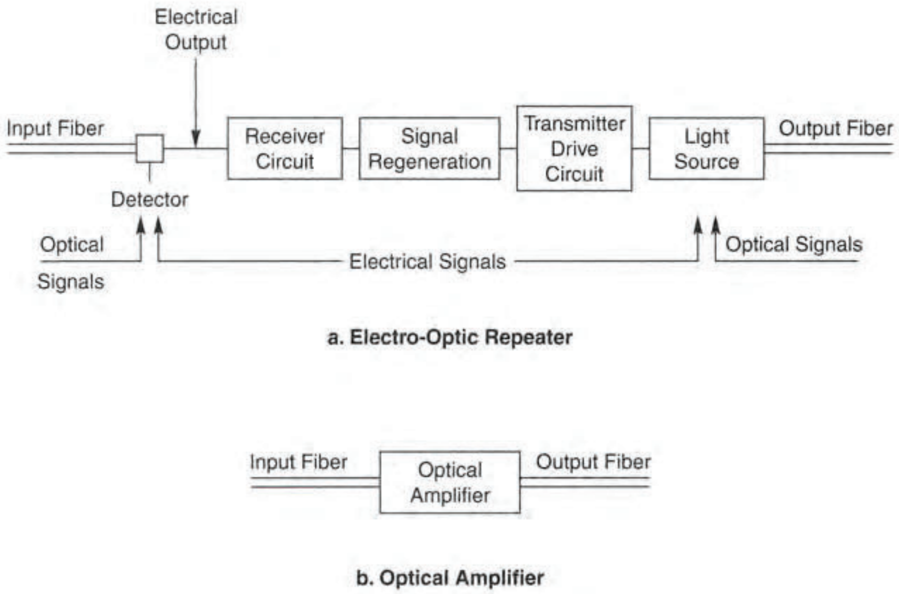
FIGURE 12.2
Electro-optic repeater and optical amplifier.



telegraphs. Today, however, *regenerator* is a distinct term with its own meaning—a device that generates a fresh version of a digital input signal by removing noise and distortion.

The standard regenerators used in today's fiber-optic systems are electro-optic devices. Like digital receivers, electro-optic regenerators convert input optical signals into electronic form, then run them through *discrimination circuits* that examine the time-varying input signal and decide which changes in signal strength are data bits and which are noise. They also contain retiming circuits that put the pulses into their proper time slots. Regeneration typically is performed at the ends of a system, with amplifiers used to boost signal strength along the route. Often regeneration is performed within the receiver stage of a large switch or other electronic device, so you won't see a big box labeled "regenerator."

3-R regeneration (re)amplifies, reshapes, and retimes pulses.

Optical regeneration is also possible, although still largely at the laboratory stage. There are two variations: *2-R regeneration* and *3-R regeneration.*

Both types amplify the signal optically, but sometimes the term *reamplification* is used to justify the "R" terminology. 2-R regenerators also reshape the pulses, using a discrimination circuit to generate fresh sharp pulses. 3-R regenerators follow that with a retiming stage. Retiming is difficult to implement optically, so 2-R regenerators are better developed.

Wavelength conversion changes the wavelength of a transmitted signal. Such conversion may be required to provide the same wavelength throughout a system, or to meet other needs of optical networks. The wavelength-conversion function is separate from amplification and regeneration, but in practice these functions may be combined. One way to convert the signal wavelength is to pass it through an electro-optic repeater that generates a different output wavelength. These devices are often called *OEO transponders,* and are essentially special-purpose repeaters or regenerators. Like regenerators, they may be built into a terminal switch at a network node, so they are hard to identify as discrete devices. As you will learn later in this chapter, some all-optical devices also can convert signal wavelengths.

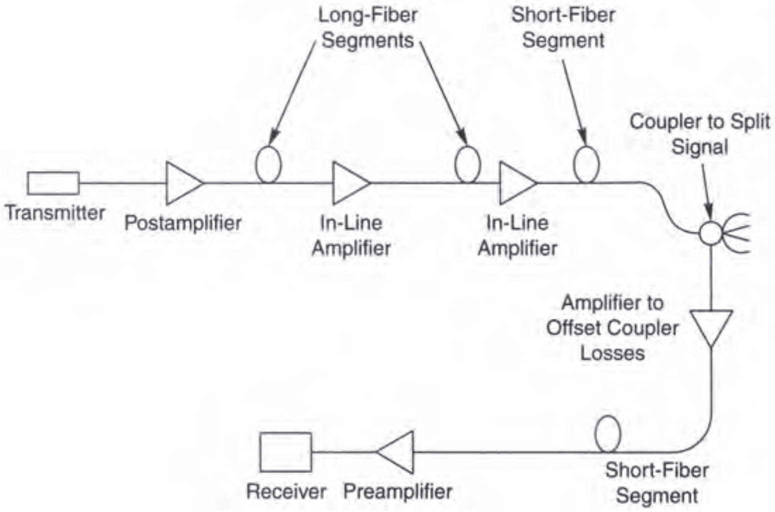


FIGURE 12.3
Roles for optical amplifiers.

System Requirements

The need for repeaters, regenerators, optical amplifiers, and wavelength converters depends on system design.

Electro-optic repeaters are rarely used today simply to amplify signals except in certain types of local-area networks, where one receiver generates an electronic signal that drives two or more transmitters. Such repeaters may be used where an electronic signal must be generated to drive a terminal device and an optical signal is needed for transmission to the next node.

An electro-optic repeater can convert wavelengths if the transmitter end emits a wavelength different from that of the input signal.

Electro-optic regenerators require expensive multiplexing and demultiplexing of signals transmitted through the same fiber at different wavelengths, so typically signals are regenerated only at the end of a system by the optical receiver. Demultiplexing is required at this point anyway, and electronic outputs are often required. In practice, regeneration is usually invisible because it is built into the receiver.

Optical amplifiers may be used at several different points in communication systems, as shown in Figure 12.3.

Optical amplification is needed in-line, after transmitters, before receivers, and after lossy components.

- *Postamplifiers* are placed immediately after a transmitter to increase strength of a signal being sent through a length of fiber. It might seem easier just to crank up the transmitter output, but that can degrade the quality of the output signal. External amplification of a lower-power transmitter output gives a cleaner signal. Postamplifiers also can generate powerful signals that can be split among many separate output fibers if a single transmitter is distributing signals to many points.
- *In-line amplifiers* compensate for signal attenuation in long stretches of fiber. The goal is to amplify a weak signal sufficiently to send it through the next segment of fiber. These generally are required in long telecommunication systems but may be used in some networks where many branching points reduce transmitted power. Signals may require regeneration after a series of many amplifiers.

- *Preamplifiers* amplify a weak optical signal just before it enters a receiver, in effect increasing the sensitivity of the receiver and stretching transmission distances.
- *Offsetting component losses* that otherwise would reduce signals to unacceptably low levels. Optical couplers must physically divide the signal among multiple terminals, which reduces the signal strength arriving at each one. For example, splitting a signal in half reduces each output to a level 3 dB below the input. Dividing a signal among 20 terminals reduces signal strength by 13 dB—assuming every output gets exactly $\frac{1}{20}$ of the input. Placing an optical amplifier before or after the lossy component can raise the signal strength to compensate for the loss.

Repeaters and Regenerators

Electro-optic repeaters essentially link two systems end to end.

You saw earlier that an electro-optic repeater or regenerator is essentially a receiver and transmitter placed back to back in a single unit. The input end performs the usual receiver functions; the output end performs the standard transmitter functions. In the middle they amplify and typically clean up the signal. You can think of them as joining two separate fiber-optic systems together end to end.

Electro-optic repeaters were widely used in long-distance fiber-optic systems installed before the mid-1990s, when optical amplifiers became available. Most of those systems operated at 1310 nanometers, the zero-dispersion wavelength in standard step-index single-mode fibers. Optical amplifiers have replaced electro-optic repeaters for boosting signal strength to extend transmission distance, and operation has shifted to the 1550-nm range where the best optical amplifiers operate.

Regeneration is normally done in electronic switches at the end of a system.

Electro-optical regeneration is largely performed within receivers or electronic switches at the end of a fiber-optic system. Operators would rather install the sensitive electronic equipment in climate-controlled buildings than in the field along the cable route.

The performance of electro-optic repeaters and regenerators depends on the internal electronic circuits. These circuits are designed to operate at specific data rates, with clock circuits set to generate pulses at the same speed as the input signal. That means that repeaters, like transmitters and receivers, must be changed if the system is to operate at a speed different from that of the original design. This is not true for optical amplifiers.

Another limitation is that electro-optic repeaters and regenerators can process only one signal at a time, so signals transmitted on separate wavelengths through the same fiber must be divided among separate repeaters or regenerators. This is not true for optical amplifiers.

Electro-optic repeaters can convert signals to different wavelengths.

Electro-optic repeaters do offer a straightforward way to convert wavelengths, which has given them a new life as OEO (opto-electronic-optical) transponders. Like a standard EO repeater, the OEO transponder converts the input optical signal to electronic form for amplification and other processing. However, the transmitter module generates a wavelength different from the input wavelength. It may not be elegant, but it works. The performance can be enhanced by using a tunable laser to generate a user-specified wavelength. As with electro-optic regenerators, this wavelength-conversion function can be buried within a larger electronic switch that processes signals at a network node.

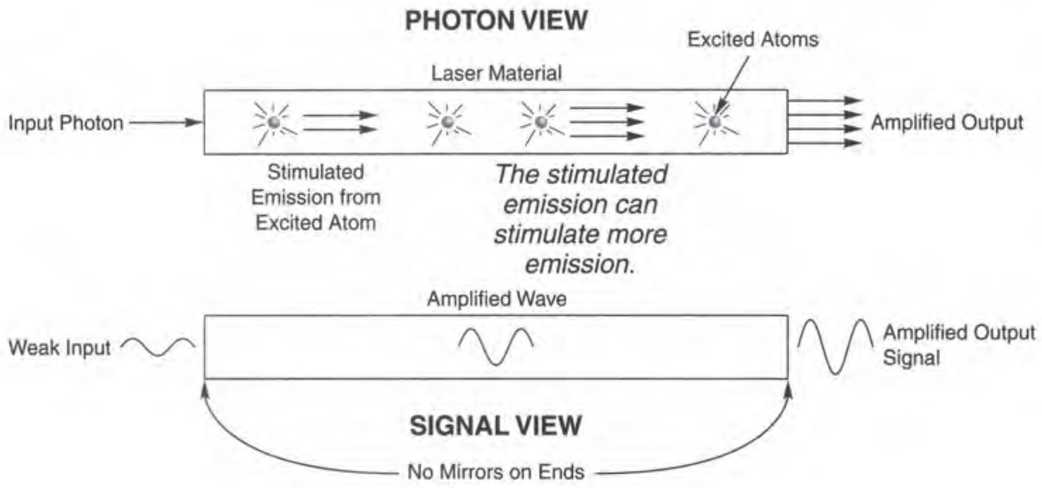


FIGURE 12.4 *Optical amplification of individual photons (top), and of a signal (bottom).*

Optical Amplifiers

You read earlier that optical amplifiers are based on the same principle as the laser. The difference between lasers and optical amplifiers is that lasers generate a signal internally, while optical amplifiers amplify a signal from another source.

Figure 12.4 sketches the idea of an optical amplifier. The amplifier material is excited so that some of the atoms store excess energy, as you saw for a laser in Chapter 9, but it is not placed between a pair of mirrors. Instead, a weak input signal enters the material, stimulating some of the excited atoms to release energy as light. The photons produced by this stimulated emission are duplicates of the photons in the input signal, at the same wavelength, in the same phase, and going in the same direction. This process multiplies the strength of the input signal as the light makes a single pass through the amplifier.

Optical amplifiers are based on stimulated emission.

The effectiveness of optical amplification depends on how well the input wavelength matches the stimulated-emission properties of the material. The probability of stimulated emission varies with wavelength, so the input wavelength must match the material's emission wavelength.

Gain and Power Levels

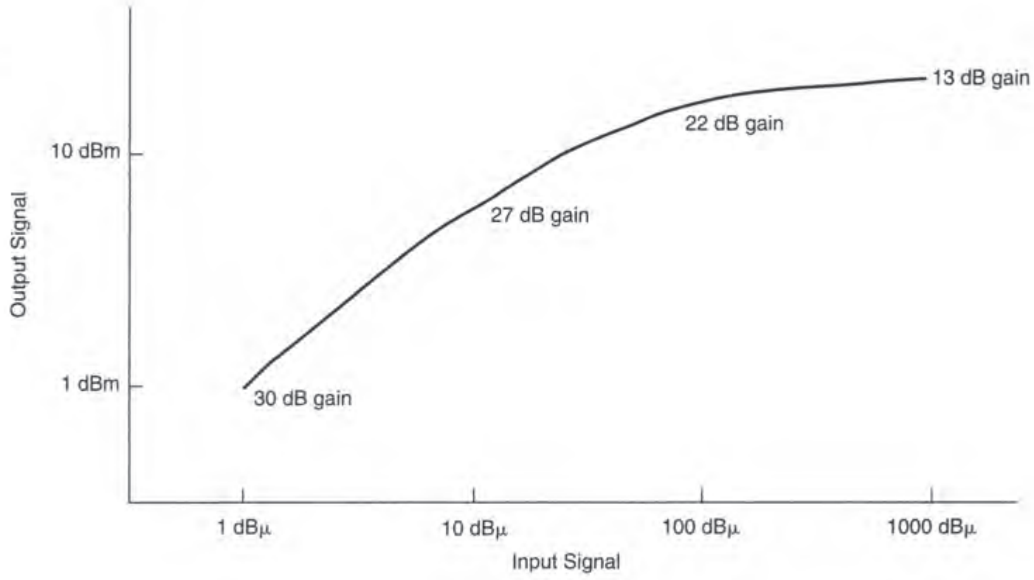
The performance of an optical amplifier is measured by the total output power and by the amount of amplification, called the *gain.* These quantities depend on several factors. For simplicity, we'll consider an input signal that consists of only a single wavelength.

The *input power* is the starting point for the amplifier. Optical amplifiers are analog devices, so as in electronic systems the power of input signal should be well above the background noise.

The *gain* is the amplification, usually measured in decibels, which depends on the input power and the amplifier design. Often gain is measured per unit length, usually as a fraction or percentage per centimeter. The gain measures how much emission the input signal can stimulate, which in turn depends on how many excited atoms are available and how easy it is to stimulate emission. The number of excited atoms, in turn, depends on

Gain depends on input wavelength and amplifier design.

FIGURE 12.5
Saturation of fiber amplifier gain.



the structure of the material, how fast the atoms are being excited, and how fast the input signal is taking away their extra energy by stimulating emission. In the real world, further complications include how uniformly the excitation energy is distributed along the amplifier.

For low input powers, the output power is the product of the input power, the gain per unit length, and the length:

$$P_{\text{output}} = P_{\text{input}} \times \text{gain} \times \text{length}$$

This is called the *small-signal approximation*, and it assumes that enough excited atoms are always available along the entire length of the amplifier.

Amplifier gain saturates at high power levels.

At higher input signals, the output power may *saturate* because too few excited atoms are available to further amplify emission. Essentially, the amplifier runs out of energy. Figure 12.5 gives an example of this effect for an erbium-fiber amplifier. The higher the input power, the lower the gain. If you keep increasing the input power, eventually you extract all the available energy from the amplifier, and raising the input power further will not produce any additional output.

Note that this saturation effect actually distorts the amplified signal, like trying to turn up an audio amplifier beyond its operating range. However, this doesn't affect digital transmission.

So far, we've considered only amplification of one optical signal at one wavelength. However, the saturation effect depends on total power at all input wavelengths in the amplification band. If you look carefully at Figure 12.5, you will notice that it takes a fair amount of input power to saturate this optical amplifier. Gain levels off when the input signal is 1 dBm, which you're unlikely to encounter at the receiver end of a system carrying only a single optical channel. This figure was plotted for an amplifier that carries wavelength-division multiplexed signals at many different wavelengths in the amplification band, and the numbers are for total input and output power.

Wavelength Range and Material

Optical amplifiers work over the range of wavelengths that can stimulate emission from the excited atoms. That is, the probability of stimulated emission varies with wavelength: It peaks at one wavelength, then drops from that level, eventually reaching zero. The wavelength range depends on the amplifier material and structure.

The best optical amplifiers, based on erbium-doped optical fibers, typically work at wavelengths from about 1530 to 1605 nm, where silica fibers have their lowest loss. These wavelengths have become standard for long-distance transmission that requires amplification. Other amplifiers are available at other wavelengths.

Erbium fiber amplifiers work from 1530 to about 1605 nm.

Optical amplification works only as long as the atoms in the amplifier are being excited. Once the excitation stops, the atoms drop to their lower energy states. In many optical amplifiers, notably erbium, these lower energy states can absorb light at the same wavelengths that are amplified when the atoms are excited. That means an erbium-doped fiber that is not being excited strongly absorbs the signal and can shut down transmission.

Types of Optical Amplifiers

Three types of optical amplifiers are now used in fiber-optic systems. Before describing them in more detail, we'll make a quick comparison.

Doped fiber amplifiers have cores doped with atoms of an element that light from an external laser can excite to a state in which stimulated emission can occur. The doped fibers are specialty products, described in Chapter 7. Pump light from the external laser steadily illuminates one or both ends of the fiber and is guided along the fiber length to excite the atoms in the core. The core guides the input signal and the amplified light. By far the most important of these amplifiers is the *erbium-doped fiber amplifier* (EDFA), which is widely used in long-distance fiber systems.

Erbium-doped fiber amplifiers are the most common optical amplifiers.

Raman fiber amplifiers are based on a process called *stimulated Raman scattering*, which also causes nonlinear effects in fibers. An atom absorbs a pump photon at one wavelength and, while it holds that extra energy, is stimulated to emit most of the energy by a second photon with longer wavelength. The effect converts light energy from the shorter wavelength to the longer one. For amplification, the fiber is pumped with strong light at one wavelength to amplify a weak signal at a longer wavelength. This is a nonlinear process with gain per unit length much weaker than in doped fiber amplifiers; but it can be spread over many kilometers of fiber, so the total amplification can be significant. It requires no special doping of the fiber core and can be produced in ordinary telecommunications fiber.

Semiconductor optical amplifiers are essentially semiconductor lasers without mirrors. A weak signal enters the junction layer and is amplified when the photons stimulate emission from recombining electron-hole pairs. The energy comes from a current flowing through a semiconductor diode, as in semiconductor lasers. The gain per unit length is much higher than in doped fiber amplifiers; but the length is much shorter, so the overall amplification is comparable. The edges of the semiconductor chip can be coated to prevent reflections, or the amplifier may be integrated within a semiconductor waveguide to avoid reflections.

We will start by looking at the erbium-doped fiber amplifier, the most widely used type. Then we'll cover other fiber amplifiers and semiconductor amplifiers.

Erbium-Doped Fiber Amplifiers

The erbium-doped fiber amplifier tremendously expanded fiber-optic transmission capacity, which fed the telecommunications bubble. Its ability to amplify wavelength-division multiplexed signals broke the traditional bandwidth bottleneck that had limited the capacity of long-distance systems. By rare good fortune, erbium has especially attractive properties for an amplifier, with gain at wavelengths of 1530 to 1625 nm, closely matching the minimum-attenuation band of standard optical fibers.

Function

Erbium-fiber amplifiers simultaneously amplify weak light signals at wavelengths across their operating range. This range varies with amplifier design, as described later in this section, but this capability is crucial for wavelength-division multiplexing. Because fiber amplifiers respond very rapidly to variations in input signal strength, they amplify signals across a wide range of modulation speeds, although the response is not unlimited.

Fiber amplifiers can be used in various locations in a system, or cascaded so one amplifies a signal that has earlier been amplified by another amplifier, as shown in Figure 12.3. In practice, the accumulation of noise limits the number of amplifiers that can be cascaded. The accumulation of noise can be reduced by limiting the gain per amplifier and reducing the spacing between amplifiers. Thus, a series of erbium-fiber amplifiers spaced 50 km apart can transmit signals farther than a series of amplifiers 100 km apart.

Structure and Operation

Optical signals are amplified by erbium atoms in the fiber core.

Figure 12.6 shows amplification in an erbium-doped fiber amplifier. Small quantities of erbium are present in the fiber core. When light excites the erbium atoms, a weak signal in the erbium amplification band guided along the fiber core stimulates emission, and the signal grows in strength along the length of the fiber.

Figure 12.7 shows the overall structure of an erbium-fiber amplifier, omitting the details inside the fiber. The input signal enters from the left (in this example, a single optical channel at 1550 nm). It passes through an optical isolator, which blocks light from going back toward the light source, and a filter, which transmits the signal wavelength but blocks the wavelength of the pump laser. Then the signal enters the erbium-doped amplifying fiber. Light from the pump laser is coupled into the other end of the erbium-doped fiber to excite erbium atoms, which amplify the signal passing through the loop of fiber. Then the amplified signal is separated from the pump at a wavelength-selective coupler on the right, and exits through another optical isolator into the next leg of the fiber-optic system.

Standard pump wavelengths are 980 and 1480 nm.

The pump light must be at specific wavelengths in order to stimulate emission from the erbium atoms. Standard pumps are semiconductor lasers that emit 980 or 1480 nm. Each wavelength has its own distinct advantages.

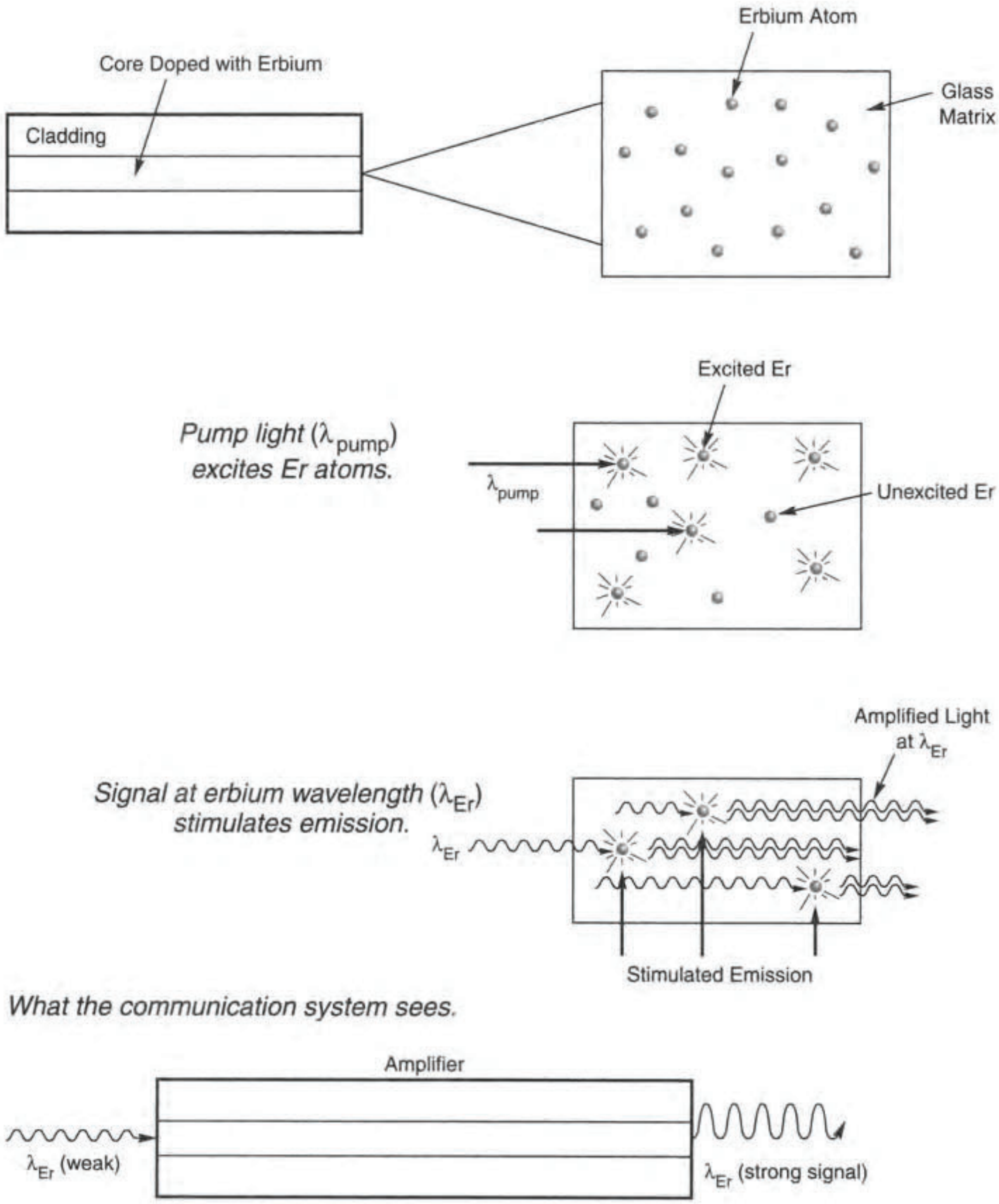
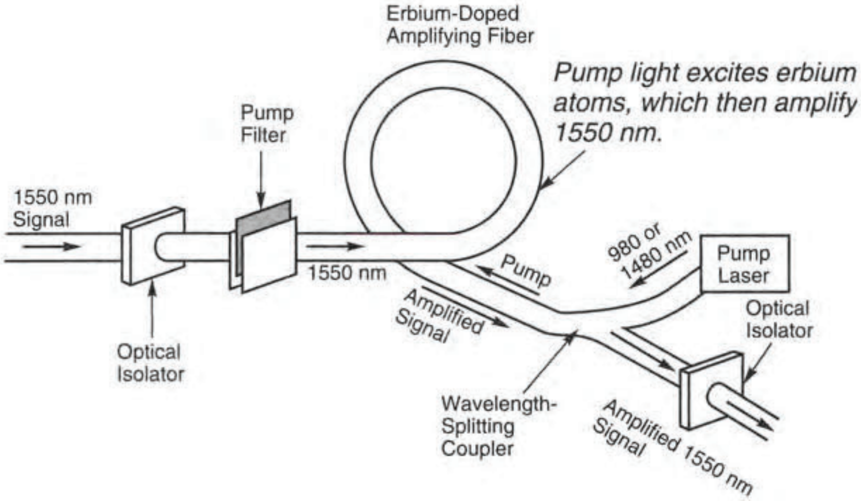


FIGURE 12.6
Amplification in an erbium-doped fiber amplifier.

Operating Wavelengths

Erbium-doped fibers can amplify light over a surprisingly wide range of wavelengths. Figure 12.8 gives an indication of this range by plotting the cross section for stimulated emission as a function of wavelengths. This cross section measures the likelihood that a photon of that wavelength can stimulate emission from an excited erbium atom. The cross section depends on the glass "host" as well as the erbium atom; it is highest for a special glass formulation containing tellurium and is somewhat lower for fluoride and silica-based

FIGURE 12.7
Erbium-doped fiber amplifier.

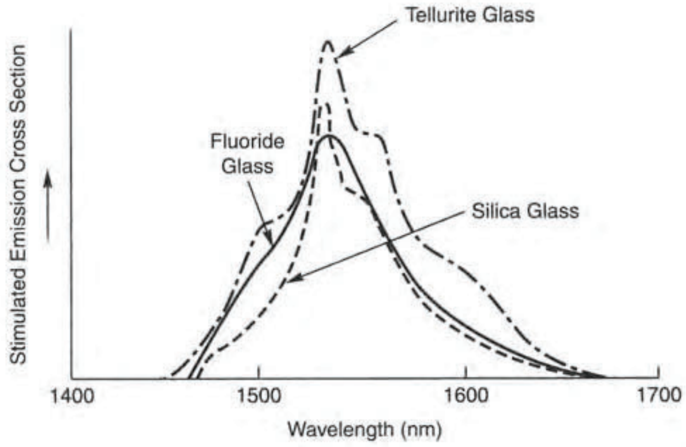


glass. (The silica glass shown has extra aluminum and phosphorus to enhance erbium emission.)

Small-signal gain of erbium-doped fiber amplifiers is not uniform and peaks at 1530 to 1535 nm.

You can't actually realize amplification across this entire range. Erbium atoms absorb light at the shorter wavelengths, damping possible amplification. In addition, the amplification process concentrates gain at the wavelengths where the probability of stimulated emission is highest. For relatively short lengths of fiber—a few meters—the gain is highest at 1530 to 1535 nm, as shown in Figure 12.9. This figure shows gain at various wavelengths for different amounts of input power. Recall that the gain is highest for small input signals. As Figure 12.9 shows, for small inputs, gain varies significantly with wavelength—by more than 10 dB from the peak between 1530 and 1535 nm to the plateau at 1540 to 1560 nm. However, for high inputs, where gain saturates, gain is more uniform across that wavelength range.

FIGURE 12.8
Stimulated emission cross section for erbium-doped fibers of various compositions.



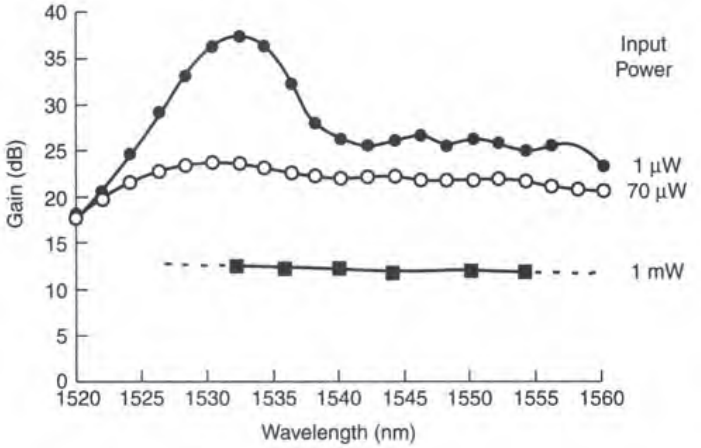


FIGURE 12.9

Erbium-fiber amplifier gain versus wavelength at different input powers. (Courtesy of Corning, Inc.)

Erbium atoms have both gain and absorption at a broad range of wavelengths near 1550 nm, as you can see in Figure 12.10. Gain is high at short wavelengths, but it is offset by high absorption, so most erbium amplifiers operate at wavelengths longer than 1530 nm. Gain drops at wavelengths longer than about 1560 nm, but the absorption also drops, and the gain remains higher than the absorption for wavelengths out to about 1625 nm. This produces a net gain for light at those wavelengths as long as the fiber is excited with pump light. Although that gain is not large, it does accumulate, allowing amplification in a long fiber. "Long" in this case means 100 m or more, but the fiber can be packaged as a coil inside a case, which opens that range of wavelengths to erbium-fiber amplifiers.

Erbium gain and absorption lines overlap in the 1550-nm region.

Design of erbium-fiber amplifiers differs for the high-gain and low-gain wavelengths. Two different types have emerged:

- *C-band* amplifiers are designed for the high-gain band from 1530 to 1565 nm and use several meters of optical fiber. C-band erbium amplifiers are by far the most widely used optical amplifier. Their gain is highest at 1530 to 1535 nm, but this bandwidth is sometimes avoided in WDM systems to keep gain uniform across the operating range. Operation at shorter wavelengths is limited by absorption and noise from amplified spontaneous emission (described later).

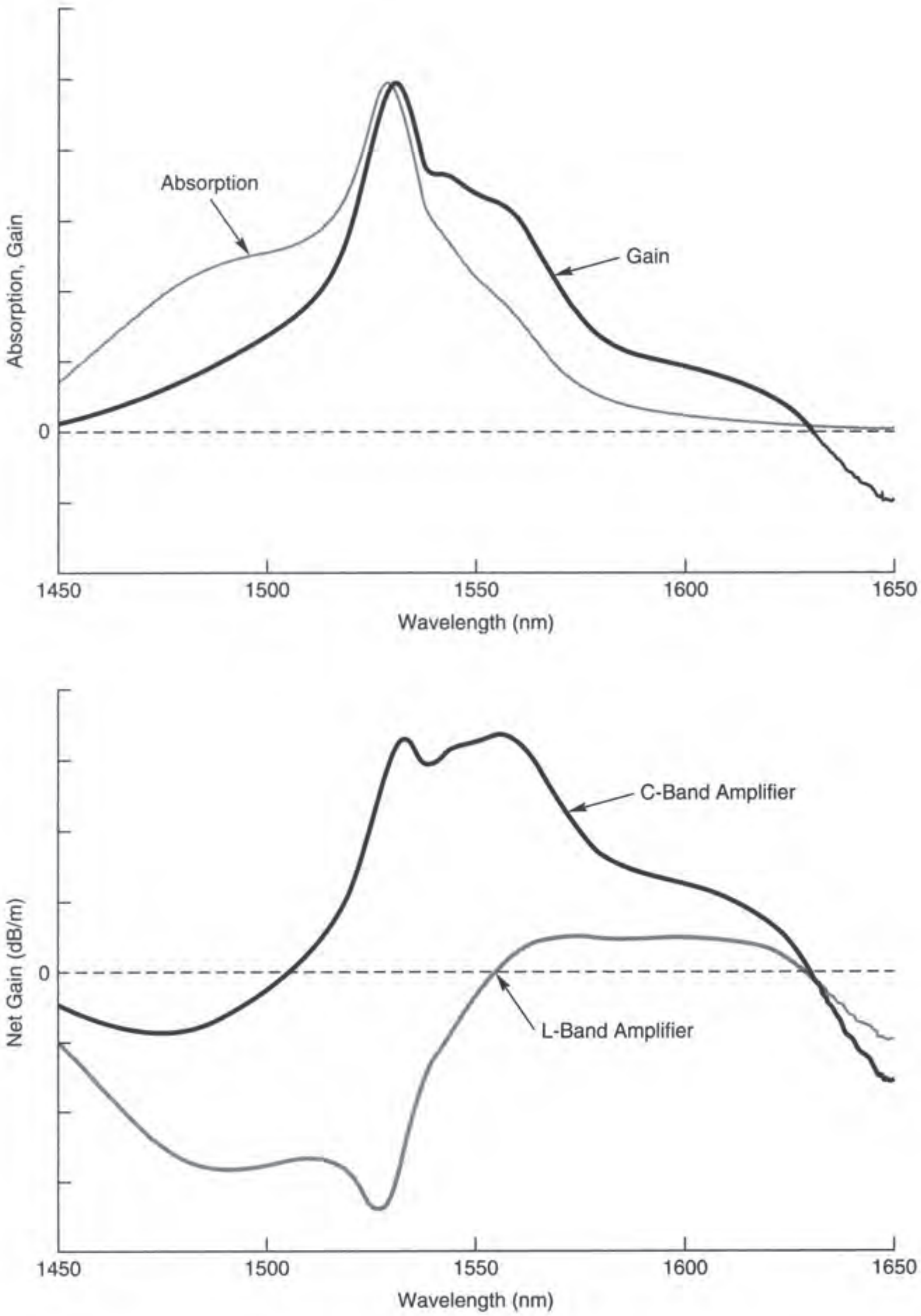
Most erbium amplifiers operate in the C-band.

- *L-band* amplifiers are designed for the lower-gain wavelengths longer than 1565 nm and use 100 m or more of erbium-doped fiber optimized for low-gain operation. Erbium-doped fiber has gain at wavelengths to 1625 nm, but in practice L-band erbium amplifiers are limited to wavelengths shorter than about 1605 nm. L-band amplifiers are not widely used with standard fibers, but they are used with zero dispersion-shifted fibers because they shift the operating range away from the zero-dispersion wavelength at 1550 nm. (WDM is impractical in the C-band in zero dispersion-shifted fibers because of four-wave mixing.)

L-band amplifiers can supplement C-band amplifiers when no more channels can be accommodated in the C-band. In practice, a 5-nm gap is left between the C- and L-bands, so the signals can be split between a pair of parallel amplifiers and both bands can be used

FIGURE 12.10

Gain and absorption in a typical erbium-doped fiber (top) and calculated gain for C-band and L-band amplifiers (bottom). (Courtesy of Nufern)



simultaneously, as shown in Figure 12.11. The long-wavelength end of the L-band depends on the manufacturer and system requirements. A typical L-band operating range is 1570 to 1605 nm, but can be extended to 1620 nm in some cases.

You should remember one other thing about erbium-doped fibers: if the pump light is turned off, the gain goes away but the absorption remains, and the fiber strongly absorbs the light it is supposed to amplify.

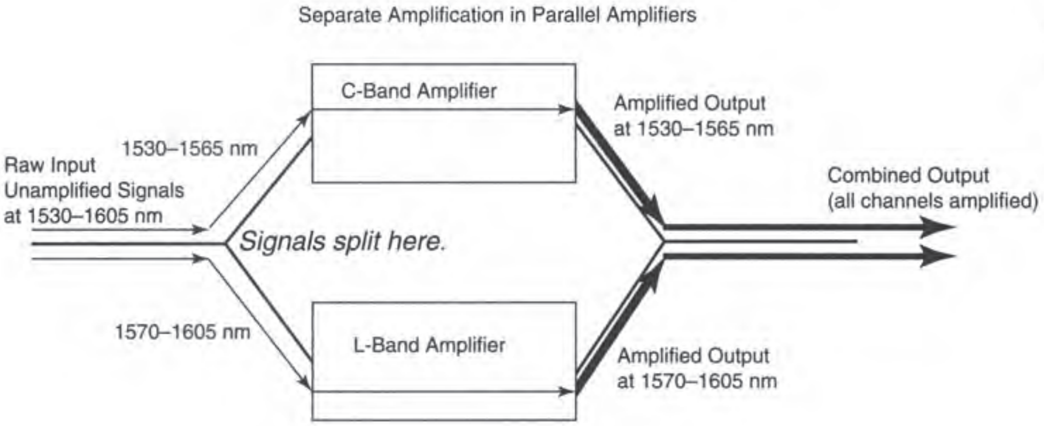


FIGURE 12.11
High- and low-band optical amplifiers in parallel.

WDM and Erbium-Fiber Amplifiers

One advantage of erbium-fiber amplifiers is their ability to simultaneously amplify signals at several different wavelengths in the erbium band. Without this ability, wavelength-division multiplexing would be cumbersome and impractical. Nonetheless, multiwavelength operation does pose some complications.

The same population of excited erbium atoms amplifies all the wavelengths of light in the signal, so all the atoms draw power from the same pump laser. Thus, if the signal contains only one wavelength, all erbium atoms are available to amplify that wavelength; but if it contains multiple wavelengths, the pump power has to be shared among them.

All optical channels share power from the same pump laser.

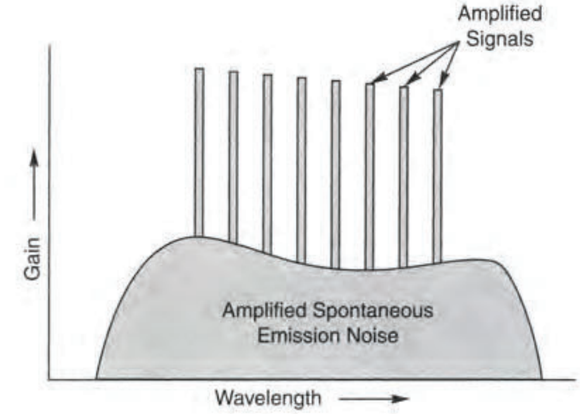
As long as the amplifier is operating in the small-signal regime, where there is power to spare, that's not a problem. However, adding more channels at the same input power can saturate the amplifier. The total output from the amplifier on all channels depends on the total input power on all channels. Figure 12.5 shows that the total output from the amplifier increases only 5 dB as the input signal increases from 10 dBµ to 100 dBµ, a sign of saturation. The effect is the same whether the total power is all on one channel or distributed among 10 input channels. At higher power levels the total available power saturates completely. If saturation limits the output from an amplifier to 100 mW at one wavelength, dividing the signal among 40 wavelengths would leave each channel with only 2.5 mW.

Adding more channels can saturate an erbium-fiber amplifier.

Another complication is that erbium-fiber amplifiers do not have uniform gain across their spectrum. As you can see in Figure 12.9, the gain peaks at 1535 nm for small signals when plenty of erbium atoms are available to amplify light. Saturation tends to reduce this differential gain, but it doesn't go away completely. Differential gain also builds up in a series of amplifiers, with the strong wavelengths getting stronger and the weak wavelengths getting weaker. This same phenomenon concentrates stimulated emission at a narrow range of wavelengths in a laser, but is undesirable when you're trying to amplify signals at multiple wavelengths.

Gain can be equalized across the erbium spectrum either by adding optical filters to reduce the peaks or by adding different types of amplifiers to boost the strength of the

FIGURE 12.12
Amplified spontaneous emission noise in a fiber amplifier.



weaker wavelengths. You'll learn more about how this works in Chapter 22, which covers optical network design.

Noise and Amplified Spontaneous Emission

As analog devices, optical amplifiers inevitably amplify any input noise that arrives with the signal. They also generate background noise by a process called *amplified spontaneous emission.*

Amplified spontaneous emission generates background noise in fiber amplifiers.

As you saw in Chapter 9, the light that starts simulated emission in a laser is emitted spontaneously when an excited atom releases its excess energy without outside stimulation. A laser resonator bounces this light back and forth through the laser cavity to amplify it by stimulated emission. Fiber amplifiers lack resonator mirrors, so they don't build up a laser beam in the same way. However, spontaneous emission that occurs within the fiber can be amplified if it's guided along the fiber, creating background noise.

Amplified spontaneous emission is spread across the whole operating range of a fiber amplifier, as shown in Figure 12.12. The power is much lower than at the amplified wavelengths, shown as peaks in Figure 12.12. However, it remains in the background and can be amplified in successive amplifiers. As a broadband noise, it's analogous to static in the background of an AM-radio signal.

Erbium-Doped Waveguide Amplifiers

Erbium can also be used in waveguide amplifiers.

Erbium atoms can amplify light by stimulated emission in rods or waveguides as well as in fibers. Rods are used in erbium lasers, and erbium-doped waveguides are used as optical amplifiers. The physics of erbium-doped waveguides are similar to those of erbium-doped fibers, although the erbium-doped waveguide confines the input signal and stimulated emission from the erbium atoms in a high-index region rather than in the core of a fiber.

The details of erbium-doped waveguide amplifiers differ considerably from those of erbium-doped fiber amplifiers. Waveguide amplifiers are much shorter than fiber amplifiers—centimeters instead of meters. This makes them more compact, but the erbium must be in higher concentrations in the waveguide to get reasonable gain in the C-band. (L-band operation is more difficult for waveguide amplifiers.) Even with the higher erbium concentration, erbium waveguides have considerably less small-signal gain than typical erbium-fiber amplifiers, so they are used for different applications.

Erbium-Amplifier Configurations

Erbium amplifiers are made for metro or long-distance applications.

In theory, erbium amplifiers can be made with a variety of optical characteristics. In practice, they generally fall into a few distinct configurations that meet specific commercial needs:

- *Metro amplifiers,* compact devices with moderate gain for use in metro networks, where only modest (10 to 20 dB) gain is needed.
- *Single-channel amplifiers* with higher gain.
- *WDM amplifiers* with higher gain and higher total power, able to amplify many channels simultaneously. These may span up to 100 km for terrestrial systems.
- *Ultra-long-haul and submarine amplifiers,* optimized to have very low noise and moderate gain. These are used with fiber spans shorter than those used in normal terrestrial long-distance systems.
- *Cable-television optimized amplifiers,* able to deliver higher total powers when signals are split among many outputs.

Other variations have been demonstrated in the laboratory. One of these is an erbium-fiber amplifier that demonstrates net gain between 1480 and 1530 nm, which are wavelengths not normally produced by erbium amplifiers. This requires pumping at 980 nm and suppressing amplified spontaneous emission, which otherwise would overwhelm the signal.

Other Doped Fiber Amplifiers

The success of the erbium-doped fiber amplifier and its compatibility with wavelength-division multiplexing enabled the telecommunications industry to shift long-distance fiber transmission from 1310 nm to the region surrounding 1550 nm. However, the broad low-loss window in low-water fibers extends from around 1260 to 1675 nm, far beyond the limits of erbium fiber. That leaves plenty of room for other optical amplifiers, especially if *coarse wavelength-division multiplexing* (CWDM) widely separates transmission wavelengths.

The International Telecommunications Union has divided the spectrum from 1260 to 1675 nm into a series of optical bands, listed in Table 12.1. Doped fiber amplifiers are available for only a few of them, but both Raman fiber amplifiers and semiconductor optical amplifiers—described below—can be used across the entire range.

Doped fiber amplifiers are available for only a few bands.

The other main types of fiber amplifiers are based on two other rare earth elements: praseodymium, which amplifies from about 1290 and 1315 nm in the *O-band,* and thulium, which amplifies between about 1450 and 1500 nm in the *S-band.* Commercial versions are available, but they're not widely used. They're expensive and few companies are that desperate for extra bandwidth.

Table 12.1 ITU Optical Bands

Band Name	Meaning	Wavelength (nm)	Amplifiers
O-band	Original	1260–1360	Praseodymium, Raman, semiconductor
E-band	Extended	1360–1460	Raman, semiconductor
S-band	Short	1460–1530	Thulium, Raman, semiconductor, erbium (experimental)
C-band	Conventional	1530–1565	Erbium, Raman, semiconductor
L-band	Long	1565–1625	Erbium, Raman, semiconductor
U-band	Ultra-Long	1625–1675	Raman, semiconductor

Raman Amplification in Fibers

Raman amplifiers shift energy from a strong pump beam to a weaker signal.

Raman amplification is fundamentally different from the amplification in erbium-doped fiber amplifiers. It involves a nonlinear interaction called *Raman scattering* that occurs between light and the atoms in a transparent solid. The interaction shifts energy from a strong pump beam to a weaker signal beam as both pass along the length of a fiber. The shift depends on the type of glass, but the wavelength depends on the pump beam; so Raman amplification can be used across a wide range of wavelengths by changing the pump wavelength.

You may remember Raman scattering from Chapter 5, where it was described as a nonlinear interaction that can shift light from the signal wavelength to other wavelengths. Raman amplification is a variation on that interaction called *stimulated Raman scattering*, which arises from the interaction among light at two different wavelengths and atoms in the glass fiber. As photons pass through the glass, they may be absorbed by atoms and almost instantly re-emitted. Before the atoms re-emit the photon, some of its energy may be transferred to vibrational modes of the solid, which changes the energy in the atoms. Thus the emitted photon sometimes has less energy than the absorbed photon.

In stimulated Raman scattering, a powerful pump beam illuminates the fiber, exciting many of the atoms, while a weaker signal beam at a longer wavelength simultaneously passes through the glass. If the wavelength separation corresponds to the vibrational energy, the signal wavelength can stimulate the atom to emit a photon at the *signal* wavelength, as shown in Figure 12.13. This process transfers energy from the strong pump beam to the weaker signal beam, amplifying the signal.

Raman amplification is available at a broad range of wavelengths, depending on the pump.

Raman amplification and ordinary amplification by stimulated emission differ in that stimulated Raman amplification shifts the wavelength of the pump beam by an amount that depends on the vibrational energy of the solid. This means that Raman amplification is not limited to specific wavelengths—it's limited to a range from the pump beam. Use a

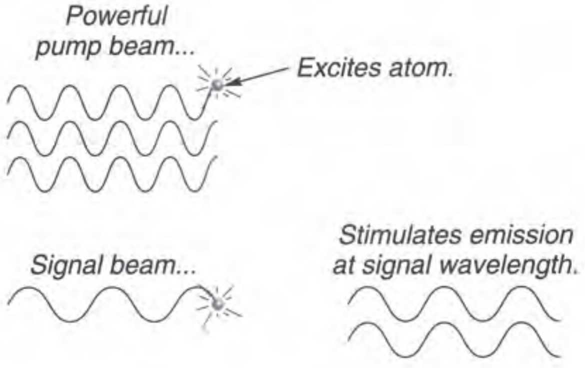


FIGURE 12.13
Stimulated Raman emission.

pump source at a different range, and you can amplify a different set of wavelengths. That means that Raman amplification can be used throughout the fiber transmission, as shown in Table 12.1.

The Raman bandwidth is measured in frequency units because it reflects a fixed energy difference. Figure 12.14 shows one example, the Raman gain of silica glass, which peaks at about 13 GHz. The wavelength shift depends on the initial wavelength. For example, a 13-GHz shift moves a 1250-nm pump about 70 nm to 1320 nm, while it moves a 1480-nm pump about 100 nm to 1580 nm. The Raman gain curve differs for glasses of other compositions.

Stimulated Raman scattering amplifies a light signal when a longer-wavelength photon stimulates an atom that has absorbed a shorter-wavelength photon to emit its extra energy at the longer wavelength. The atoms don't stay in the excited state long, so a powerful beam is needed at the shorter wavelength. But a powerful pump beam can transfer

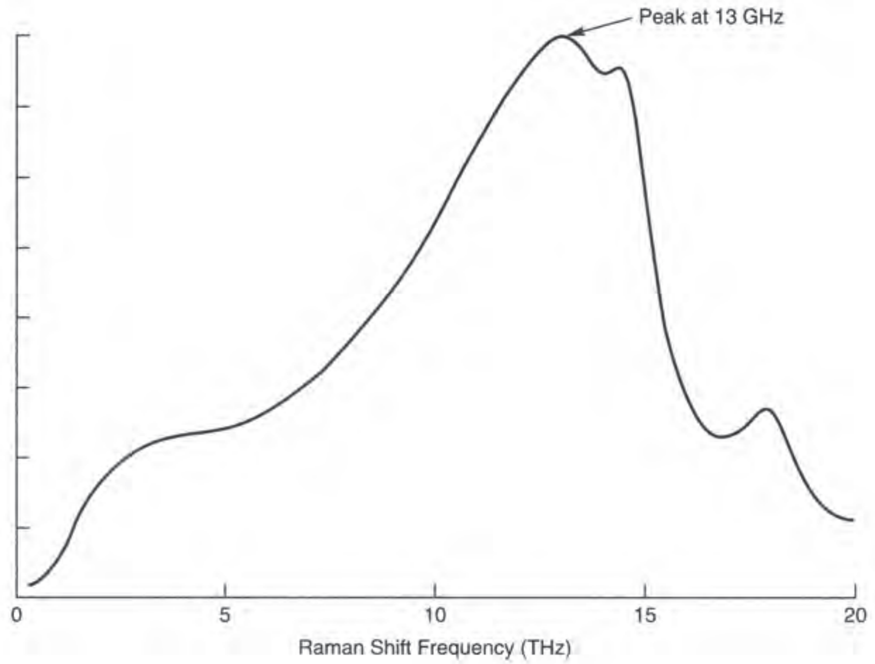
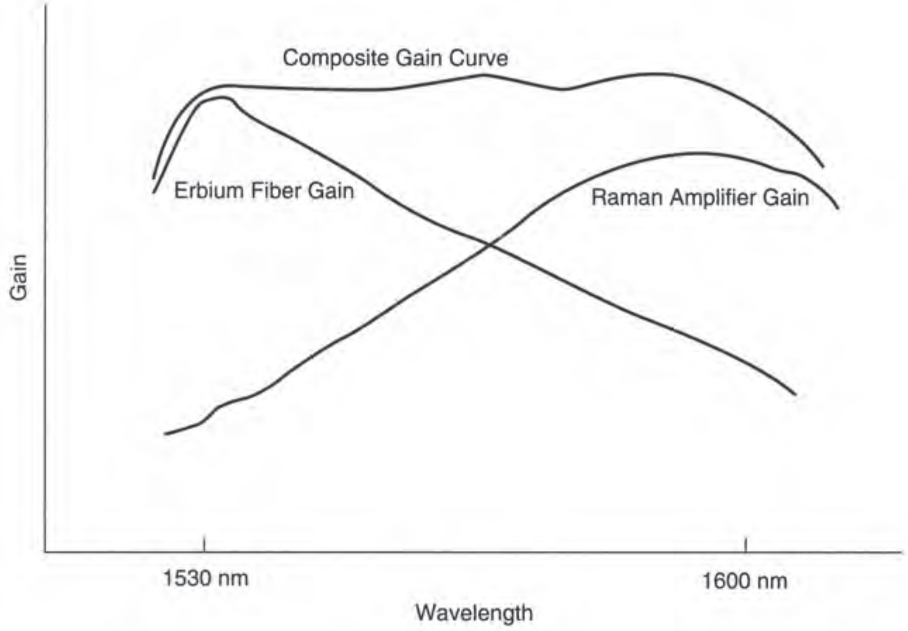


FIGURE 12.14
Raman gain of silica.

FIGURE 12.15
Raman gain equalizes spectrum of erbium amplifier to give more uniform composite gain.



energy to the longer-wavelength signal beam, amplifying it the same way stimulated emission amplifies the signal in an erbium-fiber amplifier.

Raman amplification works in transmission fibers.

Raman amplification works in ordinary silica fibers, although special fiber designs also can be used. It doesn't require adding any special light-emitting material to the fiber. However, Raman gain is low per length of fiber. The pump power must be at least several hundred milliwatts, and long lengths of fiber must be used. In practice, Raman amplification is performed along the length of a transmission fiber, although coils of fiber can be used as Raman amplification modules.

Like an erbium amplifier, a Raman amplifier can simultaneously amplify many wavelengths in its operating range. As you can see in Figure 12.14, the Raman gain peak is several terahertz, wide enough to span many optical channels in a WDM system. Raman amplifiers also have low noise. However, the overall gain of Raman amplifiers is lower than that of erbium amplifiers.

So far, the main applications for Raman amplification are in hybrid devices that include Raman and erbium amplification stages. C-band erbium amplifiers have their peak gain at the short end of that band, near 1535 nm, but silica-fiber Raman amplifiers have peak gain at the long end of their range. Adding the two gain curves together produces uniform amplification across a much wider range of wavelengths than could be obtained from either erbium or Raman amplification alone, as shown in Figure 12.15.

In a hybrid amplifier, the Raman pump source is located at the same point as the erbium-doped fiber amplifier. As shown in Figure 12.16, a coupler directs the Raman pump light down the input fiber, where it transfers energy to the weak input signal. The gain is highest at wavelengths where the erbium-fiber gain is low. Then the amplified signal enters the erbium amplifier, which has higher gain where the Raman amplification is smallest. In this way the two amplifiers add together to give more uniform gain than either one alone.

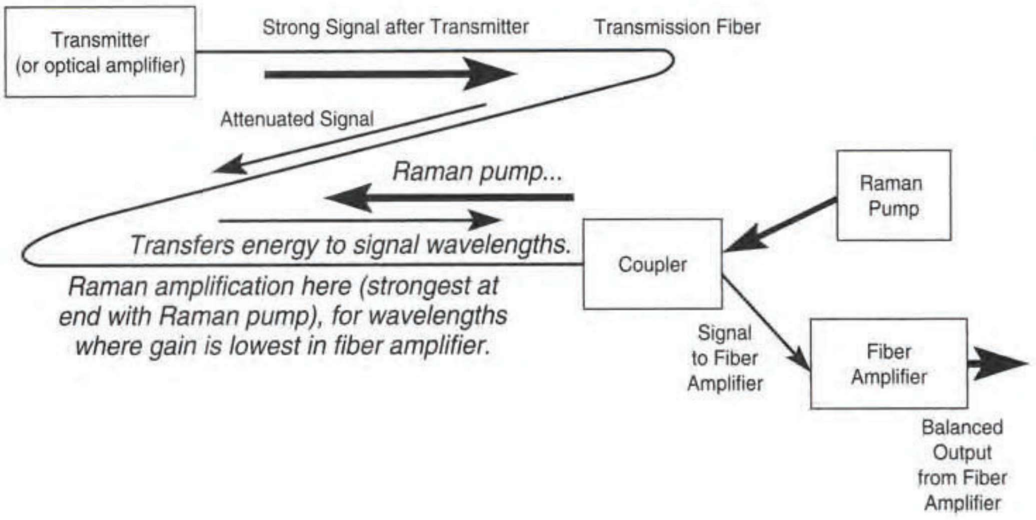


FIGURE 12.16
Layout of hybrid Raman/erbium amplifier.

Semiconductor Optical Amplifiers

In principle, any laser can serve as an optical amplifier. Just remove the mirrors and send a signal through it, as you send a signal through a fiber amplifier. Semiconductor diode lasers are logical candidates for this approach, particularly because they are the primary light sources for most fiber-optic transmitters used in applications that require amplification. Diode lasers can amplify light over a range of wavelengths and are available for the whole region from 1250 to 1675 nm as shown in Table 12.1. They have very high gain per unit length, so compact devices can provide the required amplification. They can be integrated on a semiconductor substrate with other optical components, with planar waveguides transporting the light between components like the cores of optical fibers. They also can switch and control optical signals and convert them to other forms. However, they are not as well developed as erbium-doped fiber amplifiers.

Semiconductor optical amplifiers are semiconductor lasers without reflective cavities.

Characteristics of Semiconductor Optical Amplifiers

Semiconductor optical amplifiers share some operating characteristics with other optical amplifiers. They have a characteristic gain that is high for small input signal levels but that saturates at high powers. They also have a peak output power and can amplify light across a range of wavelengths.

A crucial difference comes from their mode of operation. As in semiconductor lasers, stimulated emission comes from carrier recombination at the junction layer. This recombination occurs only when a current is flowing through the device. In a semiconductor optical amplifier, this current can be modulated, turning the amplifier off and on. When the amplifier is off, it absorbs the input signal, so nothing gets through. When the amplifier is on, it generates an amplified output signal. Thus a semiconductor optical amplifier can modulate the signal as well as amplify it. (Erbium-doped fiber amplifiers also block light when the pump laser is off, but it's impractical to modulate them by turning the pump laser off and on.)

Semiconductor optical amplifiers can switch signals off and on and be integrated with other optical components.

A second crucial difference is structural. Fiber amplifiers are fibers, discrete devices that are physically separate from transmission fibers, but which can easily be coupled to other fibers. Semiconductor optical amplifiers are planar devices—thin, flat layers like the light-emitting stripes in semiconductor lasers. As such they integrate well with other planar devices and planar waveguides, making it possible to combine them with other components on a monolithic substrate like an electronic integrated circuit. (Optical integration isn't as easy as electronic integration, but that's another matter.)

Limitations of Semiconductor Optical Amplifiers

Light is hard to transfer from an optical fiber to a semiconductor optical amplifier.

The structural difference between a fiber and a semiconductor optical amplifier underlies a major drawback of the semiconductor amplifier. It's easy to transfer light from a fiber to a fiber, or from a planar waveguide to another planar waveguide. It's not very hard to transfer light from a laser stripe into the core of a single-mode fiber. However, it's difficult to transfer light from a fiber into a planar waveguide.

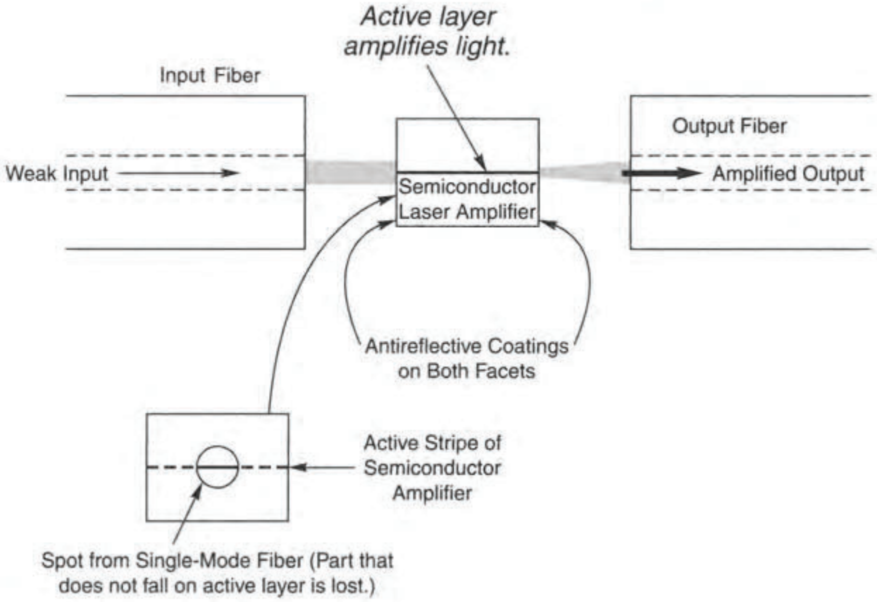
The problem is the geometry, shown in Figure 12.17, which illustrates a semiconductor optical amplifier placed between a pair of fibers. The idea is to focus light from the single-mode input fiber onto the active stripe, amplify it in the semiconductor amplifier, then focus the intense output beam into the core of the output fiber. Squeezing the beam emerging from the 9-μm core of a single-mode fiber into an active stripe less than 1 μm thick is a serious problem.

Noise levels are higher in semiconductor amplifiers than in fiber amplifiers.

Other problems center on the operating features of semiconductor optical amplifiers. One issue is a higher noise level than erbium-doped fiber amplifiers, an important problem because noise accumulates through a series of optical amplifiers.

Semiconductor optical amplifiers can respond very quickly to changes in the input signal, but this is a mixed blessing. The response is so fast that the output changes as intensity of analog input signals changes—and the gain changes with it as a function of

FIGURE 12.17
Semiconductor laser amplifier.



input power. Signal gain might be 30 dB when signal intensity is low but only 20 dB when intensity is high, leading to serious distortion of analog signals.

A more subtle problem is light reflection from the ends of the laser cavity. The high refractive index of semiconductor materials makes it difficult to completely suppress reflection from the facets at the edges of the wafer. Such reflections can introduce instabilities and noise into an optical amplifier; semiconductor optical amplifiers are particularly vulnerable to this effect because of their high gain.

An additional problem is that semiconductor optical amplifiers are sensitive to the polarization of input light, so they amplify light of different polarizations by different amounts. Standard fibers do not control the polarization of light they transmit, so uncontrolled fluctuations in polarization—normally not an issue with fiber-optic systems—can affect the amount of amplification, so the gain depends on an uncontrollable factor, which can introduce noise.

These problems have limited the use of discrete semiconductor optical amplifiers as in-line amplifiers in telecommunications systems. However, the ability to integrate semiconductor optical amplifiers with other components makes them attractive for other uses.

Integrated Semiconductor Optical Amplifiers

Semiconductor amplifiers can be integrated with planar waveguide optics.

Semiconductor optical amplifiers can be integrated with other planar optical components, an advantage that overcomes many of their disadvantages. Figure 12.18 shows how a semiconductor optical amplifier fits between an input waveguide that delivers an optical signal and a planar coupler that divides the output signal in half. The amplifier region differs from the passive components—the waveguide and the coupler—in two important ways. The amplifier region is doped to produce a junction layer in the plane of the waveguide, which is not present in the passive guides or coupler. A bias voltage also is applied across the semiconductor amplifier, causing current to flow and producing recombination at the junction layer. When the input signal passes through the amplifier zone, it stimulates emission from the recombining carriers and is amplified. Integrating the semiconductor amplifier with the waveguide prevents reflections at the ends of the amplification zone and avoids coupling losses within the integrated structure.

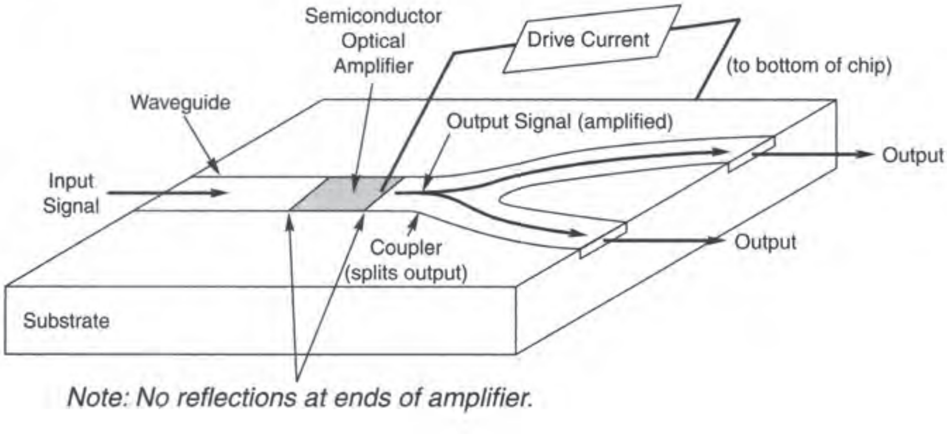


FIGURE 12.18 *Integrated semiconductor optical amplifier.*

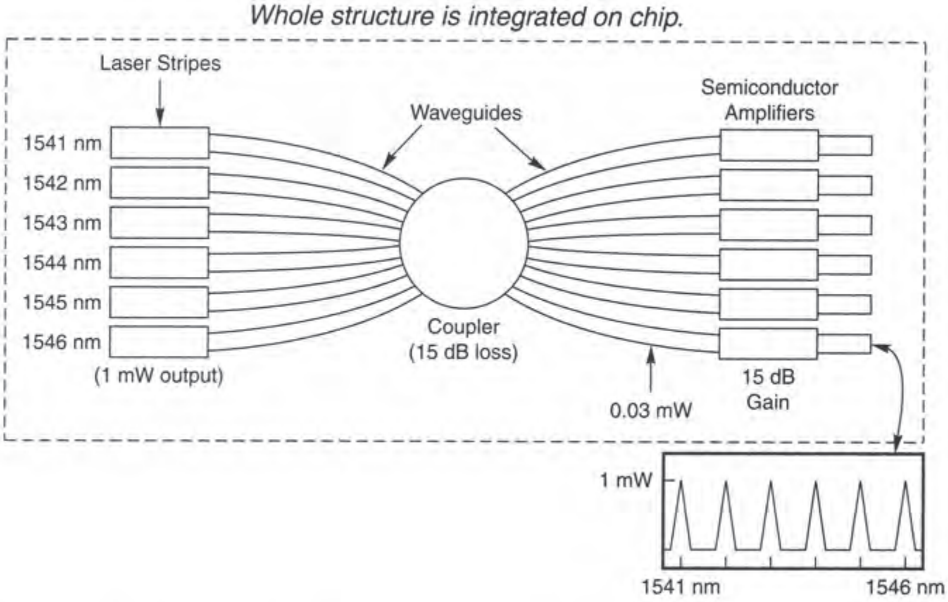


FIGURE 12.19 *Semiconductor amplifier integrated with laser array and waveguide coupler.*

Figure 12.18 shows only a few components of the integrated semiconductor optical amplifier, but you can add more if you have room on the wafer. Components that can be made in waveguide form include couplers, switches, and modulators (described in Chapters 15 and 16), although semiconductor optical amplifiers also can perform some of these functions.

Figure 12.19 shows how this capability might be used in practice. You need to multiplex the outputs of six diode lasers emitting at different wavelengths and then distribute the combined WDM signal to six locations. A simple approach is to mix the signals in a single device called a *star coupler*, shown at the middle, but the coupler and dividing the signals among the six identical outputs cause a 15-dB loss, leaving only a weak signal at each output. In this example, an initial 1-mW output from each output drops 15 dB as it passes through the coupler and then is amplified another 15 dB by the semiconductor optical amplifier, so each output includes 1 mW of light at each wavelength.

Switching, Modulation, and Signal Control

Semiconductor optical amplifiers can modulate and switch signals.

Semiconductor optical amplifiers respond to changes in drive current as quickly as diode lasers. This means that you can modulate the gain and hence the output signal by changing the drive current passing through the optical amplifier. This is a degree of signal control impractical with erbium-doped fiber amplifiers.

This type of control can be used in various ways. One simple example is switching signals in output waveguides. An input signal can be split between a pair of waveguides, each equipped with an in-path integrated amplifier. Switching the amplifier on delivers a signal to that waveguide; switching the amplifier off turns off the signal.

Much more elaborate arrangements are also possible. The gain of a semiconductor amplifier can be made to vary with the intensity of an input light signal, so the light serves to modulate the amplifier output. This arrangement can be used to convert an input signal to another wavelength if a signal at one wavelength is modulating the gain in an amplifier that is amplifying light at a different wavelength. You'll learn more about these possibilities below as you learn about optical regeneration and wavelength conversion.

Optical Regeneration

Optical regeneration has been demonstrated in the laboratory, and 2-R versions—which amplify and reshape pulses but do not retime them—have been introduced as products. The main potential application of optical regeneration is in high-speed transmission.

As transmission speeds increase, dispersion and other mechanisms reduce the distance signals can be transmitted without regeneration. Terrestrial 10-Gbit/s systems usually are limited to about 600 km, although careful design can stretch that limit for undersea systems. The impact of chromatic dispersion increases with the square of data rate, so a fiber that can transmit 10 Gbit/s for 1000 km can only transmit 40 Gbit/s for 62.5 km before regeneration. Electronic regeneration is straightforward, if expensive, at 10 Gbit/s, but optical regeneration is the only technology likely to be cost-effective at 40 Gbit/s and above.

Optical regeneration will be needed at 40 Gbit/s.

The ideal response for an optical regenerator is generating zero output for an input signal below the desired discrimination level, which is presumed to be noise, and a high output above that level, which is presumed to be an "on" signal. This replicates the function of an electronic decision circuit and usually is accomplished by combining nonlinear response with amplification. The nonlinear response peaks at the highest powers, effectively suppressing low-level signals. These principles have been used in a variety of 2-R optical regenerators, but the details are beyond the scope of this book.

3-R regeneration requires detection and recovery of a clock signal from part of the input signal. One approach is based on wavelength conversion in a semiconductor optical amplifier (a process described below) within an optical cavity that helps reshape the pulses. Modulating the amplified signal with the regenerated clock signal retimes the output.

Wavelength Conversion

The development of wavelength-division multiplexing and optical networking created a need to convert signals from one wavelength to another. As you learned earlier, one approach is simply to regenerate the input signal in an electro-optic repeater with the transmitter output at a wavelength different than the receiver input. This technology is well established and can generate tunable output if the transmitter uses a tunable laser. However, like other electro-optic repeaters, the OEO (opto-electro-optical) wavelength converter or transponder inherently depends on the input transmission format and line rate.

An alternative is all-optical wavelength conversion, which ideally should be independent of bit rate or signal format, require little power, not degrade the signal, and have tunable output. All-optical conversion devices could be used in a "transparent" network, in which

THINGS TO THINK ABOUT

A Transparent Network

Optical regeneration and wavelength conversion are among a family of technologies created during the telecommunications bubble for an "all-optical network." The goal was to manipulate signals in optical form without converting them to electronic form, building on the success of optical amplifiers. Developers began talking about "transparent" networks, where signals would remain in the form of light throughout, so—at least in theory—light could shine straight through the system. It seemed like a good idea at the time, when the demand for bandwidth seemed to be expanding indefinitely. But today it is unclear what role these technologies will play in the post-bubble world.

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signals are processed entirely in optical form without regard for the signal format or data rate. Many types are being developed, which fall into a few broad categories:

All-optical wavelength conversion should be independent of bit rate and signal format.

- *Laser converters* direct a strong input signal at one wavelength into a laser emitting continuously at another wavelength, reducing the power generated at the second wavelength. This converts the signal to the second wavelength, but essentially replaces the 1s with 0s. It also suffers from other drawbacks, including a need for high input power and a speed limit of about 10 Gbit/s.
- *Nonlinear converters* use nonlinear interactions of the optical signal with other light to produce new wavelengths. These include four-wave mixing and cross-phase modulation, described in Chapter 5. Success requires special materials that efficiently convert the light to other wavelengths (and the efficiency often is low), but the process is very fast.

An input signal can modulate output of a semiconductor amplifier at a different wavelength.

- *Optically controlled amplifiers* use a relatively weak input signal to modulate a semiconductor optical amplifier as it amplifies a second wavelength from a continuous laser. The input signal interacts with the semiconductor, changing its gain or refractive index. Changes in the refractive index, in turn, shift the phase of the transmitted light, an effect that can be used to modulate the intensity of the amplified light. The configurations required are complex, but the process is very fast and results have been encouraging.

What Have You Learned?

1. Signals require amplification because they fade with distance.
2. Amplification increases signal amplitude but is not supposed to change the shape of the received signal. Regeneration reproduces the original signal, removing noise and distortion it picks up during transmission.
3. Electro-optic repeaters convert a weak optical signal to electronic form, amplify it, and use the electronic output to drive another optical transmitter. They

consist of a receiver and a transmitter back to back. Today simple electro-optic repeaters are rarely used in the middle of a transmission line.

4. Regenerators typically are used at the ends of a transmission line or at switching nodes. They are generally part of electronic switching systems that redirect signals. Regeneration usually is done electronically, but optical regeneration has been demonstrated. 3-R regeneration (re)amplifies, reshapes, and retimes pulses; 2-R regeneration does not retime pulses.
5. Optical amplifiers directly increase the strength of an input optical signal by using the laser principle (stimulated emission). They are insensitive to data rate or signal format, and can amplify separate signals at multiple wavelengths.
6. Requirements for amplification, regeneration, and wavelength conversion depend on system design.
7. Optical amplifiers may be used immediately after a transmitter, in a transmission line, as preamplifiers, or to offset component loss.
8. Gain and output power of optical amplifiers depend on the input power and the amplifier design. Gain saturates at high total powers.
9. Optical amplifiers can simultaneously amplify many optical channels in their gain band, but the total power on all channels is limited. Gain is not uniform across the wavelength range and must be equalized in WDM systems.
10. Erbium-fiber amplifiers are the most common optical amplifiers, with gain from about 1530 to 1625 nm. In practice, they are used as C-band amplifiers from 1530 to 1565 nm and L-band amplifiers from 1570 to 1605 nm.
11. The pump bands for erbium-fiber amplifiers are 980 and 1480 nm.
12. Amplified stimulated emission is the major source of noise in erbium-fiber amplifiers.
13. Raman amplification transfers energy from a powerful pump beam to a weaker signal beam at a longer wavelength. The amplified wavelength is offset from the pump wavelength by an amount that depends on the fiber material. This makes Raman amplification available at a wide range of wavelengths.
14. Raman amplification in transmission fibers can be added to erbium amplifiers to give uniform total gain over a range of wavelengths.
15. Semiconductor optical amplifiers amplify light passing through a semiconductor junction as long as drive current passes through the junction. They are available at more wavelengths than doped fiber amplifiers and can be integrated with other waveguide components, but have performance limitations.
16. OEO transponders or repeaters can convert signal wavelength by converting the input signal to electronic form and generating a new output signal at a different wavelength. Signal wavelength also can be converted by using the signal to modulate gain of a semiconductor optical amplifier that is amplifying light at the desired wavelength.

What's Next?

Chapter 13 moves on to the connectors and splices that bridge the gaps between optical fibers, and connect them to transmitters, receivers, and other components.

Further Reading

P. C. Becker, et al., *Erbium Fiber Amplifiers: Fundamentals and Technology* (Academic Press, 1999)

International Engineering Consortium, "Raman amplification design in wavelength division multiplexing (WDM) systems tutorial," *http://www.iec.org/tutorials/raman*

Ulf Österberg, "Semiconductor optical amplifiers and wavelength conversion," Chapter 10 in Michael Bass, ed., *Handbook of Optics Vol. 4, Fiber Optics & Nonlinear Optics* (McGraw-Hill, 2001)

Yan Sun, et al., "Optical Fiber Amplifiers for WDM Optical Networks," *Bell Labs Technical Journal 4,* pp. 187–206 (Jan–Mar 1999)

Questions to Think About

1. An erbium-fiber amplifier has small-signal gain of 30 dB. If it is operated in that high-gain mode, how far can signals travel between amplifiers if fiber loss is 0.25 dB/km? Neglect all other losses.
2. An erbium-fiber amplifier is operated with higher total input power, so its gain is only 12 dB. What amplifier spacing is needed in the same type of fiber? Neglect all other losses.
3. Signals require regeneration after passing through five of the high-gain amplifiers in Question 1, but not until they have passed through 100 of the low-gain amplifiers in Question 2. What are the total spans between repeaters for the two systems?
4. An erbium-fiber amplifier can generate a maximum all-line output of 20 dBm. The input on each of 40 optical channels in its operating range is −20 dBm. If the maximum all-line output can be divided equally among all channels (an unrealistically optimistic assumption), what is the highest possible gain?
5. Gain in a C-band erbium-fiber amplifier varies 4 dB across the range from 1530 to 1565 nm. If you don't use any equalization, and the output power after passing through a series of amplifiers can vary no more than 25 dB, what is the longest series of amplifiers you can use? Assume the variation is the same for each amplifier in the series.
6. Equalization reduces the range of gain in a C-band erbium-fiber amplifier to 0.5 dB. Making the same assumptions, how many amplifiers can the signal pass through?

7. You want to install large-effective-area fiber in part of a system transmitting 40 optical channels to reduce nonlinear interactions between the wavelengths. Where should you install it and why?

Chapter Quiz

1. Amplifiers are needed

a. to overcome the threshold for driving an optical fiber.

b. to compensate for fiber attenuation.

c. only with copper-wire systems.

d. to convert optical signals into electronic form.

2. What is the difference between amplification and regeneration?

a. Regeneration retimes and cleans up the signal as well as amplifying it.

b. Regeneration does not increase signal power.

c. There is no difference.

d. Regeneration is done optically; amplification is electronic.

3. What can optical amplifiers do that electro-optic repeaters cannot?

a. compensate for fiber dispersion

b. retime signals

c. operate at a wide range of signal speeds without adjustment

d. convert signal wavelengths

4. What can an electro-optic repeater do that an erbium-doped fiber amplifier cannot do?

a. compensate for fiber dispersion

b. retime signals

c. operate at a wide range of signal speeds without adjustment

d. extend transmission distance

e. convert an input signal to a different wavelength

5. Erbium-doped fiber amplifiers operate at which of the following wavelengths?

a. 1530 to 1605 nm

b. 1280 to 1330 nm

c. 750 to 900 nm

d. at all important fiber windows

e. only at exactly 1550 nm

6. How many different wavelengths can you transmit using a fiber amplifier with operating range of 1540 to 1565 nm if your signals are spaced at the 100-GHz spacing recommended by the International Telecommunications Union? (Remember the speed of light is 299,792,458 m/s.)

a. 8
b. 16
c. 25
d. 31
e. 32

7. The gain of an erbium-doped fiber amplifier is 5 dB higher at 1535 nm than at the other wavelengths between 1540 and 1560 nm that it transmits. What do you need to do to equalize gain?

a. nothing; gain will saturate eventually
b. add a filter that attenuates 1535-nm light by 5 dB and transmits the other wavelengths without loss
c. add a filter that attenuates all wavelengths but 1535 by 5 dB
d. replace the amplifier; it's defective

8. Fiber amplifiers and semiconductor optical amplifiers both increase signal strength by

a. spontaneous emission of light at the signal wavelength.
b. stimulated emission of light at the signal wavelength.
c. Raman amplification of the signal light.
d. converting the light into electrical form and amplifying the current.
e. They share no common mechanism.

9. How does a semiconductor optical amplifier differ from a semiconductor laser?

a. Only a laser can generate stimulated emission.
b. Only an amplifier can generate stimulated emission.
c. An amplifier does not require an electric drive current.
d. An amplifier has nonreflective ends.
e. There is no difference.

10. How does a semiconductor optical amplifier differ from a fiber amplifier?

a. A semiconductor amplifier can modulate the light it amplifies more easily.
b. A semiconductor amplifier can be integrated on a wafer with other planar optical components.
c. Gain per unit length is higher in a semiconductor amplifier.
d. Semiconductor amplifiers are not widely used as in-line amplifiers.
e. All of the above.

11. How can Raman amplification supplement an erbium-doped fiber amplifier?

a. Raman amplification has higher gain.
b. Raman amplification can reduce noise.
c. Raman amplification can equalize gain across the erbium-fiber operating range.
d. Raman amplification has gain outside the erbium-fiber operating range.
e. It sounds fancier so the supplier can make more money by putting one in the same box and pretending it does something.

12. Which of the following could not be used to extend the transmission range of an O-band system transmitting at 1300 nm?

a. an electro-optic repeater
b. an electro-optic regenerator
c. a semiconductor optical amplifier
d. an erbium-doped fiber amplifier
e. a Raman fiber amplifier

13. How could you convert an input signal at 1540 nm to an output signal at 1580 nm without converting the signal to electronic form?

a. by using the input signal to illuminate a semiconductor optical amplifier that is amplifying a 1580-nm signal
b. by feeding the 1540-nm input to a C-band erbium-fiber amplifier and using the output to drive an L-band erbium amplifier
c. by using the 1540-nm input as the pump Raman amplification of a 1580-nm signal
d. with an erbium waveguide amplifier that spans both wavelengths
e. by using an electro-optic repeater with a 1580-nm laser transmitter

14. What stage is present in a 3-R optical regenerator that is absent in a 2-R optical regenerator?

a. amplification
b. retiming
c. reshaping
d. electronic conversion
e. parity checking

CHAPTER

13

Connectors and Splices

About This Chapter

Connectors and splices link the ends of two fibers both optically and mechanically. The two are not interchangeable. A *connector* is mounted on the end of a cable or optical device so it can be attached to other cables or devices. Like electrical connectors, fiber-optic connectors can be plugged and unplugged. In contrast, *splices* are permanent junctions between a pair of fiber ends. The cables attached to your television and stereo have connectors on the end so they can be plugged into other components. Splices are the optical equivalent of permanent solder joints.

This chapter starts by explaining their applications and their common operating principles, then describes connector properties and types, and splicing. Chapter 14 will cover couplers, which in fiber optics are quite different from connectors and splices.

Applications of Connectors and Splices

Connectors and splices both make optical and mechanical connections between a pair of fibers. Their job is to transfer light efficiently and hold the fibers together. They differ in how they do that job, and as a result they have different places in fiber-optic systems. You can think of connectors as being designed for connections that may have to change, while splices are used for permanent connections.

Electrical connectors are common in modular electronic, audio, or telephone equipment, although you may think of them as plugs and jacks. Their purpose is to connect two devices electrically and mechanically, such as a cable and a stereo receiver. A plug on the cable goes into a socket in the back of the receiver, making electrical contact and holding the cable in place. Both the electrical and mechanical junctions are important. If the cable falls out, it can't carry signals; if the electrical connection is bad, the mechanical connection doesn't do any good. (You'll understand the problem all too well if you've ever tried to find an intermittent fault in electronic connectors.)

Connectors make temporary connections among equipment that may need to be rearranged.

Fiber-optic connectors are intended to do the same job, but the signal being transmitted is light through an optical fiber, not electricity through a wire. That's an important difference because, as you learned earlier, the way light is guided through a fiber is fundamentally different from the way current travels in a wire. Electrons can follow a convoluted path through electrical conductors (wires) if the wires make good electric contact somewhere. However, fiber cores must be precisely aligned with each other and touch to transfer optical signals efficiently—just how precisely you'll see later.

Electrical connectors are used for audio equipment and telephones because the connections are not supposed to be permanent. You use fiber connectors for the same reason. For permanent connections, you splice or solder wires, and you splice optical fibers. Permanent connections have some advantages, including better mechanical stability and—especially for fiber optics—lower signal loss. However, those advantages come at a cost in flexibility; you don't want to cut apart a splice each time you move a computer terminal or telephone.

Splices and connectors are used in different places.

Fiber-optic connectors and splices are far from interchangeable. Connectors are normally used at the ends of systems to join cables to transmitters and receivers. Connectors are used in patch panels where outdoor cables enter a building and have their junctions with cables that distribute signals within the building. They are used where configurations may need to be changed, such as at telecommunication closets, equipment rooms, and telecommunication outlets. Examples include the following:

- Interfaces between devices and local area networks
- Connections with short intrabuilding data links
- Patch panels where signals are routed in a building
- The point where a telecommunication system enters a building
- Connections between networks and terminal equipment
- Temporary connections between remote mobile video cameras and recording equipment or temporary studios

Splices are used where junctions are permanent or where the lower loss of splices is critical. For example, long cable runs are spliced because the cable segments should never need to be disconnected. Splice loss is lower, and splices are smaller and fit into cables better. Splices generally are stronger, and with the right equipment are easier to install in the field.

In practice, this means that you usually put connectors on the ends of cables, and splices in the middle. Broken cables are repaired by splicing the fibers and mending the cable in the field. Connectors can be installed in the field or in the factory, but factory installation is easier. Sometimes the two techniques are used together to speed installations. For example, a cable may be connected to equipment in a building by splicing a fiber from the cable to a fiber pigtail attached to a factory-mounted connector.

The distinction between connectors and splices is not always a sharp one. Certain types of splices that hold fibers together mechanically can be taken apart and reused. However, you can't simply unsnap the end of the cable from the splice, as you can remove a phone cable from a wall jack. Rather it's more like opening up the wall jack and unscrewing the connections to the house wiring.

Fiber-to-Fiber Attenuation

The same basic considerations apply to transferring light between fibers in both connectors and splices. We will cover these first for connectors, then recall these principles when we discuss splices. To keep things simple, we will talk mostly about splices or connectors that transfer light between pairs of fibers, not between a fiber and a transmitter or receiver. However, the same principles apply whether light is being transferred from a light source into a fiber, or from a fiber into a detector.

The most important optical parameter of fiber connectors and splices is attenuation, the fraction of the signal power that is lost in passing through. *Loss* is measured in decibels for a mated pair of connectors or for a complete splice—that is, loss is the difference between the light entering the input fiber and the light exiting the output fiber. It isn't meaningful to talk about the loss of one connector or half a splice.

Loss is the most important optical characteristic of connectors and splices.

Typical attenuation is a fraction of a decibel for connectors and under 0.1 dB for splices. The loss depends on mechanical tolerances, and tends to be higher for small-core single-mode fibers than for larger-core multimode fibers. Generally loss is specified as a "typical" value rather than a maximum or minimum. Manufacturers specify attenuation for specific fiber types under the assumption that the same type of fiber is used on both sides of the splice or connector. As you will learn later in this chapter, mismatched fibers can have much higher loss.

The rest of this section is based on the assumption that a splice or connector joins the ends of two fibers. Connectors also can be mounted on transmitters, receivers, and other components, but although details differ, the principles are the same. This section concentrates on loss mechanisms that are important for connectors. The same principles apply to splices, but some effects are more important for one type of fiber connection than the other.

Connector and splice losses are caused by several factors, which are easier to isolate in theory than in practice. These factors stem from the way light is guided in fibers. The major ones are as follows:

- Overlap of fiber cores
- Alignment of fiber axes
- Fiber numerical aperture
- Fiber spacing
- Reflection at fiber ends

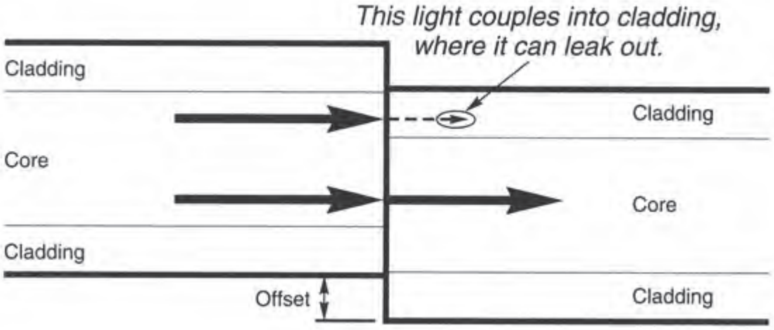
These factors interact to some degree. One—overlap of fiber cores—is really the sum of many different effects, including variation in core diameter, concentricity of the core within the cladding, eccentricity of the core, and lateral alignment of the two fibers.

Overlap of Fiber Cores

Offset of fiber cores by 10% of their diameter can cause a 0.6-dB loss.

To see how core overlap affects loss, look at Figure 13.1, where the end of one fiber is offset from the end of the other. For simplicity, assume that light is distributed uniformly in the cores of identical fibers and that the two fibers touch each other and are otherwise well

FIGURE 13.1
Offset fibers can cause loss.



aligned. The loss then equals the fraction of the input-fiber core area that does not overlap with that of the output fiber. If the offset is 10% of the core diameter, the extra loss is about 0.6 dB.

Mismatches of emitting and collecting areas also occur if core diameters differ. Suppose that the fibers were perfectly aligned but that the 50-μm nominal fiber core diameter varied within ±3 μm, a tolerance specified on a typical commercial graded-index fiber. With simple geometry, you can calculate the loss for going from a fiber with core diameter d_1 to one with core diameter d_2. (You also can use radius if you want—the factor of two differences from diameter cancels out—but usually core diameter is what's specified.) The relative difference in area is

$$\text{Loss} = \frac{(d_1^2 - d_2^2)}{d_1^2}$$

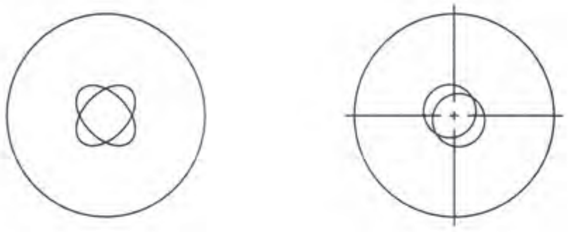
For the worst case, going from a fiber with a 53-μm core to one with a 47-μm core, the difference is a factor of 0.21. If light was distributed uniformly through the core, that fraction of the light, about 1 dB, would be lost. Fortunately things are rarely that bad, because light normally is concentrated toward the center of the core, and core diameter rarely varies as much as the maximum allowed by the specifications.

The same principles apply for single-mode fiber, but in that case the critical dimension is mode-field diameter, which is typically slightly larger than core diameter. The formula for relative loss is the same, but the tolerances are much tighter because single-mode fibers have much smaller cores. For example, a nonzero dispersion-shifted fiber has mode-field diameter of 8.4 ± 0.5 μm at 1550 nm. Although the diameter tolerance is very small, going from the largest fiber that meets these tolerances to the smallest can be costly in loss:

$$\text{Loss} = \frac{(8.9^2 - 7.9^2)}{(8.9)^2} = 0.21$$

The result is essentially the same as for the maximum variation in core diameter of 50-μm fiber, 0.21, or 1 dB. As with multimode fiber, things are rarely this bad in practice. A single-mode beam is most intense at the center of the core, and most specified single-mode connector losses are 0.1 to 0.5 dB.

It's vital to keep track of the fiber type. Serious problems result if the fiber types are mismatched, causing signals to go from a multimode fiber into a single-mode fiber. Going


a. Elliptical Cores

b. Off-Center Cores

FIGURE 13.2
Losses arise when cores are elliptical or off center.

from a 62.5-µm graded-index fiber core to a single-mode fiber with 9-µm core results in a 97.9% drop in area, which produces a 17-dB loss if the light is distributed evenly. Even going from a 62.5-µm to a 50-µm core graded-index fiber reduces area 36%, corresponding to a 1.9-dB loss if the light is evenly distributed. As mentioned earlier, light is more concentrated at the center of the core, so losses usually aren't quite that bad, although still substantial.

Core mismatches also can arise from other factors. The core may be slightly elliptical or slightly off-center, as shown in exaggerated scale in Figure 13.2. Variations in the fiber cladding dimensions can lead to misalignment in aligning the core with other fibers.

Alignment of Fiber Axes

As you learned earlier, light must be directed straight along the fiber axis to be guided through a fiber. This is very different from electronic connections, which only need to make the attached wires touch each other for electrons to pass between them. This makes alignment of fiber axes critical to low optical connection loss.

Figure 13.3 shows how losses from fiber alignment increase with the angle between the two fibers. As the angle θ between the fibers increases, light from the first fiber enters the second fiber at a larger angle to the axis. Although a light ray passing directly along the axis may still fall within the fiber's acceptance angle, other rays can leak out. Losses are worst for fibers with small numerical apertures, while fibers with larger NAs can collect light entering over a wide range of angles. A good connection should align the two fibers very closely.

Angular misalignment of fiber ends can cause significant losses.

Fiber Numerical Aperture

Differences in NA between fibers also contribute to connection losses. If the fiber receiving the light has a smaller NA than the one delivering the light, some light will enter it in

Differences in NA can contribute to connection losses.

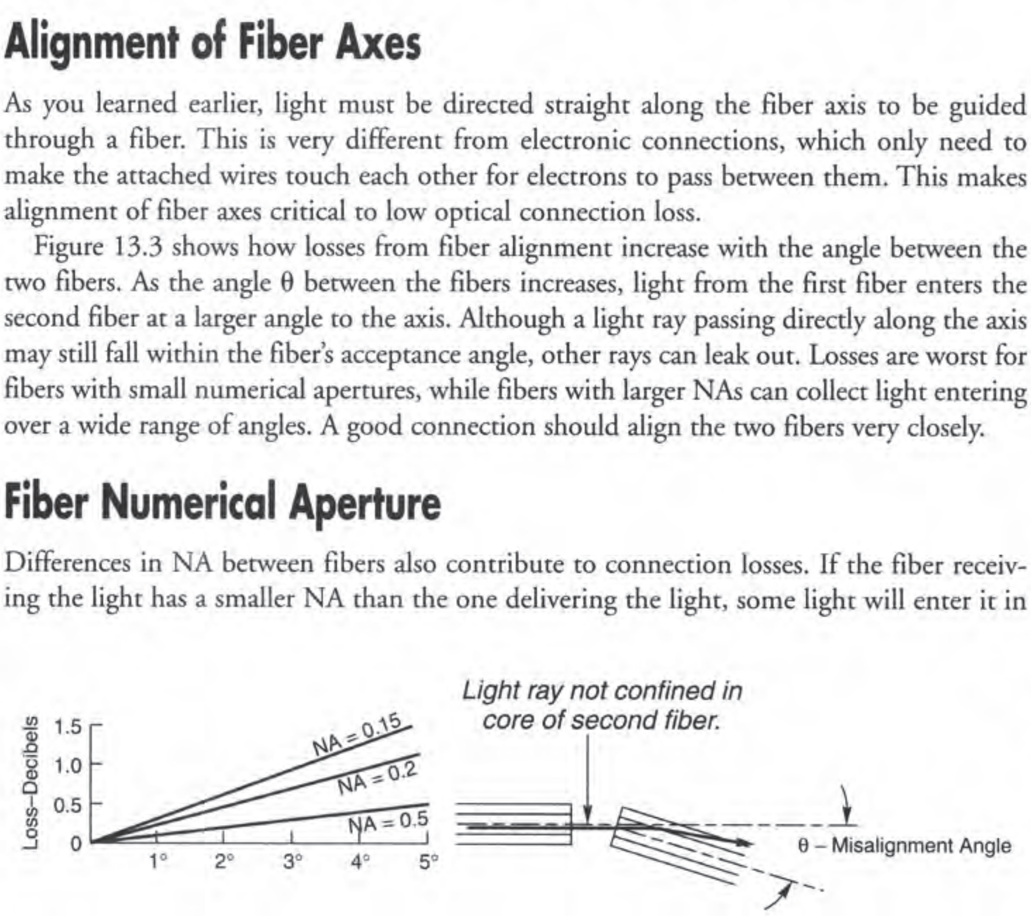
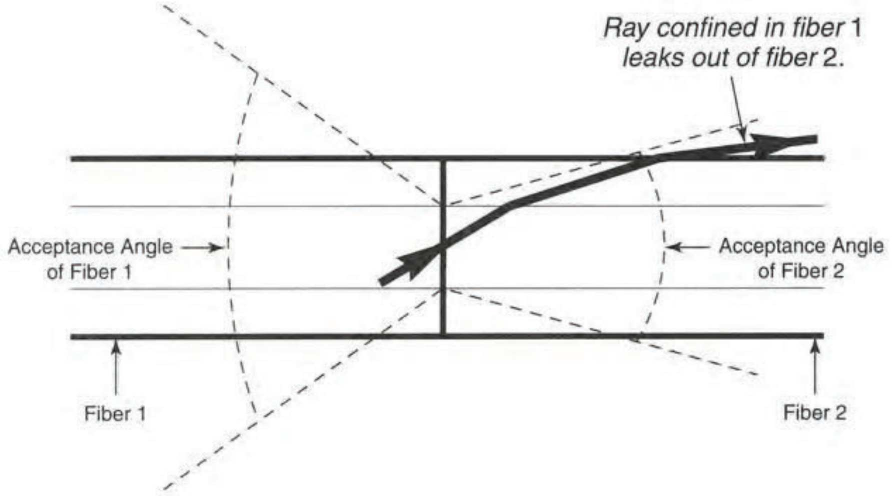


FIGURE 13.3
Misaligned fiber axes cause losses.

FIGURE 13.4
Mating fibers with different NAs can cause losses.



modes that are not confined in the core. That light will quickly leak out of the fiber, as shown in Figure 13.4. In this case, the loss can be defined with a simple formula:

$$\text{Loss (dB)} = 10 \log_{10} \left(\frac{\text{NA}_2}{\text{NA}_1} \right)^2$$

where NA_2 is the numerical aperture of the fiber receiving the signal and NA_1 is the NA of the fiber from which light is transmitted. The NA must be the measured value for the segment of fiber used (which for multimode fibers is a function of length, light sources, and other factors), rather than the theoretical NA. Note also that there is no NA-related loss if the fiber receiving the light has a larger NA than the transmitting fiber.

Spacing Between Fibers

Properly mated connectors leave no space between the fiber ends; the ends should touch each other. Two different mechanisms can cause loss if there is a gap between fibers—spreading of light emerging from the input fiber and reflection of light passing between air and glass. We'll talk about them separately, starting with the effect of light spreading.

Recall that light exits fiber in a cone, with the spreading angle—like the acceptance angle—dependent on the numerical aperture. The more the light cone spreads, the less light the other fiber can collect, as shown in Figure 13.5. The transfer losses increase as the NA of the input fiber increases because the higher NA causes the light to spread faster. The formula for the end-separation loss is rather involved, even when we assume the input and output fibers are identical.

$$Loss\,(dB) = 10 \log_{10} \left(\frac{d/2}{d/2 + \left(S \tan\left(\arcsin\left(\frac{NA}{n_0} \right) \right) \right)} \right)$$

where d is core diameter, S is the fiber spacing, NA is the numerical aperture, and n_0 is the refractive index of the material between the two fibers. Figure 13.6 shows a plot of the loss for three different fibers, two with 50-μm cores and NAs of 0.2 and 0.4 and one single-

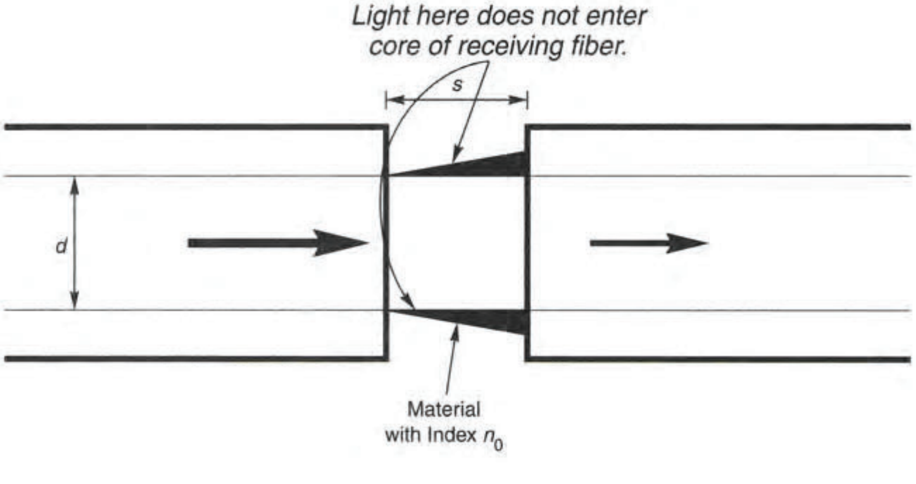


FIGURE 13.5
End-separation loss.

mode fiber with 0.15 NA; the material between the fibers is air, which has a refractive index almost equal to 1.

End-Reflection Loss

Fresnel reflection causes a 0.32 dB loss if there is a gap between fiber ends.

Leaving a space between fibers also causes end-reflection loss from a process called *Fresnel reflection*, which occurs whenever light passes between two materials with different refractive indexes. This loss occurs for all transparent optical materials, even ordinary window glass. If you look from a lighted room out into the dark, the reflections you see on the window come from Fresnel reflection. If you look carefully, you'll note they come from both the front and the back surfaces of the glass panes.

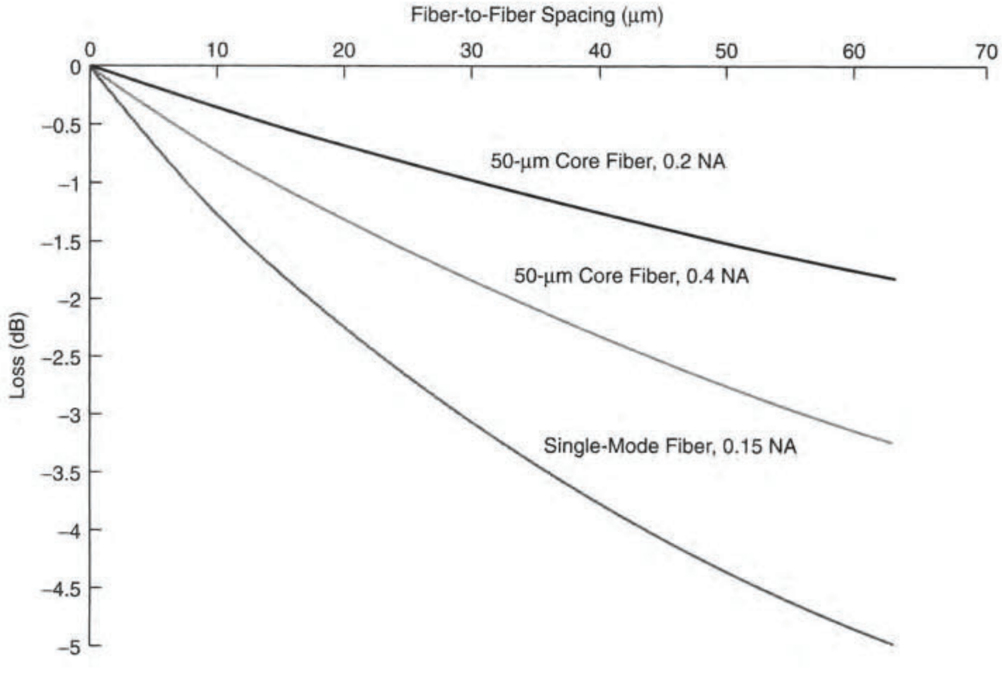


FIGURE 13.6
Loss caused by fiber spacing for three types of fiber, neglecting reflection loss.

Fresnel reflection loss depends on the difference in refractive index between the two materials. For light going from the core of a fiber with refractive index n_{fiber} into another material with refractive index n, this fraction of light reflected R is

$$R = \left(\frac{n_{\text{fiber}} - n}{n_{\text{fiber}} + n}\right)^2$$

This fraction increases with the index difference. For light going between glass and air, it is about 3.4% (0.15 dB) if the glass has a refractive index of 1.45 and 4% (0.18 dB) if the refractive index is 1.5. You can get the result directly in dB by using

$$\text{loss (dB)/surface} = -10 \log\left(1 - \left(\frac{n_{\text{fiber}} - n}{n_{\text{fiber}} + n}\right)^2\right)$$

These numbers give the loss per glass–air interface. The light suffers the same reflection in going from air back into glass, and there are two reflections in going through an interfiber gap from glass to air to glass. The total loss these two reflections cause as light goes through the gap is 0.30 to 0.36 dB, depending on the core index, with a typical value of about 0.32 dB.

This end-reflection loss is significant, generally greater than the end-separation loss. To avoid it, most connectors butt fiber ends together carefully to prevent damage to the fiber tips. In some older connectors, the space between fiber ends was filled with a transparent gel with refractive index close to that of the fiber.

Other End Losses

One dust particle can block most light transfer between a pair of single-mode fibers.

So far we have assumed that the fiber ends are cut and polished perfectly clean, and precisely perpendicular to the fiber axis. We all know things are never *that* good. The core of a single-mode fiber is less than 10 μm in diameter, so one dust particle could block virtually all light from the core. The fiber ends may not be perfect. Repeated mating and unmating of a connector can scratch the ends of fibers installed so they contact one another.

With all these loss mechanisms, it is no wonder why early developers were very worried about fiber-optic connections. (They developed multimode fiber because they did not think single-mode connections were feasible.) Tremendous progress has been made, but connection losses still can be significant in designing fiber-optic systems, as you will learn in Chapter 21. Typical losses of good single- or multimode connectors are 0.1 to 0.5 dB, while those of good splices typically are 0.1 dB or less.

The installation of a connector or splice is a critical variable, so mated fibers need to be tested. Repeated matings and unmatings can change attenuation by damaging fiber ends. Generally manufacturers specify a typical connector loss, along with changes they expect to be caused by mechanical and environmental factors during use.

Internal Reflections

Back-reflections from fiber ends can cause noise in lasers.

Back-reflections within connectors can cause problems that go beyond attenuation by affecting the performance of laser light sources. As you learned in Chapter 9, laser operation depends on reflection of light by mirrors on the two ends of the laser. Light reflected back into the laser cavity can also stimulate emission from the laser material, generating noise. Semiconductor lasers are especially sensitive to this problem, which can arise when light is reflected from an air-glass gap between two fiber ends in a connector. Analog systems used for cable-television transmission are the most vulnerable to noise produced by undesired reflection feedback into lasers.

The best way to prevent this noise is by blocking reflections. Most connectors butt the fiber ends together, which should minimize reflections by avoiding glass-air interfaces. An alternative is to fill any gap between fiber ends with a fluid or gel that has the same refractive index as the glass. "Wet" connectors are messy and rarely used, but gels may be used in mechanical splices. Fusion splices melt fiber ends together, which also fills any gap.

Reflection noise can be further reduced by cleaving and polishing the ends of the fiber so they are slanted. Thus any light reflected at the fiber junction is not directed down the fiber core. That is, the reflected light falls outside the fiber's acceptance angle and is lost. The big difficulty in this case is to make sure the slanted ends are aligned properly to avoid high losses; this requires rotating the fiber ends until they match.

Devices called *optical isolators* can suppress back-reflections in a different way: by transmitting light in only one direction. They are described in Chapter 15.

Mechanical Considerations in Connectors

So far we have concentrated on optical characteristics of fiber connections. Mechanical considerations also are important, and they differ markedly for connectors and splices. Thus we will shift from connections in general to connectors in particular. Important considerations range from size, shape, and ease of use to mechanical integrity.

Mechanical considerations are important for fiber connectors.

Virtually all fiber connectors are designed well enough to stay in place under normal conditions. Ideally they should withstand physical stress applied during their use, from the normal forces in mating and unmating to the sudden stress applied by a person tripping over a cable. Connectors also must prevent dirt and moisture from contaminating the optical interface.

Ease of Use and Size

Size and shape determine a connector's ease of use and compatibility with other equipment.

The size and shape of a connector determine its ease of use and compatibility with communications equipment. Connector design has evolved greatly over the years, as engineers have refined requirements for usability. Many early connectors were screw-on designs, adapted from coaxial cable connectors. The industry has tended away from twist-on designs to connectors that snap into place, with a latch that holds them in place until released. Like the familiar snap-in jack on modern telephones, this design is very easy to use. It also is adaptable for duplex (two-fiber) connectors simply by clamping a pair of single-fiber connectors together. Many of these designs have structures that guide the connector into place only if it is inserted in the right orientation—vital in duplex connectors. They are called *polarized connectors*, but the polarization is mechanical, not optical. Some are designed to help technicians insert connectors "blindly" into sockets they can't see, like when you're reaching behind a cabinet and plugging a connector into its socket by feel.

Density of connections has become an important consideration. The first generation of connectors were comparable in size to coaxial cable connectors, about 9 to 10 mm (0.35 to 0.4 in.) wide. A new generation of small form-factor connectors are designed to fit two (or more) fiber connections into the same space as an older single-fiber connector. As you will learn later in this chapter, some are single-fiber connectors, and some hold two or more fibers. The newer designs also can snap into place in tight confines when connectors are closely packed on equipment.

Durability

Typical fiber connectors are specified for 500 to 1000 matings. Most can be torn from cable ends by a sharp tug.

Durability is a concern with any kind of connector. Repeated mating and unmating of fiber connectors can wear mechanical components, introduce dirt into the optics, strain the fiber and other cable components, and damage exposed fiber ends. Typical connectors for indoor use are specified for 500 to 1000 mating cycles, which should be adequate for most uses. Few types of equipment are connected and disconnected daily. Specifications typically call for attenuation to change no more than 0.2 dB over that lifetime.

Connectors are attached to cables by forming mechanical and/or epoxy bonds to the fiber, cable sheath, and strength members. (Usually the fiber is epoxied, and the other bonds are crimped.) That physical connection is adequate for normal wear and tear but not for sudden sharp forces, such as those produced when someone trips over an indoor cable. That sharp tug can detach a cable from a mounted connector, because the bond between connector and fiber is the weakest point. The same is true for electrical cords, and the best way to address the problem is to be careful with the cables.

Because sharp bends can increase losses and damage fibers, care should be taken to avoid sharp kinks in cables at the connector (e.g., where a cable mates with a connector on a patch panel). Fibers are particularly vulnerable if they have been nicked during connector installation. Care should also be taken to be certain that fiber ends do not protrude from the ends of connectors. If fiber ends hit each other or other objects, they can easily be damaged, increasing attenuation.

Environmental Considerations

Fiber ends must be kept free of contaminants to avoid excess losses.

Most fiber-optic connectors are designed for use indoors, protected from environmental extremes. Keeping them free from contaminants is even more important than it is for electrical connectors. Dirt or dust on fiber ends or within the connector can scatter or absorb light, causing excessive connector loss and poor system performance. This makes it unwise to leave fiber-optic connectors open to the air, even indoors. Many connectors and patch panels come with protective caps for use when they are not mated. These caps are the sort of things that are easily lost, but they should not be.

Special hermetically sealed connectors are required for outdoor use. As you might expect, those designed for military field use are by far the most durable. Military field connectors are bulky and expensive, but when sealed they can be left on the ground, exposed to mud and moisture. They are designed to operate even after having one end stuck in mud and wiped out with a rag! Normally, nonmilitary users will avoid outdoor connectors or house them in enclosures that are sealed against dirt and moisture.

Connector Structures

A wide variety of fiber-optic connectors have been developed, but the number of basic design approaches is more limited. The two most common approaches differ in how they align the fibers: One mounts the fibers in a cylindrical ferrule, the other aligns them in V-shaped grooves in a flat substrate. A third approach with limited applications expands the beam from the fiber to reduce sensitivity to mechanical tolerances.

Ferrule-Based Connectors

Ferrules center and align the fiber in the connector.

The common elements of ferrule-based connectors are shown in generic form in Figure 13.7. The fiber is mounted in a long, thin cylinder called a *ferrule*, with a hole sized to match the fiber cladding diameter. The ferrule centers and aligns the fiber and protects it from mechanical damage. The fiber end is at the end of the ferrule, where it can be polished smooth. The ferrule is mounted in a connector body, which is attached to the cable structure. A strain-relief boot protects the junction of the connector body and the cable.

Ferrules are typically made of metal or ceramic, but some are made of plastic. The protective plastic coating is stripped from the fiber before it is inserted in the ferrule. The hole through the ferrule must be large enough to fit the clad fiber and tight enough to hold it in a fixed position. Standard bore diameters are 126 + 1/−0 μm for single-mode connectors and 127 + 2/−0 μm for multimode connectors, but some manufacturers supply a range of sizes (e.g., 124, 125, 126, and 127 μm) to accommodate the natural variation in fiber diameter. Adhesive is typically put in the hole before the fiber is pushed in to hold the fiber in place. The fiber end may be pushed slightly past the end of the ferrule and then polished to a smooth face.

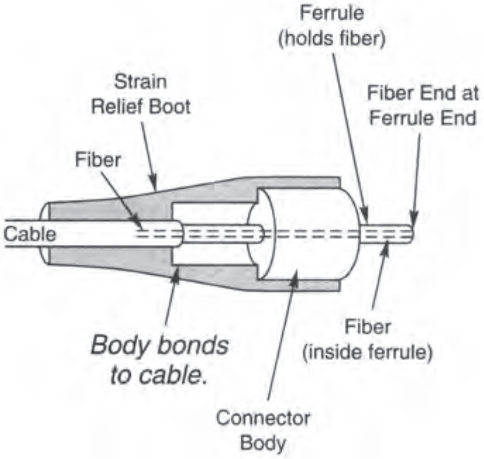


FIGURE 13.7
A simplified generic ferrule fiber connector.

The ferrule may be slipped inside another hollow cylinder (also called a sleeve) before it is mounted in the connector body. The body, typically made of metal or plastic, includes one or more pieces that are assembled to hold the cable and fiber in place. Details of assembly vary among connectors; cable bonding is usually to strength members and the jacket. The end of the ferrule protrudes beyond the connector body to slip into the mating receptacle. A strain-relief boot is slipped over the cable end of the connector to protect the cable-connector junction.

Special ferrule connectors are used for operation at high powers. Heat from light absorption at the junction can damage standard epoxies and fiber coating materials, so the coatings must be removed (they often are anyway) and special high-temperature epoxies must be used. Quartz sleeves may be added to protect the fiber tip, especially at higher powers.

V-Groove Connectors

V-groove connectors can align fibers in connectors.

V-groove connectors avoid the need for a ferrule by aligning two fiber ends in a V-groove structure. One approach is by pressing a free fiber down into a groove and butting it up against another fiber already installed in the groove. An alternative is to align fibers in V grooves in a substrate, fix them in place, then mate two V-grooved elements together. If the grooves are accurately spaced, the fiber ends match accurately, just as ferrules do. In a sense, the grooved material serves the same function as a ferrule.

V-groove structures are easily adaptable for multifiber connectors by etching multiple grooves in each element to align them to mate the fibers they contain end-to-end. Guide pins can be added to the V-groove elements to mate them accurately.

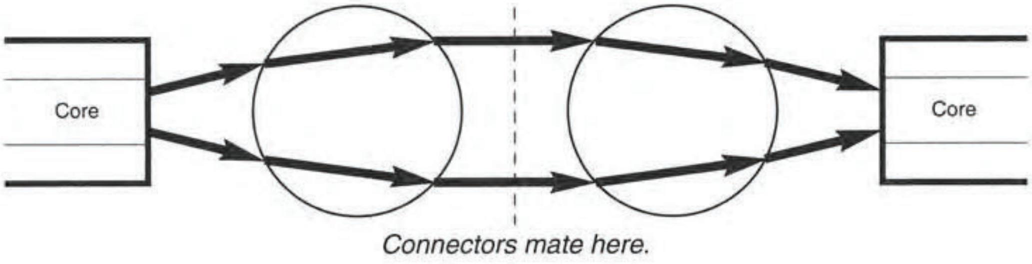
Expanded-Beam Connectors

Military field cables often use expanded-beam connectors.

Expanded-beam connectors are limited to applications where large tolerances are required, such as military field cables. As shown in Figure 13.8, light diverging as it exits the input fiber passes through a spherical lens, which collimates the light rays so they are parallel. Then a spherical lens attached to the output cable focuses the light rays into the output fiber.

This expands the beam diameter by a factor of 10 or more for multimode fiber, and by a larger factor for single-mode fiber, spreading the optical signal over a larger region. This design prevents dirt from blocking all or most of the beam, or small misalignments from causing high attenuation. In practice, expanded-beam connectors are mostly for cables used outdoors or in hostile environments where connectors can't be protected.

FIGURE 13.8
Operation of an expanded-beam connector.



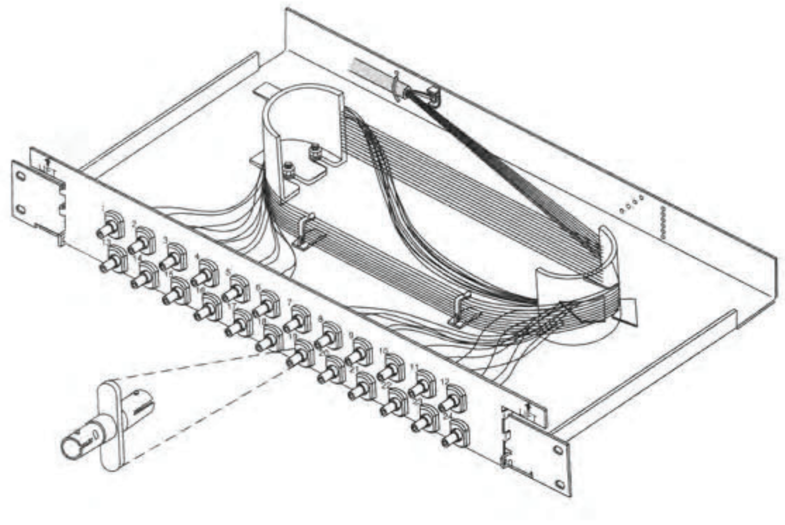


FIGURE 13.9
Connector panel. (Courtesy of Corning Cable Systems, Hickory, N.C.)

Mating Connectors

Most standard fiber connectors lack the male-female polarity often seen in electronic connectors. Instead, the fiber connector is plugged into an adapter, which serves as an interface to another connector, or is mounted on a transmitter, receiver, or service box. This arrangement is similar to that of standard American telephone wiring, where cables are terminated with standard jacks that fit into any telephone or wall socket. Two cables can be connected by plugging jacks into both sides of an adapter.

Most fiber connectors plug into adapter interfaces.

In fiber systems, connectorized cables normally plug into adapters mounted on transmitters, receivers, junction boxes, or other devices. Transmitters and receivers are often packaged with internal fiber links between the adapter on the outside of the box and the laser or detector on the inside. In a junction box or patch panel, a cable may be divided into individual fibers that run to an array of connector adapters, ready to take single-fiber connectors, as shown in Figure 13.9. Remember that the adapters are what you see on the outside of the box.

Adapters offer the advantage of flexibility in cabling because they can accept one type of connector on one side and a different type on the other.

Connector Installation

Users face trade-offs when deciding whether to install connectors in the field or in a factory. Tight tolerances are easier to reproduce in a factory, but field installation gives more flexibility in meeting system requirements and performing on-the-spot repairs. Manufacturers have developed connectors optimized for each environment.

Fiber connectors can be installed in the field or in the factory.

Factory installation employs trained technicians working in a controlled environment with all the specialized equipment needed to do the job right, so you can buy ready-to-use cables. That works well for standard lengths of connectorized jumper cables, but not for longer cables of varied lengths needed for intrabuilding or interbuilding use.

One alternative is to supply cable segments with factory-mounted connectors on one end and fiber pigtails on the other. Splicing in the field is generally easier than installing connectors, but it does require special equipment. This approach works best for loose-tube cables containing many fibers.

Field installation of a complete connector enhances flexibility, but results depend on both the skill of the technician and the connector design. Installing a connector in the field generally requires more time, tools, and skill than splicing a premounted connector. It works best for tight-buffered cables. Some manufacturers supply field connectorization kits with the most sensitive internal alignments already done.

Multifiber Connectors

Multifiber cables may be broken out to individual fibers, each with its own connector.

Most cables contain multiple fibers, and the complexity of installing connectors increases with the number of fibers involved. The cable may be broken out into individual fibers, with connectors on the end of each fiber, or two or more fibers may terminate in the same connector. Breakout cables often terminate in a patch panel, as shown in Figure 13.9.

The simplest case is the *duplex* connector, which links cables that contain a pair of fibers, one transmitting in each direction. Duplex connectors may consist of two single-fiber connectors side by side in a single housing, or a single connector that mounts two fibers. In practice, duplex connectors are *polarized* so they can be mated in only one way, with the two fibers connected to their counterparts transmitting in the same direction. Attach a duplex connector the wrong way, and you have the transmitters sending signals to each other while the two receivers stare at each other through a dark fiber, each waiting in vain for the other to send a signal.

Multifiber connectors simultaneously connect many fibers, greatly simplifying installation and reducing space requirements. This approach requires arranging the fibers in a fixed format in the cable and mating them to corresponding fibers in another cable that uses the same format. Loss in multifiber connectors tends to be higher than for single-fiber connectors, but the space and labor savings can be worthwhile. Generally multifiber connectors are used with ribbon cables.

Polarization-Maintaining Connectors

The concept of connector polarity can be confusing in optics, where light is also polarized. You may encounter two variations on the concept in fiber connectors.

You are most likely to encounter polarity when dealing with duplex connectors, which require you to know which fiber is transmitting in which direction. You need to keep track of this polarity in order to connect fibers so they always send signals from the transmitter to the receiver.

Polarization-maintaining connectors are rare, but important when they are used. They connect polarization-maintaining fibers, which transmit light in a way that maintains the optical polarization of the light waves. Polarization-maintaining connectors align fibers so that they retain the polarization orientation of the light.

Standard Connector Types

Many connector designs have been standardized by the IEC and other organizations.

During the 1980s, almost every manufacturer of fiber-optic connectors seemed to have its own design. Some remain in production, but much of the industry has shifted to standardized connector types, with details specified by standards organizations such as the

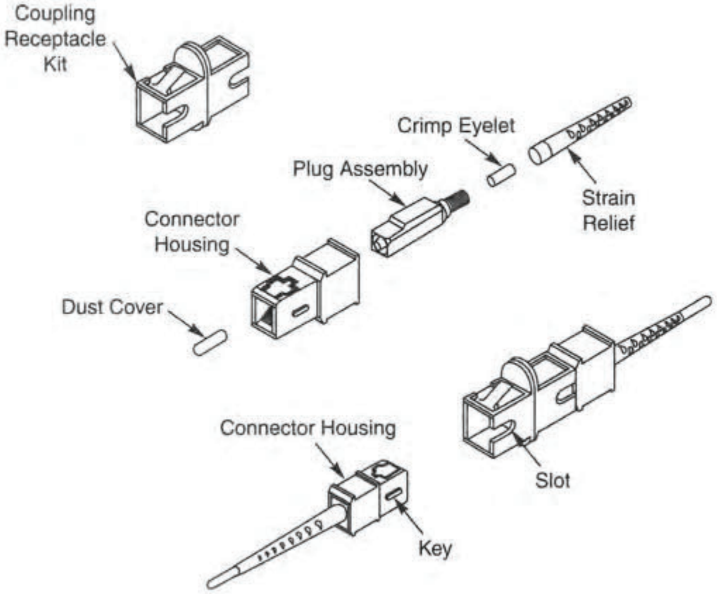


FIGURE 13.10
SC connector, expanded and assembled. (Courtesy of AMP Inc.)

Telecommunications Industry Association, the International Electrotechnical Commission, and the Electronic Industries Association. Standards groups, in turn, have developed standards for more than two dozen connector types, most of them widely used types and some of them new types developed for emerging needs.

I can't hope to cover the whole variety of connectors in any detail; that's best done by consulting catalogs and product specifications. However, I will discuss a few examples of important types used for single- and multimode glass fibers. Other types of connectors may be used for plastic fibers and large-core fibers. I divide them loosely into families, which sometimes overlap: single-fiber connectors that snap or twist in place, polarizing connectors, multifiber connectors, and small form-factor connectors.

Snap-in Single-Fiber Connectors (SC)

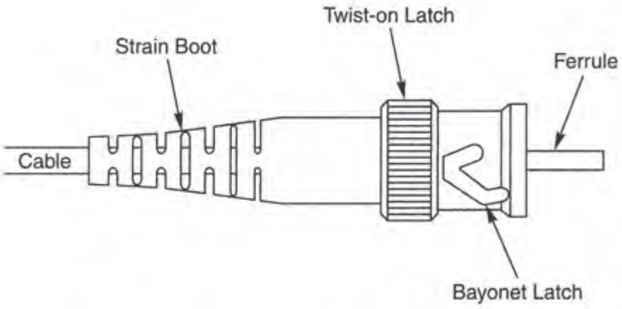
Figure 13.10 shows a widely used snap-in connector, the SC connector developed by Nippon Telegraph and Telephone of Japan. It is built around a cylindrical 2.5-mm ferrule that holds the fiber, and it mates with an interconnection adapter or coupling receptacle. Pushing the connector latches it into place, without any need to turn it in a tight space, so a simple tug will not unplug it. It has a rectangular 9-by-7.9 mm cross section that allows high packing density on patch panels and makes it easy to package in a polarized duplex form that assures the fibers are matched to the proper fibers in the mated connector.

The SC is a widely used snap-in single-fiber connector.

Twist-on Single-Fiber Connectors (ST and FC)

Figure 13.11 shows a widely used twist-on connector, the ST connector long used in data communications. It may look familiar because it is one of several fiber connectors that evolved from designs originally used for copper coaxial cables. Like the SC, it is built

FIGURE 13.11
ST connector.



around a 2.5-mm cylindrical ferrule and mates with an interconnection adapter or coupling receptacle. However, it has a round cross section and is latched into place by twisting it to engage a spring-loaded bayonet socket.

Another design for a twist-on connector is the FC (sometimes called FC-PC). Its structure is similar to that of the ST, but it is threaded and screws in place rather than twisting to latch. One drawback of such twist-on connectors is that they generally cannot be mounted in pairs as a duplex connector.

Duplex Connectors

Duplex connectors are keyed to mate in only one orientation.

Standard plug-in connectors like the SC can be mounted side by side to make duplex connectors. Some of the small form-factor connectors described later also come in duplex versions, notably the MT-RJ.

Other duplex connectors have been developed for specific types of networks as part of the network standards. One example is the *fixed shroud duplex* (FSD) connector specified by the Fiber Distributed Data Interface (FDDI) standard, as shown in Figure 13.12. Another is the *retractable shroud duplex* (RSD) connector developed by IBM for local-area networks.

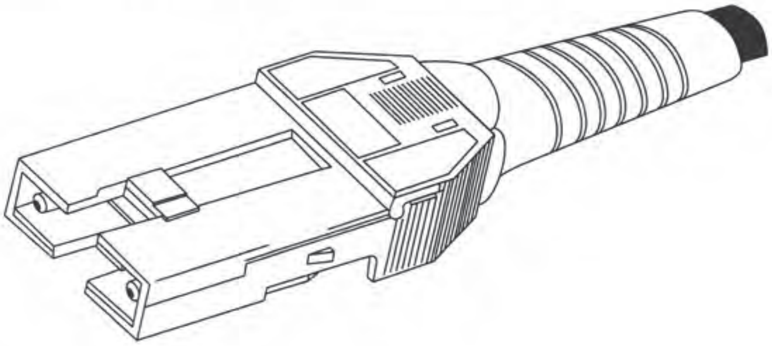
Some network standards specify duplex connectors as integral parts of transmitters and receivers (or combined transceivers).

MT Multifiber Connectors

MT connectors align fibers in V grooves.

An important family of multifiber connectors is built up around the MT V-groove element (a noncylindrical ferrule), which aligns many fibers parallel to each other, as shown in

FIGURE 13.12
Fixed shroud duplex (FSD) connector for FDDI network. (Courtesy of Corning Cable Systems, Hickory, N.C.)



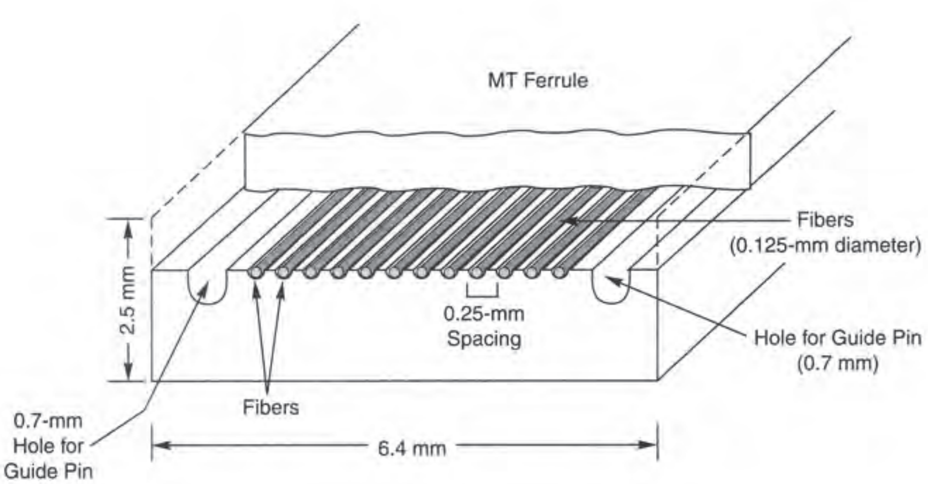


FIGURE 13.13
MT ferrule holds a dozen fibers in parallel grooves.

Figure 13.13. As you may suspect from the arrangement, the MT connector was developed for multifiber ribbon cable. Coatings are removed before the fibers are mounted in the grooves, leaving 125-μm fibers mounted on 250-μm centers. The ferrules include a pair of 0.7-mm holes, parallel to the fibers on the other edges of the structure. These holes accommodate precision metal guide pins, which align the mated elements with tight tolerances to match up the fibers.

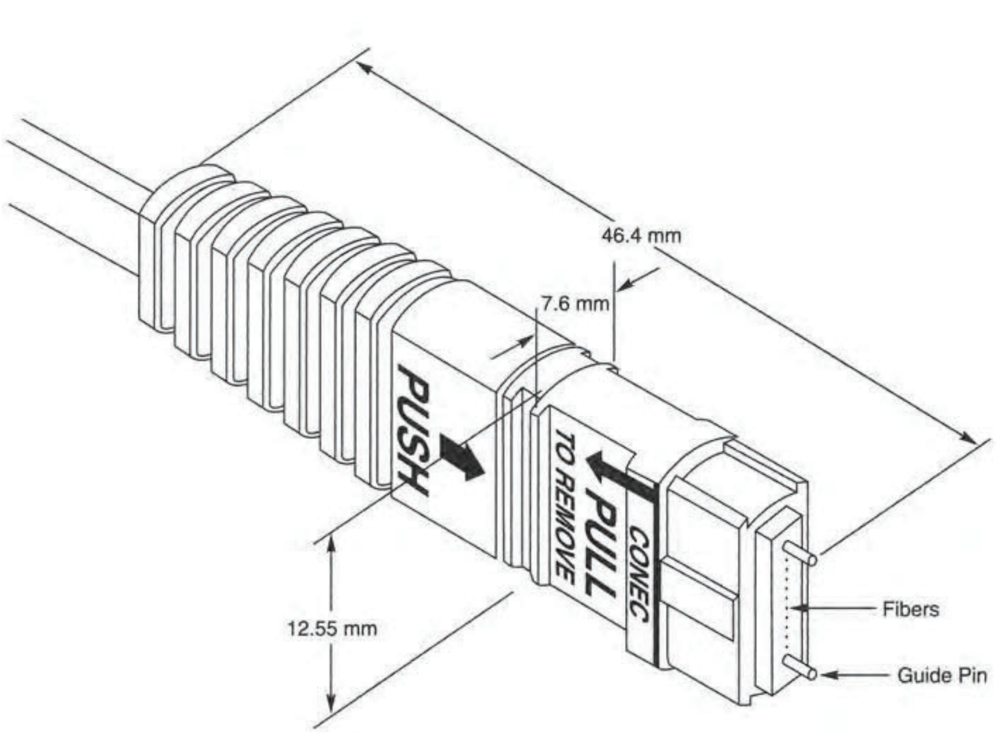
Pairs of MT ferrules can be mated together with guide pins and held in place with metal clips. Alternatively, the MT ferrules can be mounted within connector bodies, which mate together, usually with an adapter, while the guide pins align the ferrules precisely with each other. Many of these designs have male–female polarity.

Depending on details of the design, the guide pins may be supplied separately for insertion when the connectors are mated or may be installed permanently in one ferrule (typically one that is permanently mounted in a case rather than on a cable). It is the guide pins that assure the precise alignment of fiber ends. The connector bodies provide the mechanical force holding the ferrules in place; typically they are spring-loaded and snap into position, like SC connectors. There are a variety of connectors built around MT ferrules, including the small form-factor duplex MT-RJ.

One such design is the rectangular-format MPO connector, shown in Figure 13.14. A pair of connectors mate in an adapter. The male connector (shown in the figure) has the guide pins; the female connector does not. Some companies have modified designs with minor differences, such as allowing two plugs to mate with each other without an adapter between them. These connectors are intended for installations that require many fiber connections. Some versions include up to 72 fibers. The MPO must be factory-installed.

Trying to align many fibers at once stresses mechanical tolerances, so typical losses of multifiber connectors can be higher than those of single-fiber connectors, up to about 1 dB. (Duplex connectors typically have about the same loss as single-fiber connectors.) However, multifiber connectors greatly reduce installation costs for multifiber systems.

FIGURE 13.14
Male MPO connector assembly (Courtesy of US Conec.)



Small Form-Factor Connectors

Small form-factor connectors fit into tighter spaces.

A number of small form-factor connectors have been developed in recent years to fill the demand for devices that can fit into tight spaces and allow denser packing of connections. Some are miniaturized versions of older connectors, built around a 1.25-mm ferrule rather than the 2.5-mm ferrule used in SC-type connectors. Others are based on smaller versions of MT-type ferrules, or other designs. Most have a push-and-latch design that adapts easily to duplex connectors and feels like a phone jack. Figure 13.15 shows a sampling. Typical dimensions are 5-mm square for the plug end of the connector, with ferrule in the middle, and 10-by-13 mm for a duplex adapter.

The MT-RJ duplex connector shown in Figure 13.15(a) is derived from the MT design and used for intrabuilding communications. The two fibers (not shown in the drawing) are held in a miniature two-fiber ferrule, and the connector's overall size is about the same as the standard RJ45 jack used on home telephone cables. These two fibers are hard-to-see dots on the front of the ferrule, between the two larger holes used for the alignment pins. A spring pushes the guide pins through the ferrule and the whole assembly into the housing. MT-RJ connectors are designed as plugs and jacks, like RJ45 phone connectors, and can sit in the same slot in a wall plate as the phone connector. Adapters can be used for mating the MT-RJ, but are not required.

The LC connector in Figure 13.15(b) borrows features from both electronic telephone jacks and the SC fiber connectors. Externally it resembles a standard RJ45 phone jack. Internally, it's a miniature version of the SC, with its plastic case holding a 1.25-mm ceramic ferrule that mates in an adapter. The LX.5 connector also uses a 1.25-mm ferrule in a miniature SC-like plastic case, but has an integral end cap that automatically

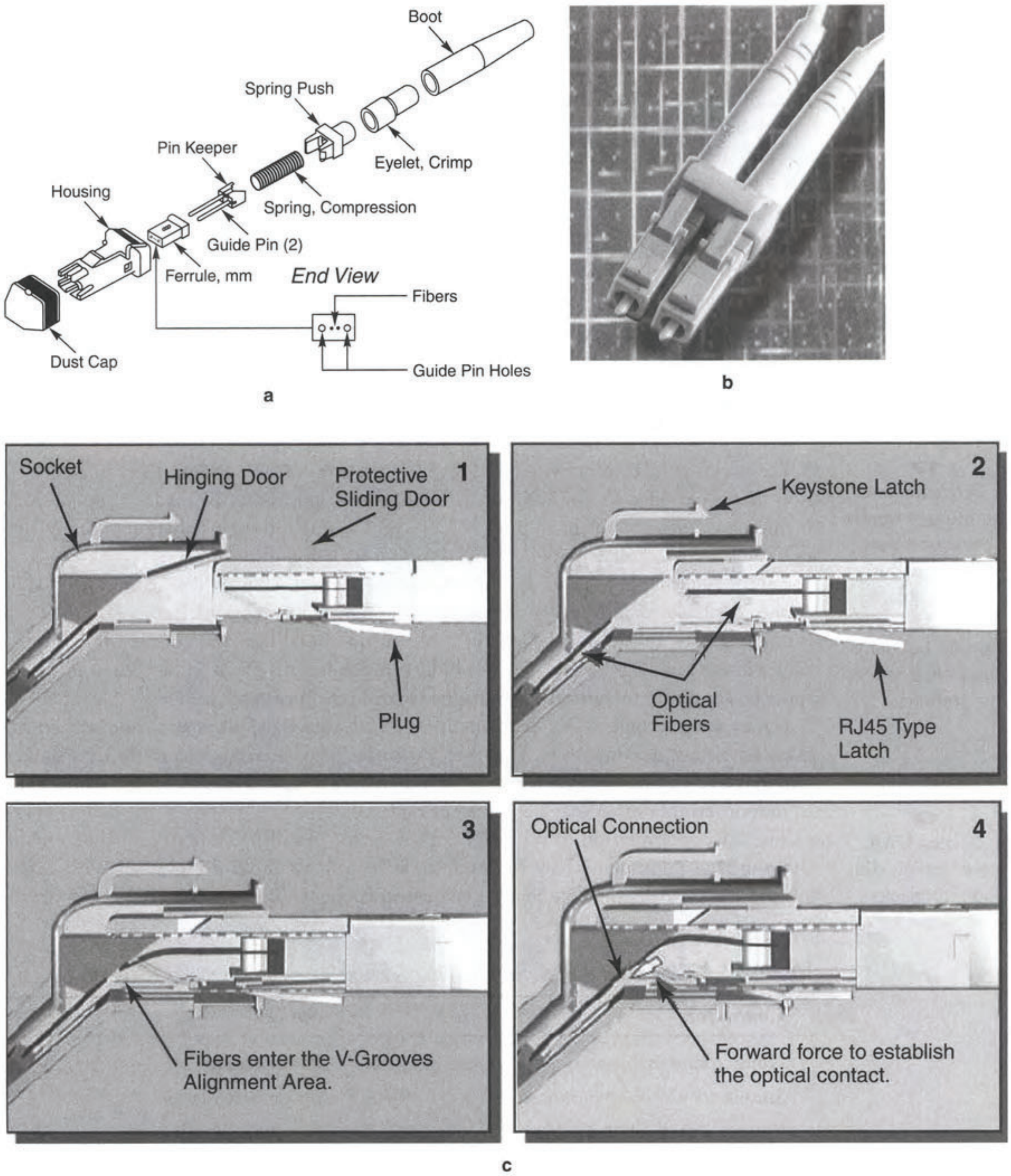


FIGURE 13.15

Small form-factor connectors. (a) MT-RJ connector. (Courtesy of Tyco Electronics) (b) Duplex LC connector. (Courtesy of Agere Systems) (c) VF-45 connector. (Courtesy of 3M Telecom Systems Division) slides out of the way when plugged into an adapter, then slips back to cover the ferrule when removed.

The MU connector is another miniature version of the SC built around a 1.25-mm ferrule, but unlike the LC retains the push–pull external latching mechanism of the SC. Other small form-factor connectors, also built around 1.25-mm ferrules, differ in details such as latching mechanism and assembly procedures. One small form-factor connector, the Fiber-Jack, is based on a 2.5-mm ferrule.

V-groove connectors have also been developed as small form factors. The VF-45 connector shown in Figure 13.15(c) has covers that slide away when the plug and socket are mated. The fibers in the socket are mounted in V grooves in a substrate that is at a 45° angle to the fibers on the plug. The mating process slides the fibers in the plug into the V grooves, where pressure holds them in place, avoiding the need for precision ferrules.

Splicing and Its Applications

Splices make permanent bonds between fibers. Applications include joining lengths of cable outside buildings and emergency repairs.

Splices weld, glue, or otherwise bond together the ends of two optical fibers in a connection that is intended to stay connected. "Temporary" splices may be made in special cases, including emergency repairs to broken cables and testing during installation or renovation of a cable system. Splices may be made during installation or repair.

Splices generally have lower loss and better mechanical integrity than connectors, while connectors make system configuration much more flexible. Table 13.1 compares their features. Typically, splices join lengths of cable outside buildings, and connectors terminate cables inside buildings. Splices may be hidden inside lengths of cable, or housed in special splice boxes; connectors are typically attached to equipment or patch panels at cable interfaces.

It may seem strange to list "permanent" as an advantage of splices and "nonpermanent" as an advantage of connectors. However, each has its advantages. A splice to fix a broken underground cable should be permanent, but you don't want to attach cables permanently to indoor terminals that may be moved or replaced.

Splices have lower attenuation than connectors.

The lower attenuation of splices is important for installing systems that span tens to thousands of kilometers. Bare fiber comes in lengths to about 25 km, but most cables are too bulky to fit that much on a manageable spool. In practice, outdoor cables are

Table 13.1 Comparison of connector and splice advantages

Connectors	*Splices*
Nonpermanent	Permanent
Simple to use once mounted	Lower attenuation
Factory installable on cables	Lower back-reflection
Allow easy reconfiguration	Easier to seal hermetically
Provide standard interfaces	Usually less expensive per splice
	More compact

spliced in the field at least every several kilometers, or more often depending on the configuration.

The physical characteristics of splices are important in many outdoor applications. The spliced cables must withstand hostile outdoor environments, so the splices are housed in protective enclosures. (Fibers spliced during cable manufacture are protected by the cable structure that surrounds them.) Generally outdoor enclosures are sealed to protect against moisture and temperature extremes, but can be re-opened if repairs or changes are needed—like their electronic counterparts on copper cables.

Splicing Issues and Performance

Three main concerns in splicing are the optical characteristics of the finished splice, its physical durability, and the ease of splicing.

Attenuation and Optical Characteristics

Splices align fibers more accurately than connectors, so they have lower attenuation.

The same factors that contribute to loss in connectors can cause splice loss, although differences between the two processes mean that some mechanisms are less important for splices than for connectors.

Splices bond the two fiber ends together by melting (fusing) them, gluing them, or mechanically holding them in a tight structure. This tends to align the fibers with tighter tolerance than in a connector, giving lower attenuation. As long as these processes bond the two fiber ends together with no intervening air space, they largely eliminate fiber-spacing loss and minimize back-reflection.

Differences between the fibers being spliced cause *intrinsic losses.* Mechanisms include variations in the size and shape of the fiber core, core eccentricity or offset, and differences in refractive-index profile. The inevitable manufacturing tolerances cause slight variations even in nominally identical fibers. These mechanisms are the same as those affecting connector loss, which you learned earlier.

Good splices can have loss near 0.05 dB.

Extrinsic losses arise from the nature of the splice itself. They depend on alignment of the fiber ends, quality of end preparation, refractive-index matching between ends, contamination, end spacing, waveguide imperfections at the junction, and angular misalignment of bonded fibers. Again, the same mechanisms affect connector loss, although their impacts may differ.

Typically intrinsic and extrinsic losses are comparable in magnitude for well-made splices. Fortunately, the total splice loss often is less than the arithmetic sum of the two types. Total loss can be very low, near 0.05 dB, in properly made splices, but imperfect junctions can suffer from high loss. A single 10-μm dust particle in the wrong place can block the core of a single-mode fiber. With proper tools and procedures, attenuation is comparable for splices of single- and multimode fibers. (Measurement anomalies can make some splices seem to be "gainers," but this effect is not real.)

Back-reflection normally is very low in good splices. High back-reflection or attenuation is a sign of a defective splice.

Specified values for splice loss assume the fibers are correctly matched. As in connectors, mismatched fibers can cause significant losses. For single-mode fibers, the most important mismatches are in mode-field diameter. This may be inevitable when different fibers are being spliced together for dispersion management. Natural variations in fiber characteristics can raise loss above the average values of 0.05 to 0.1 dB. The worst type of mismatch is splicing multimode fiber to single-mode with light going into the single-mode fiber, which can cause attenuation of nearly 20 dB. Such mistakes can happen because virtually all telecommunication fibers have the same 125-μm core diameter. Color-coding in cables identifies individual fibers, but does not distinguish different types.

Strength

Fibers are more vulnerable to damage at splices. Stripping the plastic coating can damage the fiber surface.

If you pull a spliced copper wire, you expect the splice to fail long before the wire itself fails. Optical fibers likewise are more vulnerable at splices, with the specific mechanisms depending on the splice type.

Stripping coatings from fibers can damage them before splicing, causing microcracks that later become points of failure. This is particularly likely for mechanical stripping. In fusion splicing, contaminants can weaken the melted zone, while thermal cycling from heating and cooling can weaken adjacent parts of the fiber. In practice, fusion splices tend to fail near the splice interface, but not exactly at the junction point.

Typically both mechanical and fusion splices are protected by coatings, claddings, and/or jackets that bond to the fibers and protect them from mechanical and environmental stresses.

Ease of Splicing

Splices often are made in the field, making the ease of splicing a critical concern. This has led to the development of special equipment, which I'll describe in more detail below.

Types of Splicing

There are two basic approaches to fiber splicing: *fusion* and *mechanical.* Fusion splicing melts the ends of two fibers together so they fuse, like welding metal. Mechanical splicing holds two fiber ends together without welding them, using a mechanical clamp and/or glue. Each approach has its distinct advantages. Fusion splicers are expensive, but they require almost no consumable costs, and fusion splices have better optical characteristics. Mechanical splicing requires less equipment (and no costly fusion splicer), but consumable costs per splice are much higher.

Fusion Splicing

Fusion splicing welds fiber ends together.

Fusion splicing is performed by butting the tips of two fibers together and heating them so they melt together. This is normally done with a fusion splicer, which mechanically aligns the two fiber ends, then applies a spark across the tips to fuse them together. Typical splicers also include instruments to test splice quality and optics to help the technician align the

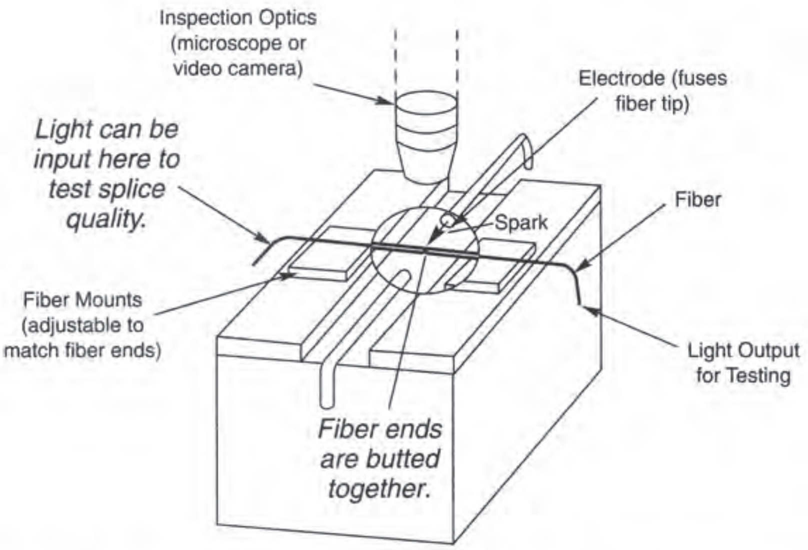


FIGURE 13.16

Key components of a fiber splicer.

fibers for splicing. Typical splice losses are 0.05 to 0.2 dB, with more than half below 0.1 dB. The basic arrangement of a fiber splicer is shown in Figure 13.16.

Individual fiber splicers are designed differently, but all have the common goal of producing good splices reliably. Many are automated to assist the operator. They are expensive instruments, with prices starting at thousands of dollars and reaching tens of thousands of dollars for the most sophisticated models. Major differences center on the degree of automation and the amount of instrumentation included. Most models share the following key elements and functions:

- A fusion welder, typically an electric arc, with electrode spacing and timing of the arc adjustable by the user. The discharge heats the fiber junction. Portable versions are operated by batteries that carry enough charge for a few hundred splices before recharging. Factory versions operate from power lines or batteries.
- Mechanisms for mechanically aligning fibers with respect to the arc and each other. These include mounts that hold the fibers in place, as well as adjust their position. More expensive splicers automate alignment and measurement functions.
- A video camera or microscope (generally a binocular model) with magnification of 50 power or more so the operator can see the fibers while aligning them.
- Instruments to check optical power transmitted through the fibers both before and after splicing. Typically, light is coupled into a bent portion of the fiber on one side of the splice and coupled out of a bent portion on the other side. With proper calibration, this can measure the excess loss caused by the splice. (This may be missing from inexpensive field splicers.)

Before fusion splicing, plastic coatings must be removed from the fiber, and the end must be cleaved perpendicular to the fiber axis.

Fusion splicing involves a series of steps. First, the fiber must be exposed by cutting open the cable. Then the protective plastic coating or jacket must be stripped from a few millimeters to a few centimeters of fiber at the ends to be spliced. The fiber ends must be cleaved to produce faces that are within 1° to 3° of being perpendicular to the fiber axis. The ends must be kept clean until they are fused.

The next step is alignment of the fibers, which may be done manually or automatically. After preliminary alignment, the ends may be "prefused" for about a second with a moderate arc that cleans their ends and rounds their edges. These ends are then pushed together, allowing power transmission to be tested to see how accurately they are aligned. After results are satisfactory, the arc is fired to weld the two fiber ends together. Care must be taken to ensure proper timing of the arc so the fiber ends are heated to the right temperature. After the joint cools, it can be recoated with a plastic material to protect against environmental degradation. The spliced area can also be enclosed in a plastic jacket. The entire splice assembly is then enclosed mechanically for protection, which in turn is mounted in a splice enclosure. The case around the individual splice provides strain relief.

Mechanical Splicing

Mechanical splicing gives higher losses but requires simpler equipment than fusion splicing.

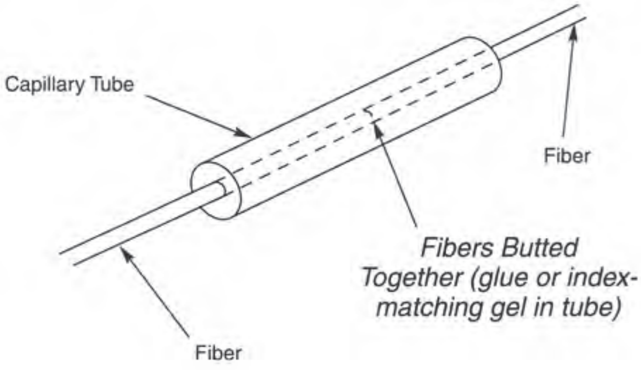
A capillary splice holds two fiber ends in a thin tube.

Mechanical splices join two fiber ends either by clamping them within a structure or by gluing them together. A variety of approaches have been used in the past, and many are still in use. The extremely tight tolerances in splicing single-mode fiber often require special equipment not needed for splicing multimode fiber. Those extra requirements typically make single-mode splicing more expensive.

In general, mechanical splicing requires less costly capital equipment but has higher consumable costs than fusion splicing. This can tilt the balance toward mechanical splicing for organizations that don't perform much splicing, or for emergency on-site repair kits. Mechanical splices tend to have slightly higher loss than fusion splices, but the difference is not dramatic. Back-reflections can occur in mechanical splices, but they can be reduced by using epoxy to connect the fibers, or by inserting into the splice a fluid or gel with a refractive index close to that of glass. This index-matching gel suppresses the reflections that can occur at a glass–air interface. There are several types.

The *capillary splice* relies on inserting two fiber ends into a thin capillary tube, as shown in Figure 13.17. The plastic coating is stripped from the fiber to expose the cladding, which is inserted into a tube with an inner diameter that matches the outer diameter of the clad

FIGURE 13.17
Capillary splice joins two fibers.



fiber. The two fiber ends are then pushed into the capillary until they meet (often with index-matching gel inserted to reduce reflections). Compression or friction usually holds the fiber in place, although epoxy may also be used.

Alignment of the fiber ends depends on mechanical alignment of the outside of the fibers. The result is a simple splice that is easy to install and can compensate for differences in the outer diameters of fibers. However, it is not designed to compensate for other differences between the fibers being joined.

The *rotary* or *polished-ferrule* splice is a more elaborate type that can compensate for subtle differences in the fibers being spliced. As with other splices, the plastic coating is first removed from the fiber. Then each fiber end is inserted into a separate ferrule, and its end is cleaved and polished to a smooth surface. The two polished ferrules then are mated within a jacket or tube, and rotated relative to each other while splice loss is monitored. The ferrules are fixed in place at the angle where splice loss is at a minimum. Although this technique is more complex and time-consuming than capillary splicing, it offers a more precise way of mating fibers. Its sensitivity to rotation of the fiber around its axis makes it suitable for splicing polarization-sensitive fibers.

Fibers also can be spliced by butting them together in V-shaped grooves, as shown for fiber ribbons in Figure 13.18. (Recall that MT-family connectors and the VF-45 connector also butt fibers together in V grooves.) The fibers are placed in opposite ends of the same groove, and are pushed together until they contact. Then a separate matching plate is applied on top. The fiber ends can be inserted into separate grooved plates, which can have covers applied and the ends polished before they are mated with another plate, as in MT-family connectors. The *V-groove splice* is particularly useful in multifiber splicing of ribbon cables, where each parallel fiber slips into a separate groove. Special splicers are sold for this purpose.

V-groove splices are valuable for multifiber ribbon cables.

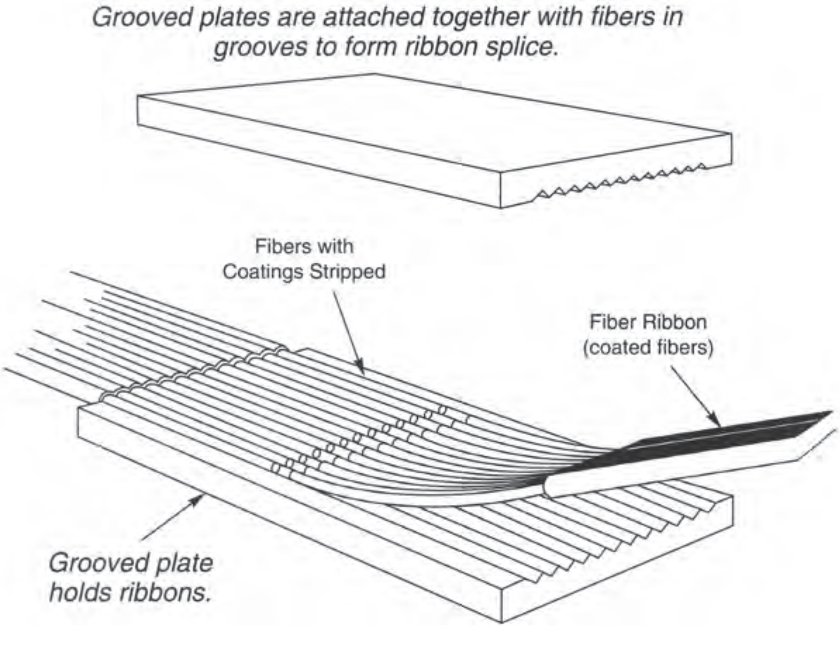


FIGURE 13.18

Mass-splicing of 12-fiber ribbon in V-grooved plate.

The *elastomeric splice* has an internal structure similar to that of a single-fiber V-groove splice, but the plates are made of a flexible plastic held in a sleeve, and the groove is tapered toward the center. The plates are assembled in a sleeve before the fibers are installed. First an *index-matching gel* or epoxy is inserted into the hole, then one fiber is inserted until it reaches about halfway through the splice. Then the second fiber is inserted from the other end until it pushes against the first. This type of splice is useful in field kits for emergency fiber repairs by technicians with little fiber experience, giving typical loss of 0.25 dB, adequate for such repairs.

A *reusable splice* is a mechanical splice in which the fibers are clamped in place but not glued. The V-groove splice in Figure 13.18 is one example. The plates may be held together by screws or clamps, which can be released to remove one fiber and replace it with another. Although reusable splices are not truly permanent, they are used in places where change is unlikely. Their installation requires a technician with special tools, not just an ordinary user who wants to plug in a different telephone or computer.

Splicing Requirements

Commercial splicing equipment is designed to serve a variety of needs and be used in a variety of environments. Fusion splicing normally is done by technicians who work primarily with fiber, whether installing new cables or repairing existing ones. Telephone companies may have vans equipped with specialized fiber equipment for these purposes. Fusion splices tend to be used mostly for cables with long outdoor runs, where loss is a major concern.

Mechanical splices are more likely to be used by nonspecialists to repair shorter cables indoors, where final loss of the cable is less important than fixing it promptly. For example, the technician responsible for maintaining a corporate local-area network may use mechanical splices to patch a damaged indoor cable, or to make a few splices needed to reconfigure the system. The cost per splice is higher than fusion splicing, but the overall cost is much lower because of the high cost of a fusion splicer.

Splice Housings

Fiber-optic splices require protection from the environment, whether they are indoors or outdoors. Splice enclosures help organize spliced fibers in multifiber cables, and also protect splices from strain and contamination.

Splice housings organize splices in multifiber cables.

Splice housings typically contain a rack such as the one shown in Figure 13.19, which contains an array of individual splices. This rack is mounted inside a case that provides environmental protection. Individual fibers broken out from a cable lead to and from the splices. To provide a safety margin in case further splices are needed, an excess length of fiber is left in the splice case. Like splice enclosures for telephone wires, fiber-optic splice cases are placed in strategic locations where splices are necessary (e.g., in manholes, on utility poles, or at points where fiber cables enter buildings).

Fiber splice enclosures should be designed to

- Hold cable strength member tightly
- Block entrance of water

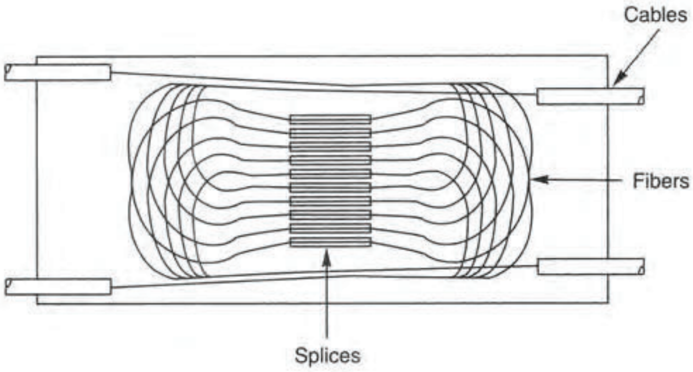


FIGURE 13.19
Splices arrayed inside housing.

- Provide redundant seals in case one level fails
- Electrically bond and ground any metal elements in the cable (e.g., strength members and armor)
- Be re-enterable if the splice must be changed or repaired
- Organize splices and fibers so they can be readily identified
- Provide room for initial splicing and future modifications
- Leave large enough bend radii for fibers and cables to avoid losses and physical damage

What Have You Learned?

1. Connectors hold fiber ends together in a temporary connection. They are used where equipment may need to be rearranged.
2. Splices permanently attach and align fiber ends. They are used for permanent junctions while installing or repairing fiber.
3. The most important optical specification of connectors and splices is attenuation, the loss in transferring a signal between fibers.
4. Causes of loss include mismatch of fiber cores, misalignment of fiber axes, differences in numerical aperture, spacing between fibers, reflection at fiber ends, and dirt in fiber junctions. Alignment tolerances are tighter for small-core single-mode fibers than for larger-core multimode fibers.
5. Fresnel reflection causes a 0.32-dB loss if there is an air gap between fiber ends. To avoid this, fibers are butted together in connectors or spliced together mechanically.
6. Back-reflection is an important parameter because it can cause noise if the light returns to laser transmitters. Butting fiber ends together, fusion splicing, or filling the junction between fibers can reduce this reflection. So can angled connectors.

7. Mechanical properties of connectors are important. They should withstand hundreds of matings, keep fiber ends clean, and hold cables in place.
8. Most connectors contain cylindrical ferrules that hold the fiber inside a connector body. Most fiber-optic connectors lack male–female polarity and mate through interconnection adapters or coupling receptacles.
9. Many types of connectors have been marketed and remain available, but only a few are in wide use.
10. Duplex connectors are used for pairs of fibers, one carrying signals each way. Multifiber cables may be attached to multifiber connectors or broken out to individual connectors.
11. Standard-form connectors include the snap-in SC and the twist-on ST and FC.
12. Small form-factor connectors are about half the size of standard-form connectors. They include the LC, MT-RJ, MU, Fiber-Jack, and VF-45.
13. Splices are normally made in the field; connectors usually are installed in the factory.
14. Splices have lower attenuation than connectors.
15. Fusion splices melt two fiber ends together; they are made with expensive fusion splicers. Typical loss of a fusion splice is less than 0.1 dB.
16. Mechanical splices hold fiber ends together mechanically or with glue. Losses are slightly higher than fusion splices, but they do not require a costly fusion splicer to install.
17. Splices are mounted in indoor or outdoor enclosures for protection against stress and the environment.

What's Next?

In Chapter 14, I will look at fiber-optic couplers, which join three or more fiber ends, and other passive optical components. Chapter 15 will cover the optics used in wavelength-division multiplexing.

Further Reading

Bob Chomycz, *Fiber Optic Installer's Field Manual* (McGraw-Hill, 2000). See Chapter 11, "Splicing and Termination."

Hassaun Jones-Bey, "Connector pace accelerates to meet telecomm demand," *Laser Focus World,* September 1999, pp. 137–139

Gerd Keiser, *Optical Fiber Communications* (McGraw-Hill, 2000). See Chapter 5, "Power Launching and Coupling," for general discussion of light transfer.

Kathleen Richards, "SFF connector battle is far from over," *Lightwave,* October 1999, pp. 43–46

Note that manufacturers often have detailed information on their own connectors.

Questions to Think About

1. What is the loss caused by core-diameter mismatch when going from a single-mode step-index fiber with 9-μm core to a graded-index multimode fiber with 50-μm core?
2. You are transferring light from a 62.5/125-μm graded-index fiber with $NA = 0.275$ to a single-mode step-index fiber with 9-μm core and $NA = 0.13$. You're going to lose a lot of light from the core-size mismatch. How much loss comes from the *NA* mismatch? How much from the area mismatch, assuming even light distribution?
3. You saw earlier that Fresnel reflection loss for an air gap between a pair of fibers is 0.32 dB. Recall that the loss depends on the difference between the refractive indexes of the material in the gap and the glass. If you have water with refractive index of 1.33 in the gap, what is the Fresnel loss?
4. If two step-index fibers with core radius a are offset a distance d from each other, as shown in Figure 13.1, the area of the two cores that overlap is

$$A_{\text{overlap}} = 2a^2 \arccos \frac{d}{2a} - d\left(a^2 - \frac{d^2}{4}\right)^{0.5}$$

   Suppose your connector makes a 1-μm error in aligning the otherwise identical cores of two step-index single-mode fibers with 9-μm cores. How much loss does that cause?

5. Using the formula of Question 4, go back and estimate how precisely the same step-index single-mode fibers would have to be aligned to have offset loss of only 0.3 dB. (*Hint:* You can try the formula for different values of offset if you program it into a computer spreadsheet.)
6. Why can't two twist-on connectors be assembled into a unit as a duplex connector?
7. A major telephone carrier puts you in charge of field repairs for a major urban center. You need to outfit a special truck for skilled technicians to use in repairing breaks in overhead and buried cables. What type of splicer do you buy?
8. A large retail company hires you to manage its data-transmission networks. The company has many regional offices in separate cities, each with fiber running to a dozen desks. You want to supply every office with a repair kit in case someone trips over a cable. What type of splice equipment do you buy?

Chapter Quiz

1. Connectors

   a. permanently join two fiber ends.
   b. make temporary connections between two fiber ends or devices.
   c. transmit light in only one direction.
   d. merge signals coming from many devices.

2. Index-matching gel

   a. holds the fibers in place.
   b. keeps dirt out of the space between fiber ends.
   c. prevents reflections at fiber ends.
   d. eliminates effects of numerical aperture mismatch.
   e. all of the above

3. What is the excess loss caused by the mismatch in core diameters when a connector transmits light from a 62.5/125 multimode fiber into a 50/125 multimode fiber?

   a. 0 dB
   b. 0.19 dB
   c. 0.8 dB
   d. 1.9 dB
   e. 12.5 dB

4. The largest excess loss probably will occur in which case?

   a. transfer of light from a single-mode to a multimode fiber
   b. when an air gap of 2 μm is left between identical fibers
   c. when a 20-μm soot particle is spliced near the core of a pair of single-mode fibers
   d. when a 2° angle is left between a pair of fibers when they are spliced
   e. when index-matching gel is left out of a mechanical splice

5. How many matings and unmatings is a typical fiber-optic connector rated to survive?

   a. 100
   b. 1000
   c. 10,000
   d. 100,000
   e. 1 million

6. Ferrules do what in a fiber-optic connector?

   a. relieve strain on the cable
   b. allow adjustment of attenuation

c. hold the fiber precisely in place

d. prevent back-reflection

7. How does an SC connector attach mechanically to an adapter or patch panel?

a. It pushes straight in and snaps into place.

b. with a special tool

c. It must be screwed into place.

d. It twists with a bayonet-type latch.

e. only with duct tape

8. Which of the following mechanisms is *not* used in small form-factor connectors?

a. Latching in place like telephone jacks.

b. Twisting in place like coaxial-cable connectors.

c. 1.25-μm miniature ferrules.

d. V-groove alignment.

e. Mounting a pair of fibers in a single ferrule.

9. Splices

a. permanently join two fiber ends.

b. make temporary connections between two fiber ends or devices.

c. transmit light in only one direction.

d. merge signals coming from many devices.

10. Typical splice loss is around

a. 0.01 dB.

b. 0.1 dB.

c. 0.5 dB.

d. 0.8 dB.

e. 1.0 dB.

11. What would happen if fibers with identical outer diameters but different core diameters were spliced together?

a. The splice would fail mechanically.

b. Loss would be high in both directions.

c. Loss would be high going from the large-core fiber to the small-core fiber, and low in the opposite direction.

d. Loss would be high going from the small-core fiber to the large-core fiber, and low in the opposite direction.

e. impossible to predict

12. Splice housings are important because they

a. reduce splice attenuation.

b. protect splices from physical and environmental stresses.

c. prevent hydrogen from escaping from splices.
d. allow measurement of splice attenuation.
e. contain light sources.

13. Identify the connector type that is *not* a small form-factor type.

a. MT-RJ
b. VF-45
c. LC
d. ST
e. Fiber-Jack

14. Which connector mounts two fibers in the same ferrule?

a. MT-RJ
b. VF-45
c. LC
d. ST
e. Fiber-Jack

CHAPTER

14

Couplers and Other Passive Components

About This Chapter

A variety of components manipulate optical signals in fiber-optic systems. They fall into two broad categories: *passive components* that require no outside power supply, and *active components* that draw external power. This chapter covers couplers and other passive components that are not involved in wavelength-division multiplexing. Chapter 15 covers WDM optics including couplers, and Chapter 16 covers switches, modulators, and other active components.

Couplers split input signals into two or more outputs, or combine two or more inputs into one output. As you will learn, optical coupling is more complex than its electronic counterpart because of the nature of optical signals. This chapter will explain how optical couplers work and describe the technologies used. It also will cover other important passive components not intended specifically for WDM applications, including attenuators and optical isolators.

Coupler Concepts and Applications

Couplers connect three or more points.

Connectors and splices join two fiber ends together. That's fine for sending signals between two devices, but many applications require connections to more than two devices. A coupler makes fixed connections among three or more points. (Switches also make connections among three or more points, but they're active devices that make temporary connections and are covered in Chapter 16.) Some couplers are called *taps* because they divert part of a signal going through a communication system to another point.

Optical couplers are often packaged inside a box, which protects the coupler from the environment. This box typically has connector adapters on the outside, as shown in

FIGURE 14.1
Optical coupler is packaged with connectors on the outside.

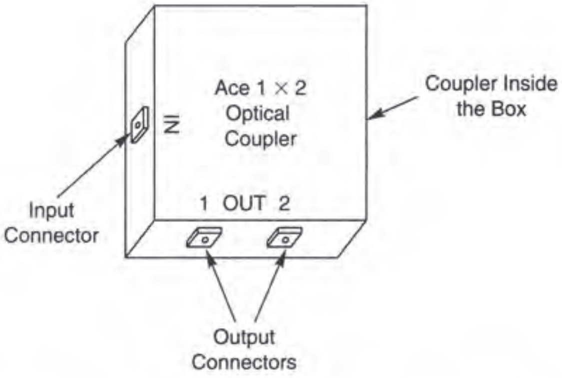


Figure 14.1, so the packaged optical coupler includes optical connectors. That may sound strange, but it's really no different from a telephone line splitter that has one plug for the input line and two for the output lines.

Couplers are used in many places that you may not notice. For example, you need a coupler to connect both a telephone and an answering machine to the same telephone line. The coupler may plug into the wall and give you two adjacent sockets, one for the phone and the other for the answering machine. It may be attached to the back of the answering machine, so you see two sockets, one for the line to the wall, the other for the line to the phone. Or it may be inside a single unit that contains both a phone and answering machine, dividing the signals between the two units in the same box. But the coupler must be there.

Couplers and taps are easy to make for electronic equipment. Electric current flows as long as you have physical contact between conductors; you don't have to line them up carefully, as you must with fiber cores. In addition, electronic signals usually are in the form of voltage. If you hook 1, 2, or 20 identical resistors across an *ideal* voltage source, each will see the same voltage signal as shown in Figure 14.2. Of course, putting more resistors in parallel across a *real* voltage source lowers the total resistance, so the voltage across the load will drop, depending on transmission-line resistance and other source characteristics. However, if the system is carefully designed, many loads in parallel will all have voltages close to what they would see individually. Thus electronic coupling can be as simple as hooking up wires to a signal source.

An optical signal must be divided among output ports, reducing its strength.

Optical signals are transmitted and coupled differently than electrical signals. First, you have to direct light into fiber cores, not merely make physical contact anywhere on the conductor. In addition, the nature of the optical signal is different. An optical signal is not a potential, like an electrical voltage, but a flow of signal carriers (photons), similar in some ways to an electrical current. Unlike a current, an optical signal does not flow *through* a receiver on its way to ground. The optical signal *stops* in the detector, which absorbs the light. That means you cannot put multiple fiber-optic receivers in series optically, because the first would absorb all the signal (except in very rare circumstances). If you want to divide an optical signal between two or more output ports, they must be in parallel. However, because the signal is not a potential, you cannot send the whole signal to all the ports. You must divide it between them, so no terminal receives a signal as strong as the input. Divide an optical signal equally between two terminals, and each gets half, as shown in Figure 14.2.

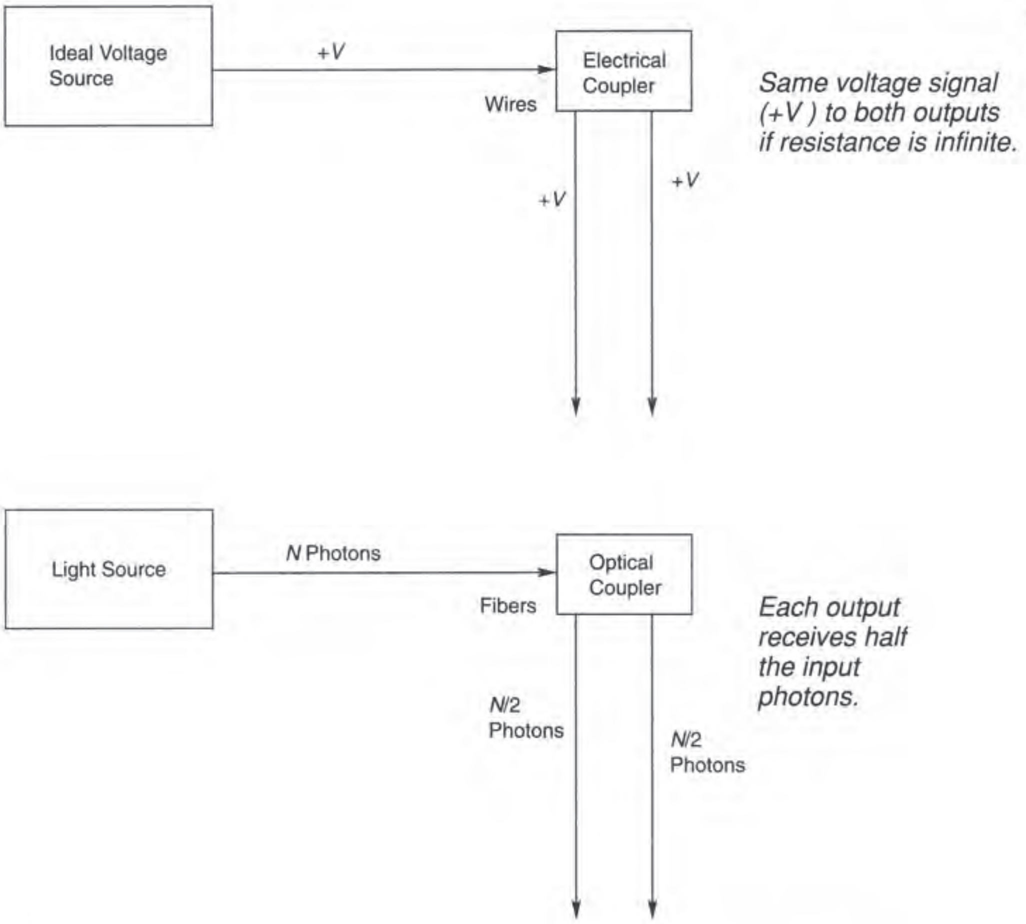


FIGURE 14.2
Optical and electronic couplers.

The need to divide an optical signal limits the number of terminals that can be connected to a passive coupler, which divides the input photons. With more ports, less signal reaches each one if the signal is divided equally, as shown in Table 14.1. Each doubling of the number of outputs reduces signal strength by 3 dB. Add too many outputs, and the signal grows too weak to detect reliably. The maximum number of ports depends on receiver sensitivity and other elements of system design.

The loss shown in Table 14.1 is the best case possible, assuming all the input light emerges from one of the outputs. In practice, things aren't that good, particularly if the coupler has many output ports. You can divide a signal in half efficiently, but dividing it into 50 or 100 equal parts is harder; some inevitably gets lost, reducing output signal strength. The difference between input signal and the sum of all the outputs (P_1 to P_n) is called *excess loss.*

$$\text{Excess loss (dB)} = -10\log\left(\frac{(P_1 + P_2 + \cdots + P_n)}{P_{\text{input}}}\right)$$

Note that Table 14.1 assumes the input signal is divided equally among the output ports. This does not have to be the case; you can design couplers that send 90% to one output

Table 14.1 Loss from splitting signals equally in passive couplers with no excess loss

Number of Output Ports	Fraction of Input in Each Output	Loss in dB
2	0.5	3.01
4	0.25	6.02
5	0.2	6.99
8	0.125	9.03
10	0.1	10
15	0.067	11.76
20	0.05	13.01
25	0.04	13.98
50	0.02	16.99
100	0.01	20
200	0.005	23.01
400	0.0025	26.02
1000	0.001	30

and 10% to a second. It also assumes that the couplers are passive devices, which draw no input power and merely divide the input power among output ports. Most couplers fall into that category, but there are a few exceptions, which I will explain later.

Coupler choice and design depend on applications.

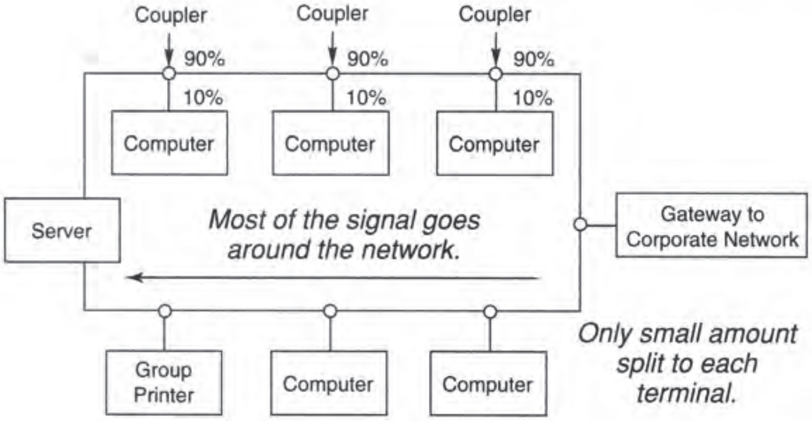
Couplers have many different applications, so many types have been developed, which divide signals in different ways. Dividing signals between two outputs is the simplest example. As shown in Figure 14.3, couplers may need to split off a small fraction of the signal for each of several terminals, deliver identical signals to many different terminals, or direct different wavelengths to different places. Each of these applications requires a different type of coupler.

In the local-area network of Figure 14.3(a), you need to direct a small fraction of the optical signal from the server to each terminal. Thus you might use a coupler that transmits 90% of the signal through the network and diverts only 10% to each terminal. (This turns out to be rather inefficient, because coupler losses accumulate around the ring, so real local-area networks usually use different architectures.)

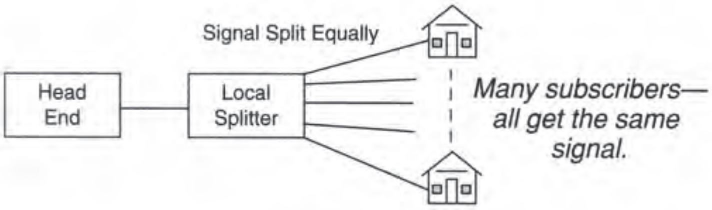
For cable-television distribution, shown in Figure 14.3(b), you want to divide the same signal into many equal portions, one for each subscriber. For this application, you use a simple 1-to-*n* splitter, which divides the signal equally among *n* outputs.

For wavelength-division demultiplexing, shown in Figure 14.3(c), you want to separate several wavelengths carried in the same fiber and distribute them to different places. Although you can consider this as a type of coupler, wavelength-division multiplexing has become so important it is covered separately in Chapter 15.

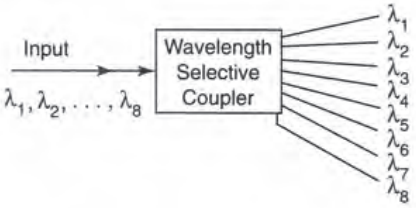
These examples highlight some functions couplers can serve in fiber-optic systems. They can combine signals from different sources, separate signals carried at different wavelengths



a. Local-Area Network



b. Cable Television



c. Wavelength-Division Demultiplexing

FIGURE 14.3 *Different coupler applications: (a) tapping signals in a local-area network; (b) delivering cable television to many subscribers; and (c) splitting wavelengths.*

and route them to different destinations, or split signals among two or more receivers. Note that the couplers do not change the signals; they merely combine, divide, or separate them.

Coupler Characteristics

Several optical characteristics determine the use and function of couplers. The most important of these are:

- Number of input and output ports
- Signal attenuation and splitting

- Directionality of light transmission (which way the light goes through the coupler)
- Wavelength selectivity
- Type of transmission: single- or multimode
- Polarization sensitivity and polarization-dependent loss

Number of Ports

The number of input and output ports depends on the application.

Various applications require different numbers of input and output ports. For example, to split one input between two outputs, you need a 1-by-2 (1 input, 2 output) coupler. To divide one signal between 20 outputs, you need a 1-by-20 coupler. And if you want to combine 10 inputs and distribute the combined signal to 10 outputs, you need a 10-by-10 coupler.

Outputs are usually, but not always, distinct from inputs.

In most cases, the inputs are distinct from the outputs, but in some cases they are not. For example, a 1-by-2 coupler implicitly is dividing the signal from one input port between a pair of different output ports. However, it is not automatically clear if a 10-by-10 coupler has 10 terminals that serve as both inputs and outputs, or 10 inputs and 10 distinct outputs (a total of 20 terminals). Usually the input and output ports are distinct, but not always, depending on the technology chosen, as you will learn later.

Signal Splitting and Attenuation

The number of ports alone does not tell how the signal is divided among them. Most couplers divide signals equally among all output ports, but some divide the light unequally. For example, a coupler that follows an optical amplifier may split off 1% of the output signal to an optical performance monitor, which verifies that all the expected optical channels are present in the output. Another example is unequal division of a signal between fibers delivering signals to receivers at different distances from the coupler.

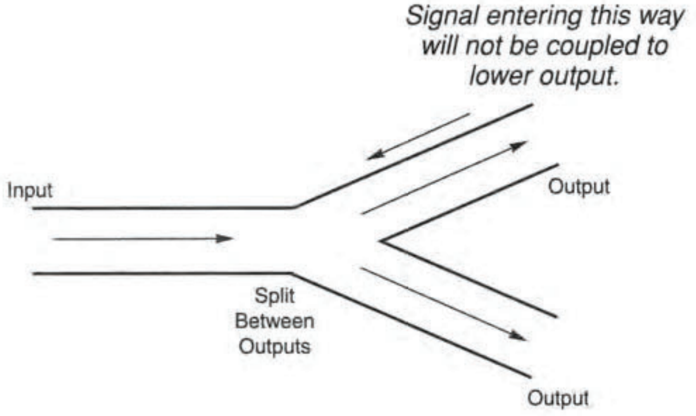
Both signal splitting and excess loss contribute to port-to-port attenuation. As you saw in Table 14.1, a 3-dB loss is inevitable when splitting an optical input signal equally between two outputs. A coupler that delivers 90% of the input to one output and 10% to the other has loss of 0.46 dB on the 90% port and 10 dB on the 10% port. Excess loss, as mentioned earlier, is essentially the light wasted within the coupler, which does not reach one of the outputs. Generally excess loss is small, but it is not safe to ignore. Specified port-to-port losses include both splitting losses and excess loss.

Port-to-port attenuation also may be specified for *undesired* light, such as signals going the wrong way through a directional coupler, or wavelengths that are supposed to go out other output ports. These values essentially measure noise.

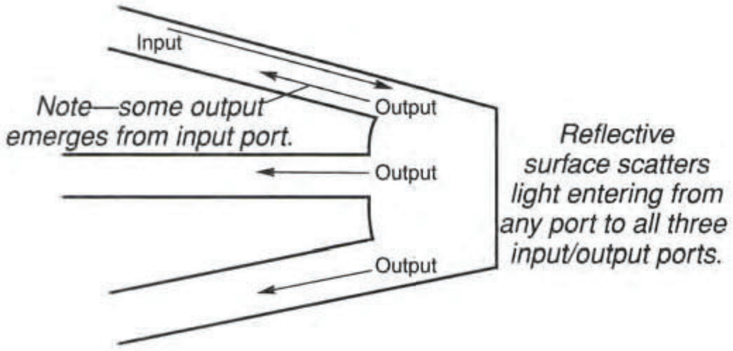
Directionality

Transmission depends on which way light goes in a directional coupler.

Many couplers are sensitive to the direction of light passing through them. They're not exactly one-way streets, but they tend to keep light going in the same direction. Figure 14.4(a) shows an example of one such *directional coupler*, where incoming light branches between two diverging outputs, like a waveguide that splits. Light that enters the



a. Directional Coupler



b. Nondirectional Coupler

FIGURE 14.4

Directional and nondirectional couplers.

left port is split between the two outputs on the right side of the figure. However, if light enters the upper-right port, virtually all of it will go to the left port because of the coupler geometry. (A small fraction of light will reach the lower right port, but the loss will be high.) It's as if the waveguides were grooves and you were rolling marbles down them—once in a while the marble might bounce out the lower-right port, but most times it would go to the right.

Other couplers show little or no sensitivity to light direction. Figure 14.4(b) is one example, where light entering from the three ports on the left is reflected from a mirror on the right, which scatters light to all three ports. It doesn't matter which port the light enters; reflected light emerges from all three—including the input port. Such a coupler mixes the light from all inputs and delivers it to all outputs.

Most directional couplers are really *bidirectional* devices; that is, they can transmit light in either direction, but the light keeps going in that direction. The 1-by-2 coupler in Figure 14.4(a) is such a device. If you direct light through the upper-right port, it will keep going in the same direction and emerge through the single port at the left. Note the difference from a *nondirectional* coupler. In a bidirectional coupler, light going in a port on either side emerges only from the ports on the other. In a nondirectional coupler, light going in any one port emerges from all the ports, including the input. There isn't much demand for truly nondirectional couplers, but they can be made if you need them.

Generally, directionality or bidirectionality is an advantage in couplers, because it sends the signal in the direction you want it. Light headed in the wrong direction—back toward the transmitter in an input fiber, for example—can cause problems such as generating noise in laser transmitters.

Directionality or suppression of reflection back toward the source generally is measured in decibels. If a 1-mW (0-dBm) signal goes through a coupler with 50-dB directionality, only 0.01 μW (−50 dBm) will go in the wrong direction.

Wavelength Range and Selectivity

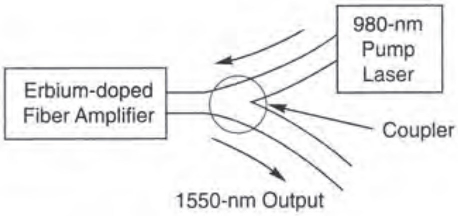
The mechanisms that divide or combine light in couplers typically depend in some way on the wavelength of light being transmitted. In some cases the dependence may be quite small, so the coupling ratio varies little between, say, 1200 and 1650 nm. In others the variation can be quite strong, directing wavelengths just a nanometer apart out different ports. These extremes represent two different classes of couplers.

Properties of wavelength-insensitive couplers vary little with wavelength.

Wavelength-insensitive couplers change their transmission little over their intended operating range. They are used in applications where light of all wavelengths is supposed to be treated equally. For example, a wavelength-insensitive coupler would be used in a system where the transmitter wavelength is not specified precisely, but the coupler has to split the signal the same way over the entire range of possible operating wavelengths. Such couplers also may be used to divide multiwavelength signals so all outputs contain all optical channels. One example would be splitting off a small fraction of optical amplifier output to an optical performance monitor to verify transmission on all channels between 1530 and 1565 nm. Performance of these couplers is specified as the same within a certain tolerance over a range of operating wavelengths.

Wavelength-selective couplers intentionally send light of different wavelengths in different directions. They are used in wavelength-division multiplexing, covered in Chapter 15. As you will learn, there are various types. Some separate widely spaced wavelengths, such as the 980-nm light from pump lasers and 1550-nm band optical signals in optical amplifiers, as shown in Figure 14.5. Others separate optical channels that are spaced closely in wavelength. The devices usually are called wavelength-division multiplexers (or demultiplexers), but strictly speaking they are special-purpose couplers.

FIGURE 14.5
Wavelength-selective coupler.



Coupler transmits 980-nm pump through top port and 1550-nm amplifier output through bottom port.

Other Transmission Sensitivities

As you will learn later in this chapter, several technologies can be used for couplers. Some of these coupler designs are limited to either single- or multimode fiber. These should be clearly identified.

Light transmission in some couplers is a function of the polarization of light, which can cause an effect called *polarization-dependent loss.* That is, the transmission of vertically polarized light differs from that of horizontally polarized light. This can be a problem because most fiber-optic systems do not constrain polarization. If the coupler loss depends on polarization, random variations in input polarization can essentially modulate the light output, inducing noise and degrading signal quality. The larger the polarization-dependent loss, the more significant this noise becomes.

Coupler Types and Technologies

Couplers may look superficially similar, but there are several distinct families and various underlying technologies. The names vary to some extent among manufacturers. The configurations or types reflect the function of the coupler. Various technologies are used.

Coupler Configurations

Coupler configurations define the function, often by the number of input and output ports. The four main types are shown in Figure 14.6 and described next:

T and Y couplers, sometimes called *taps,* are three-port devices, which split one input between two outputs. They may divide the signal equally between the two outputs or split it in some other ratio. Some T couplers are analogous to electrical taps that take part of a signal from a passing cable and relay it to a terminal; they are often shown as one fiber coming off a cable in a T configuration, as in Figure 14.6. Others have a Y-shaped geometry, with two outputs branching at an angle from one input, and are called Y couplers. The directional coupler in Figure 14.4(a) is an example of a Y coupler. They are often—but not always—directional.

T couplers are three-port devices.

Tree, or 1-to-n, couplers generally take a single input signal and split it among multiple outputs, as shown in Figure 14.6. Some have a pair of inputs that are each divided among multiple outputs. Some may combine multiple inputs to one or two outputs, so they actually are combiners. They are generally directional.

Star couplers get their name from the geometry used to show their operation in diagrams such as in Figure 14.6, a central mixing element with fibers radiating outward like a star. They have multiple inputs and outputs, often (but not always) equal in number. There are two basic types. One type is directional, mixing signals from all input fibers and distributing them among all outputs, like the upper star coupler in Figure 14.6, often made by fusing fibers together. These are bidirectional devices because they also can transmit light in the opposite direction. A second is nondirectional, instead taking inputs from all fibers and distributing them among all fibers—both input and output—as with the lower star coupler shown in Figure 14.6.