CHAPTER

9

Light Sources

About This Chapter

Fiber-optic systems require light sources that can be modulated with a signal and transfer that optical signal efficiently into a fiber. The two primary types are light-emitting diodes (LEDs) and semiconductor lasers (also called *diode lasers*). This chapter covers important considerations for fiber-optic light sources, the basic principles of LEDs and lasers, and the main types of these light sources used in fiber-optic systems. It also briefly describes fiber lasers.

This chapter will teach you what you should know about lasers and LEDs to work with fiber optics, but it does not cover all types of lasers. Chapter 10 covers how light sources are incorporated into fiber-optic transmitters. Chapter 11 covers receivers, which convert optical signals back to electronic form at the other end of the fiber. Optical amplifiers, which are closely related to diode lasers and fiber lasers, are mentioned in this chapter, but covered in detail in Chapter 12.

Light Source Considerations

The primary light sources for fiber-optic communications are *semiconductor lasers* (often called *laser diodes* or *diode lasers*) and *light-emitting diodes* (LEDs). Fiber-optic light sources must meet several requirements. The wavelength must fall within a window transmitted by the optical fiber being used. The power must be adequate for the signal to reach the receiver or optical amplifier at the other end of the fiber, but not so high that it causes nonlinear effects in the fiber or overloads the receiver. The range of wavelengths should not be so wide that it affects transmission bandwidth. The emitted light must be modulated in some way so it carries a signal, then transferred efficiently into the transmitting fiber.

Wavelength, spectral width, and power are major light-source considerations.

The same considerations apply to optical amplifiers, which must be matched to the signal wavelengths they are supposed to amplify and designed not to distort input signals.

The most widely used optical amplifiers are based on the erbium-doped fibers described in Chapter 7.

The general range of wavelengths a light source can emit depends on its composition. The specific range of wavelengths depends on its structure, and special structures are needed to select narrow ranges of wavelengths or to vary the wavelength.

Let's look in more detail at these important considerations.

Operating Wavelength

Signal attenuation and bandwidth depend on wavelength.

Both signal attenuation and pulse dispersion in a fiber depend on operating wavelength. Transmission bands are picked to match windows of low absorption or low dispersion, or to take advantage of inexpensive light sources. The choice depends on the fiber and the application.

Glass fibers are used for telecommunications at wavelengths between about 1280 and 1620 nm. The most common bands are near 1310 nm, the zero-dispersion wavelength of standard single-mode fiber, and at 1530–1565 nm, where fiber attenuation is at a minimum. Many glass-fiber links spanning only a couple of kilometers operate at 780–850 nm, where inexpensive laser sources are available. Plastic fibers have relatively low loss at 650 nm.

Single-frequency lasers limit chromatic dispersion.

Chromatic dispersion depends on the range of wavelengths emitted by the light source, called the *spectral width*. The broader the spectral width, the higher the dispersion and the lower the transmission bandwidth available. Standard LEDs have spectral widths of 30 to 50 nm, so they can only be used over limited distances for low-bandwidth signals. Low-cost diode lasers have spectral widths of 0.5 to 3 nm, as shown in Figure 9.1, so they can be used for higher-speed signals over longer distances. Generally, sending signals at speeds much above 1 Gbit/s over tens of kilometers requires narrow-line or *single-frequency* lasers with spectral widths below 0.01 nm. You'll learn about the differences in structure that lead to these spectral widths later in this chapter.

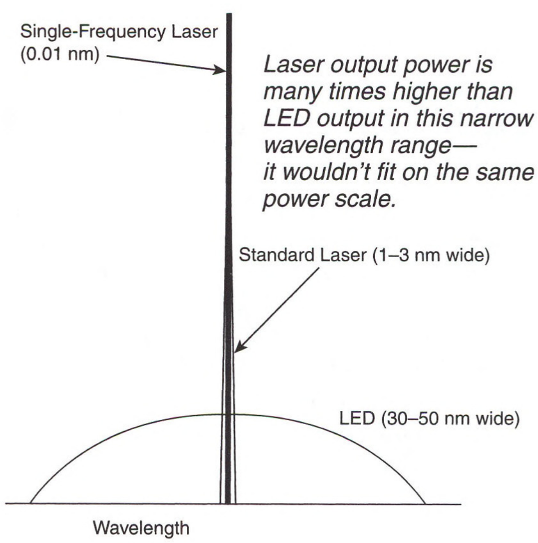


FIGURE 9.1 *Comparison of LED and laser spectral widths.*

Wavelength-division multiplexing requires light sources that emit light in specific wavelength bands or slots. The light sources must emit a stable narrow band of wavelengths, so they don't drift into adjacent bands. Nominally one source is needed for each optical channel.

Some lasers can be *tuned* to change the wavelengths at which they emit light. This is attractive for systems that require many different wavelengths of laser light because it avoids the need for a different fixed laser at each wavelength. The trade-offs are expense and the need to stabilize the laser to emit at the same wavelength over a long period.

Output Power and Light Coupling

Power from communications light sources can range from more than 100 mW for certain lasers to tens of microwatts for LEDs. Not all that power is useful. For fiber-optic systems, the relevant value is the power delivered into an optical fiber. That power depends on the angle over which light is emitted, the size of the light-emitting area, the alignment of the source and fiber, and the light-collection characteristics of the fiber, as shown in Figure 9.2.

The light intensity is not uniform over the entire angle at which light is emitted but rather falls off with distance from the center. Typical semiconductor lasers emit light that spreads at an angle of 5° to 20°; the light from LEDs spreads out at larger angles.

Losses of many decibels can easily occur in coupling light from an emitter into a fiber, especially for LEDs with broad emitting areas and wide emitting angles. This makes it important to be sure you know if the power level specified is the output from the device or the light delivered into the fiber.

The output power from semiconductor lasers and LEDs is proportional to the drive current. This allows *direct modulation* of the output light by varying the drive current passing through the device. The alternative is *external modulation* of light from a steady source using a device called a *modulator,* which changes its transparency in response to a separate signal.

Diode lasers and LEDs can be modulated directly.

Direct modulation is like flicking a light switch off and on, and external modulation is similar to opening and closing a shutter in front of the light. External modulation is more expensive, but gives better performance. A laser operated with a steady drive current has a narrower spectral width than one that is modulated directly.

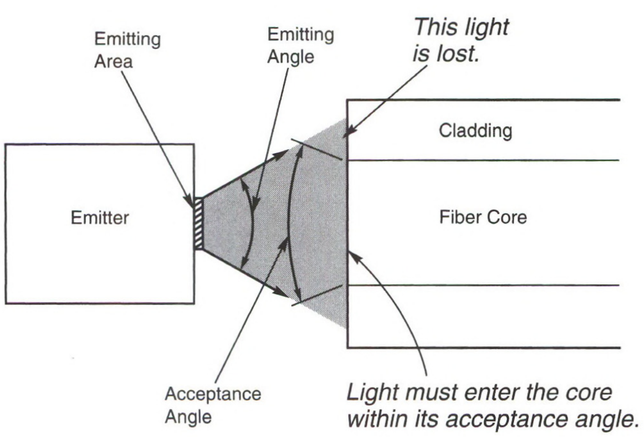


FIGURE 9.2
Light transfer from an emitter into a fiber.

Speed, wavelength, and linearity are critical factors in modulation. Direct modulation is faster for lasers than for LEDs, and external modulation can be even faster. Direct modulation also can affect wavelength because the refractive index of a semiconductor varies with the current passing through it, causing the output wavelength to vary, an effect called *chirp*. Modulation linearity is also important, particularly for analog communications. You will learn about modulation formats in later chapters.

Cost/Performance Trade-offs

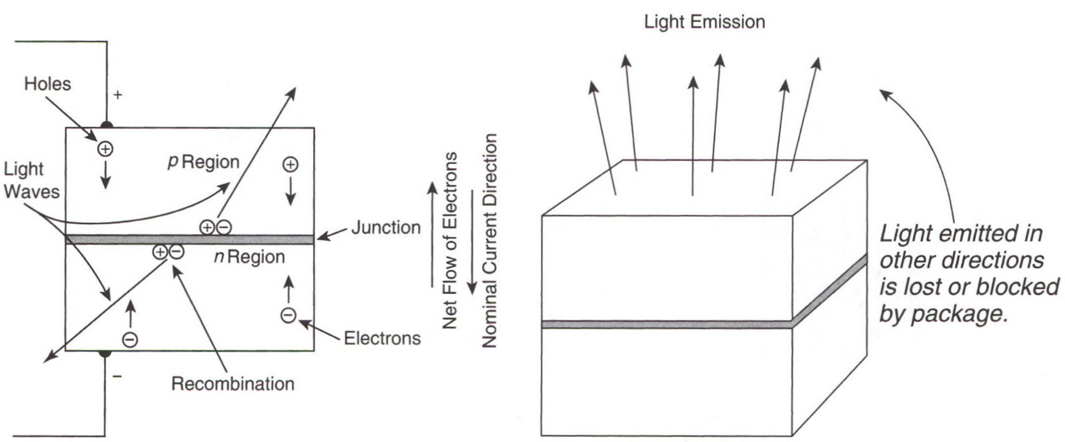
As any student of engineering reality would expect, light sources with the most desirable characteristics cost the most. The cheapest light sources are LEDs with slow rise times, large emitting areas, and relatively low output power. Diode lasers with narrow bandwidths in the 1530- to 1620-nm band, where optical fibers have their lowest losses, are the most expensive. The higher-power and narrower-line emission of lasers comes at a marked price premium, with the narrowest-line lasers costing the most. The only real performance advantage of LEDs is generally longer lifetime than some lasers.

LED Sources

An LED emits light when a current flows through it.

The basic concept of a light-emitting diode is shown in Figure 9.3. The diode is made up of two semiconducting regions, each doped with impurities to give it the desired electrical characteristics. The *p* region is doped with impurities having fewer electrons than atoms they replace in the semiconductor compound, which create "holes" where there is room for electrons in the crystalline lattice. The *n* region is doped with impurities that donate electrons,

FIGURE 9.3
LED operation.



a. Current Flow and Light Emission in an LED **b. LED as Packaged (surface-emitting)**

which leave extra electrons floating in the crystalline matrix. Applying a positive voltage to the *p* region and a negative voltage to the *n* region causes the electrons and holes to flow toward the junction of the two regions. If the voltage is above a certain (low) level, which depends on the material in the thin *junction layer,* the electrons drop into the holes, releasing energy in a process called *recombination.* As long as that voltage is applied in the same direction, electrons keep flowing through the diode and recombination continues at the junction.

In many semiconductors, notably silicon and germanium, the released energy is dissipated as heat—vibrations of the crystalline lattice. (Light emission from porous silicon is a special case that depends on the microstructure of the silicon crystal.) In other materials, usable in LEDs, the recombination energy is released as a photon of light, which can emerge from the semiconductor material. The most important of these semiconductors, *gallium arsenide* and related materials, are called *III-V* compounds because they are made of elements from the IIIa and Va columns of the periodic table:

IIIa	*Va*
Aluminum (Al)	Nitrogen (N)
Gallium (Ga)	Phosphorus (P)
Indium (In)	Arsenic (As)
	Antimony (Sb)

A new technology is developing around semiconducting polymers. These are plastics that have the electrical characteristics of semiconductors. (Conventional plastics are insulators, because they bond electrons tightly.) As with their crystalline counterparts, semiconducting plastics can be doped to make *p* and *n* materials, and electrical devices, including LEDs, can be made from them.

The wavelength emitted by a semiconductor depends on its internal energy levels. In a pure semiconductor at low temperature, all the electrons are bonded to atoms in the crystalline lattice. As temperature rises, some electrons in this *valence band* jump to a higher-energy *conduction band,* where they are free to move about in the crystal. The valence and conduction bands are separated by a void where no energy levels exist—the band gap that gives semiconductors many of their useful properties.

Exciting an electron from the valence band to the conduction band creates a *hole* in the valence band, an atom that is missing an electron and thus has a positive charge. This hole can move when an electron from another atom replaces the missing electron, leaving a hole in the electron shell of the other atom. The process is repeated in each newly created hole, and so the holes "move" within the crystal. Low levels of electrons and holes exist naturally in semiconductors, but their number can be increased by doping the semiconductor with atoms that create *p* or *n* regions where holes or electrons dominate. When an electron drops from the conduction band to the valence band (i.e., when it recombines with a hole), it releases the difference in energy between the two levels, as shown in Figure 9.4.

The usual LED wavelengths for glass fibers are 820 or 850 nm.

The band gap between the energy levels—and hence the energy released and the wavelength emitted—depends on the composition of the junction layer of the semiconductor diode. The

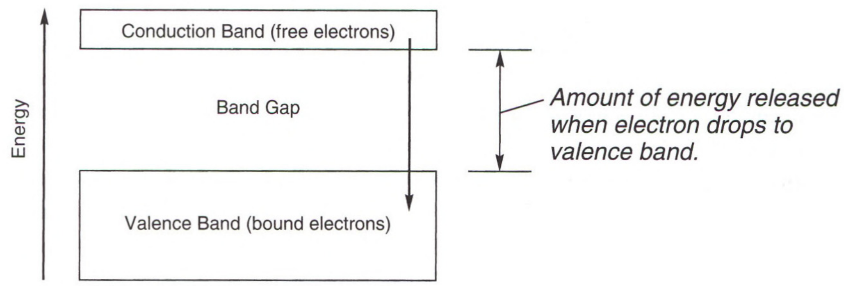


FIGURE 9.4
Semiconductor energy levels.

near-infrared LEDs used with short glass-fiber systems have active layers made of *gallium aluminum arsenide* (GaAlAs) or *gallium arsenide* (GaAs). Pure gallium-arsenide LEDs emit near 930 nm. Adding aluminum decreases the drive current requirements and increases the energy gap so light emission is at 750 to 900 nm. Generally only the thin junction layer is made of GaAlAs, with the rest of the diode GaAs, so these devices generally are called GaAs LEDs. The usual LED wavelengths for fiber-optic applications are 820 or 850 nm. At room temperature, the typical 3-dB spectral bandwidth of an 820-nm LED is about 40 nm.

The band-gap energy also can be measured in electron volts, the amount of energy needed to move one electron through an electric field of one volt. With no bias voltage applied, this potential forms at the junction layer, so no light is generated unless a current is flowing through the LED (as you would expect). A forward bias overcomes this potential at the junction layer, allowing current to flow through the LED and generating light at the junction.

Visible LEDs are used with plastic fibers, which transmit poorly in the infrared.

LEDs made of other semiconductor compounds emit different wavelengths. Gallium arsenide phosphide (GaAsP) LEDs emitting visible red light around 650 nm are used with plastic fibers, which transmit poorly at GaAlAs wavelengths. GaAsP LEDs are lower in performance than GaAlAs LEDs, but they cost less and are fine for short, low-speed plastic fiber links.

InGaAsP emits at 1200 to 1700 nm.

The most important compound for high-performance fiber-optic lasers is *indium gallium arsenide phosphide* (InGaAsP) made of indium, gallium, arsenic, and phosphorus mixed so the number of indium plus gallium atoms equals the number of arsenic plus phosphorus atoms. The resulting compound is written as $In_xGa_{1-x}As_yP_{1-y}$, where x is the fraction of indium and y is the fraction of arsenic. These so-called quaternary (four-element) compounds are more complex than ternary (three-element) compounds such as GaAlAs but are needed to produce output at 1200 to 1700 nm. LEDs are rarely used at these wavelengths.

Other LED characteristics depend on device geometry and internal structure. The description of LEDs so far hasn't indicated in which direction they emit light. In fact, simple LEDs emit light in all directions, as shown in Figure 9.3, and are packaged so most emission comes from their surfaces. The light is emitted in a broad cone, with intensity falling off roughly with the cosine of the angle from the normal to the semiconductor junction. (This is called a Lambertian distribution.)

More complex internal structures can concentrate output of *surface-emitting* LEDs in a narrower angle, by such means as confining drive current to a small region of the LED. Such designs typically require that the light emerge through the substrate, which can cause losses. One way to enhance output and make emission more directional is to etch a hole in the substrate to produce what is called a *Burrus diode,* after its inventor Charles A. Burrus of Bell Laboratories. A fiber can be inserted into the hole to collect light directly from the junction layer.

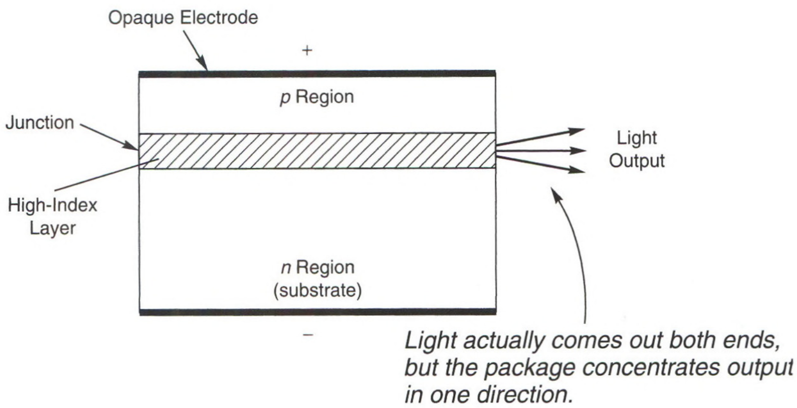


FIGURE 9.5
An edge-emitting LED.

A fundamentally different configuration is the *edge-emitting diode,* shown in Figure 9.5. Electrical contacts cover the top and bottom of an edge emitter, so light cannot emerge there. The LED confines light in a thin, narrow stripe in the plane of the *p-n* junction. This is done by giving that stripe a higher refractive index than the surrounding material, a waveguide that functions like an optical fiber, and channels light out both ends where it can be coupled into a fiber. One disadvantage is that this increases the amount of heat the LED must dissipate.

An edge-emitting diode emits light from its ends.

In general, the more complex the LED structure, the brighter and more tightly collimated the emitted light. Shrinking the emitting area and the region through which current passes also decreases rise time and, thus, enhances possible modulation bandwidth. Of course, as with other devices, the greater complexity comes at higher cost. A diode laser goes a step further.

The Laser Principle

LEDs, like the sun, fluorescent lamps, and incandescent bulbs, generate light by a process called *spontaneous emission.* Atoms or molecules accumulate extra energy, then release it on their own accord, without outside stimulation, as they drop from a high-energy state to a lower-energy state. In contrast, lasers use a process called *stimulated emission,* and to understand it we'll take a very quick tour through basic physics.

LEDs generate light by spontaneous emission.

Atoms and Energy Levels

Atoms and molecules can store only certain amounts of energy, occupying discrete states called *energy levels.* When they absorb light, they rise from one energy level to a higher one. When they drop from a higher energy level to a lower one, they release energy. In the jargon of physics, when they make a *transition* between states, they can emit a *photon,* which as you learned earlier is a unit of light energy. (The atoms don't always release energy as light, but we won't worry about these details.)

Nearly 90 years ago, Albert Einstein said an excited atom could release a photon in two different ways. One was spontaneous emission, when the atom drops to a lower energy level on its own. The other was a process that nobody had observed at the time, stimulated emission, which Einstein predicted would occur when a photon triggered the atom to release its energy as a second photon of exactly the same energy as the first in the same direction. If we look at the photons as waves, we find that the second light wave is precisely in phase with the wave that stimulated its emission, making the two waves *coherent.* Coherence organizes light waves, making them act like a troop of soldiers marching in step instead of a crowd spreading in all directions as they leave a stadium.

Laser light is stimulated emission.

The laser is based on the growth of stimulated emission in a material. A single photon spontaneously emitted in a transition can stimulate other atoms to release their extra energy as identical photons. If the conditions are just right, this produces a cascade of emission that is all in phase and coherent—a laser beam.

Excitation

The first step in producing stimulated emission is to excite the atoms to a suitable high-energy state. This can be done by passing an electric current through the laser material or illuminating it with light that can excite the atoms.

In a semiconductor laser, the excitation comes from the current passing through the junction layer. When current carriers recombine, the free electron lingers near the hole that captured it before dropping into the valence band. As long as the electron lingers in the conduction band, it can release its energy by either spontaneous or stimulated emission. The same is true for other laser materials.

However, excitation alone is not enough. LEDs are excited, but they don't produce stimulated emission.

Population Inversions

Stimulated emission requires a population inversion.

You need photons of the right energy to stimulate emission, and the most likely source of those photons is stimulated emission from atoms dropping from the same energy level. The chance of producing stimulated emission depends on how many atoms are in the upper and lower energy levels. Normally more atoms are in the lower-energy states, so a photon is more likely to be absorbed by an atom in the lower state than to stimulate emission from an atom in the upper state.

To produce a cascade of stimulated emission, you need to have more atoms in the higher energy state than the lower energy state of the transition, a condition called a *population inversion.* Figure 9.6 shows the idea, where the dots represent the number of atoms in each energy level. First, something excites the atoms to a high energy state. Atoms don't stay very long in most high-energy states, releasing their energy quickly, so they drop to a lower state. In this case, they drop into a longer-lived state that is described as *metastable* because atoms stay in it an unusually long time. The atoms linger in this state, called the *upper laser level,* long enough for stimulated emission to occur.

The stimulated emission wouldn't get very far if there were more atoms in the lower level, but in this case the atoms quickly drop down to an even lower state. This sustains a population inversion, which means more atoms in the excited state than in the lower state. But that isn't the whole story.

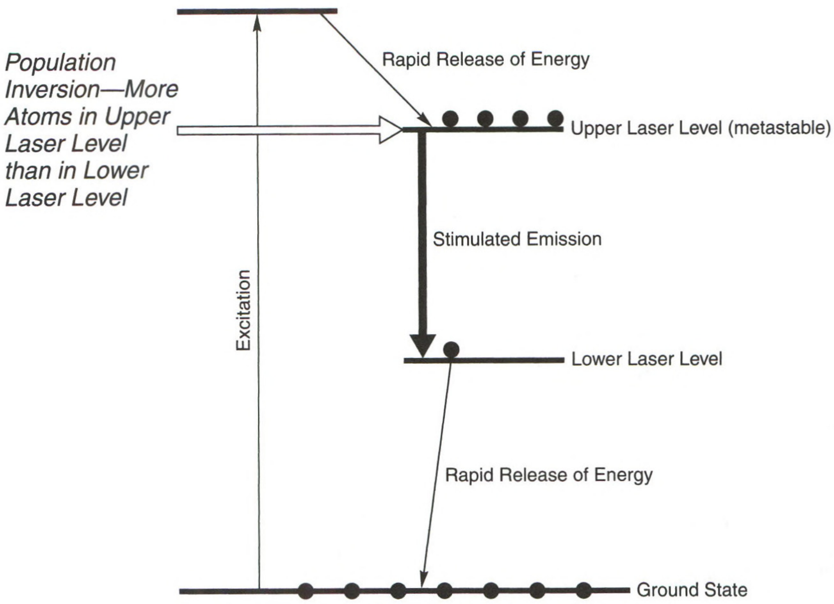


FIGURE 9.6
Energy levels and population inversion on a laser transition (bold arrow).

Amplification and Oscillation

In the presence of a population inversion, stimulated emission can amplify light at the right wavelength. Figure 9.7 shows the amplification of a weak input signal as it passes through an optical amplifier. Each input photon stimulates the emission of other photons, which in turn can stimulate the emission of others. As a result, the output signal is stronger than the input.

Stimulated emission amplifies light. Gain measures the amplification.

A quantity called *gain* measures increase in signal strength as a signal passes through the amplifier. For example, if the gain is 10% per centimeter and you started with 10 input photons, you would have 11 photons after one centimeter. In general, the power $P(L)$ at a length L along the fiber would be

$$P(L) = P_{\text{input}}\,(1 + \text{gain})^{L}$$

as long as the signals are small. (The available power is limited and saturates at some point.) Optical amplifiers have proved invaluable in fiber-optic systems, but they are not lasers.

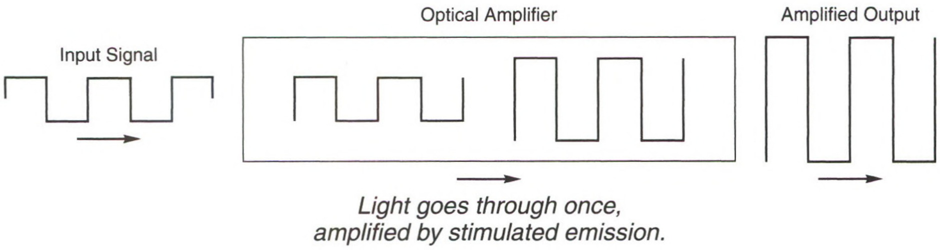


FIGURE 9.7
Optical amplification of a weak external signal by stimulated emission.

A laser is a light oscillator, which generates its own signal.

The word *laser* was coined as an acronym for *light amplification by the stimulated emission of radiation,* but that phrase glosses over the critical distinction between amplification and *oscillation.* A laser is a *light oscillator,* not a light amplifier.

An amplifier boosts the strength of an external signal, but doesn't generate a signal on its own. An oscillator generates a signal internally at a wavelength or frequency determined by its structure. The spark that starts laser oscillation is a spontaneously emitted photon, which stimulates emission of another photon, starting a cascade of other photons. A pair of mirrors on opposite ends of the device keeps the oscillation going. Light bounces back and forth between the mirrors, as shown in Figure 9.8, stimulating the emission of more photons on each pass. The pair of mirrors form a *resonant cavity.* One mirror reflects all light that strikes it, but the other mirror transmits a fraction of the light, which becomes the laser beam.

Reflection of light back and forth between the mirrors makes it pass multiple times through more excited laser material, amplifying the light more than is possible on a single

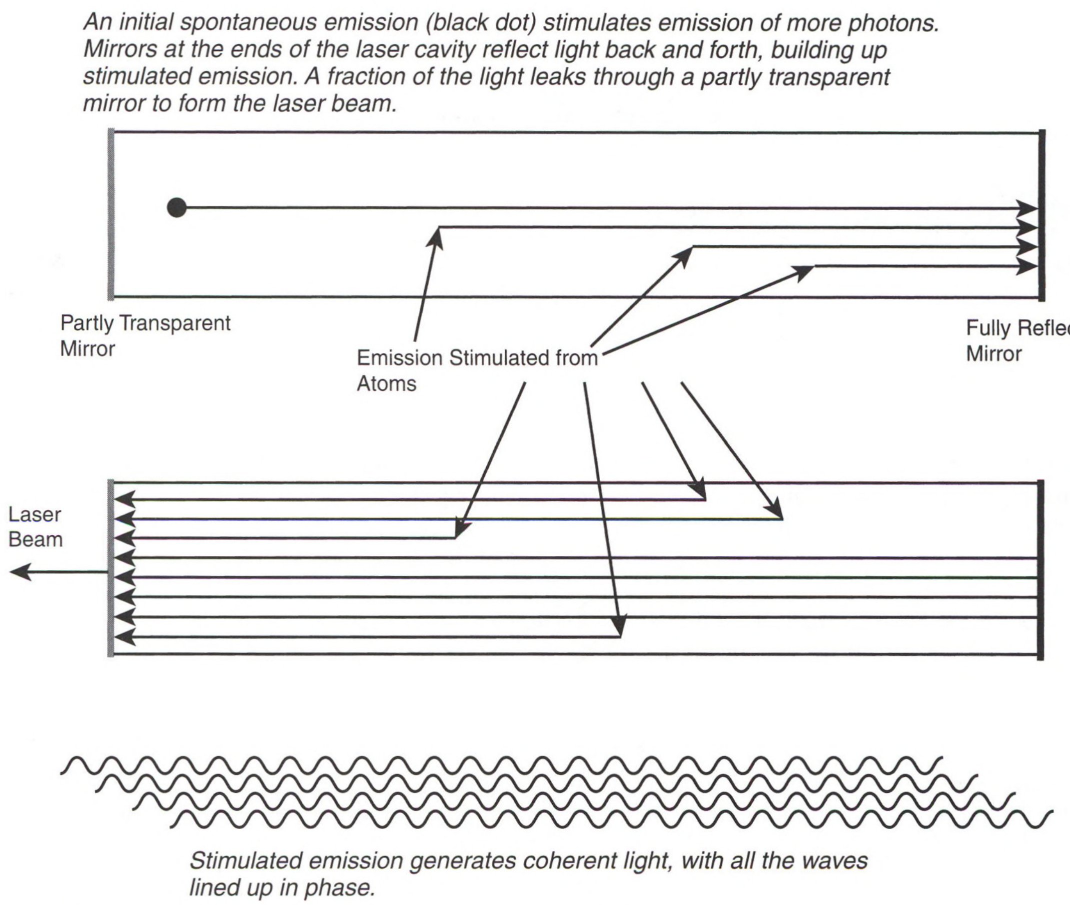


FIGURE 9.8
Laser emission from a resonant cavity.

pass. The mirrors select light that bounces back and forth in a line between them, so only light aimed in that direction is amplified, which concentrates the light emission into a narrow beam, as shown in Figure 9.8.

Each laser material has its own characteristic gain, which varies with the wavelength and conditions in the laser medium. Stimulated emission produces the strongest amplification at wavelengths where the gain is strongest, and laser oscillation further narrows the range of wavelengths. The laser structure determines how much the spectral width is narrowed.

Optical Amplifiers in Fiber Optics

Optical amplifiers deserve special attention here because they are very important in fiber-optic communications. By amplifying a weak optical signal, an optical amplifier increases the distance the signal can be transmitted. An optical amplifier is essentially a laser without mirrors at the ends. The light makes a single pass, instead of bouncing back and forth between mirrors, and is amplified by the gain within the amplifier, as shown in Figure 9.7. Two types of optical amplifiers are particularly important in fiber optics.

Optical amplifiers boost the strength of weak signals.

The *semiconductor optical amplifier* is a diode laser with its ends coated or integrated with semiconductor waveguides so they don't reflect light. (Semiconductors have a high refractive index, so they reflect some of the light trying to leave the crystal.) You'll learn more about this amplifier in Chapter 12.

The *erbium-doped fiber amplifier* is an optical fiber with erbium added to its core, as described in Chapter 7. It can amplify weak light signals that pass through it under the proper conditions. You'll learn more about its operation in Chapter 12.

We'll turn now to lasers because this chapter is about signal sources. We focus first on semiconductor lasers, starting with the simplest common type, because they are the usual type used in fiber optics. Later in this chapter, you'll learn about fiber lasers.

Simple Semiconductor Lasers

Like LEDs, semiconductor lasers are two-terminal devices called *diodes* in which holes flow through a *p region* and electrons flow through an *n region* to cause recombination in a junction layer separating the regions. Generally, diode lasers and LEDs use the same materials. The key differences are in their manner of operation and in the internal structures that control their operation.

Semiconductor lasers resemble LEDs in important ways.

LEDs produce spontaneous emission from electrons that release their surplus energy as they fall from the conduction band into the valence band. Diode lasers produce stimulated emission, which involves extracting light energy from the recombining electrons before they can spontaneously emit light. This extraction process requires concentrating the excitation energy to produce the population inversion required for laser action in the junction layer. This in turn requires a laser resonator, higher drive currents than those used in LEDs, and confinement of both the excitation and the generated light. We'll start with the simplest type of laser, called a *Fabry-Perot laser,* and describe each of these factors, then move on to other types of lasers.

Fabry-Perot Laser Cavities

Fabry-Perot diode lasers emit from the edge of the chip.

As you learned earlier, laser action occurs when light bounces back and forth within a resonant cavity, stimulating emission from excited atoms. The simplest type of resonant cavity is a pair of parallel mirrors, as shown in Figure 9.8. This is called a *Fabry-Perot cavity* after the two men who first used this arrangement to observe the interference of light waves.

In a gas laser, the two mirrors are on opposite ends of a tube containing the laser gas. In a semiconductor laser, the two mirrors are opposite edges of the semiconductor chip. One edge has a coating that reflects most of the light back into the semiconductor. (Typically a small amount of the light is transmitted so laser power can be monitored.) The opposite edge transmits more light, which emerges as the laser beam. (Semiconductors have high refractive indexes, which means they naturally reflect much of the light back into the solid and so may not require special reflective coatings.)

Some semiconductor lasers are called *edge emitters* because the light emerges from the edge of the chip, not from the surface. As with LEDs, the light is generated in the junction layer. Recall that edge-emitting LEDs are used in communications, as shown in Figure 9.5.

Stripe-Geometry Lasers

A stripe-geometry laser confines light in the junction layer.

A stripe-geometry laser, shown in Figure 9.9, confines light both vertically and horizontally within the junction layer. The junction layer itself is thin, typically a fraction of one micrometer.

The vertical confinement is created by making the *p-n* junction—called the *active layer* of the laser—of a semiconductor compound that has a refractive index slightly higher than

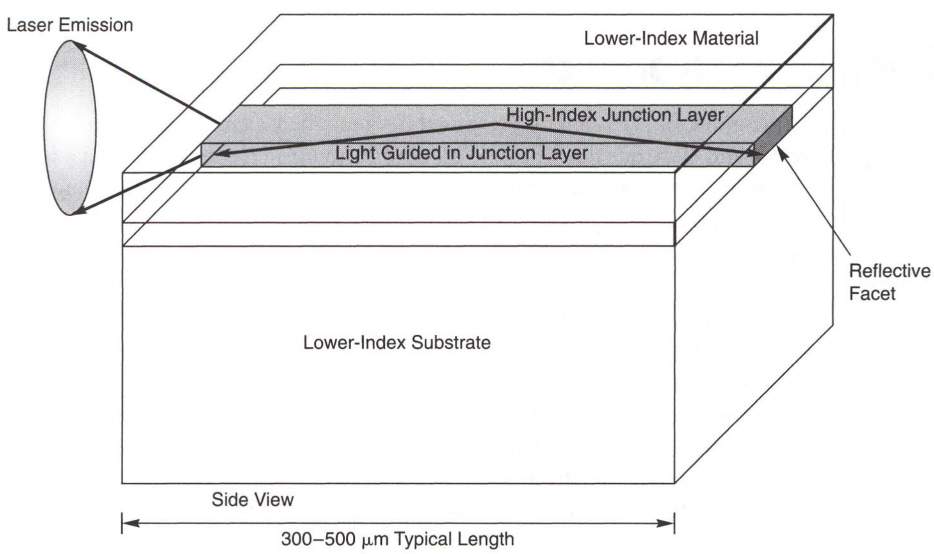


FIGURE 9.9 *A double-heterojunction stripe-geometry laser*

that of the p and n layers above and below it. This is done by changing its composition slightly, such as by adding a small amount of aluminum to gallium arsenide, which creates a boundary with different refractive index called a *heterojunction* between the two layers. The refractive-index difference between the junction layer and the layers above and below it creates a waveguide effect, which confines light in the junction plane, just as the lower-index cladding confines light in the core of an optical fiber. This layered structure is called a *double heterojunction* or *double heterostructure* and was a crucial step in the development of semiconductor devices, for which Herbert Kroemer and Zhores Alferov shared the 2000 Nobel Prize in Physics.

A stripe-geometry laser also confines laser action within a narrow stripe, typically only a few micrometers wide, in the junction layer. In telecommunications lasers, this area is usually a narrow high-index stripe in the junction layer so the difference in refractive index guides light in the horizontal plane just as the heterojunction guides light vertically. This index-guiding limits the laser to oscillating in a single mode and matches the core size of single-mode fibers.

A double heterojunction confines light in the junction plane.

Another approach is to limit current flow to a narrow stripe in the junction layer by depositing insulating layers that block current flow in other regions. This limits the population inversion to the narrow stripe where current flows, thus confining laser gain to the stripe. Lasers that only use *gain-guiding* do not confine light as well as index-guided lasers, but they are adequate for some purposes, and the two types of guiding can be combined in the same device.

There are many variations in the internal design of stripe-geometry diode lasers. Several layers of various compositions may be used to control the flow of current and light. In general, the more tightly the layers confine light, the more efficiently they produce a population inversion in the junction layer, and the more efficient the laser. Quantum well structures fabricated in the junction layer constrain where electrons and holes can recombine, improving light confinement and enhancing the performance of diode lasers.

We won't go into depth on these designs because this book focuses on fiber optics. Instead, we will concentrate on differences in design that affect the function and performance of diode lasers.

Laser and LED Performance

A first step in understanding diode laser performance is to compare the operation of lasers and LEDs. Like an LED, a laser requires a drive voltage greater than the bandgap voltage in order to generate light. Both diode lasers and LEDs must be forward-biased, with positive bias applied to the p-type material and negative bias to the n material.

A profound difference between lasers and LEDs is their behavior as the drive current increases from zero. At low currents, both devices generate some light by spontaneous emission from recombining carriers, although lasers in general are inefficient. However, once the drive current exceeds a threshold value, the laser begins to generate stimulated emission, which increases much faster with drive current, as shown in Figure 9.10. Above this *threshold current,* a diode laser generates light much more efficiently than an LED. No such threshold exists for an LED.

Laser operation begins above a threshold current.

The threshold is the point where the optical gain in the laser cavity exceeds the loss. As drive current increases, more carriers recombine, and are available for stimulated emission.

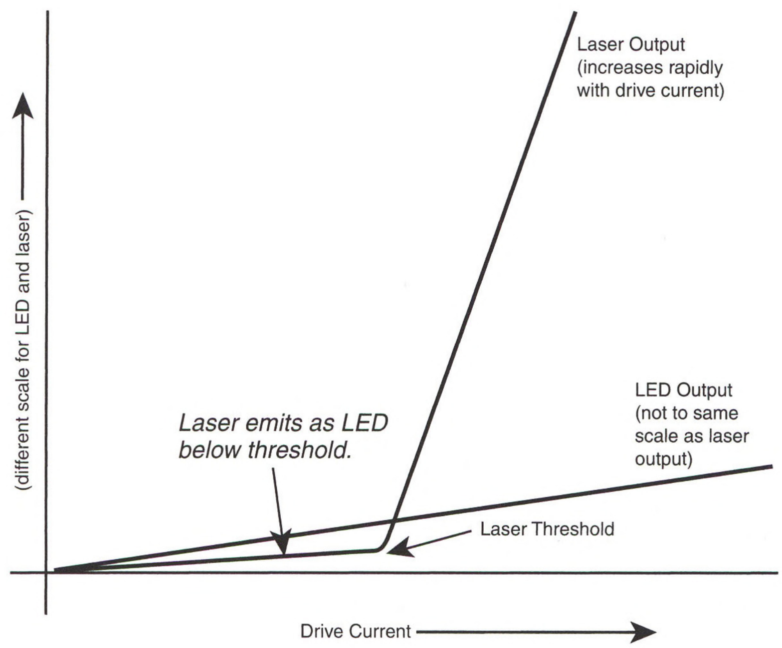


FIGURE 9.10
LED and laser power/current curves.

This increases the gain within the laser resonator. Below threshold, the gain that light makes in a round trip of the laser cavity is lower than the losses it suffers from absorption and light escaping through the end mirrors. At threshold, the gain exceeds the loss, and above threshold stimulated emission increases very rapidly with drive current, as shown in Figure 9.10. Although the curve looks steep, the increment in output power does not exceed the increment in input power. Laser efficiency can be measured in two ways, either overall efficiency comparing the output power to input power, or the *slope efficiency,* which measures the extra power generated per increment in drive current. Diode lasers are much more efficient than LEDs, with slope efficiencies that can reach tens of percent.

Diode lasers are much more efficient than LEDs.

LEDs don't have resonant cavities, because their light-emitting surfaces are made to suppress reflection, so they don't produce stimulated emission or have a threshold. That means their output increases steadily as drive current increases from zero, but the rate of increase is much less.

The threshold current is an important figure of merit for diode lasers. Below the threshold, most of the input energy must be dissipated as heat; above the threshold, much of the input energy emerges as light. In general, the lower the threshold, the better the laser's efficiency and performance. Reducing the laser threshold also tends to increase laser lifetime because it reduces the heat dissipation and operating temperature.

Another important difference between lasers and LEDs is that the laser emits a much narrower range of wavelengths. Figure 9.10 shows that spontaneous emission from an LED varies across a range of wavelengths. Stimulated emission varies in the same way, but the amplification process builds up the difference because photons at the peak wavelength are more likely to stimulate emission than those away from the peak. You'll learn more about how this works when we describe laser wavelengths later in this chapter.

Vertical Cavity Diode Lasers

The edge-emitting laser is a tried-and-true design, but its emission from the edge of the chip can be a significant practical disadvantage. Many edge-emitting lasers can be fabricated at one time on a single wafer, but the entire wafer must be cleaved before each individual laser can be mounted and tested. Lasers that emit from the surface of the chip can be tested while still on the wafer, making them easier to package and produce, and thus lower in cost. This has led to the development of the *vertical-cavity surface-emitting laser* or VCSEL.

VCSELs emit from their surface, perpendicular to the junction layer.

The resonant cavity in a VCSEL is perpendicular to the junction layer and vertical in the wafer, so the laser output emerges from the surface, as shown in Figure 9.11. This is a device rather different from an edge-emitting laser. Amplification in a VCSEL occurs only in the thin junction layer, so the light can be amplified by only a small amount in each pass through the laser cavity. In contrast, light in an edge-emitting laser passes through the entire length of the junction layer (a few hundred micrometers) on each pass, so it is amplified much more. To compensate for the lower gain within the VCSEL cavity, the mirrors must reflect more light than those used in edge-emitting lasers.

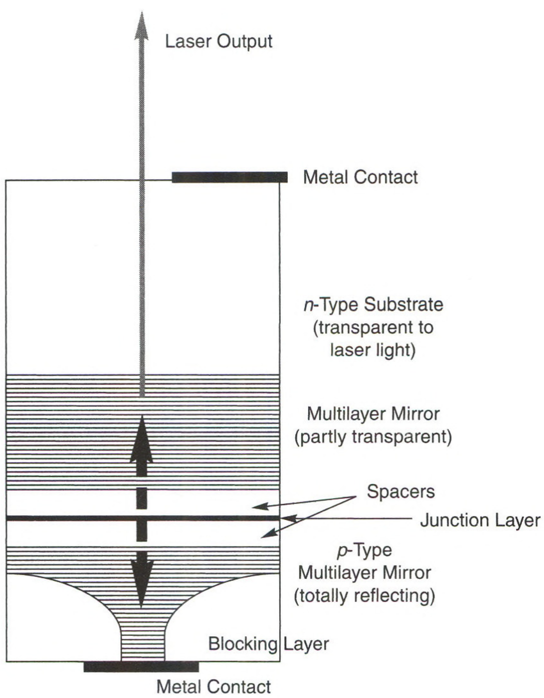


FIGURE 9.11
A vertical-cavity surface-emitting laser.

VCSEL mirrors normally are made with standard semiconductor processing techniques. They are composed of a series of layers with alternating compositions, so they selectively reflect a narrow range of wavelengths. Which wavelengths the mirrors reflect depends on the thicknesses and refractive indexes of the layers. (You may remember the concept from the discussion of fiber Bragg gratings in Chapter 7. It's a basic principle of optics that was developed decades ago.)

A VCSEL emits from a round spot typically 5 to 30 μm across on the surface of the wafer. This spot is larger than the core of a single-mode fiber, but smaller than the core of a multimode fiber. It is also larger than the output spot of an edge-emitting laser, so diffractive effects do not make a VCSEL beam spread out as rapidly. The beam is also circular, unlike the oval beam from an edge emitter.

In addition to being easy to manufacture and package, VCSELs have low threshold currents and are quite efficient in converting input electrical power into light. This means they consume less power and dissipate less heat than edge-emitters. They also have a longer lifetime and can be directly modulated at data rates well above 1 Gbit/s.

VCSELs can be made in two-dimensional arrays. They are easy to test and mount.

Unlike other diode lasers, VCSELs can be made in two-dimensional arrays covering the surface of a wafer, and these individual lasers can be modulated separately. Such arrays are attractive for optical switching and signal processing, to produce beams for transmission through optical fibers or free space.

Currently, VCSELs are the favorite fiber-optic lasers for wavelengths of 750 to 1000 nm. Longer wavelengths have proved more difficult because materials that emit light at those wavelengths don't work well for the multilayer mirrors used in VCSELs.

Laser Reliability

LEDs are more reliable than edge-emitting lasers.

Early GaAs lasers were unreliable, but great improvements have been made. Nonetheless, LEDs are more reliable than edge-emitting diode lasers because the lasers have higher current densities and optical power outputs. Threshold current can be an index of laser reliability; the lower the threshold, the longer-lived the laser. VCSELs, which have very low thresholds, are the most reliable lasers.

Operating temperature is a major factor in laser reliability; increasing temperature shortens lifetimes, and elevated temperatures are used in accelerated-aging tests. Threshold currents increase with operating temperature, increasing the waste heat generated within the laser, which further increases temperature and degrades efficiency. Gallium arsenide is more vulnerable than InGaAsP to this problem, which can lead to thermal runaway. To control heat buildup and efficiency decreases, many laser transmitters are built with active temperature stabilization, such as thermoelectric coolers. Most lasers are packaged with heat sinks, even if active cooling is not required.

Laser output declines with age.

Output power of diode lasers tends to decline slowly with age. To compensate for this decline, the transmitter can be designed to slowly increase drive current so the output power remains constant. A laser operated in this way is said to fail when it no longer delivers the required output power.

Diode lasers are particularly vulnerable to damage from electrostatic discharges. Careful handling and proper packaging can overcome this problem, but you should be aware of its potential and always ground yourself when handling lasers.

Laser Wavelength

The output wavelength of diode lasers is central to their use in fiber-optic systems. Both the peak wavelength emitted and the range of wavelengths are important for system performance. The composition of the semiconductor in the junction layer determines the wavelengths where a laser (or LED) can emit light. The device structure determines which wavelengths in that range the laser can emit. We'll start by looking at the materials, then turn to the structures used to produce particular effects.

Semiconductor Laser Materials

Diode lasers are made on GaAs or InP substrates.

Earlier in this chapter, you learned that the LEDs and diode lasers used in fiber-optic systems are made of *III-V semiconductor* compounds. The laser structure consists of a series of layers on a substrate wafer. The composition of the substrate is chosen to be compatible with the composition of the other layers, which in turn are chosen to work with the composition of the junction layer. In practice, substrates are made of two-element compounds, gallium arsenide or indium phosphide, which are easier to produce in bulk than the three- or four-element compounds used for the active layers.

The principal compounds used are:

- $Ga_{(1-x)}Al_xAs$ on GaAs for 780 to 850 nm
- $In_{(1-x)}Ga_xAs$ on GaAs for 980 nm
- $In_{(1-x)}Ga_xAs_{(1-y)}P_y$ on InP for 1100 to 1700 nm

Emission wavelength depends on the composition of the junction layer.

The subscripts indicate the relative fractions of each element. Indium, gallium, and aluminum are all Group III elements and can be interchanged with each other. Arsenic and phosphorus are Group V elements and can be interchanged with each other. Compounds containing three elements are called *ternary*, and those containing four elements are called *quaternary*. As you will learn later, 980- and 1480-nm lasers are used to pump optical amplifiers, while others are used as signal sources.

The composition of the active layer determines the peak gain wavelength. For example, the gain of InGaAsP peaks at 1310 nm for a composition of $In_{0.73}Ga_{0.27}As_{0.58}P_{0.42}$. As you learned earlier, the process of stimulated emission amplifies the peak wavelength more than other wavelengths, narrowing the range of output wavelengths from the broad spectrum seen in an LED to the narrower range of a diode laser, shown in Figure 9.1. Other layers may have slightly different composition, and the whole structure is deposited on a substrate of either GaAs or InP, which are much easier to make in the large volumes needed for substrates.

Laser Spectral Range

Fabry-Perot lasers have spectral widths of 1 to 3 nm.

The spectral range of diode lasers depends on their structure as well as their composition. The simple edge-emitting Fabry-Perot laser described earlier, with one mirror at each end, has a bandwidth of 1 to 3 nm concentrated on multiple narrow lines, as shown in Figure 9.12. These multiple lines arise from the nature of the resonant cavity.

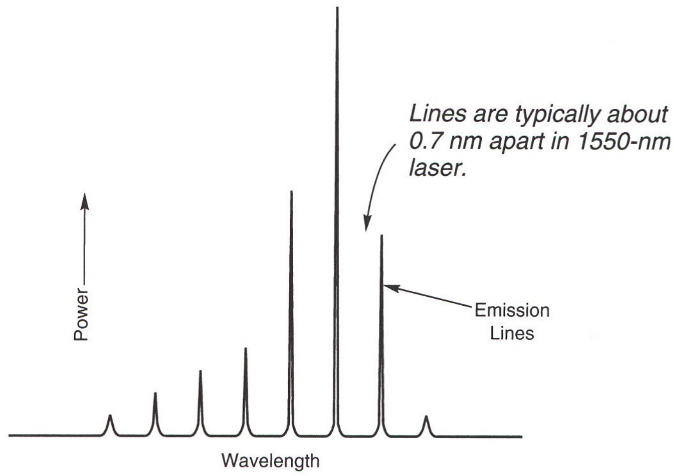


FIGURE 9.12
Wavelengths in multiple longitudinal modes.

For light to resonate within the laser cavity, the round-trip distance between the mirrors must equal an integral number of wavelengths. Thus, a laser cavity with length L in a laser material with refractive index n can resonate at wavelengths λ defined by

$$2nL = N\lambda$$

where N is an integer and where the laser material has large enough gain. Each wavelength spike in Figure 9.12 corresponds to a different value of N. The spikes span the range of wavelengths where the gain is highest.

Each spike in Figure 9.12 is a separate *longitudinal mode* of the laser, which means a resonance along the length of the laser cavity. (The modes across the width of a laser or an optical fiber are *transverse modes,* defined by the width of the laser or fiber; narrow-stripe diode lasers operate in a single transverse mode.) Each of these longitudinal modes has much narrower spectral width than the entire envelope of modes emitted by the laser. The spacing between longitudinal modes depends on the cavity length and wavelength. The longer the cavity length (measured in wavelengths), the closer the modes are spaced. Edge-emitting Fabry-Perot diode lasers have short cavities, only about 500 μm long, and their modes are about 0.6 nm apart at 1300 nm or about 0.7 nm apart at 1550 nm.

Minor fluctuations during operation can make edge-emitting Fabry-Perot lasers "hop" between modes, shifting the emission wavelength suddenly. The emission peak in Figure 9.12 moves from one longitudinal mode to another. This and other problems typically limit Fabry-Perot edge-emitting lasers to transmission rates less than 1 Gbit/s and to coarse versions of wavelength-division multiplexing with widely separated optical channels.

The same principles apply to VCSELs, but their cavities are much shorter than those of edge-emitters, so their longitudinal modes are tens of nanometers apart instead of a fraction of a nanometer. This means that in practice VCSELs emit a single longitudinal mode and can transmit at much higher speeds than edge-emitting Fabry-Perot lasers.

Single-Frequency Lasers

For high performance, low dispersion, and closer spacing of optical channels, laser emission must be limited to a single longitudinal mode or, equivalently, to a single frequency. This has led to development of more elaborate laser resonators. Figure 9.13 shows three leading approaches.

Single-frequency lasers are needed for high-speed transmission.

The *distributed-feedback (DFB) laser,* in Figure 9.13(a), has a series of corrugated ridges on the semiconductor substrate, which scatter light back into the active layer. This provides feedback like the cavity mirrors on a Fabry-Perot laser, although the details of the physics are different. The *distributed Bragg reflection (DBR) laser* shown in Figure 9.13(b) works in much the same way, but the grating is etched in a region outside the zone that is pumped by electric current. In both cases, the grating ridges are spaced evenly so they scatter only a narrow range of wavelengths back into the active layer of the laser. The active layer of the laser amplifies only this selected range of wavelengths, producing very narrow spectral bandwidths at a nominal "single frequency." The wavelength depends on the line spacing in the grating and the refractive index of the semiconductor. Recall that Bragg reflection is the same effect that selects the wavelengths reflected by a fiber Bragg grating.

Distributed-feedback and distributed Bragg reflection lasers emit only a single frequency.

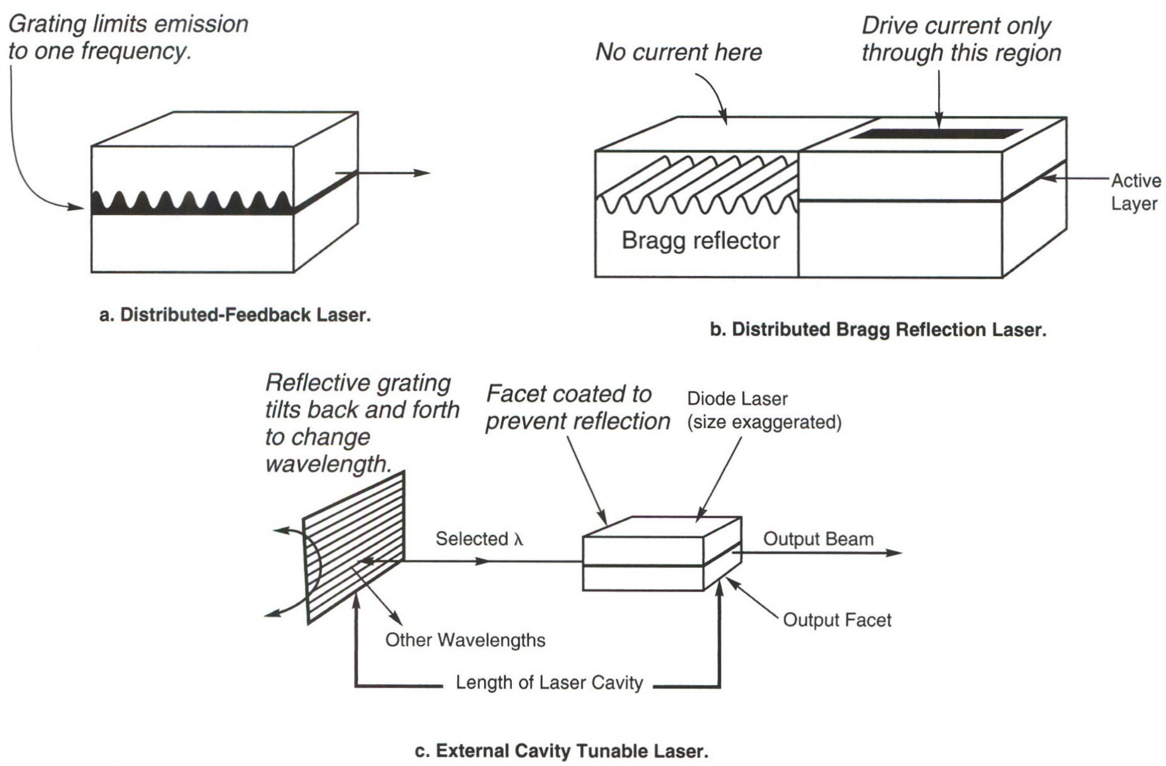


FIGURE 9.13
Three single-frequency lasers.

A different way to stabilize laser wavelength is by placing an edge-emitting semiconductor laser within an external cavity, which selects the emission wavelength. This requires coating one or both facets to suppress reflection back into the semiconductor, and adding one or two external mirrors to extend the resonator cavity beyond the laser chip. A wavelength-selective element also is added to the laser cavity. In the simple design of Figure 9.13(c), the tuning element is a diffraction grating, which serves as one external mirror, reflecting light at an angle that depends on its wavelength. (You can get the same effect by inserting a prism or some other wavelength-selective component into the laser cavity, but diffraction gratings are easier to use.) The laser chip emits a range of wavelengths, but when they strike the grating, most wavelengths are reflected at angles that take them away from the laser chip. Only a very narrow range of wavelengths are at the right angle to be reflected back into the laser chip for further amplification. This limits output to a single frequency.

Distributed-feedback and distributed Bragg reflection lasers are the types most often used to generate a single, fixed wavelength with very narrow spectral width. However, there is growing interest in lasers with output that can be tuned to emit at precise wavelengths.

Tunable Lasers

Tunable lasers can simplify logistics.

An external cavity laser is a good starting point for discussing *tunable lasers,* which can be changed in wavelength. You have already seen how a diffraction grating can reflect a single wavelength back into the laser chip for amplification, building up emission at a single wavelength. Turning the grating changes what wavelengths are reflected back to the laser chip, which changes the laser's output wavelength.

As you will learn later, wavelength tunability is an attractive property for lasers used in WDM systems and measurement instruments. Standard lasers emit only a fixed wavelength, so a system with 80 different wavelengths requires 80 different models of laser. Moreover, the service department needs spares for every one of those 80 different laser models. If a telephone company wants to install 80-channel systems, its maintenance department would need to stock every site with spares for each of the 80 wavelengths. The logistics could become a nightmare.

Tunability also can enhance the flexibility of optical networking. For example, it sometimes may be necessary to move an optical channel from one wavelength to another, because the same wavelength isn't available along its entire route. Using a tunable laser to generate the new signal would allow the wavelength to be changed without switching lasers. The laser might be tunable continuously across the spectrum, but system design would be easier if lasers were preset to emit precisely at standard wavelengths. Users would then select an optical channel, just as viewers select a channel on a modern television set, without having to adjust the laser to match the desired frequency. The technology is still young, but several approaches have been developed.

Changing the length of a VCSEL cavity can tune its wavelength.

We saw earlier that the resonant wavelength depends on the length of the laser cavity. Changing the cavity length has little effect on edge-emitting lasers, because their longitudinal modes are less than a nanometer apart. However, it can tune the wavelength significantly because a VCSEL cavity can be made very short, micrometers long rather than hundreds of micrometers long for edge-emitters. With a short enough cavity, only a single

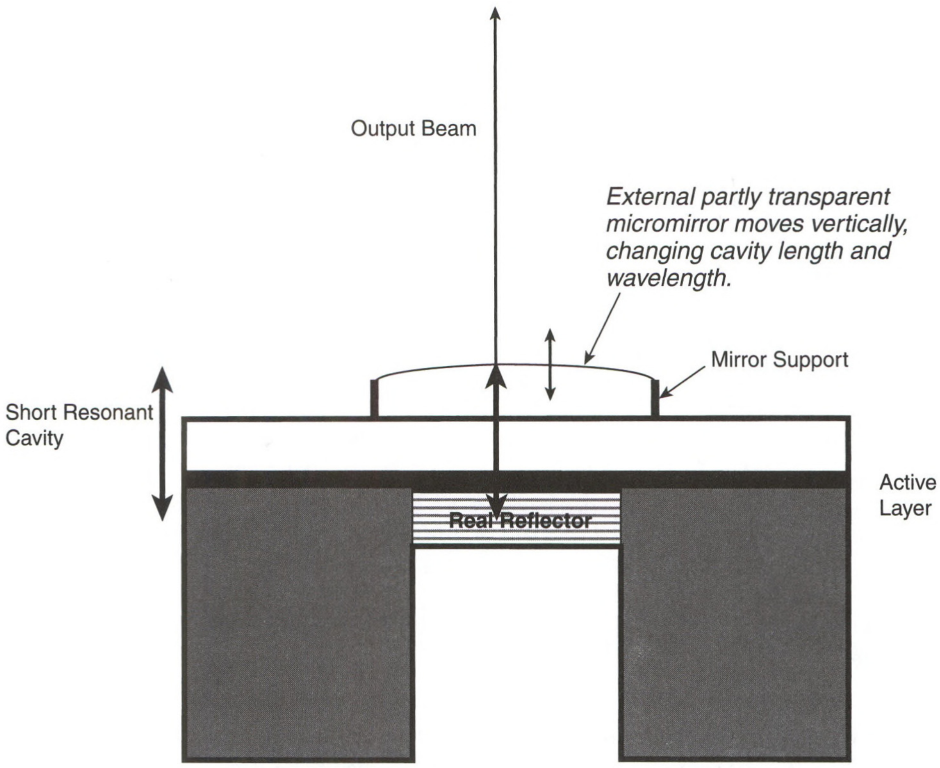


FIGURE 9.14
Tunable VCSEL relies on a moving external micromirror to change cavity length and thus wavelength.

longitudinal mode falls within the laser's gain band. This makes possible the sort of tunable VCSEL shown in Figure 9.14. A thin, partly transparent mirror is held above the VCSEL by a movable micro-electromechanical system (MEMS) device. Vertical motion of the MEMS mirror changes the resonant wavelength in the VCSEL cavity, tuning the wavelength by over 30 nm in the laboratory.

Distributed-feedback and distributed Bragg reflection lasers can be tuned in other ways. As you saw earlier, the wavelengths selected depend both on the grating period and on the refractive index of the material. Changing the temperature of the material can change both, by causing thermal expansion (or contraction) of the laser material as well as by directly affecting refractive index. Passing a current through a material also affects the refractive index. Generally these changes are relatively small, and allow turning over only several nanometers.

Tuning ranges can be extended to tens of nanometers by using more elaborate distributed Bragg reflectors. One example is the *sampled-grating distributed Bragg reflector (SG-DBR)*, which contains regions with different grating spaces that reflect a comb-like series of regularly spaced wavelengths. To make a tunable laser, slightly different separate sampled-grating reflectors are fabricated on each end of the active region of the laser. The laser can oscillate only at a wavelength reflected by the gratings on both ends, which can be tuned independently by changing current level or temperature. These changes shift the reflection peaks of the individual grating only slightly, but this small shift causes a much larger shift

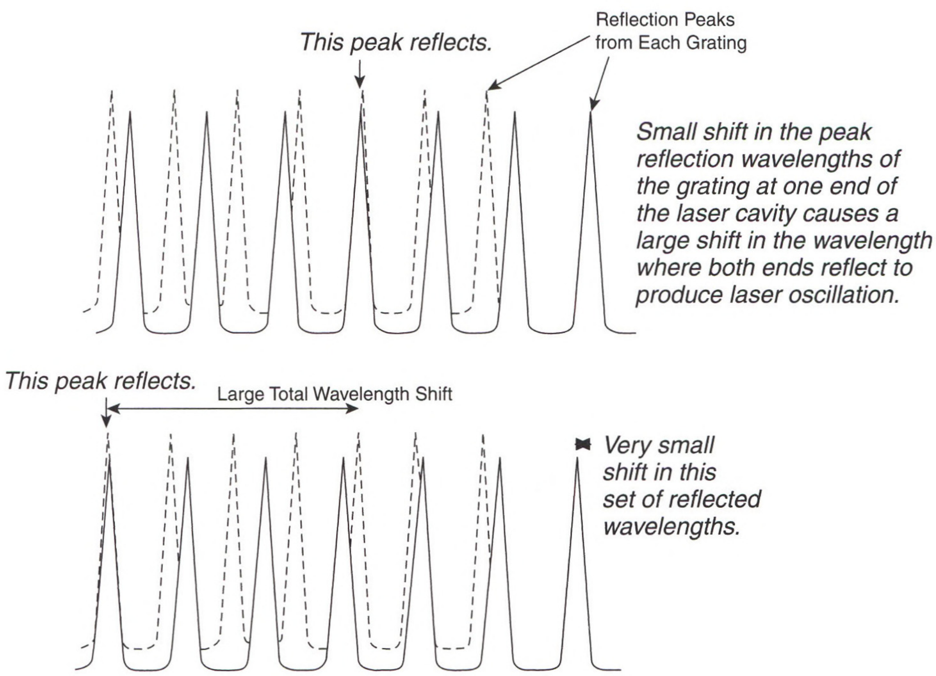


FIGURE 9.15
Tuning of sampled-grating distributed Bragg reflector laser.

in the wavelength at which both gratings reflect to allow laser oscillation, as shown in Figure 9.15. This is sometimes called a vernier effect, because a vernier scale works in the same way to amplify the size of a small change. A related approach is the *grating-assisted coupler and sampled reflector* (GCSR) laser, which combines a sampled-grating reflector with other elements to tune the output wavelength.

Another approach to tuning is selecting one laser stripe from an array of several on a single semiconductor substrate. For example, if each of 12 stripes had a tuning range of 3 nm, and their center wavelengths were 3 nm apart, they could combine to cover a 36-nm range. The device could tune across one laser's 3-nm range, then switch to the next laser and tune over its range.

Other tunable lasers also are in development. They face a number of practical challenges. Tunable lasers must be locked to the right wavelengths so they don't drift during operation. They also must be affordable, reliable, and compatible with standard telecommunications equipment. The spread of tunable lasers was stalled by the telecommunications downturn.

Modulation and Wavelength Chirp

External modulation avoids laser wavelength chirp, which causes chromatic dispersion.

Direct modulation via changing the drive current is the simplest and cheapest way to modulate the output of a diode laser. Unfortunately, it has the undesirable side effect of shifting the laser's wavelength during the emitted pulse. The electron density in the semiconductor changes as the current changes, and the semiconductor's refractive index varies with the electron density. This means that modulating the current effectively changes the optical path length in the semiconductor, which equals the refractive index n times the physical distance

THINGS TO THINK ABOUT

Lasers and the Bubble

The telecommunications bubble promoted the development of new types of lasers with very narrow spectral width and tunable output wavelength. System manufacturers wanted narrow-line lasers so they could pack as many wavelengths into as many channel slots as possible, which would enable a single optical fiber to carry huge volumes of telecommunications traffic. They also wanted the tunable lasers so they could change the wavelength, which would enable them to switch signals in their networks and to reduce their inventory of different-wavelength lasers. This led to the development of new types of lasers that could offer the desired performance, although at a high cost.

After the bubble collapsed, system operators discovered that they really didn't need all that bandwidth, or all those wavelengths going through a single fiber. Instead, they wanted lower-cost systems that could match their more modest transmission requirements. The bubble made new technology available, but some of it is still sitting on the shelf, waiting for demand to increase.

through the semiconductor L. From the earlier equation for the resonant wavelength in an optical cavity, you can see that this means wavelength λ changes by an amount $\Delta\lambda$:

$$\Delta\lambda = \frac{2(\Delta n \times L)}{N}$$

where Δn is the change in refractive index and N is an integer, the number of wavelengths needed to make a round trip in the cavity. Although the change, called *chirp,* is small, it occurs during every laser pulse, so every pulse contains a broader range of wavelengths than it otherwise would include. The resulting dispersion can impair long-distance transmission at speeds above about 1 Gbit/s.

The cure for chirp is to drive the laser with a steady current, then modulate the steady beam externally. This is done by applying the signal to a modulator, so the fraction of the laser beam it transmits varies in proportion to the signal. You'll learn more about modulators in Chapter 16; for now all you need to know is that they modulate beam intensity but do not affect its wavelength. External modulators also are very fast, working at speeds to 40 Gbit/s. They generally are used in long-distance systems transmitting at 2.5 Gbit/s or higher.

Driving the laser source with a steady current also improves its inherent wavelength stability, because any modulation induces fluctuations in laser properties.

As mentioned earlier, wavelength is temperature-sensitive, so stabilizing the laser's operating temperature controls variations in its wavelength. Stabilization is required for high-speed transmitters.

Fiber Lasers

Fiber lasers are excited by light from pump lasers, not by electric current.

Fiber lasers and amplifiers rely on the same laser principle as the semiconductor lasers we have covered so far. However, they use a different type of laser medium: a glass or crystalline material that is transparent but doesn't conduct electricity. Instead of getting their energy directly from an electric current passing through a semiconductor junction, fiber lasers are excited by light from an external source, usually a semiconductor laser that is called the *pump laser.* In this section you'll learn about fiber lasers; fiber amplifiers, which lack mirrors and a resonant cavity, are covered in Chapter 12.

A semiconductor laser is not considered a solid-state laser.

Fiber lasers are part of a larger group called *solid-state lasers,* in which light from an external source excites atoms in a glass or crystal rod to produce stimulated emission. The first laser was a solid-state laser, in which a photographic flashlamp excited chromium atoms in a ruby rod that had its ends coated with silver. From an optical standpoint, a fiber is just a very thin rod. And from a laser standpoint, a semiconductor laser is *not* a solid-state laser.

Solid-state lasers can be pumped by light from the sides or the ends. Fiber lasers often are excited by a pump laser on one end, as shown for an erbium-doped fiber laser in Figure 9.16. The light-emitting atoms (erbium in this case) are concentrated in an inner core, while the pump light is guided by an outer core, an arrangement described in Chapter 7. This concentrates the laser beam in the small inner core. In the design shown, one mirror transmits pump light and reflects the laser wavelength, while the other mirror transmits the laser beam and reflects the pump light. Generally one mirror reflects all light at the laser wavelength, while the output mirror transmits some of the light and reflects the rest to sustain laser oscillation. The thin fiber can be curved, and if it is long, it may be coiled.

Fiber lasers cannot be directly modulated.

Fiber lasers cannot be directly modulated like semiconductor lasers. They can be powered by a steady source to generate a continuous beam, which can be modulated externally with a signal. Alternatively, they can use optics to produce a series of pulses shorter than one picosecond (10^{-12} s) spaced at regular intervals; this process is called *modelocking.* Simple modelocked pulses don't carry information, but external modulation can add a signal by switching pulses on or off.

Like semiconductor lasers, fiber lasers can emit light at a range of wavelengths, depending on their composition. The specific wavelength emitted by a continuous laser is determined by the cavity optics: The output can be at a fixed wavelength, or tuned across a range of wavelengths. Modelocked pulses inherently contain a much wider range of wavelengths than a continuous beam, so they can be used as broad-spectrum light sources.

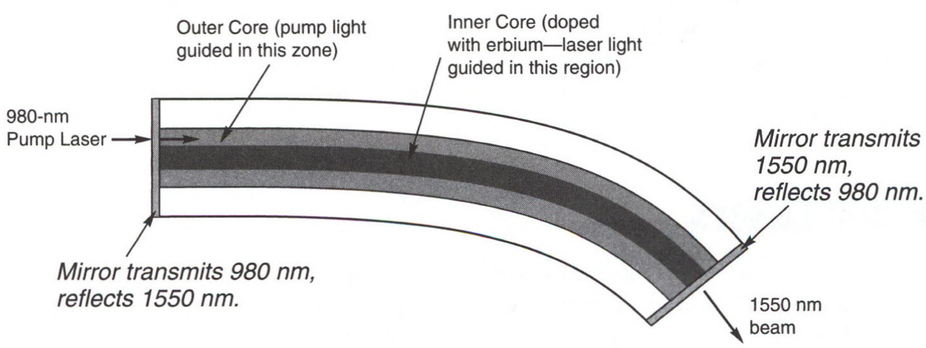


FIGURE 9.16 *Erbium-doped fiber laser pumped at 980 nm emits 1550 nm.*

Types of Fiber Lasers

Many types of fiber lasers have been developed, but only a few have found significant applications. The most important fiber lasers are:

- *Erbium-doped fiber lasers,* which typically emit at 1530 to 1620 nm and can be pulsed or continuous. Like erbium-doped fiber amplifiers, they are excited by light at wavelengths of 980 or 1480 nm. Their main applications are in communications, measurement instruments, and research.
- *Ytterbium-doped fiber lasers,* which operate at 1030 to 1120 nm and can generate powers above one kilowatt at their peak wavelength (near 1070 nm). They are being developed for industrial and military applications.
- *Thulium-doped fiber lasers,* emitting at 1750 to 2200 nm for research use.

Other Solid-State Laser Sources

Other solid-state lasers also can be signal sources in fiber-optic systems. As in fiber lasers, light from an external source excites atoms in a solid material between a pair of mirrors. The laser material is a glass or crystal host doped with atoms that emits light by stimulated emission. However, the laser material is usually shaped as a rod, is much shorter than a typical fiber laser, and lacks an internal light-guiding structure.

Diode-pumped neodymium lasers can generate more than a watt near 1300 nm.

The most important of these are crystalline neodymium lasers, in which the rare earth neodymium is doped into crystals called YAG (for yttrium aluminum garnet) or YLF (for yttrium lithium fluoride). These lasers can be excited by GaAs diode lasers emitting near 800 nm. The primary neodymium output line is near 1060 nm, but there are secondary lines at 1313 and 1321 nm in YLF and 1319 nm in YAG. Those fall right in the 1300-nm fiber window, but are not available from fiber lasers.

Like erbium-fiber lasers, solid-state neodymium lasers cannot be modulated directly; they require external modulators. Their big attraction is their ability to generate high power—more than a watt near 1300 nm. That's more than you want to send signals through a single length of fiber, but it can be split among many fibers to carry the same signals to many terminals, for network communications or cable television signal distribution.

What Have You Learned?

1. Wavelength, spectral width, output power, and modulation speed are key considerations in fiber-optic light sources.
2. Modulating the light source by changing the drive current is called direct modulation; it works for diode lasers and LEDs. External modulation uses a separate external device to modulate a steady beam from a light source.
3. LEDs and semiconductor lasers are both semiconductor diodes that emit light when current in the diode causes electrons and holes to recombine at the

junction between *p*- and *n*-type material. The electrons drop from the conduction band into the valance band.

4. The output wavelength of an LED or diode laser depends on the composition of its junction layer. GaAlAs junctions, fabricated on GaAs substrates, emit at 780 to 850 nm. InGaAsP junctions, made on InP substrates, emit at 1200 to 1700 nm.
5. LEDs produce spontaneous emission; lasers produce stimulated emission. The word *laser* comes from *light amplification by the stimulated emission of radiation.*
6. Red LEDs emitting at 650 nm are used with plastic fibers. GaAlAs LEDs emitting at 820 or 850 nm are used with short runs of glass fiber.
7. Laser light is produced by the amplification of stimulated emission as light is reflected back and forth between a pair of mirrors. A population inversion is needed to produce stimulated emission and laser action. A laser is a light oscillator and emits more power than an LED.
8. Stimulated emission amplifies light; gain measures the strength of the amplifier. Optical amplifiers boost the strength of weak signals, but lack mirrors and do not oscillate.
9. Fabry-Perot diode lasers emit from the edge of the junction layer and the side of the chip. They have spectral widths of 1 to 3 nm and emit multiple longitudinal modes.
10. A double-heterojunction laser sandwiches the junction layer between layers of lower refractive index to confine light vertically. A narrow stripe of high-index material in the junction plane confines light horizontally.
11. Laser operation begins when the drive current exceeds a threshold value. Laser power rises rapidly above threshold.
12. Vertical-cavity surface-emitting lasers (VCSELs) have mirror layers fabricated above and below the junction layer, so they emit their beam from their surface rather than their edge. Their output can be coupled easily into a multimode fiber.
13. Single-frequency lasers oscillate in a single longitudinal mode to generate the narrow-line output needed for high-speed transmission. The most common types are distributed-feedback (DFB), distributed Bragg reflection (DBR), and external-cavity lasers.
14. Laser wavelength can be tuned by adjusting the cavity mirrors or changing the refractive index in the cavity. Tunable lasers simplify logistics in WDM systems and optical networks and are used in measurement instruments.
15. Fibers that have cores doped with light-emitting elements are used in fiber lasers. Light from a laser or other external source excites the light-emitting elements, producing stimulated emission that oscillates between mirrors on the ends of the fiber. The most important fiber lasers in fiber optics are erbium-doped fiber lasers, which emit at 1530 to 1620 nm.

What's Next?

Now that I have described light sources, Chapter 10 will cover fiber-optic transmitters that use these light sources.

Further Reading

Govind P. Agrawal, *Semiconductor Lasers: Past, Present and Future* (AIP Press, 1995)

Jeff Hecht, *Understanding Lasers* (IEEE Press, 1994)

C. Breck Hitz, J. J. Ewing, and Jeff Hecht, *Introduction to Laser Technology,* 3rd ed. (IEEE Press, 2001)

Questions to Think About

1. Below threshold a diode laser emits some light by spontaneous emission. Why does it behave like an LED?
2. A diode laser has a threshold current of 12 milliamperes. That current passes through a stripe 5 μm wide and 500 μm long. What is the current density in amperes per square centimeter?
3. The diode laser in Problem 2 emits 5 mW of light. The junction layer is 0.5 μm thick. If the light is evenly distributed across the end of the active layer, what is the optical power density in W/cm^2?
4. InGaAsP has a refractive index of about 3.5. A Fabry-Perot laser emitting multiple longitudinal modes at a nominal wavelength of 1550 nm has a cavity 500 μm long. What is the wavelength difference between two adjacent longitudinal modes?
5. Suppose the laser in Problem 4 was a VCSEL with cavity length only 10 μm, and for the time being forget about the difficulty of making InGaAsP VCSELS. Calculate the separation between two modes using the same technique.

Chapter Quiz

1. Operating wavelengths of GaAlAs LEDs and lasers include
   a. 820 and 850 nm.
   b. 500 nm.
   c. 1300 nm.
   d. 1550 nm.
   e. none of the above

2. Light emission from an LED is modulated by
   a. voltage applied across the diode.
   b. current passing through the diode.
   c. illumination of the diode.
   d. all of the above

3. Which of the following statements about the difference between semiconductor lasers and LEDs are true?
   a. Lasers emit higher power at the same drive current.
   b. Lasers emit light only if drive current is above a threshold value.
   c. Output from LEDs spreads out over a broader angle.
   d. LEDs do not have reflective end facets.
   e. All of the above

4. Laser light is produced by
   a. stimulated emission.
   b. spontaneous emission.
   c. black magic.
   d. electricity.

5. The spectral width of a Fabry-Perot semiconductor laser is about
   a. 2 nm.
   b. 30 nm.
   c. 40 nm.
   d. 850 nm.
   e. 1300 nm.

6. A distributed-feedback laser is
   a. a laser that emits multiple longitudinal modes from a narrow stripe.
   b. a laser with a corrugated substrate that oscillates on a single longitudinal mode.
   c. a laser made of two segments that are optically coupled but electrically separated.
   d. a laser that requires liquid-nitrogen cooling to operate.

7. Which of the following is an important advantage of external modulation of lasers?
   a. simpler operation
   b. does not require electrical power
   c. no extra devices needed
   d. avoids wavelength chirp that could cause dispersion

8. What guides light in a narrow-stripe edge-emitting laser?

a. reflective layers on the edges of the laser wafer

b. The stripe has higher refractive index than surrounding material, so it functions as a waveguide.

c. coatings applied above and below the junction

d. light entering it from an external optical fiber

9. Which of the following is *not* true for VCSELs?

a. VCSELs emit light from their surfaces.

b. VCSEL beams are rounder than those from edge-emitting lasers.

c. VCSELs can be made easily from GaAs or InGaAsP compounds.

d. VCSELs have low-threshold currents.

e. VCSELs have multilayer coatings as their resonator mirrors.

10. A Fabry-Perot diode laser operating at 1.3 μm has a cavity length of 500 μm and a refractive index of 3.2. How far apart are its longitudinal modes? (*Hint:* First estimate the number of waves that could fit into the cavity; then calculate the wavelengths of modes N and $N + 1$.)

a. 0.013 nm

b. 0.053 nm

c. 0.53 nm

d. 5.3 nm

e. 0.13 μm