total pulse spreading. Material and waveguide dispersion add together to give a wavelength-dependent *chromatic dispersion*, mentioned in Chapter 4. Fibers also experience polarization-mode dispersion. Both quantities are independent of each other and of modal dispersion. That means you have to take the square root of the sum of the squares to get total pulse spreading:

$$\Delta t_{\text{total}} = \sqrt{(\Delta t_{\text{modal}})^2 + (\Delta t_{\text{chromatic}})^2 + (\Delta t_{\text{polarization-mode}})^2}$$

Polarization-mode dispersion is small enough that it doesn't matter in multimode fibers, so for that case the equation becomes

$$\Delta t_{\text{total}} = \sqrt{(\Delta t_{\text{modal}})^2 + (\Delta t_{\text{chromatic}})^2}$$

Likewise, single-mode fibers have no modal dispersion (other than polarization-mode dispersion), so the equation becomes

$$\Delta t_{\text{total}} = \sqrt{(\Delta t_{\text{chromatic}})^2 + (\Delta t_{\text{polarization-mode}})^2}$$

Chromatic Dispersion and Wavelength

Chromatic dispersion depends on the range of wavelengths in the optical signal.

Chromatic dispersion is the pulse spreading that arises because the velocity of light through a fiber depends on its wavelength. It is measured in units of picoseconds (of pulse spreading) per nanometer (of spectral width of the optical signal) per kilometer (of fiber length). The total pulse spreading due to chromatic dispersion, $\Delta t_{\text{chromatic}}$, is calculated by multiplying the fiber's characteristic chromatic dispersion by the range of wavelengths generated by the light source ($\Delta\lambda$) and the fiber length:

$$\Delta t_{\text{chromatic}} = \text{chromatic dispersion (ps/nm-km)} \times \Delta\lambda \text{ (nm)} \times \text{fiber length (km)}$$

The characteristic chromatic dispersion of a fiber is a function of wavelength. It is normally the largest type of dispersion in single-mode fiber systems. As you learned in Chapter 4, chromatic dispersion is the sum of two components, material and waveguide dispersion, which can cancel each other at certain wavelengths. In standard step-index single-mode fiber, material and waveguide dispersion add to zero near 1310 nm. Dispersion shifting moves the zero-dispersion point to other wavelengths, generally longer. To understand chromatic dispersion, we need to look at both material and waveguide dispersion.

Material dispersion arises from variations in refractive index with wavelength.

Material dispersion arises from the change in a material's refractive index with wavelength. The higher the refractive index, the slower light travels. Thus as a pulse containing a range of wavelengths passes through a material, it stretches out, with the wavelengths with lower refractive index going faster than those with higher indexes. Like absorption, dispersion is a function of the individual material, which changes with wavelength. Communication fibers are nearly pure silica (SiO_2), so their characteristic material dispersion is essentially the same as that of pure fused silica. Figure 5.7 plots both refractive index and material dispersion of fused silica against wavelength.

Note that material dispersion has a positive or negative sign, unlike the modal dispersion. You can think of this sign as indicating how the refractive index is changing with wavelength, although that's an oversimplification. The physical meaning of the sign is a bit

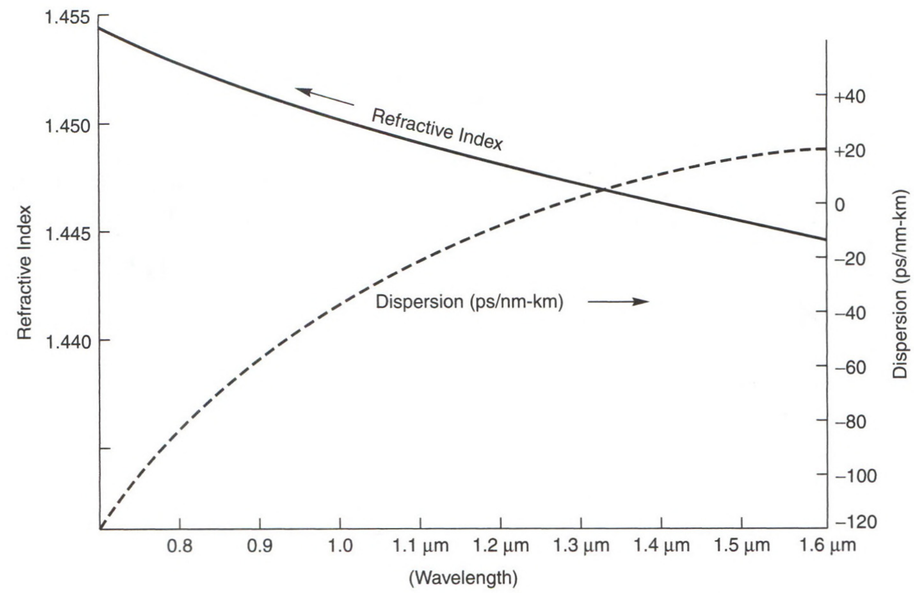


FIGURE 5.7
Material dispersion and refractive index of silica as a function of wavelength.

obscure, but the signs are important in combining material dispersion and waveguide dispersion to calculate total chromatic dispersion. Although chromatic dispersion also has a sign, the calculations for total pulse spreading cancel it out because the formula uses the square of the pulse spreading caused by chromatic dispersion.

As Figure 5.7 shows, the magnitude of material dispersion is large at wavelengths shorter than 1.1 μm. High material dispersion at 850 nm makes chromatic dispersion high at that wavelength, limiting the transmission speed possible even in single-mode fiber. The real benefits of single-mode transmission come from operating at longer wavelengths where the material dispersion is small.

Waveguide dispersion is a separate effect, arising from the distribution of light between core and cladding. Recall that waveguide properties are a function of the wavelength. This means that changing the wavelength affects how light is guided in a single-mode fiber. For a step-index single-mode fiber, the waveguide dispersion is relatively small, but can be important. More complex refractive index profiles can increase waveguide dispersion, such as the dispersion-compensating fiber in Figure 4.11(f). Like material dispersion, waveguide dispersion has a sign that indicates how changing wavelength affects dispersion.

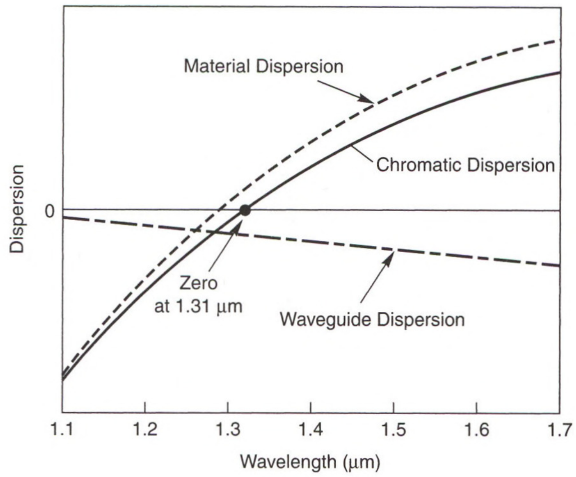
Waveguide dispersion arises from changes in light distribution between core and cladding.

For most practical purposes, chromatic dispersion is the sum of material and waveguide dispersion.

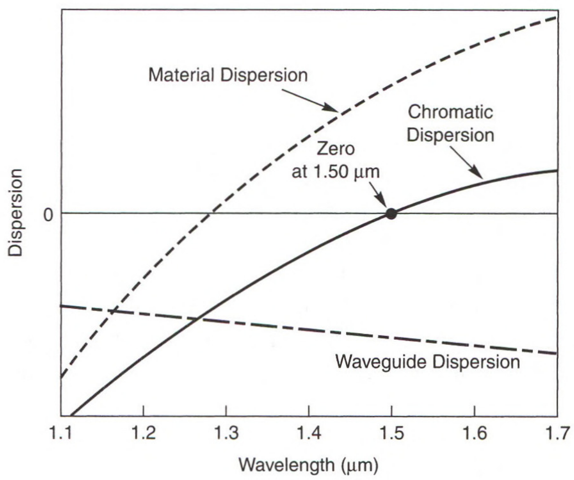
$$\mathrm{Disp}_{\mathrm{chromatic}} = \mathrm{Disp}_{\mathrm{material}} + \mathrm{Disp}_{\mathrm{waveguide}}$$

Remember that the signs are important. From a physical standpoint, what happens is that the variation with wavelength caused by waveguide dispersion can offset (or add to) that caused by material dispersion. Dispersion shifting is done by designing fibers to have large negative waveguide dispersion, which offsets positive material dispersion at wavelengths longer than 1.28 μm, shifting the region of low chromatic dispersion near the erbium-fiber

FIGURE 5.8
Different amounts of waveguide dispersion combine with material dispersion to produce different chromatic dispersion.



ITU G.652
Step-Index Single-Mode Fiber: Adding waveguide dispersion shifts zero chromatic dispersion to 1.31 μm.



ITU G.655
Nonzero Dispersion-Shifted Fiber: Larger waveguide dispersion shifts zero chromatic dispersion to 1.50 μm.

amplifier band. As mentioned earlier, generally the zero-dispersion wavelength is chosen to be a little longer or shorter than the 1530- to 1620-nm erbium-fiber band. Figure 5.8 shows how waveguide and material dispersion combine for step-index single-mode fiber and one type of nonzero dispersion-shifted fiber.

A Closer Look at Chromatic Dispersion

The descriptions of material, waveguide, and chromatic dispersion have been a bit vague because the formal definitions depend on some concepts that require a bit of extra work, a few equations, and a dash of calculus to understand. To delve more deeply, let's consider the case of material dispersion, which is the simplest because it depends only on how the refractive index of the material varies with wavelength. (Chromatic and waveguide dispersion work similarly, but the details are more complex.)

Recall that the velocity of light passing through a material depends on its refractive index. Since the refractive index varies with wavelength, so does the velocity of light in the material. Suppose that the material has a refractive index n_1 at wavelength λ_1 and an index n_2 at wavelength λ_2. The time each wavelength takes to pass through a length of glass L is

$$t = \frac{Ln}{c}$$

If you calculate the difference between the transit times at the two wavelengths, you get what is called the *group delay time,*

$$\text{Group delay} = t_1 - t_2 = \frac{Ln_1}{c} - \frac{Ln_2}{c} = \frac{L}{c}(n_1 - n_2)$$

which measures the difference in travel time for the two wavelengths. This is the same as the pulse spreading through a fiber denoted by Δt.

From a physical standpoint, the group delay is the slope of the curve that plots refractive index as a function of wavelength, shown in Figure 5.9(a) on a different scale that shows its curvature better than Figure 5.7. If you know elementary calculus, that slope is the first derivative of how refractive index n varies with wavelength:

Group delay is the slope of the plot of refractive index versus wavelength.

$$\text{Group delay} = \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right) = \Delta t$$

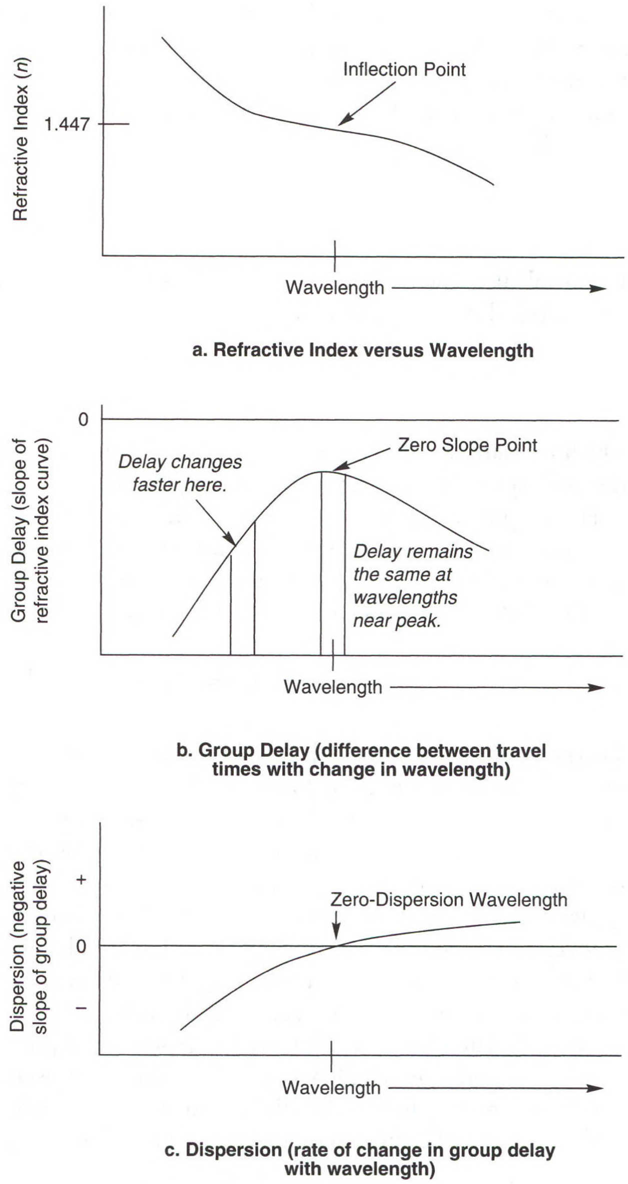
This group delay is plotted in Figure 5.9(b). You can think of group delay time as the actual pulse spreading Δt—measured in units of time—caused by the change in refractive index over a range of wavelengths. Remember, however, that this is a time delay, *not* the characteristic material dispersion of the fiber. Characteristic dispersion measures not the *magnitude* of the delay in units of time, but how fast the group delay is *changing* with wavelength (generally for a unit length of the fiber rather than for the entire length). This *characteristic material dispersion* is measured in units of picoseconds (of time) per nanometer (of wavelength range) per kilometer (of fiber length). Multiply it by the length of the fiber and the range of wavelengths, and you get the group delay Δt.

You calculate characteristic material dispersion D_{material} as the rate of change of the group delay with wavelength, which is equivalent to measuring the slope of the group delay curve with respect to wavelength. If you divide through by fiber length, and take the differential rate of change in group delay with wavelength, you get

$$D_{\text{material}} = \frac{1}{L} \times \left(\frac{d\,(\text{group delay})}{d\lambda}\right) = \frac{-\lambda}{c} \times \frac{d^2n}{d\lambda^2}$$

This is the characteristic material dispersion, plotted in Figure 5.9(c), and it represents the slope of the group delay curve. To see what it means graphically, compare it with the plot of group delay in Figure 5.9(b). The group delay is nearly constant at its peak value, so the values are virtually the same at the two wavelengths near the peak (vertical lines). However, at shorter wavelengths the group delay is changing much faster, so the values differ much more at two wavelengths the same distance apart (vertical lines at the left).

FIGURE 5.9
Material dispersion is the slope of the slope (or the second derivative) of a plot of refractive index versus wavelength.



You can calculate the total pulse spreading over the length of the fiber, Δt, by multiplying this characteristic dispersion by fiber length L and wavelength range $\Delta\lambda$. This gives:

$$\Delta t = D_{\text{material}} \times L \times \Delta\lambda = \frac{-L\lambda\Delta\lambda}{c} \times \frac{d^2 n}{d\lambda^2}$$

Thus the characteristic material dispersion is proportional to the *second derivative* (or, equivalently, to the slope of the slope) of the plot of refractive index versus wavelength, not directly to the slope of the refractive index curve itself. To reiterate, it's also the slope of the group delay, which measures the travel time through the fiber as a function of wavelength. The *slope* of the group delay curve, in contrast, measures how *fast* the group delay changes with wavelength, which is the characteristic material dispersion. This rate of change of group delay is zero at the peak of the group delay curve, which comes at 1.28 μm in silica fibers. This also is the point where the slope of the refractive-index curve stops decreasing with increasing wavelength and starts increasing again. (Because the refractive index decreases as wavelength increases, the slope is a negative number, plotted below zero on Figure 5.9(b).) Mathematically, the zero material-dispersion wavelength is a maximum of the group velocity curve and a point of inflection in the refractive-index plot.

Dispersion is the slope of group delay, or the second derivative of the plot of refractive index versus wavelength.

Figure 5.9(c) plots characteristic material dispersion. Recall that the formula carries a negative sign, which it gets from the negative value of group delay. The minus sign means that characteristic material dispersion is negative at wavelengths where the group delay curve is rising (i.e., has positive slope), and positive where the middle curve is dropping (i.e., has negative slope).

The components of waveguide dispersion work in a similar way, but the physical relationships are more complex. As you saw earlier, waveguide dispersion has a sign, which matters when adding it to material dispersion to get chromatic dispersion, the number given in product specifications. The sign also matters when compensating for chromatic dispersion to reduce pulse spreading. Chromatic dispersion works like material dispersion; it measures the rate of change of the group delay for all chromatic dispersion, not just for material dispersion.

The signs don't matter when combining the effects of chromatic dispersion with other dispersion, because the pulse spreading enters those equations as squares. As you've probably learned the hard way, it's easy to lose track of signs that don't have an obvious physical meaning. This can happen very easily with material, waveguide, and chromatic dispersion, so don't be surprised if you spot the wrong signs. In normal single-mode fibers, the dispersion should be negative at wavelengths shorter than the zero-dispersion wavelength, and positive at longer wavelengths.

Dispersion Slope and Specifications

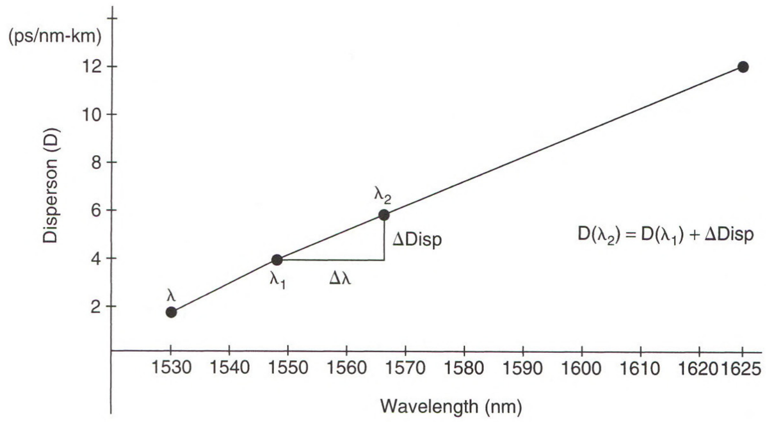
In practice, engineers approximate chromatic dispersion by assuming it varies linearly over a defined limited range of wavelengths. That is, they plot dispersion at a pair of wavelengths, draw a straight line between them, and assume that the dispersion at intermediate wavelengths falls between them, as shown in Figure 5.10. If the two wavelengths are λ_1 and λ_2, and the characteristic chromatic dispersions at those wavelengths are $D(\lambda_1)$ and $D(\lambda_2)$, this means that dispersion $D_{\text{chromatic}}$ at intermediate wavelength λ is

$$D_{\text{chromatic}}(\lambda) = \left(\frac{D(\lambda_2) - D(\lambda_1)}{\lambda_2 - \lambda_1} \times (\lambda - \lambda_2)\right) + D(\lambda_2)$$

Specification sheets often give these equations with the ranges of dispersion and wavelength for which they are valid. Typically there are separate equations for the 1530- to 1565-nm range of C-band erbium-doped fiber amplifiers and the 1565- to 1625-nm L-band.

Look closely at the equation, and you can see that it actually multiplies the *dispersion slope* (change in dispersion over a range of wavelength) by the change in wavelength from

FIGURE 5.10
Extrapolating fiber dispersion at an intermediate wavelength.



Dispersion slope gives change in dispersion over a range of wavelengths.

one endpoint, and adds the dispersion at that endpoint. Thus the equation translates in more descriptive terms to

$$D_{\text{chromatic}}(\lambda) = [(\text{dispersion slope}) \times (\Delta\lambda)] + D(\text{ endpoint})$$

Remember this is the slope of *chromatic* dispersion, although the normal term is just "dispersion slope."

Dispersion slope tells how dispersion changes with wavelength. Normally this change is very small over the range of wavelengths generated by a single laser transmitter. However, it is important in wavelength-division multiplexed systems, which carry many optical channels spanning tens of nanometers in wavelength. We will take a closer look later in this chapter.

Specification sheets typically do *not* plot chromatic dispersion directly as a function of wavelength, but give the chromatic dispersion that may be found at a range of wavelengths, such as 2.6 to 6.0 ps/nm-km at 1530 to 1565 nm. These numbers do not mean that the fibers have 2.6 ps/nm-km dispersion at 1530 nm and 6.0 ps/nm-km at 1565—they mean that the values in this range of wavelengths fall within this "box." As with other specified values, they allow for a range of manufacturing tolerances, so the specified dispersion slope will not always match the slope calculated from the extremes of chromatic dispersion and wavelength.

Source Bandwidth and Chromatic Dispersion

Unlike the pulse spreading caused by other types of fiber dispersion, the spreading caused by chromatic dispersion depends strongly on the light source. If we take $D_{\text{chromatic}}(\lambda)$ as the characteristic dispersion of a unit length (1 km) of fiber, the total pulse spreading from chromatic dispersion $\Delta t_{\text{chromatic}}$ is

$$\Delta t_{\text{chromatic}} = D_{\text{chromatic}}(\lambda) \times \Delta\lambda \times \text{Length}$$

where Δλ is the range of wavelengths in the optical signal in nanometers and *Length* is the fiber length in kilometers. This means that the spectral bandwidth of the light source is a parameter that system designers can adjust to limit the effects of chromatic dispersion. The higher the data rate, the more important narrow-band sources become, as you will learn in later chapters.

Chromatic Dispersion Compensation and Tailoring

We saw earlier that pulse dispersion is cumulative, building up along the length of a fiber system. In general, this means that adding more fiber only makes pulse dispersion worse. However, it is possible to reduce total *chromatic* dispersion by adding a length of fiber with chromatic dispersion of the opposite sign. For example, you could add a length of fiber with negative chromatic dispersion at 1550 nm to a system containing fiber with positive dispersion in that band. The idea is similar to using waveguide dispersion to offset material dispersion, but in this case the compensation is done by splicing together two fibers with different chromatic dispersion, as shown in Figure 5.11. The dispersion-compensating fiber could be added in a length of cable, but it's often installed in modular form in an equipment rack near a receiver or optical amplifier. In long-distance systems, lengths of the two types of fiber alternate, so chromatic dispersion does not build up to excessive levels before being reduced.

Combining fibers with chromatic dispersion of opposite signs can compensate for chromatic dispersion, yielding low overall pulse spreading.

A typical dispersion-compensating fiber has high negative waveguide dispersion that gives it a negative chromatic dispersion that typically is several times the magnitude of the positive chromatic dispersion of the transmission fiber. Thus compensation requires a shorter length of the dispersion-compensating fiber. That is important because compensating fiber typically has higher attenuation than transmission fibers. Compensating fiber also usually has a small effective area, making it more vulnerable to nonlinear effects, so it is used at the receiving end of the system, where lower power reduces nonlinear effects.

Typically, dispersion is compensated over a range of wavelengths, but it's easiest to calculate requirements if you look just at one wavelength. Suppose you want to have total chromatic dispersion of +2 ps/nm-km at the 1530-nm short end of the erbium-fiber band over a 1000-km system. You are using nonzero dispersion-shifted transmission fiber with

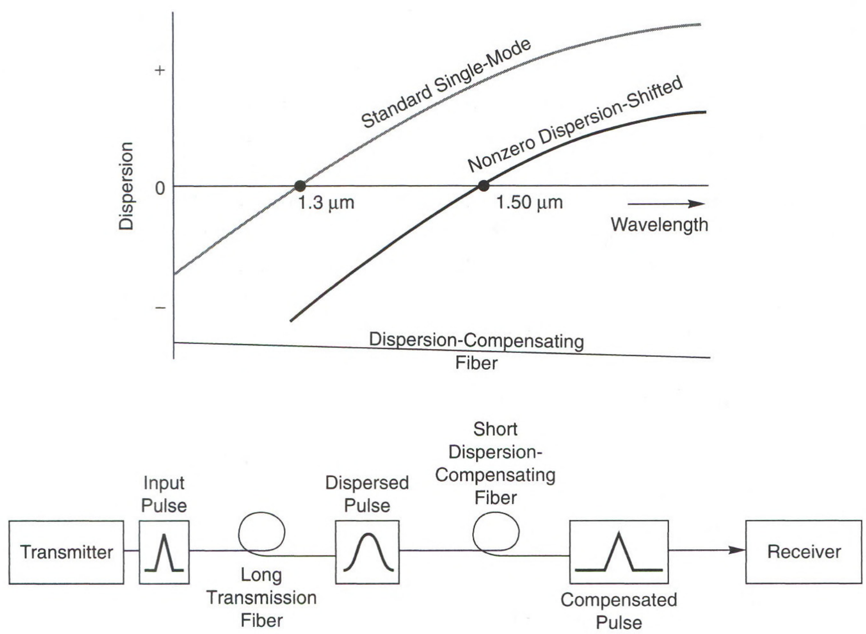


FIGURE 5.11
Dispersion compensation.

dispersion of $+8$ ps/nm-km at that wavelength, and you can buy dispersion-compensating fiber with dispersion of -100 ps/nm-km at 1530 nm. You can use the general formula

$$D_{net} L_{total} = D_{transmission} L_{transmission} + D_{comp} L_{comp}$$

where D_{net} is the net dispersion for the entire system, L_{total} is the total length (assuming the compensating fiber is part of the transmission path), $D_{transmission}$ and $L_{transmission}$ are the dispersion and length of the transmission fiber, and D_{comp} and L_{comp} are dispersion and length of the compensating fiber. Plug the numbers in, and you see

$$2000 \text{ ps/ns} = +8\ L_{transmission} - 100\ L_{comp}$$

Since you know that $L_{transmission} + L_{comp} = 1000$ km, you can work out that you need 944 km of nonzero dispersion-shifted transmission fiber and 56 km of compensating fiber. Thus you need about 1 km of compensating fiber for every 17 km of transmission fiber.

You can use the same ideas to calculate the dispersion compensation needed for upgrading existing fiber systems. Other approaches to chromatic dispersion also are possible. One example is an optical delay line that would delay signals a certain amount depending on their wavelength, so the slower signals could catch up. A dispersion-compensating fiber in a box could serve as such a delay line.

Multiwavelength Transmission and Dispersion

WDM transmission requires dispersion compensation over a range of wavelengths.

Dealing with chromatic dispersion is more complex in systems that carry multiple wavelengths. Wavelength-division multiplexing requires management of chromatic dispersion over the entire range of wavelengths that are transmitting optical channels. Typically that can span tens of nanometers in systems with fiber amplifiers, 35 nm in systems with *C-band* erbium-fiber amplifiers, 55 nm in systems with *L-band* erbium-fiber amplifiers, or 95 nm in systems with both.

That range of wavelength is large enough for chromatic dispersion to differ significantly among optical channels. Just in the erbium-fiber C-band, the difference can accumulate to 2 ps/nm-km with reduced-dispersion-slope (0.045 ps/nm^2-km) fibers, and to 4 ps/nm-km with other nonzero dispersion-shifted fibers. This becomes important because it means different optical channels may require different amounts of dispersion compensation.

Dispersion management also becomes more complex as the range of wavelengths increases. The dispersion slopes of dispersion-compensating fibers do not match and offset those of transmission fibers, so residual differences remain. These accumulate over distance and can become significant for long-distance, high-speed systems. Additional components or a mix of dispersion-compensating and transmission fibers may be needed.

Polarization-Mode Dispersion

Fibers have low levels of birefringence that affect light in the two polarization modes differently.

In Chapter 4, you learned that a single-mode fiber actually transmits light in two distinct polarization modes. The electric fields of the two modes are perpendicular to each other, or *orthogonal* in the jargon of physics. Normally the two behave just the same in the fiber, so from a physical standpoint they are called *degenerate*, which means they can't be distinguished.

The existence of two polarization modes wouldn't matter if optical fiber and all the forces applied to it were perfectly symmetrical. However, nothing is perfect. Stresses within the fiber and forces applied to it from the outside world cause slight differences in the refractive index experienced by light in the two polarization modes. This effect is called *birefringence.*

Internal stresses make some crystals strongly birefringent. In calcite the refractive index differs more than 10% for the two polarization axes, which makes objects seen through a calcite prism look double-exposed. Manufacturing stresses produce only a tiny difference—around one part in 10 million (10^{-7})—in optical fibers, but that tiny effect can become significant when very fast pulses go through long lengths of fiber. If that birefringence was uniform along the length of the fiber, light in the faster polarization mode would travel about one wavelength farther ahead of the slower mode every 10 meters, as shown in Figure 5.12. However, the effect is not that simple because the difference—called *differential group delay*—fluctuates in a seemingly random manner, producing *polarization-mode dispersion* (PMD).

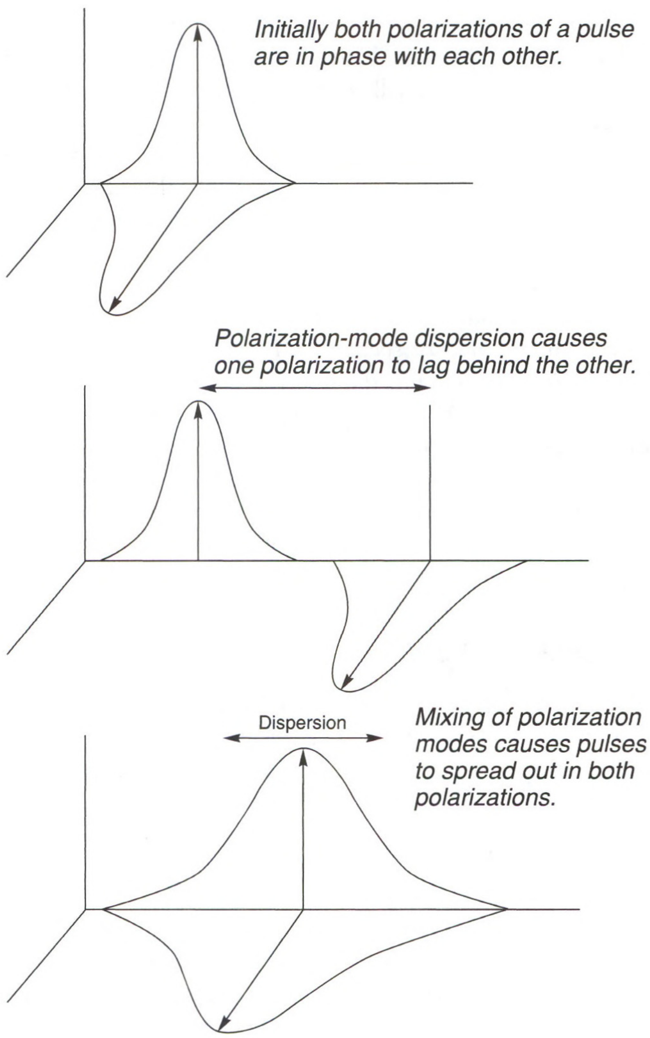


FIGURE 5.12
Polarization-mode dispersion.

Pulse spreading due to PMD varies statistically over time.

The effects that cause differential group delay are basically random background effects. Minor fluctuations in manufacturing processes generate very-low-level stresses that vary along the length of the fiber. The environmental stresses on fibers change continually, with such factors as temperature, wind loading, and low-level vibrations. Thus the differential group delay varies with time all along the length of the fiber, like a low-level background noise. In addition, light can shift randomly between polarization modes in normal single-mode fibers. Thus differential group delay, $\Delta\tau_{DGD}$, does not accumulate consistently along the fiber, but on average grows larger with distance, as shown at the bottom of Figure 5.12. The increase in the average value is proportional to the square root of fiber length L times a characteristic polarization-mode dispersion for the fiber D_{PMD}.

$$\Delta t_{\mathrm{DGD}} = D_{\mathrm{PMD}} \times \sqrt{\text{fiber length}}$$

The instantaneous differential group delay is what matters for signal transmission, and this quantity varies statistically around the average value. When it exceeds the allowable value for the system, it can cause transmission errors. Usually these errors appear as a brief series of incorrect bits in a random outage.

Typical values of polarization-mode dispersion for installed fiber are 0.05 to 1 picosecond per root kilometer. Fiber now in production has characteristic PMD values below 0.1 ps/km$^{-1/2}$, but cabling and installation can change that value. Environmental conditions also can change the value. For example, winds blowing on overhead cables can raise the instantaneous values of characteristic PMD to more than 1 ps/km$^{-1/2}$.

The potential effects of polarization-mode dispersion were not considered significant until several years ago, so manufacturers did not specify PMD values for earlier fibers. Because cabling and installation also are important, the best way to be sure of PMD in installed fibers is to measure them in place. Other components also exhibit polarization-mode dispersion, which must be considered in budgeting for overall system PMD.

Polarization-mode dispersion is less of a problem than chromatic dispersion, and PMD compensation technology is still in the early stages of development. In practice, PMD is not significant at data rates of 2.5 Gbit/s or less. But careful control is required for long-distance transmission at higher speeds.

Dispersion and Transmission Speeds

So far we have considered the effects of dispersion on instantaneous pulses, but real pulses are not instantaneous. In digital systems, the initial pulse starts with a duration $\Delta t_{\mathrm{input}}$, then experiences spreading due to dispersion of $\Delta t_{\mathrm{dispersion}}$. The output pulse length is not the direct sum of the two pulse durations but the square root of the sum of their squares:

$$\Delta t_{\mathrm{output}} = \sqrt{\Delta t_{\mathrm{input}}^2 + \Delta t_{\mathrm{dispersion}}^2}$$

This gives the pulse width at the end of the system, and it is these pulses that have to be resolved for the system to operate properly.

Dispersion limits maximum data rate.

The degree of overlap at which *pulse dispersion* causes problems in digital systems depends on the design. One rough guideline for estimating the maximum bit rate is that the interval between pulses should be four times the dispersion, or, equivalently,

$$\text{Maximum bit rate} = \frac{1}{4\,\Delta t_{\text{dispersion}}}$$

Thus, if pulses experience about 1 ns of dispersion, the maximum bit rate is about 250 Mbit/s. It isn't quite this simple in practice because performance depends on other factors as well as dispersion, but it's a useful guideline. For polarization-mode dispersion the usual guideline is more stringent, that the dispersed pulse should be no more than 1/10th as long as the interval between pulses, to allow a safety margin for brief periods of more pulse spreading. Note that these figures consider only dispersion, not the input pulse length, jitter, or receiver rise time. Different guidelines relate total system rise time to maximum bit rate, which depend on data transmission format.

Dispersion also affects analog transmission in roughly the same way that it limits bit rates in digital systems. Instead of lengthening digital pulses, dispersion smears out the whole analog waveform, effectively attenuating the highest frequencies in the signal. This limits the analog bandwidth, the frequency at which the detectable signal has dropped 3 dB (50%) compared to lower frequencies.

Transmission capacities of graded-index and step-index multimode fiber often are specified in terms of bandwidth, typically megahertz-kilometers, rather than as dispersion. You can roughly convert that to total system response time Δt_{total} using the formula

$$\text{Bandwidth (MHz)} = \frac{350}{\Delta t_{\text{total}}}$$

Nonlinear Effects

Normally light waves or photons transmitted through a fiber have little interaction with each other, and are not changed by their passage through the fiber (except for absorption and scattering). However, there are exceptions arising from the interactions between light waves and the material transmitting them, which can affect optical signals. These processes generally are called *nonlinear effects* because their strength typically depends on the square (or some higher power) of intensity rather than simply on the amount of light present. This means that nonlinear effects are weak at low powers, but can become much stronger when light reaches high intensities. This can occur either when the power is increased, or when it is concentrated in a small area—such as the core of an optical fiber.

Nonlinear effects are interactions between light waves, which can cause noise and crosstalk.

Nonlinear optical devices have become common in some optical applications, such as to convert the output of lasers to shorter wavelengths by doubling the frequency (which halves the wavelength). Most nonlinear devices use exotic materials not present in fiber-optic systems in which nonlinear effects are much stronger than in glass. The nonlinearities in optical fibers are small, but they accumulate as light passes through many kilometers of fiber.

Nonlinear effects are weak in optical fibers, but accumulate over long distances.

Nonlinear effects are comparatively small in optical fibers transmitting a single optical channel. They become much larger when *dense wavelength-division multiplexing* (DWDM) packs many channels into a single fiber. DWDM puts many closely spaced wavelengths into the same fiber where they can interact with one another. It also multiplies the total power in the fiber. A single-channel system may carry powers of 3 milliwatts near the transmitter. DWDM multiplies the total power by the number of channels, so a 40-channel system carries 120 mW. That's a total of 2 mW per square micrometer—or 200,000 watts per square centimeter!

Several nonlinear effects are potentially important in optical fibers, although some have proved more troublesome than others. Some occur in systems carrying only a single optical channel, but others can occur only in multichannel systems. We'll look at each of them in turn, focusing on the more important ones.

Brillouin Scattering

Brillouin scattering scatters light back toward the transmitter, limiting transmitted power.

Stimulated Brillouin scattering occurs when signal power reaches a level sufficient to generate tiny acoustic vibrations in the glass. This can occur at powers as low as a few milliwatts in single-mode fiber. Acoustic waves change the density of a material, and thus alter its refractive index. The resulting refractive-index fluctuations can scatter light, called *Brillouin scattering.* Since the light wave being scattered itself generates the acoustic waves, the process is called *stimulated Brillouin scattering.* It can occur when only a single channel is transmitted.

In fibers, stimulated Brillouin scattering takes the form of a light wave shifted slightly in frequency from the original light wave. (The change is 11 gigahertz, or about 0.09 nanometer for a 1550-nm signal.) The scattered wave goes back toward the transmitter. The effect is strongest when the light pulse is long (allowing a long interaction between light and the acoustic wave), and the laser linewidth is very small, around 100 megahertz. Under such conditions, it can occur at power levels as little as 3 mW in single-mode fibers. However, the power level needed to trigger stimulated Brillouin scattering increases as pulse length decreases, so the effect becomes less severe at higher data rates.

Brillouin scattering directs part of the signal back toward the transmitter, effectively increasing attenuation. The small frequency shift effectively confines the effect to the optical channel generating the effect at present channel spacings, so it does not create crosstalk with other channels. However, it does limit the maximum power a single length of fiber can transmit in one direction. As input power increases, the fraction of power scattered in the opposite direction rises sharply, and the fiber essentially becomes saturated.

Optical signals going in the wrong direction can cause serious problems, so optical isolators must be added to block Brillouin scattering. In general, isolators are placed at transmitters and optical amplifiers, limiting the effects of stimulated Brillouin scattering to a single fiber span between isolators. Special modulation schemes and careful design also can reduce the effects of Brillouin scattering.

Self-Phase Modulation

An optical channel modulates its own phase by self-phase modulation, which can broaden the range of wavelengths.

The refractive index of glass varies slightly with the intensity of light passing through it, so changes in signal intensity cause the speed of light passing through the glass to change. This process causes intensity modulation of an optical channel to modulate the phase of the optical channel that creates it, so the effect is called *self-phase modulation.* As the optical power rises and falls, these phase shifts also effectively shift the frequencies of some of the light; the shifts are in opposite directions at the rising and falling parts of the pulse. The overall result is to spread the bandwidth of the optical channel by an amount that depends on the rate of change in optical intensity as well as on the nonlinear coefficient of the fiber material. Like stimulated Brillouin scattering, it can occur in a single-channel system.

The spectral broadening caused by self-phase modulation produces dispersion-like effects, which can limit data rates in some long-haul communication systems, depending on the fiber type and its chromatic dispersion. For ultrashort pulses (less than one picosecond) with very high peak powers, self-phase modulation can be very strong, generating a broad continuum of wavelengths. Self-phase modulation also stabilizes pulses called solitons, so they propagate along the fiber with a constant shape, although attenuation reduces their amplitude. This makes soliton transmission an effective way to overcome self-phase modulation.

Cross-Phase Modulation

Systems carrying multiple-wavelength channels are vulnerable to *cross-phase modulation* as well as self-phase modulation. In this case, variations in the intensity of one optical channel cause changes in the refractive index affecting other optical channels. These changes modulate the phase of light on other optical channels, in addition to self-phase modulation of the same channel.

In cross-phase modulation, one channel modulates the phase of other channels.

The strength of cross-phase modulation increases with the number of channels, and becomes stronger as the channel spacing becomes smaller. There are ways to mitigate this effect, but it can limit transmission speed.

Four-Wave Mixing

Normally multiple optical channels passing through the same fiber interact with each other only very weakly, making wavelength-division multiplexing possible. However, these weak interactions in glass can become significant over long fiber-transmission distances. The most important is four-wave mixing (sometimes called four-photon mixing) in which three wavelengths interact to generate a fourth.

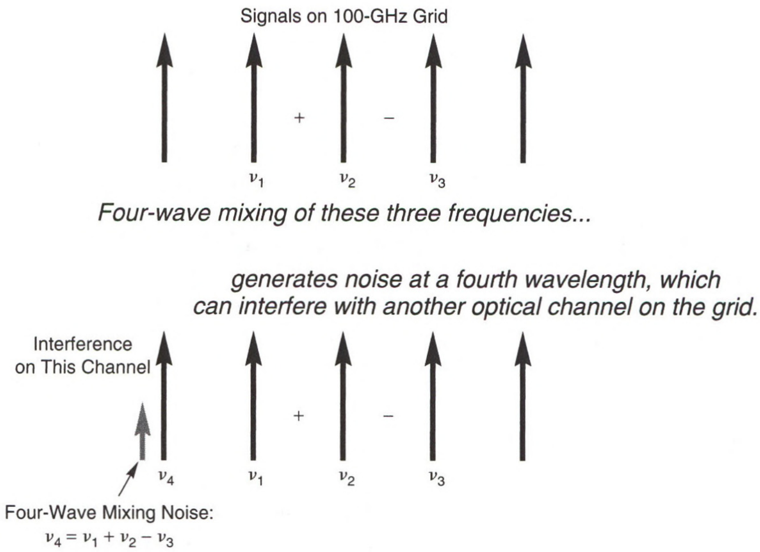
Four-wave mixing generates crosstalk among optical channels, noise that can limit WDM systems.

Four-wave mixing is one of a broad class of *harmonic mixing* or *harmonic generation* processes. The idea is that two or more waves combine to generate waves at a different frequency that is the sum (or difference) of the signals that are mixed. Second-harmonic generation or frequency doubling is common in optics; it combines two waves at the same frequency to generate a wave at twice the frequency (or, equivalently, half the wavelength). This can happen in optical fibers, but the second harmonic of the 1550 nm band is at 775 nm, far from the communications band, so it doesn't interfere with any signal wavelength.

Four-wave mixing is the strongest nonlinear effect that mixes the frequencies of optical channels in the 1550-nm band to generate noise in that band. As shown in Figure 5.13, three waves combine to generate a fourth frequency. If each frequency is designated by ν, the new frequency, ν_4, is

$$\nu_4 = \nu_1 + \nu_2 - \nu_3$$

FIGURE 5.13
Four-wave mixing produces noise that interferes with other optical channels in a DWDM grid.



In DWDM systems, the optical channels are typically close and spaced on a frequency grid typically separated by 100 or 200 GHz. This means that if ν_1 is the starting point, ν_2 is at a frequency 100 GHz higher, and ν_3 is another 100 GHz higher,

$$\nu_4 = \nu_1 + \nu_1 + 100 \text{ GHz} - \nu_1 - 200 \text{ GHz} = \nu_1 - 100 \text{ GHz}$$

which falls smack on top of another optical channel on the grid. The beating together of two frequencies, ν_1 and ν_2, also can cause four-wave mixing:

$$\nu_4 = \nu_1 + \nu_1 - (\nu_1 + 100 \text{ GHz}) = \nu_1 - 100 \text{ GHz}$$

Four-wave mixing accumulates if signals remain in phase over long distances, which occurs when dispersion is near zero.

Four-wave mixing is a weak effect, but it can accumulate if the signals on the optical channels remain in phase with each other over long distances. This happens when chromatic dispersion is very close to zero. Pulses transmitted over different optical channels, at different wavelengths, stay in the same relative positions along the length of the fiber because the signals experience near-zero dispersion. This amplifies the effect of four-wave mixing, and builds up the noise signal, which interferes with a fourth channel on the grid. (This problem led to abandonment of zero dispersion-shifted fibers.) To overcome this problem, the zero-dispersion point has to be moved out of the DWDM band. With even modest dispersion, the signals at different wavelengths quickly drift out of phase with each other, reducing four-wave mixing.

Raman Scattering

Stimulated Raman scattering transfers power between signals at different wavelengths.

Stimulated Raman scattering occurs when light waves interact with molecular vibrations in a solid lattice. In simple Raman scattering, the molecule absorbs the light, then quickly re-emits a photon with energy equal to the original photon, plus or minus the energy of a molecular vibration mode. This has the effect of both scattering light and shifting its wavelength.

When a fiber transmits two suitably spaced wavelengths, stimulated Raman scattering can transfer energy from one to the other. In this case, one wavelength excites the molecular vibration, then light of the second wavelength stimulates the molecule to emit energy—

at the second wavelength. The Raman shift between the two wavelengths is relatively large, about 13 terahertz (100 nm in the 1550-nanometer window for silica fibers), but it can produce some crosstalk between optical channels. It also can deplete signal strength by transferring light energy to other wavelengths outside the operating band. (This process also can be used to amplify signals, as you will learn in Chapter 12.)

Careful choice of wavelengths can reduce the interference between Raman scattering and other channels. Nonetheless, Raman scattering does impose limits on DWDM systems with many optical amplifiers. Its effects are more serious on the shorter wavelengths in a multiwavelength system.

Mechanical Properties

So far, I have concentrated on the optical properties of fibers. You also need to understand their most important mechanical properties. Although most fibers are assembled into cables with highly automated equipment, installation of cables, connectors, and other components often requires handling individual fibers.

Glass fibers are coated with plastic as they are drawn into fiber form. The plastic coating eases handling and protects the fiber's outer surface from physical damage. The standard cladding diameter of communications fibers is 125 μm or 0.125 mm (0.005 in.), thin enough to be difficult to handle or process mechanically. Plastic coating doubles this diameter to 250 μm (0.01 in.), making them easier to pick up and process. Typically this coating consists of two layers, an inner one with outer diameter 245 μm that provides mechanical protection, and a thin outer coating that color-codes the fiber for cabling.

A plastic coating with outer diameter 250 μm covers glass fibers.

Thin glass fibers are reasonably flexible. Individual telecommunications fibers can be bent into a loop with 5-cm (2-in.) diameter without damage or significant effect on the signal, and left that way indefinitely. Equipment used in installation is designed to accommodate that degree of bending. You sometimes can get away with bending fibers more but don't count on it—and you'll never get away with the sort of sharp bend that can be used for copper wires. Thicker glass fibers cannot be bent as tightly. Plastic optical fibers (described in Chapter 6) are more flexible than thick glass fibers.

In theory, a mechanically perfect glass fiber can withstand a tension of 2 million pounds per square inch (14 gigapascals or 14 giganewtons per square meter). In practice, inevitable minor surface flaws reduce this to about 500,000 lb/in^2 (3.5 GPa) or less.

The fact that fibers break at randomly distributed surface flaws has some important consequences. The longer the fiber, the more likely it is to contain a flaw that will cause it to break when a certain stress is applied. To weed out the most harmful of these weak points, fiber manufacturers use a simple *proof test* that applies a load to a length of the fiber as they wind it onto the reel. The load applies a specified tension along the length of the fiber. If any part of the fiber cannot withstand that tension, it breaks at the weak point.

Fibers are subjected to a proof test to assure they have a minimum strength.

Manufacturers typically proof test fibers under a load of 100,000 lb/in^2 (0.7 GPa), so weaker fibers don't make it out of the plant because they break during the stress test. This doesn't mean you can hold an elephant in the air on a single fiber—fibers are small, and pounds per square inch measures the load applied to a solid square inch of glass, not a thin fiber. (Figure it out yourself and you'll be surprised.) But the numbers do show that glass fibers can withstand reasonable handling, despite our instinctive feeling that glass is fragile.

A glass fiber will snap if pulled sharply, apparently without stretching at all. Fiber is difficult to break with your hands, but can snap if you trip on them. Fibers can break inside a cable without obvious damage to the cable. But a closer look would reveal that the glass does stretch elastically until it reaches its breaking strength, and it stretches several percent beyond its original length before snapping. Copper wires deform plastically, stretching by more than 20% before breaking.

Fiber failure normally starts at a flaw or microcrack in the glass surface. Application of stress spreads the crack, leading quickly to failure if the applied force is beyond the fiber's strength. Flaws are distributed randomly along the surface, and statistics can be used to estimate the chance of failure.

Fibers can suffer from two types of aging. *Dynamic fatigue* arises from the short-lived stresses applied to the fiber either by installation or the temporary environmental effects. Underground cables are affected by the stress of pulling them into a duct, while aerial cables are affected by gusts of wind and snow loading during winter.

Static fatigue is the growth of flaws that occurs while the fiber is maintained under constant conditions. The flaws may grow because of moisture or other environmental factors, or because the cable structure is pulling on the fiber. Moisture is the most common problem because it slowly reacts with silica. Static fatigue is very low unless the stress is more than 20% of the proof-test stress.

The plastic coating on the fiber is important as a protection against moisture and physical damage to the surface. Experience has shown these coatings to be quite effective.

What Have You Learned?

1. Signal loss is the sum of loss coupling light into a fiber, and of scattering and absorption in the fiber.
2. Material absorption depends on wavelength and is cumulative with distance. Impurities cause absorption peaks.
3. Losses from atomic scattering are higher at shorter wavelengths; scattering losses also are cumulative with distance.
4. Fiber attenuation is the sum of scattering and absorption, measured together in decibels per kilometer.
5. The logarithmic decibel scale is preferred for calculating attenuation and transmission losses. Total attenuation of a fiber is the characteristic loss in decibels per kilometer times the length in kilometers.
6. The larger the fiber core, the more easily it can collect light from a light source.
7. Some light is guided short distances along the cladding in cladding modes. Leaky modes are only partly confined in the fiber core.
8. Dispersion produces pulse spreading that can limit transmission speeds in both analog and digital systems. The main types of dispersion are modal, chromatic, and polarization. Total pulse spreading is the square root of the sum of the squares of the pulse spreading from all three types of dispersion.

9. Material and waveguide dispersion add together to give chromatic dispersion; both can have a positive or negative sign. The pulse spreading caused by chromatic dispersion is proportional to the spectral bandwidth of the transmitter as well as the length of fiber.
10. Material dispersion is a characteristic of the fiber material, which varies with wavelength. It measures the change in group delay with wavelength, which in turn measures the change in refractive index with wavelength.
11. Waveguide dispersion arises from changes in waveguide properties and the distribution of light in the fiber with wavelength.
12. Waveguide and material dispersion can cancel each other to give zero chromatic dispersion if their signs are opposite. Adjusting waveguide dispersion can shift the zero-dispersion wavelength.
13. Fibers with opposite signs of chromatic dispersion can be combined in sequence to compensate for chromatic dispersion in a system.
14. Long wavelength-division multiplexed (WDM) systems require dispersion management over their entire range of wavelengths. Dispersion slope, the change in dispersion with wavelength, is an important consideration.
15. Polarization-mode dispersion arises from slight fluctuations in the refractive index experienced by light of different polarizations. The pulse spreading varies randomly with time.
16. Nonlinear effects are interactions between light waves, which generate noise and crosstalk. They become important at high power densities that can occur in single-mode fibers.
17. Four-wave mixing among optical channels is the most important potential noise source in WDM systems. It accumulates over long distances when fibers have very low dispersion.
18. Bare glass fibers are coated with plastic to protect their surfaces and ease handling. Glass fibers are quite strong, if they lack surface flaws.

What's Next?

Now that we've talked about fiber structures and characteristics, Chapter 6 will cover fiber materials and manufacture.

Further Reading

Paul Hernday, "Dispersion Measurements," in Dennis Dirickson, ed., *Fiber Optic Test and Measurement* (Prentice Hall, 1998)

Luc B. Jeunhomme, *Single-Mode Fiber Optics: Principles and Applications* (Dekker, 1990)

Donald B. Keck, ed., *Selected Papers on Optical Fiber Technology* (SPIE Milestone Series, Vol. MS38, 1992)

Gerd Keiser, *Optical Fiber Communications*, 3rd ed. (McGraw-Hill, 2000)

Advanced Treatments:

John A. Buck, *Fundamentals of Optical Fibers* (Wiley InterScience, 1995)

Ajoy Ghatak and K. Thyagarajan, *Introduction to Fiber Optics* (Cambridge University Press, 1998)

Questions to Think About

1. The amount of Rayleigh scattering by atoms is proportional to λ^{-4}. How is this related to why the sky looks blue?
2. Can you write a formula that converts loss in decibels into the fraction of power remaining?
3. You have a fiber that transmits a single mode at 850 nm, and a light source with bandwidth of 1 nm. Its chromatic dispersion is about −80 ps/nm-km. What is the maximum data rate that fiber could transmit 100 km, neglecting attenuation, based only on the guideline on page 115 (bit rate = $1/(4 \times \Delta t_{disp})$)?
4. Estimate the attenuation at 850 nm from Figure 5.2. Assume you need an optical amplifier to boost signal strength after every 30 dB of fiber loss. How far can the fiber transmit signals before it requires an optical amplifier? Which of the limitations in Questions 3 and 4 do you think was the main reason 850-nm systems were never viable for long-distance transmission?
5. Why is it more difficult to compensate for dispersion in a DWDM system than in one transmitting only a single optical channel?
6. Write a formula for how much dispersion-compensating fiber you need to add to an existing system with $L_{existing}$ km of fiber to reduce dispersion to a desired value D_{net}.
7. Four-wave mixing normally occurs only at high powers in glass, yet it can cause significant crosstalk in single-mode fibers. If you have a fiber with effective area of 50 μm^2, what is the power per square centimeter in the fiber if it carries 100 optical channels at 3 mW each?

Chapter Quiz

1. A 1-m length of fiber transmits 99.9% of the light entering it. How much light will remain after 10 km of fiber?
   a. 90%
   b. 10%
   c. 1%

d. 0.1%

e. 0.0045%

2. A fiber has attenuation of 0.00435 dB/m. What is the total attenuation of a 10-km length?

a. 0.0435 dB

b. 1.01 dB

c. 4.35 dB

d. 43.5 dB

e. We cannot tell without knowing the wavelength.

3. If 10 mW of light enters the 10-km fiber in Problem 2, how much light remains at the output end?

a. 0.00045 mW

b. −33.5 dBm

c. −3.5 dBμ

d. all of the above

e. none of the above

4. You lose 1.0 dB coupling a 1-mW light source into an optical fiber. You need a signal of 0.1 mW at the other end. How far can you send a signal through fiber with attenuation of 0.5 dB/km?

a. 1.8 km

b. 10 km

c. 18 km

d. 20 km

e. 40 km

5. You transmit an instantaneous pulse through a 20-km multimode fiber with total dispersion of 10 ns/km at the signal wavelength. What will the pulse length be at the end?

a. 200 ns

b. 100 ns

c. 50 ns

d. 20 ns

e. 10 ns

6. You transmit a 100-ns pulse through the same fiber used in Problem 5. What will the pulse length be at the end?

a. 300 ns

b. 224 ns

c. 200 ns

d. 150 ns

e. 100 ns

7. You transmit an instantaneous pulse through a 20-km single-mode fiber with chromatic dispersion of 10 ps/nm-km at the signal wavelength. The spectral width of the input pulse is 2 nm. What is the pulse length at the end of the fiber?

a. 400 ps
b. 250 ps
c. 200 ps
d. 100 ps
e. 32 ps

8. You transmit an instantaneous pulse through a 20-km single-mode fiber with chromatic dispersion of 10 ps/nm-km at the signal wavelength. This time you've spent an extra $2000 for a super-duper laser with spectral width of only 0.002 nm. What is the pulse length at the end of the fiber?

a. 30 ps
b. 20 ps
c. 4 ps
d. 1 ps
e. 0.4 ps

9. A single-mode fiber has material dispersion of 20 ps/nm-km and waveguide dispersion of -15 ps/nm-km at the signal wavelength. What is the total chromatic dispersion?

a. 35 ps/nm-km
b. 25 ps/nm-km
c. 5 ps/nm-km
d. 0 ps/nm-km
e. -35 ps/nm-km

10. You send 200-ps pulses through a 100-km length of the fiber in Problem 9, using a laser with spectral width of 0.002 nm. What is the width of the output pulse?

a. 1 ps
b. 200 ps
c. 250 ps
d. 400 ps
e. 500 ps

11. Your boss says you can't have the extra $2000 for the super-duper narrow-bandwidth laser, so you have to use the cheap model with 2-nm spectral linewidth in the system in Problem 10. What's the width of the output pulse?

a. 200 ps
b. 250 ps
c. 500 ps

d. 1000 ps

e. 1020 ps

12. An optical fiber 125 μm in diameter can withstand a force of 600,000 lb/in^2. What's the heaviest load it could support?

a. a 4-ton elephant

b. a 1/2-ton cow

c. a 95-lb weakling

d. a 10-lb rock

e. a 5-oz. hamster

13. Your job is to send a signal at the highest data rate possible through 2500 km of fiber with polarization-mode dispersion of 1 ps/km$^{-1/2}$. Neglecting all other types of dispersion, what is the best you can do, remembering that polarization-mode dispersion should accumulate to no more than 1/10th the interval between pulses?

a. 10 Gbit/s

b. 5 Gbit/s

c. 2 Gbit/s

d. 1 Gbit/s

e. 100 Mbit/s

14. Suppose you only had to transmit signals 400 km through the same fiber. What is the maximum data rate, again neglecting all other dispersion and remembering that polarization-mode dispersion should accumulate to no more than 1/10th the interval between pulses?

a. 10 Gbit/s

b. 5 Gbit/s

c. 2 Gbit/s

d. 1 Gbit/s

e. 100 Mbit/s