CHAPTER

12

Amplification, Regeneration, and Wavelength Conversion

About This Chapter

The previous three chapters have shown how transmitters and receivers send and receive signals in a fiber-optic system. Sometimes signals need a boost or special processing somewhere along the line to reach the final receiver in intelligible form. Optical amplifiers, repeaters, and regenerators give them that needed boost. Signals also may need to be converted from one wavelength to another as they are transmitted through a system.

In this chapter, you will learn about the differences among repeaters, regenerators, optical amplifiers, and wavelength converters; the functions they perform; and the technologies they use. Repeaters and regenerators are electro-optic devices, closely related to transmitters and receivers because they convert optical signals to electronic form. Optical amplifiers are purely optical devices, related to the lasers described in Chapter 9. Optical regeneration also is possible, but not widely used. Wavelength conversion is a separate function that may be performed optically or electro-optically.

Amplification and Regeneration

Signals suffer noise, distortion, and attenuation when traveling through any transmission medium. The further the signal goes, the more noise accumulates, the more the signal is distorted, and the more the signal fades in strength. As you learned in Chapter 11,

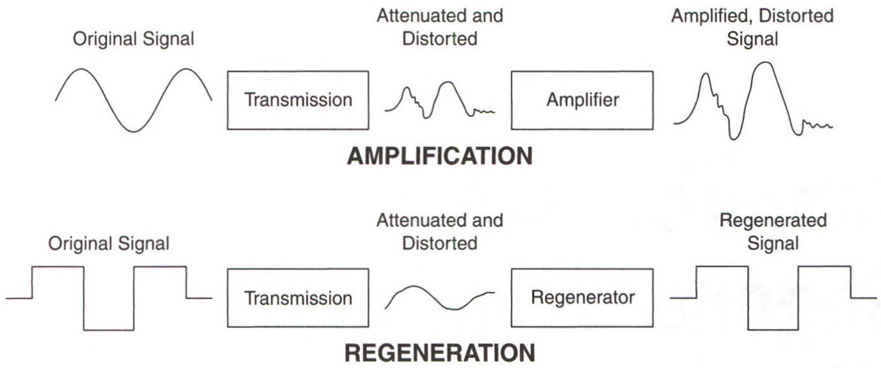


FIGURE 12.1
Amplification and regeneration.

receivers can regenerate the original signal, but only if the output signal is reasonably strong and of good quality. If a digital signal fades below a certain level, the bit error rate rises rapidly. If an analog signal fades too far, it's lost in the noise.

Amplification increases signal amplitude but does not reshape the signal.

Communication systems can avoid this problem by amplifying or regenerating the signals along the way. The two processes are different, as you can see in Figure 12.1. *Amplification* multiplies the amplitude of a weak input signal but doesn't clean it up or reshape it. It's like turning up the volume if you're listening to a distant AM radio station or a cassette tape that was recorded too faintly. The signal is loud, but it's still distorted. In practice, amplification itself can add some noise and distortion. *Regeneration* processes a weak input signal to regenerate the original input, like the digital receiver described in Chapter 11. The output is a clean signal. Regeneration also amplifies the signal to the proper strength. The operation of a regenerator depends on the signal being digital. (It's very hard to remove noise and distortion from analog signals.)

Regeneration reproduces the original signal, removing noise and distortion.

Each amplifier can increase signal strength by only a certain amount. If more amplification is needed to span a long distance, multiple amplifiers can be spaced along the length of the system to amplify the signal repeatedly. Each time the signal strength drops a certain amount, another amplifier is added. The amplification must be done before noise or distortion start to overwhelm the signal. Once the quality of a digital signal drops too much, regeneration is needed as well as amplification.

Optical and Electronic Transmission

The principles of amplification and regeneration are the same for optical and electronic signals (although optical signals can go much longer distances through fibers than electronic signals can go through copper cables). Technical details and terminology do differ, however.

Noise and distortion as well as attenuation generally are lower in optical fibers than in copper cables, so amplifiers are spaced much farther apart in optical systems. In practice, an optical signal may pass through several amplifiers before it must be regenerated. For example, an optical signal may pass through four optical amplifiers 80 kilometers apart before requiring regeneration. If more amplifiers are spaced closer together, noise and distortion can be diminished and regenerator spacing can be increased further. The spacing of video amplifiers on coaxial cables typically is one kilometer or less. Actual amplification and regeneration requirements depend on the system design.

Functions and Terminology

The terminology has evolved considerably over the years, and can be confusing because it is not applied consistently. We've already seen that amplification and regeneration have different meanings, so you may be wondering where repeaters come in. To understand that, you need a very quick history lesson.

Repeaters were first used in long-distance electrical telegraph systems to detect faint input signals and repeat them automatically for transmission through another length of wire. The signals were dots and dashes, so the repeater both amplified the signal (by generating a new one) and cleaned it up (by replacing it with a fresh signal). When telephone systems began spanning long distances, they borrowed the name "repeater" for electronic amplifiers that amplified weak input signals.

Repeaters were first used to extend telegraph transmission.

The first fiber-optic systems also used repeaters, which consisted of a receiver and a transmitter placed back to back. The receiver converted the input signal to electronic form and amplified it, then the transmitter took the electronic input and generated a new optical signal to span the next length of fiber. The term "repeater" was still accurate because the receiver-transmitter pair *repeated* the input signal on a new length of fiber.

The first practical *optical amplifiers* were invented in the late 1980s. They rely on the laser principle to amplify optical input. The weak input signal stimulates the emission of light, which amplifies the signal strength. An optical amplifier is inherently an analog device, so its output signal is what you put in, but amplified in strength and with a dash of noise added. If the signal is noisy to start with, the optical amplifier multiplies the input noise by the same factor as the input signal. Yet optical amplifiers have a compelling simplicity, and—because they leave signals in optical form—they can amplify light at a range of wavelengths passing through the fiber. They can simultaneously amplify separate optical signals carried at different wavelengths without scrambling the signals, so one optical amplifier can boost the strength of many optical channels transmitted by the same fiber. As you will learn later in this chapter, there are several different types of optical amplifiers.

Optical amplifiers are based on the laser principle.

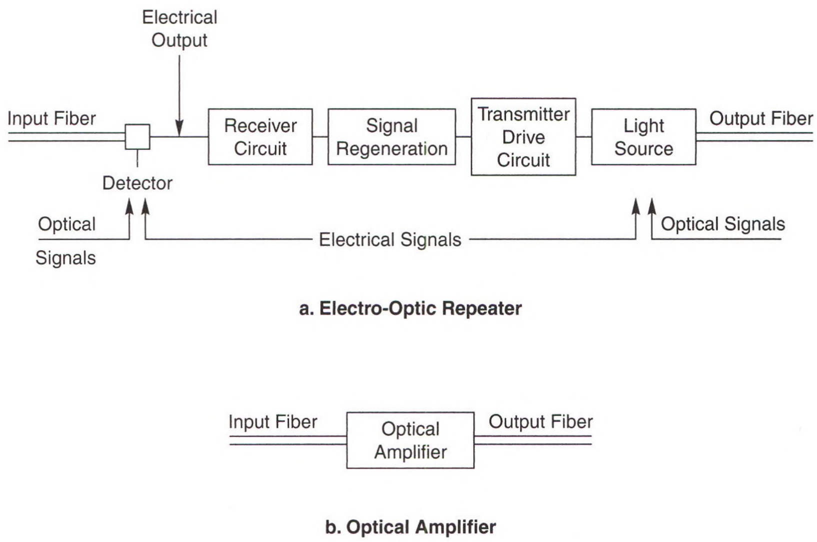
Although repeaters and optical amplifiers perform similar functions, they have different meanings in fiber optics. A repeater is specifically an electro-optic (or opto-electronic) device that converts input light into electronic form for processing, then generates an output optical signal. An optical amplifier is an *all-optical* device that never converts the optical signal into electronic form. Figure 12.2 illustrates the difference.

Recall that an optical receiver can process only one optical channel at a time; and while one optical amplifier can amplify signals at several separate wavelengths, separate repeaters are needed for each optical channel. This has proved to be a compelling advantage, so optical repeaters are considered obsolete for long-distance transmission. (You will hear of "repeaters" used in submarine fiber-optic cable, but that's an anachronism. Undersea cables use optical amplifiers, but they're called "repeaters" because they are packaged in the same type of case used for electro-optic repeaters.)

Optical amplifiers can amplify separate signals at different wavelengths.

Repeaters have sometimes been called "regenerators," and the term "regenerative repeater" has been used for repeaters that actually regenerated the original signal, as on electrical

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.

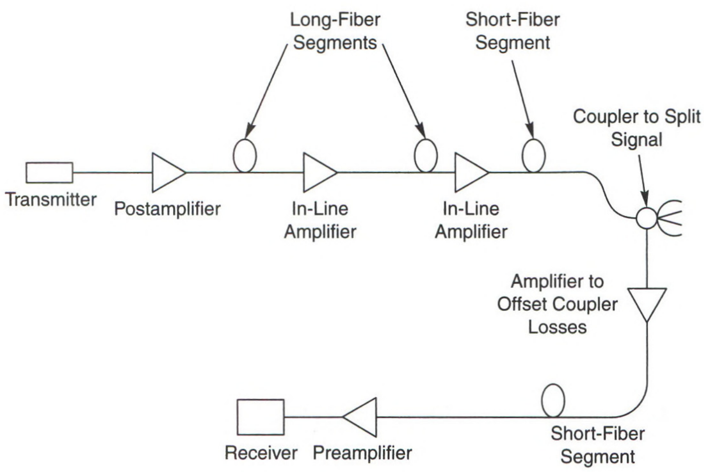


FIGURE 12.3
Roles for optical amplifiers.

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.

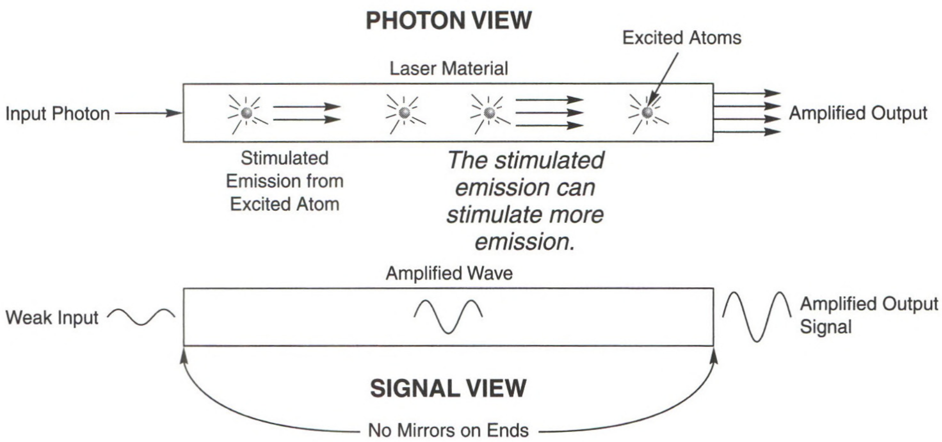


FIGURE 12.4
Optical amplification of individual photons (top), and of a signal (bottom).

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.

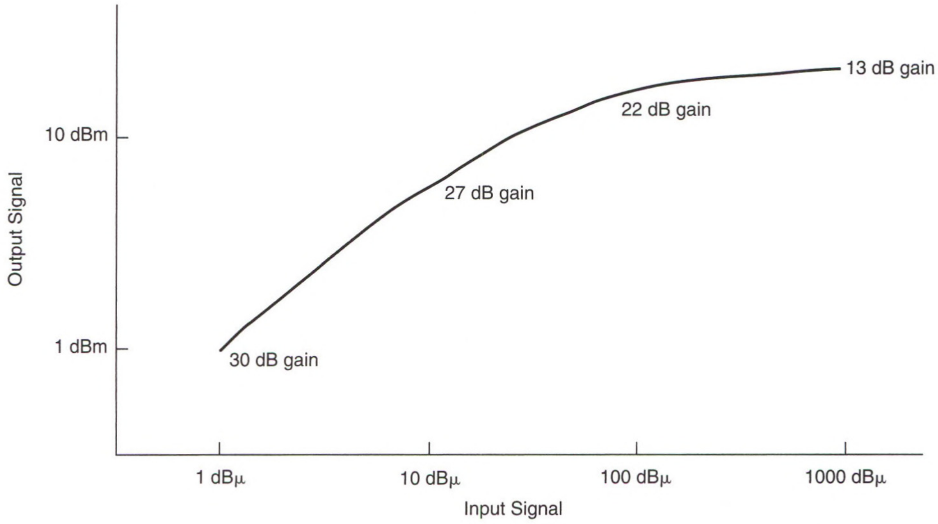


FIGURE 12.5
Saturation of fiber amplifier gain.

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.

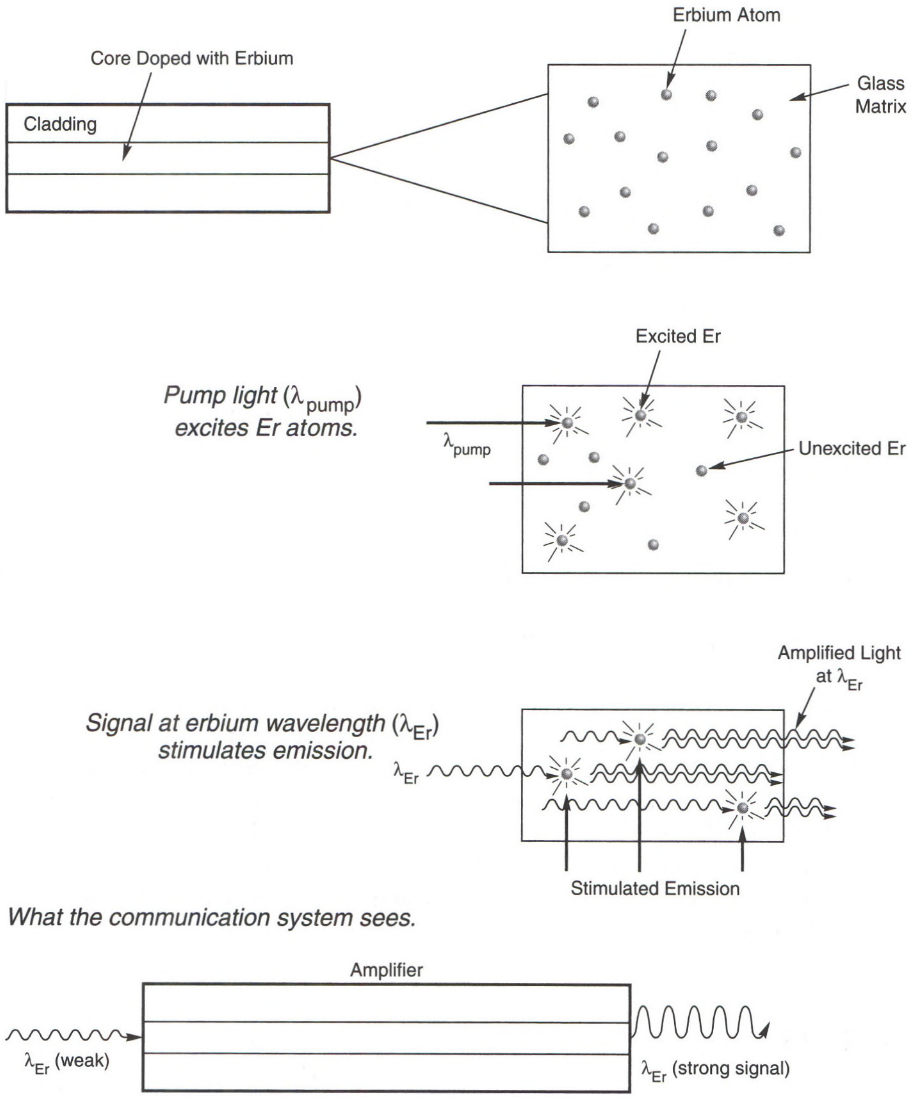
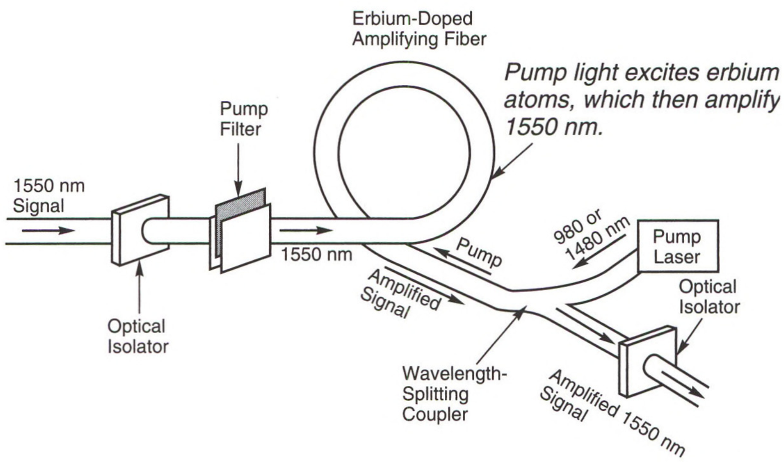


FIGURE 12.6
Amplification in an erbium-doped fiber amplifier.

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.

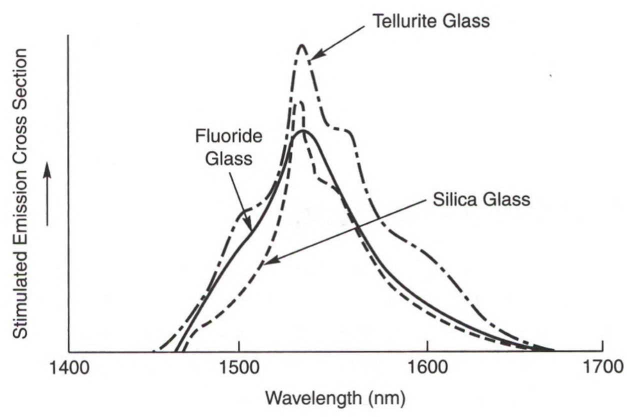


glass. (The silica glass shown has extra aluminum and phosphorus to enhance erbium emission.)

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.



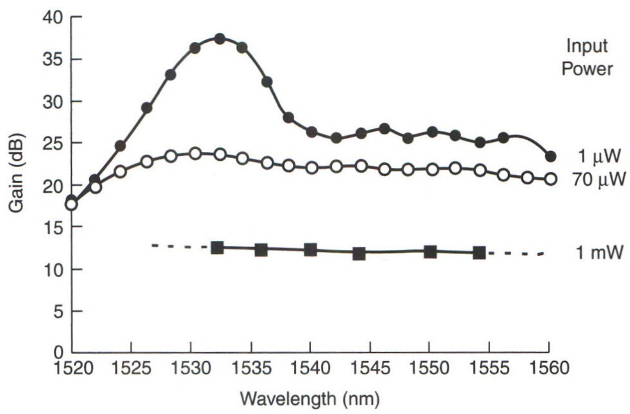


FIGURE 12.9
Erbium-fiber amplifier gain versus wavelength at different input powers. (Courtesy of Corning, Inc.)

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

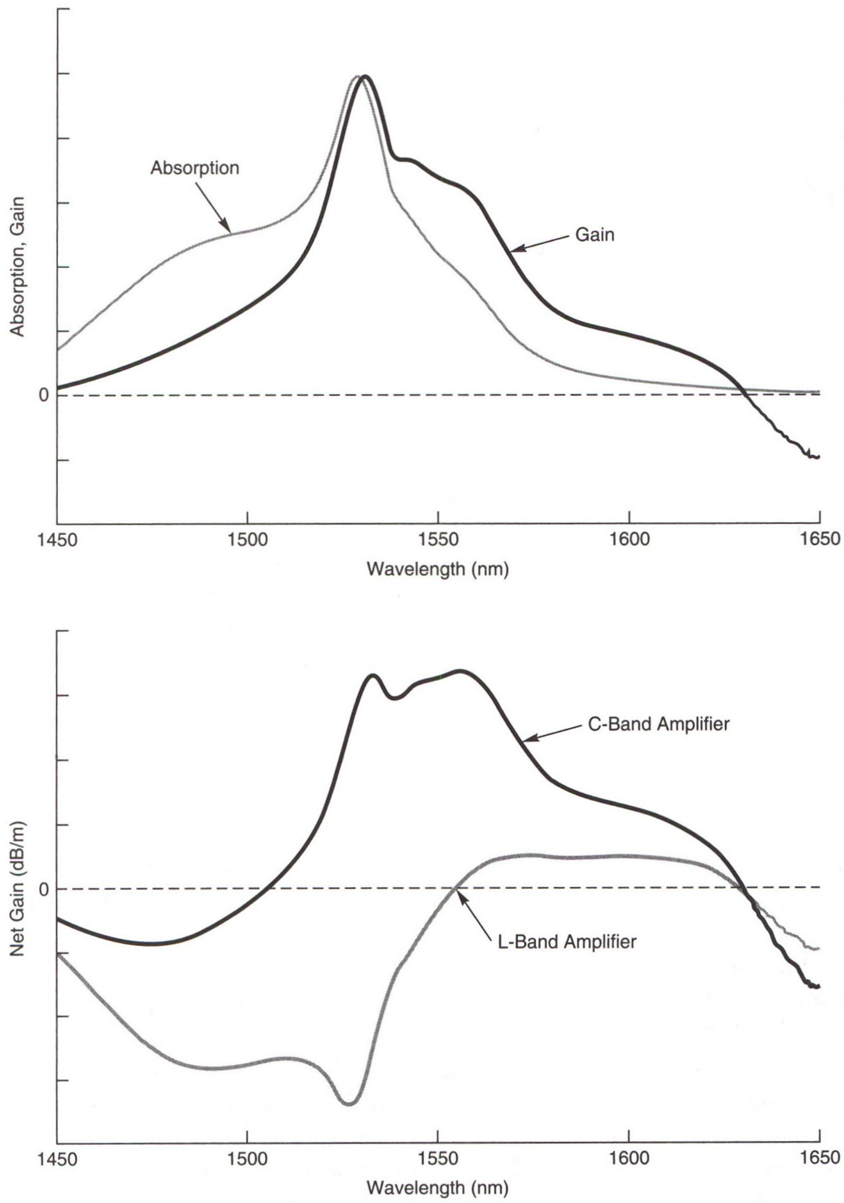


FIGURE 12.10 *Gain and absorption in a typical erbium-doped fiber (top) and calculated gain for C-band and L-band amplifiers (bottom). (Courtesy of Nufern)*

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.

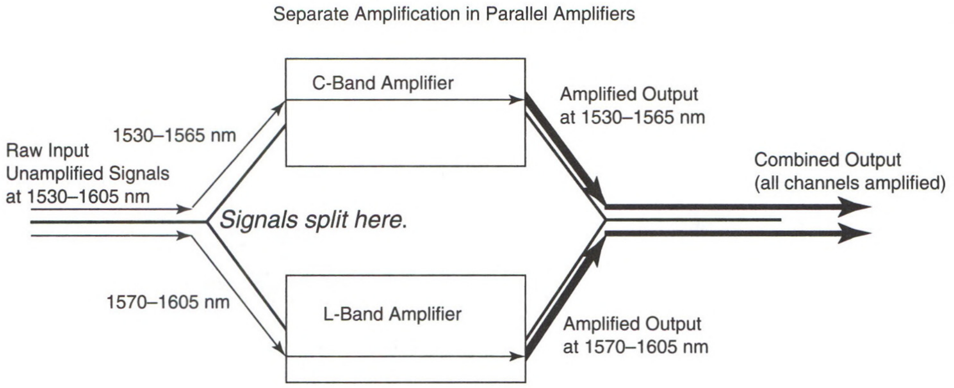


FIGURE 12.11
High- and low-band optical amplifiers in parallel.

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.

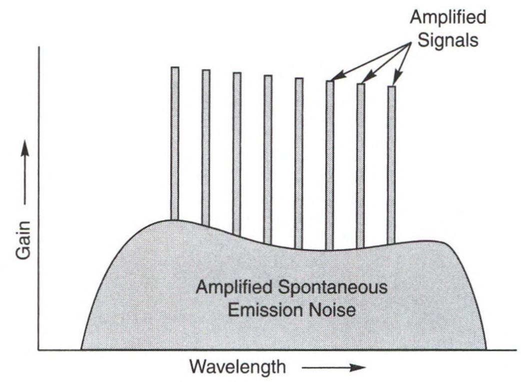
As long as the amplifier is operating in the small-signal regime, where there is power to spare, that's not a problem. However, adding more channels at the same input power can saturate the amplifier. The total output from the amplifier on all channels depends on the total input power on all channels. 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.

Doped fiber amplifiers are available for only a few bands.

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.

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

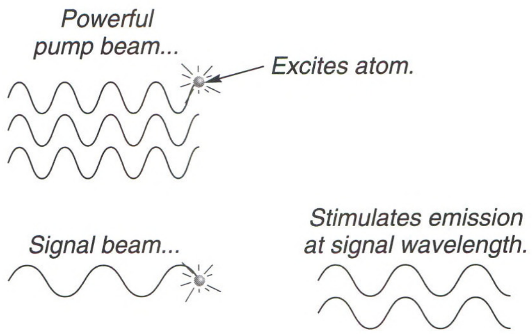


FIGURE 12.13
Stimulated Raman emission.

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

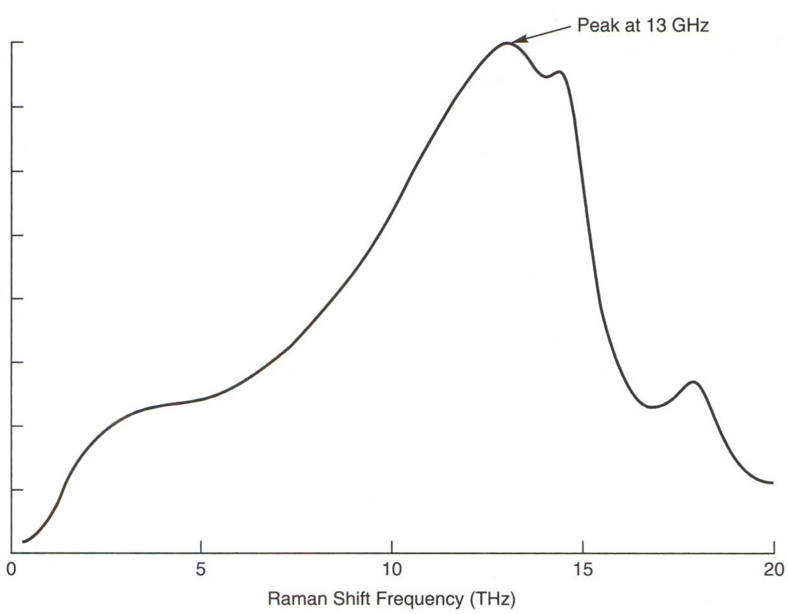


FIGURE 12.14
Raman gain of silica.

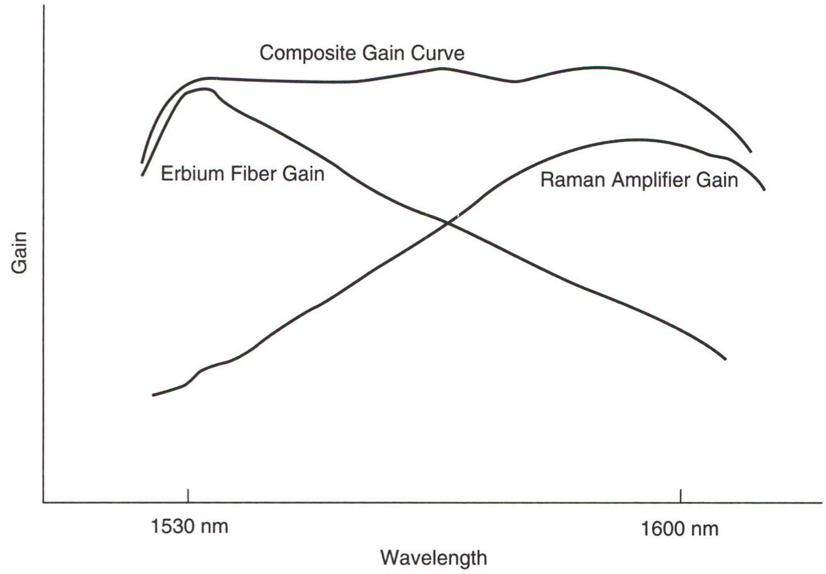


FIGURE 12.15
Raman gain equalizes spectrum of erbium amplifier to give more uniform composite gain.

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.

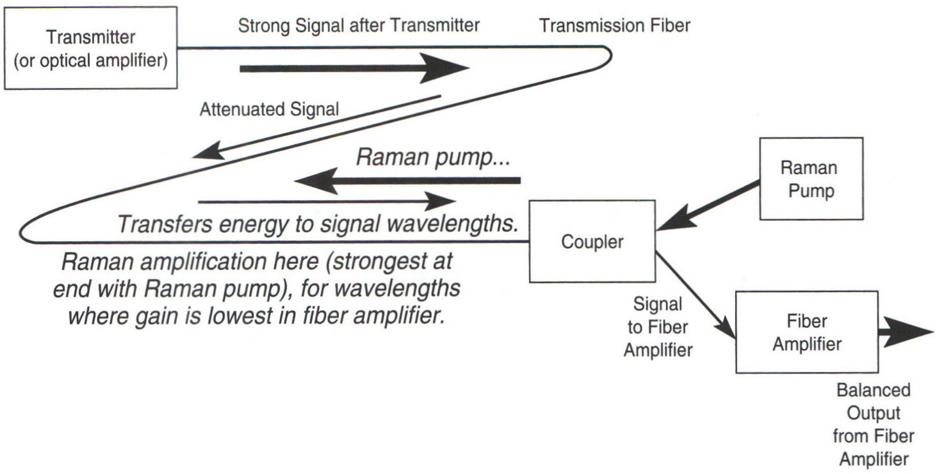


FIGURE 12.16
Layout of hybrid Raman/erbium amplifier.

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.

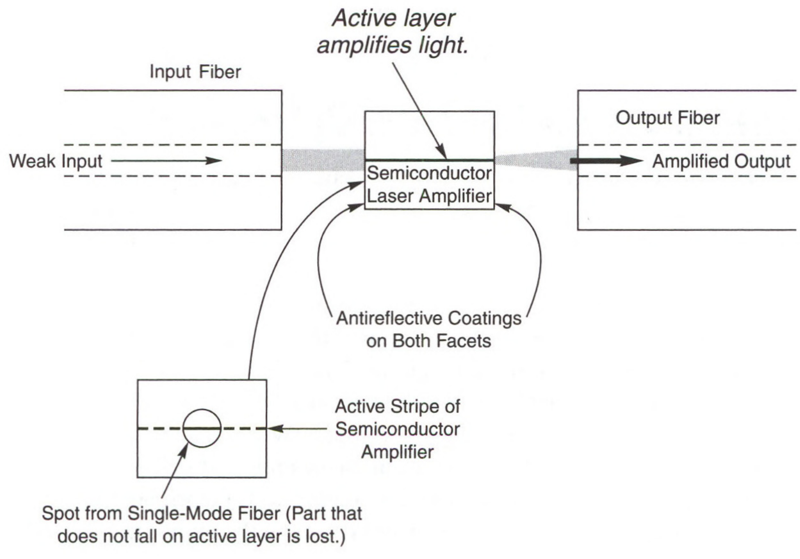
The problem is the geometry, shown in Figure 12.17, which illustrates a semiconductor optical amplifier placed between a pair of fibers. The idea is to focus light from the single-mode input fiber onto the active stripe, amplify it in the semiconductor amplifier, then focus the intense output beam into 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 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.

Semiconductor amplifiers can be integrated with planar waveguide optics.

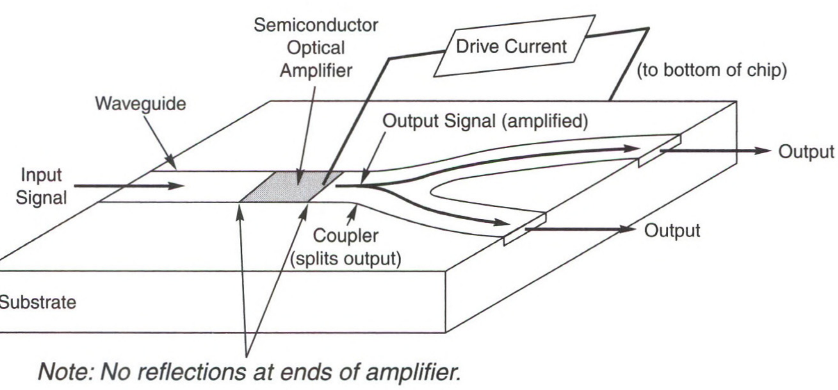


FIGURE 12.18
Integrated semiconductor optical amplifier.

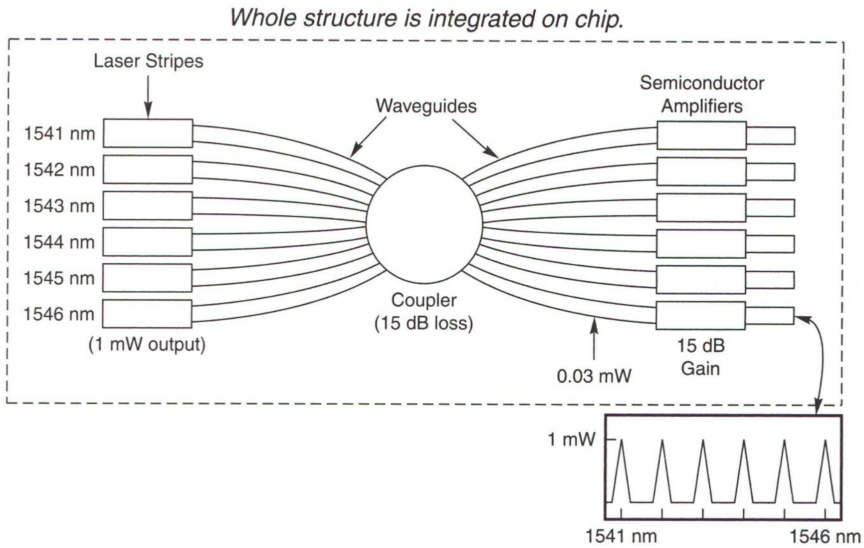


FIGURE 12.19 *Semiconductor amplifier integrated with laser array and waveguide coupler.*

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

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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