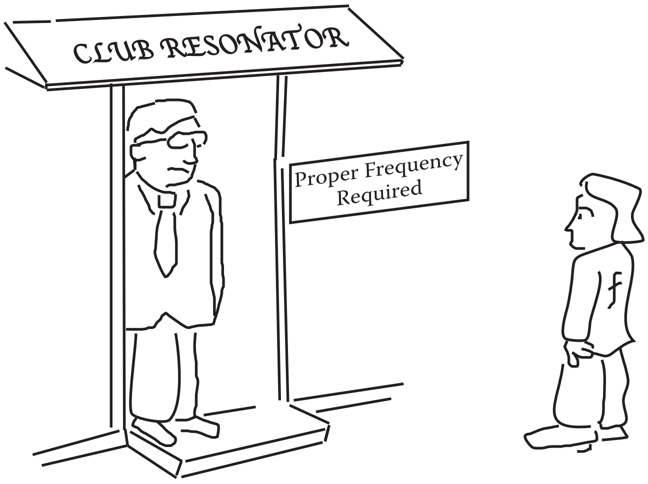

A laser resonator is like an exclusive nightclub—only certain frequencies are allowed.

IN-DEPTH LOOK 14.1: LASER RESONATOR FREQUENCIES

As explained above, in a resonator of length L, the only allowed wavelengths of light are those for which a whole number of half-wavelengths fit exactly between the two walls. If we denote the wavelength by λ, and the whole number by the symbol m ($m = 1,2,3,\ldots$), we can state this condition as an equation.

$$m \cdot \left(\frac{\lambda}{2}\right) = L$$

We can use this equation to determine the allowed frequencies of the light in the resonator. Recall that wavelength equals the distance traveled by a wave during a time equal to one oscillation period T, which also equals one divided by frequency ($1/f$). Denoting the speed of light by c, as usual, we have $\lambda = c/f$. The condition above then gives:

$$m \cdot \left(\frac{c}{2f}\right) = L$$

Multiplying both sides by f and dividing both sides by L gives allowed resonating frequencies:

$$f = m \cdot \left(\frac{c}{2L}\right) \quad (m = 1,2,3,\ldots)$$

14.5 HOW A LASER WORKS

A laser is a device that emits a highly directional beam of pure-colored, coherent light. To make a laser, we combine the idea of light amplification with the idea of a resonator. **Figure 14.9** shows the layout of a laser, consisting of a gain medium with an energy pump to transfer energy to the electrons in the medium's atoms and two reflective mirrors at the ends, making a resonator for light. A large circle shows an atom that contains stored energy and can contribute to light amplification. A small circle shows an atom that has no stored energy and will absorb (not amplify) light.

The resonator is made having two mirrors, one each placed at the ends of the gain medium. A mirror does not necessarily reflect 100% of the light incident on it. A mirror that reflects less than 100% of the incident light is called a partially reflecting

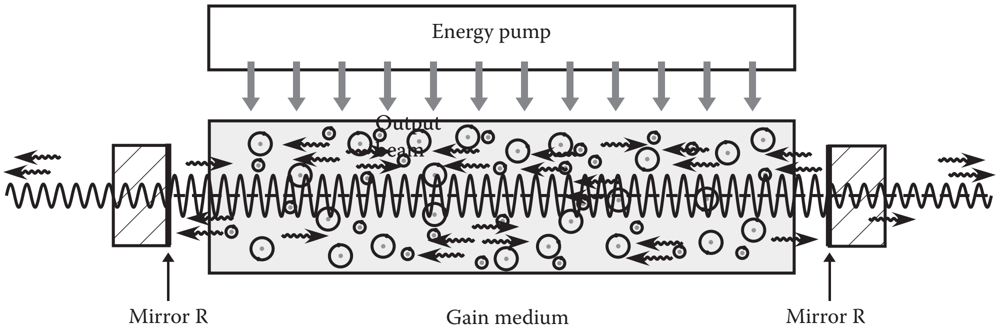

FIGURE 14.9 A laser consists of a resonator made with two reflecting mirrors, with a gain medium inside. Large circles indicate atoms containing stored energy. Small circles indicate atoms not containing stored energy.

mirror. An example of such a mirror can be found in one-way sunglasses, with reflectivity equal to 0.90. This means that 90% of the light hitting either surface (inside or outside) is reflected back, and 10% is transmitted through. The ***reflectivity*** of a mirror equals the fraction of incident power that is reflected when a light beam hits the mirror, as illustrated in **Figure 14.10**. That is,

$$R = \frac{P(reflected)}{P(incident)}, \quad P(reflected) = R \cdot P(incident)$$

The value of the reflectivity of each mirror making up the resonator is denoted by the symbol *R*. The value of *R* is between 0 (no reflection) and 1 (total reflection).

QUICK QUESTION 14.1

Expain how "one-way" sunglasses work. That is, why can the wearer see an onlooker, but on a sunny day the onlooker cannot see the wearer's eyes? Consider that mirror reflectivities are symmetric with respect to inside and outside.

A partially reflecting mirror is typically made by coating a thin layer of aluminum or other material onto the surface of a clear piece of glass. This thin layer is shown in Figure 14.9 as a bold line. Mirrors behave symmetrically; that is, the ***reflectivity*** of light is the same regardless of which side of the mirror the light is incident on.

Now we are in a position to understand how a laser works, as illustrated in **Figure 14.11**. Initially, the pump excites the electrons in atoms in the gain medium to states of

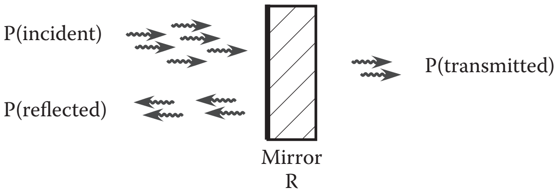

FIGURE 14.10 Light is incident on a partially reflecting mirror. A fraction *R* of the light power is reflected and the rest is transmitted.

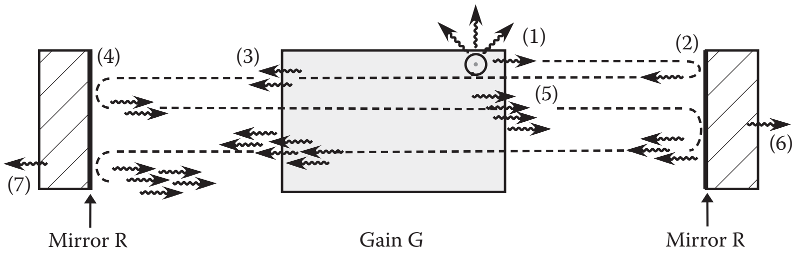

FIGURE 14.11 The sequence of events in laser operation. In this way of representing light, the number of wavy arrows indicates the power in the light beam.

higher energy. Then a sequence of events leads to laser operation (numbers correspond to numbers in parentheses in the figure).

1. A small amount of light is emitted from the gain medium by spontaneous emission, most of which travels in directions away from the mirrors.
2. Some of this emitted light travels toward one of the mirrors, where a fraction R of it is reflected back into the medium.
3. The reflected light beam returning from the mirror is amplified as it passes once through the gain medium, increasing the light power by a factor G.
4. The light travels beyond the gain medium and strikes the other mirror, where a fraction R is reflected back toward the medium.
5. The light again passes through the gain medium, being amplified by a factor G.
6. Some of the light striking the mirror transmits through it, creating an output beam from the laser. The reflected light beam returning from the mirror is amplified as it passes through the gain medium, increasing the power by a factor G.

This process is repeated over and over.

To summarize, each time the light goes through the gain medium and then reflects from a mirror, the power of the light is multiplied by the factors R and G. The mirror reflectivity R is less than 1. For laser action to occur, the gain G should be greater than one. Two cases can occur, depending on the product of R and G:

1. If $R \bullet G < 1$, there is a net loss of light on each round trip through the resonator. There is no build up of laser light. The laser is OFF. We say the laser is below threshold.
2. If $R \bullet G > 1$, there is a net increase of light on each round trip. Laser light builds up. The laser is ON. We say the laser is above threshold.

The gain G increases as you increase the pump power. A very slight change of pump power can cause the laser to go from OFF to ON. For example, consider a laser, for which the mirrors have reflectivity equal to $R = 0.90$. To have $R \bullet G > 1$, we must have the value of R be greater than 1.11. For example, if $R = 1.12$, the product of R and G equals 1.008, which is greater than 1. If instead $R = 1.10$, the product of R and G will equal 0.99, and the laser will be OFF.

replace *R* by *G*
3 times

An analogy to illustrate this high sensitivity to the pump power can be seen in the behavior of a public address (PA) system. A PA system consists of a microphone, an amplifier, and a speaker, as in **Figure 14.12**. You may know that if you turn up the volume (gain) on the PA's amplifier just a little too high, you will hear an uncontrolled, very loud squeal. This is caused by feedback—allowing the sound from the

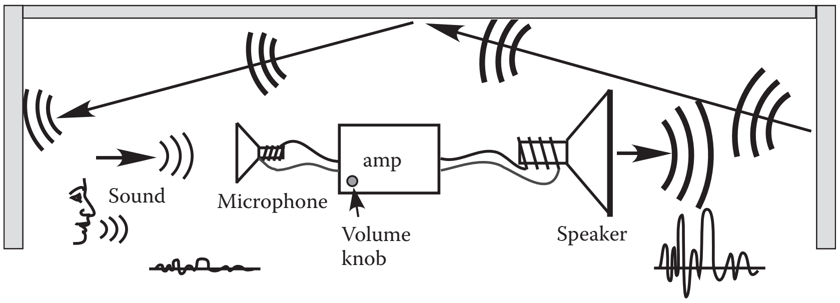

FIGURE 14.12 Feedback in a PA system. A person whispering acts analogously to spontaneous emission in a laser to start the self-oscillation of the system.

speaker's output to be picked up by the microphone, amplified, and sent into the speaker's input. ***Feedback*** is the sending of an amplifier's output back into its own input. In the case of a PA system, reflections of sound waves from walls and the ceiling can create a path for feedback. The room acts as a resonator. The sound energy is reflected and picked up by the microphone multiple times, being amplified each time. This effect is called self-oscillation, because the squeal that is heard often has a particular tone or frequency, although that frequency was not introduced into the microphone intentionally. Rather, the background noises (traffic, etc.) near the microphone contain many frequencies, and only certain of those efficiently travel around the feedback path, being reinforced. If the PA gain is turned down just slightly, the self-oscillation stops.

Optical feedback is needed for a laser to operate. Optical feedback is caused if, after being amplified by the gain medium, the light is sent back into the gain medium. Light is passed through an amplifier many times as a result of mirror reflections. Atoms in the amplifier medium may emit light of various colors, but the only light that experiences self-oscillation is the light having frequency that is resonant with the resonator and is proper for stimulated emission by the atoms. This is a highly selective condition and leads to the nearly pure color of laser light. Furthermore, the properties of stimulated emission guarantee that the emitted light has the same frequency and travels in the same direction as the initially present light. This means the light beam is nearly monochromatic and is highly directional. The light is coherent, with all wave fronts oscillating in phase and lining up in an orderly manner.

In a laser with $R \bullet G > 1$, the light has net gain upon each round trip in the resonator. On the other hand, the power in the light cannot grow indefinitely after the laser is switched ON. This is because the ***pump source*** is providing a fixed amount of power (J/sec) to the gain medium, and energy conservation prevents the laser from emitting a light beam containing more power than is provided by the pump. A little while after the energy pump source is switched on, the laser power builds up to a certain level and remains constant. We define the ***efficiency*** of the laser as the ratio of the laser light output power to the input pump power.

$$Efficiency = \frac{P(laser\ output)}{P(pump)}$$

For a typical red helium-neon gas-tube laser, the efficiency is approximately 0.001, or 0.1%, whereas for a semiconductor diode laser it is as high as 0.70, or 70%.

To summarize, the necessary parts of a laser are:

1. A gain medium.
2. A pump source to maintain most of the atoms in states of higher energy.
3. A light-energy resonator, made with mirrors, to provide feedback of the emitted light to the medium, while leaking out a small fraction of the light to create an output light beam.

14.6 THE HELIUM-NEON LASER

An important type of laser is the gas laser, the most common example of which is the helium-neon laser, or HeNe laser. It emits a nearly monochromatic red beam with wavelength 632 nm, and is inexpensive (about $200). HeNe lasers became commonly used in supermarket checkout scanners in the late 1980s, although now semiconductor lasers, which are more compact, have replaced them.

It is interesting to contrast a HeNe laser with a neon fluorescent lamp, which we discussed in Chapter 9, Section 9.3 concerning atomic vapor lamps. Neon lamps can be seen commonly in store windows, where the glass tube holding the red-glowing neon gas is twisted into the shapes of letters making words for advertising. Although such a lamp has the proper type of atoms—neon—with which to make a laser, there is not enough energy stored in the atoms to create gain, and there is no resonator. Therefore, the light it emits is just spontaneous emission, which is not directional and is not coherent.

HeNe lasers are constructed as in **Figure 14.13**. The mixed helium and neon gases are contained in a glass tube, which has mirrors glued directly to its ends. The example shown here has a flat, highly reflecting (R = 0.999) mirror glued to one end, and a second, curved, mirror (with R = 0.99) at the other end. Light partially reflects off the curved mirror and passes back through the gas in the tube, where it is amplified and reflected by the flat mirror. The output light beam emerges from the lower-reflectivity, curved mirror.

The three required laser elements for a typical HeNe laser are:

1. Gain medium—a mixture of helium (85%) and neon (15%) atomic gases.
2. Pumping—electrical current creates an ionized gas (a gas with some of the atoms' electrons removed from the atoms and free to move in the spaces between atoms), allowing electrical current to flow.
3. Resonator—a flat mirror and curved mirror.

One of the mirrors is curved to keep the returning light tightly focused in a narrow beam, as in **Figure 14.14**. This is needed because the inner bore of the gas tube is quite small, and the light must pass through the bore for it to be amplified sufficiently on each pass. In a HeNe gas laser, the gain factor G is quite small, approximately G = 1.02. This requires that the mirror reflectivity be greater than R = 0.98.

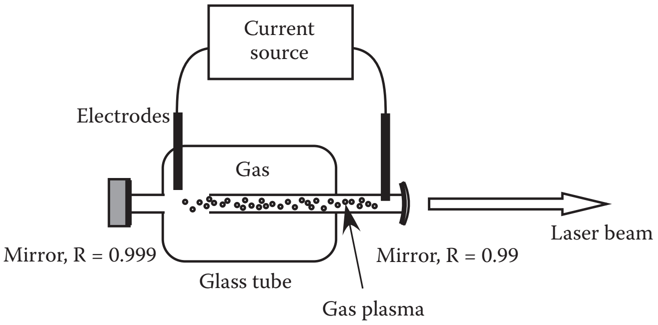

FIGURE 14.13 Helium-neon (HeNe) laser.

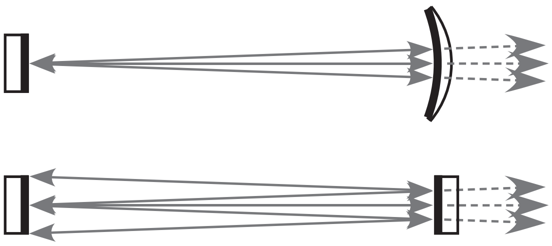

FIGURE 14.14 Laser resonators having one flat and one curved mirror serve to keep the light beam or mode confined to the axis of the laser tube. A laser resonator made with two flat mirrors will not confine the beam as it reflects back and forth—the beams spread out, as shown in the bottom panel.

When electrical current passes through the gas, the fast-moving electrons collide with the He atoms, exciting some of their electrons to higher energy. These excited He atoms then collide with Ne atoms, transferring their electron excitation to the electrons in the Ne atoms. The Ne-atom electrons then undergo stimulated emission, amplifying any passing light of the proper frequency. The electric current deposits approximately 1 W of its power in the ionized gas, and only 1 milliwatt (mW) of that deposited power goes into the emitted laser beam. The rest is dissipated as heat. That is, the efficiency of a HeNe laser is quite low—only approximately 0.1%.

IN-DEPTH LOOK 14.2: EXTREME LASER FACTS

Scientists and engineers love lasers because they offer the possibility of extreme behavior. This allows scientists to probe nature on very fine scales and to burn holes through solid objects. To find out about extreme lasers—the X-GAMES™ of LASERS—I asked some experts[1] about the biggest, "baddest," shortest, longest, slowest, fastest, and smallest lasers they knew of. These stats are from circa 2007 and are not necessarily the record holders but are important representatives of each category. The numbers in parentheses correspond to references given at the end of the chapter, where more information can be found.

Highest-energy laser pulse: 150 kilojoules (kJ) in a 10-nanosecond pulse. The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in Livermore, California, achieved this result in 2005. The energy contained in the 150-kJ pulse is equivalent to a 1-ton automobile traveling at about 60 miles per hour. Soon, the NIF aims to achieve a pulse energy of a couple of megajoules. All of this energy will slam into a tiny pellet containing deuterium—a form of hydrogen—in an effort to induce nuclear fusion, which may serve as a futuristic source of power, as well as aiding in nuclear-weapons research [1].

Shortest laser pulse: Just under 1 femtosecond (fsec), or 10^{-15} sec. This subfemtosecond pulse was created at the Max Planck Institute for Quantum Optics in Garching, Germany, and is less than the time for a single oscillation cycle of a visible light wave. How short is this pulse? The duration of this pulse is to 10 sec as 10 sec is to the age of the Earth! To make such a short pulse, researchers have to generate light containing all colors from the visible region well into the ultraviolet region of the spectrum. Such a pulse of light looks white to the eye. This is very different from typical lasers, which emit a single color [2].

Highest instantaneous power: Just over 1 PW, or petawatt (i.e., 10^{15} W). This was first achieved at the Lawrence Livermore National Laboratory in 1996. This unimaginably high power exceeded the entire electrical generating capacity of the United States by more than 1,200 times, but was over in such a short time—440 fsec—that it produced "only" 680 J of energy. Because laser light can be focused to a very small spot, the focused energy density reached the equivalent of 30 billion J in a volume of 1 cubic centimeter, far larger than the energy density inside of stars. At such high energy densities, the electric field of the light is so strong that electrons become accelerated to almost the speed of light! [3]

Highest average power: More than 1 MW (megawatt) of continuous output power. This dangerously high level of power was first achieved by the Mid-Infrared Advanced Chemical Laser (MIRACL), at the High Energy Laser Systems Test Facility at White Sands Missile Range, New Mexico. Because the power is so high, it is operated only for seconds at a time, producing several megajoules of energy in an outburst [4].

"Baddest" laser: The U.S. Air Force's airborne laser, a close relative of the MIRACL, described above, is mounted in a modified Boeing 747-400F freighter aircraft. It produces

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[1] Thanks to Wayne Knox, the Director of The Institute of Optics at the University of Rochester; Philip H. Bucksbaum, Director of the Stanford PULSE Center at Stanford Linear Accelerator Center (SLAC); and Roger Falcone, Director of the Advanced Light Source, Lawrence Berkeley National Laboratory.