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# Lasers

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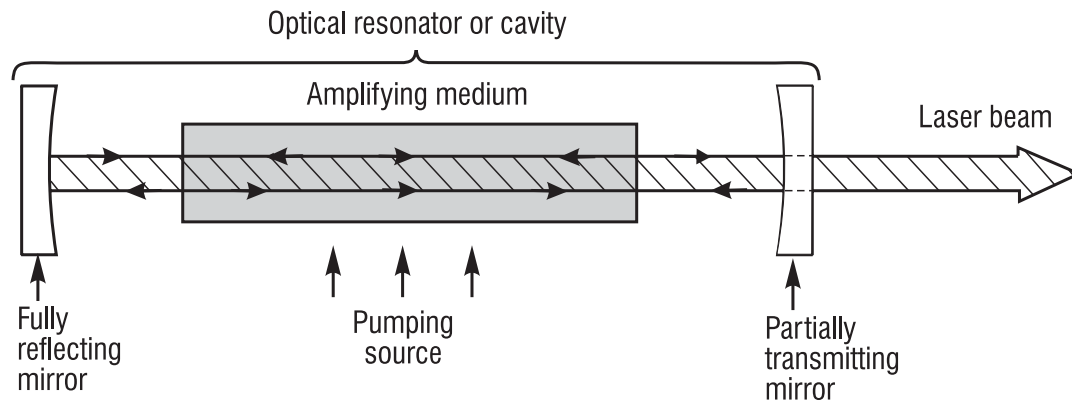
Lasers are devices that amplify or increase the intensity of light to produce a highly directional, high-intensity beam that typically has a very pure frequency or wavelength. They come in sizes ranging from approximately one-tenth the diameter of a human hair to that of a very large building. Lasers produce powers ranging from nanowatts to a billion trillion watts ( $10^{21}$  W) for very short bursts. They produce wavelengths or frequencies ranging from the microwave region and infrared to the visible, ultraviolet, vacuum ultraviolet, and into the soft-X-ray spectral regions. They generate the shortest bursts of light that man has yet produced, or approximately five million-billionths of a second ( $5 \times 10^{-15}$  sec).

Lasers are a primary component of some of our most modern communication systems and are the probes that generate the audio signals from our compact disk players. They are used for cutting, heat treating, cleaning, and removing materials in both the industrial and medical worlds. They are the targeting element of laser-guided bombs and are the optical source in both supermarket checkout scanners and tools (steppers) that print our microchips.

Because of the special stimulated nature of the laser light source, and the apparatus needed to produce laser light, laser photons are generally not as cheap to produce or to operate as are other light sources of comparable power. We presently do not use them to light our rooms, as lamp bulbs for our flashlights, as headlights for our automobiles, or as street lamps. Lasers also don't generally provide "white light" but instead produce a specific "color" or wavelength, depending upon the laser used.

The word **LASER** is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Stimulated emission of radiation is a natural process first identified by Einstein. It occurs when a beam of light passes through a specially prepared medium and initiates or stimulates the atoms within that medium to emit light in exactly the same direction and exactly at the same wavelength as that of the original beam. A typical laser device (Figure 5-1) consists of an amplifying or gain medium, a pumping source to input energy into the device, and an optical cavity or mirror arrangement that reflects the beam of light back and forth through the gain

medium for further amplification. A useful laser beam is obtained by allowing a small portion of the light to escape by passing through one of the mirrors that is partially transmitting.



**Figure 5-1** Basic laser components including gain medium, pumping source, and mirror cavity

## Prerequisites

Before you begin working with this module, you should have completed Modules 1-1, *Nature and Properties of Light*; 1-2, *Light Sources and Laser Safety*; 1-3, *Basic Geometrical Optics*; and 1-4, *Basic Physical Optics*. In addition you will need a working knowledge of algebra, exponents, and logarithms.

## Objectives

When you finish this module you will:

- understand how lasers operate
- understand how gain or amplification is produced
- know how various beam characteristics occur
- know about longitudinal and transverse modes
- design laser amplifiers
- design laser cavities or resonators
- understand unstable resonators
- be familiar with Q-switching
- understand mode locking
- be familiar with how a variety of laser types work and be familiar with their wavelengths, power capabilities, and beam properties
- know about the laser's unique properties (different from other light sources), which are essential in a variety of applications

## Scenarios

Three types of job functions involving lasers are those in laser manufacturing relating to designing, assembling, and testing of lasers; those relating to using lasers in various types of applications; and those associated with field servicing of lasers.

**Assembling and testing lasers**—John is involved in designing, assembling, and installing a laser amplifier, cavity mirrors, and the associated optical elements into the laser assembly. He is also challenged by carrying out critical functions such as mirror alignment, using a reference laser to obtain a coarse alignment, and then doing a fine alignment by observing the beam quality and the output power. John might have to determine the optimum transmission of the laser output mirror to match the laser gain, and test it to obtain the maximum power from the laser. In this case, Equation 5-10 of this module might be a useful start to the optimization. Designing procedures for testing the quality and cleanliness of the optics as well as checking the beam quality with a commercial mode analyzer would also be important job functions.

**Using lasers in various applications**—Rod had a large number of opportunities when he sought a job in the area of laser applications. He found that the area covered such a wide range that he couldn't investigate all of them. He found the largest single application of lasers to be in materials interactions and materials processing. In one job possibility, Rod would be involved in setting up robotic systems to drill holes, heat treat metals, ablate materials, etc. Related job functions included designing and/or setting up beam-pointing systems, beam-focusing controls, beam-power and beam-quality measurements, and automatic feeding of materials. All are very necessary functions of a laser technician. Rod also investigated the area of medical lasers where he would be involved in arranging beam-delivery systems for laser surgery or setting up and operating laser diagnostic tools. Communication was another possibility. One particularly interesting job involved installing and testing fiber laser amplifiers both for undersea communication and for local area networks. Computers also intrigued Rod. In that area he found that he could work in optical memory storage and retrieval where he would be involved in establishing critical alignment and operation specifications for information storage. Military applications were also an exciting area. Intriguing projects in the military included working on the development of laser-guided weapons, laser range finders, and laser radar.

**Field service**—Donna decided she didn't want to have to work in only one location, so she investigated the possibility of being a field service technician, which would include installation and troubleshooting. In such a job, Donna would be able to travel around a given territory testing and repairing lasers and the associated equipment. The job would require significant troubleshooting skills, which appealed to her. Also she found that many of the jobs would involve extensive travel over a specific portion of the country. During job interviews, Donna was told that she would need a knowledge of not only the laser system but also the equipment that uses the laser.

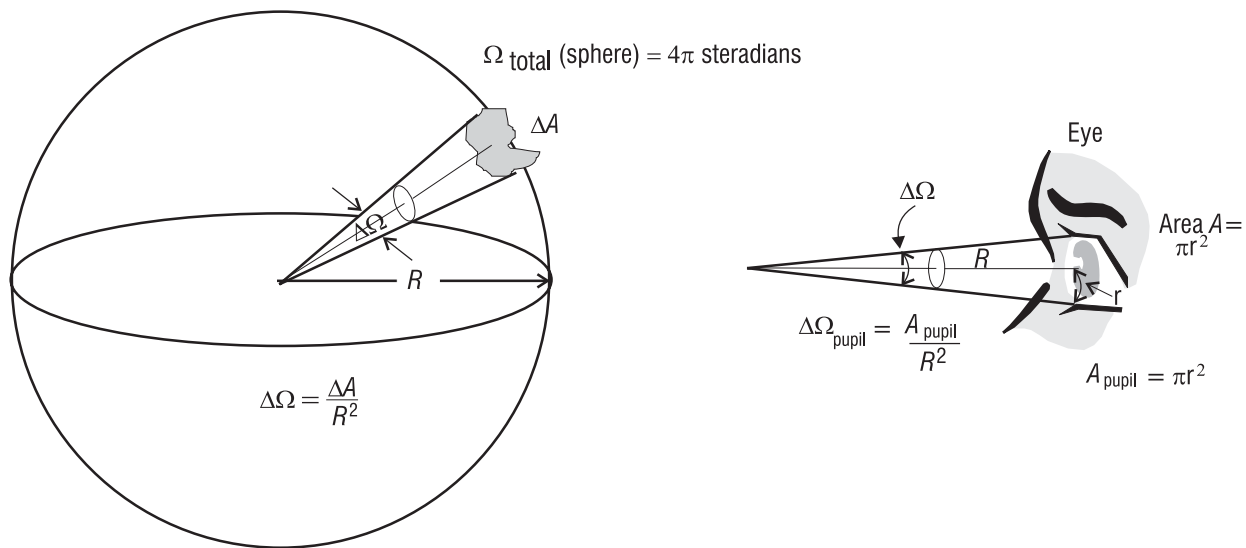
## Opening Demonstration

A laser is generally a very simple device. If you were standing in the center of a circle of people, each of them approximately one meter away from you, and you held a lighted match above your head, each person in the circle would see the match as having the *identical* brightness, that of a relatively weakly radiating yellowish-orange flame. This occurs because the light is radiating equally in all directions. Let's assume that you could take all the light radiating from the match and concentrate it into a single direction, say into the entrance pupil of one person's eyes. If you could do that, the intensity of the light would increase many orders of magnitude and could possibly damage the person's eye. That is how a laser is made, by redirecting the light that normally would be emitted in all directions from a material and concentrating that light into a single direction. It takes special properties of the radiating material to provide that concentration, and ordinary matches are not a material that can do that. The match was used only as an example to stress the simplicity of the concept of a laser.

Measure the diameter of the pupil of your partner's eye. You can then compute the partial solid angle  $\Delta\Omega$  that would be intercepted by that pupil as a fraction of the total solid angle ( $\Omega = 4\pi$  steradians) that the light is radiating in all directions. The partial solid angle  $\Delta\Omega$  is defined as the area  $A$  of the intercepting detector, in this case the pupil of the eye, divided by the square of the distance  $R$  from the source (lighted match) to the pupil or

$$\Delta\Omega = \frac{A}{R^2} \quad (5-1)$$

as shown in Figure 5-2. In this case the area  $A$  would be  $A = \pi r^2$  where  $r$  is the radius of the



**Figure 5-2** Diagram showing a partial solid angle defined by an area  $\Delta A$  and by the pupil of an eye.

pupil of the eye. The amount of enhancement or gain  $G$  (dimensionless) the beam would achieve in undergoing this redirection is then the ratio of the total solid angle (light emitted in all directions) to that intercepted by the eye or

$$G = \frac{\Omega}{\Delta\Omega} \quad (5-2)$$

Based upon the value of  $G$  you obtain, you can then appreciate, with this simple demonstration, the capabilities of the laser and how such intense light beams might be produced.

Your instructor can demonstrate the purity of color of the laser beam and the low beam divergence. Your instructor can use either a prism or a transmission-diffraction grating to transmit both the beam from a flashlight and a laser beam, such as a helium-neon laser or a laser pointer, onto a screen in a darkened room. The light from the flashlight must be passed through a small aperture (approximately the diameter of the laser beam) before it is incident upon the prism to make a fair comparison with the laser. This will show how the flashlight is composed of a rainbow of colors, whereas the laser has a very discrete color or wavelength. It will also show the different beam divergences by demonstrating how little the laser beam expands (in the vertical direction) compared to the flashlight. (The comparison must be made in the vertical direction because the colors of the flashlight are expanded through the prism in the horizontal direction.)

## Basic Concepts

### I. REQUIREMENTS FOR A LASER

#### A. Laser gain medium

Nearly all lasers are produced as a result of electrons jumping from an excited energy level within a radiating species to a lower-lying energy level and, in the process, radiating light that contributes to the laser beam. Those radiating species can include:

**atoms** such as in the red helium-neon (HeNe) laser, the visible and ultraviolet argon ion and helium-cadmium (HeCd) lasers, and the green and yellow copper vapor lasers (CVL)

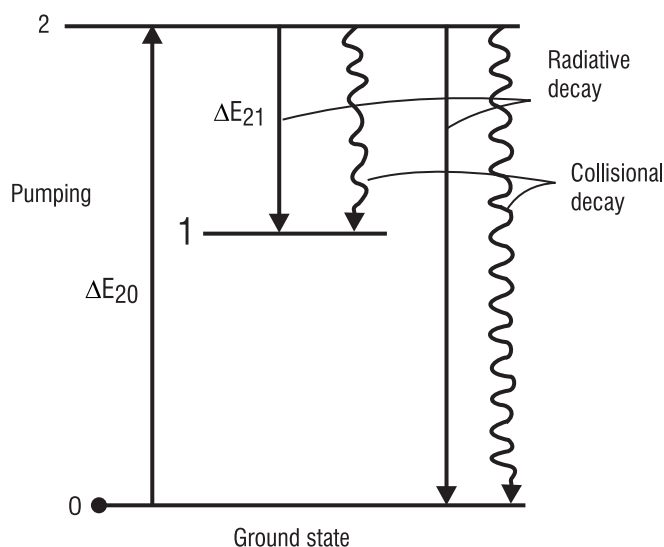
**molecules** such as in the infrared carbon dioxide (CO<sub>2</sub>) laser, the ultraviolet excimer lasers such as ArF and KrF, and the pulsed N<sub>2</sub> laser

**liquids** such as those involving various organic dye molecules dilutely dissolved in various solvent solutions

**dielectric solids** such as those involving neodymium atoms doped in YAG or glass to make the crystalline Nd:YAG or Nd:glass lasers

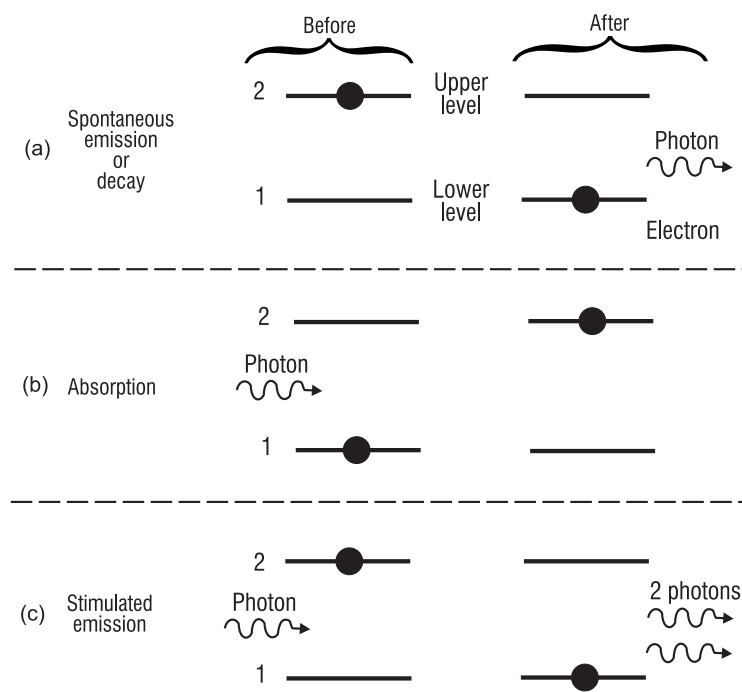
**semiconductor materials** such as gallium arsenide or indium phosphide crystals or various mixtures of impurities blended with those and other semiconductor species

Each of the above species contains a lowest energy level referred to as the ground state in which the electrons predominantly reside at room temperature, as indicated by level 0 in Figure 5-3.



**Figure 5-3** Simplified energy diagram of an atom showing excitation and emission processes

The electrons are moved to higher-lying (excited) levels such as 1 and 2 by means of various pumping processes that will be described in the next section. They then decay back to lower-lying levels within a period of time called the lifetime of the level, and eventually find their way back to the ground state when the pumping source is removed. There are three types of processes involving the interaction of light beams with atoms that have electrons residing in various energy levels. Examples of those are depicted in Figure 5-4. First an electron residing in level 2 can spontaneously jump to level 1, radiating a photon of light when it does so. That process is known as *spontaneous emission* as indicated in Figure 5-4a. Most excited energy



**Figure 5-4** The three radiation processes that can occur when light interacts with matter (atoms)

levels undergo spontaneous emission. Each level has a specific lifetime  $\tau$  over which it will remain in that level before decaying to a lower-lying level. That lifetime is determined by the interactions of the electron with the other electrons and nuclei of that atom. Typical lifetimes of electrons residing in specific levels that decay by radiating in the visible portion of the spectrum are of the order of 10–100 nsec. Of course the ground state cannot decay further and thus has infinite lifetime. The photon radiated during spontaneous emission has the exact wavelength  $\lambda_{21}$  and frequency  $\nu_{21}$  corresponding to the difference in energy  $\Delta E_{21}$  of the two involved energy

$$\Delta E_{21} = h\nu_{21} = \frac{hc}{\lambda_{21}} \quad (5-3)$$

levels (1 and 2 in this case) according to the relationship in which  $h$  is Planck's constant such that  $h = 6.63 \times 10^{-34}$  joule-sec and  $c$  is the speed of light,  $c = 3 \times 10^8$  m/sec. Also the wavelength  $\lambda_{21}$  is generally given in meters (often expressed in micrometers ( $\mu\text{m}$ ) or nanometers (nm)). Because different materials have different energy-level arrangements, they radiate at different wavelengths and thus emit different colors or frequencies of light that are specific to the material. Nearly all the light we see originates from such transitions between energy levels of various kinds of matter.

The second process is *absorption*, shown in Figure 5-4b, which occurs if the atom has its electron in level 1 of Figure 5-3 and a photon of light of wavelength  $\lambda_{21}$  collides with the atom. During the collision, the photon is absorbed by the atom and the electron is moved up to the higher energy level 2. This process is the way light interacts with practically all of matter. It can happen from any energy level that is occupied (generally the ground state) and always boosts the atom to a higher-lying level while eliminating the photon. This often results in heating of the absorbing material.

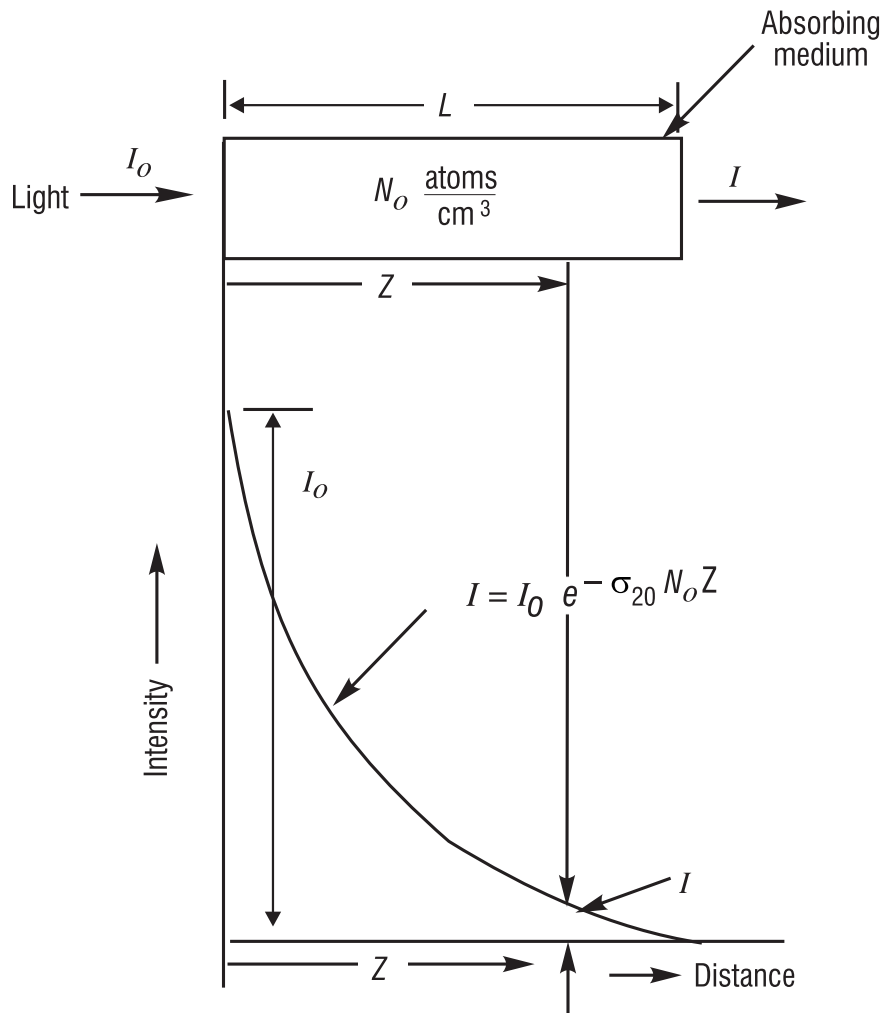
The third process, shown in Figure 5-4c, is referred to as *stimulated emission*. It results when an electron is in a higher-lying level, such as level 2 in Figure 5-3, and a photon of light of wavelength  $\lambda_{21}$  collides with the atom. During the collision the photon stimulates the atom to radiate a second photon having exactly the same energy  $\Delta E_{21}$  (and wavelength according to Equation 5-3) as that of the incident photon and traveling in exactly the same direction in order to satisfy the laws of conservation of energy and momentum. Hence, one photon leads to two identical photons, which, in effect, leads to an amplification process. A photon has been gained at the expense of the loss of energy stored within the atom.

When a large group of atoms is assembled and irradiated with light, most of those atoms are in the ground-state energy level (see Figure 5-3). If the photons of the impinging light have the appropriate energy  $\Delta E_{20}$  for example, as indicated in Figure 5-3, the light will be absorbed according to the following expression for the variation of intensity  $I$  with the distance  $L$  into the material

$$I = I_0 e^{-\sigma_{20} N_0 L} \quad (5-4a)$$

in which  $I_0$  is the intensity of the beam when it first reaches the atoms,  $\sigma_{20}$  is referred to as the cross section for absorption or emission of those two levels, and  $N_0$  is the population density of atoms residing in level 0 (number of atoms per unit volume). If  $N_0$  is in atoms/cm<sup>3</sup> and  $L$  is in cm, the absorption cross section  $\sigma_{20}$  must be expressed in units of area or cm<sup>2</sup> (hence the name

cross section). Equation 5-4a indicates that the amount of beam absorption depends on both the number density of atoms residing in level 0 and the length  $L$  or thickness of the medium comprising those atoms as indicated in Figure 5-5. Also, the exponential factor suggests quite rapid absorption if the exponent is large. For example,  $e^{-2} = 0.135$  and  $e^{-4} = 0.018$ . Hence, if either the length of the medium or the population is doubled, the beam intensity drops by nearly a factor of 8! Chemists have used this effect for many decades to measure the concentration of a material dissolved into a solvent. Equation 5-4a is known as Beer's law, and the product  $\sigma_{20} N_0$  is referred to as the absorption coefficient. This absorption process is also one of the techniques used in pumping lasers in order to transfer population to level 2 from level 0, as will be discussed later.



**Figure 5-5** Intensity variation versus depth  $z$  into an absorbing sample

The absorption described above could have been equally applied if population initially existed in level 1, and light of energy  $\Delta E_{21}$  and wavelength  $\lambda_{21}$  would be absorbed by the medium according to the following equation.



$$I = I_0 e^{-\sigma_{21} N_1 L} \quad (5-4b)$$

An alternative situation will now be considered. Suppose that we were able to “pump” (excite) a significant amount of population of the medium from level 0 to level 2 according to Equation 5-4a. Also, for the time being let us assume that there is no population in level 1. (This is an unlikely scenario but we will do this as a “thought” experiment for illustrative purposes.) Then again, let us consider having a beam of photons of energy  $\Delta E_{21}$  and wavelength  $\lambda_{21}$  enter the medium. According to the earlier discussion, and considering the process described in Figure 5-4c, the only process that can occur is stimulated emission, and we would expect more photons to be generated as the beam progresses. That is exactly what happens! Since the absorption indicated in Figure 5-4b and also described in Equation 5-4a is a symmetrical process with the stimulated emission process of Figure 5-4c, it is not surprising that the beam evolves in a similar way to that of Equation 5-4a except that a sign reversal must be made in the exponent to reflect the process of photon production instead of photon absorption. This can be described mathematically in the equation below

$$I = I_0 e^{+\sigma_{21} N_2 L} \quad (5-5)$$

in which we now have the population density  $N_2$  in the expression along with the appropriate cross section  $\sigma_{21}$ .

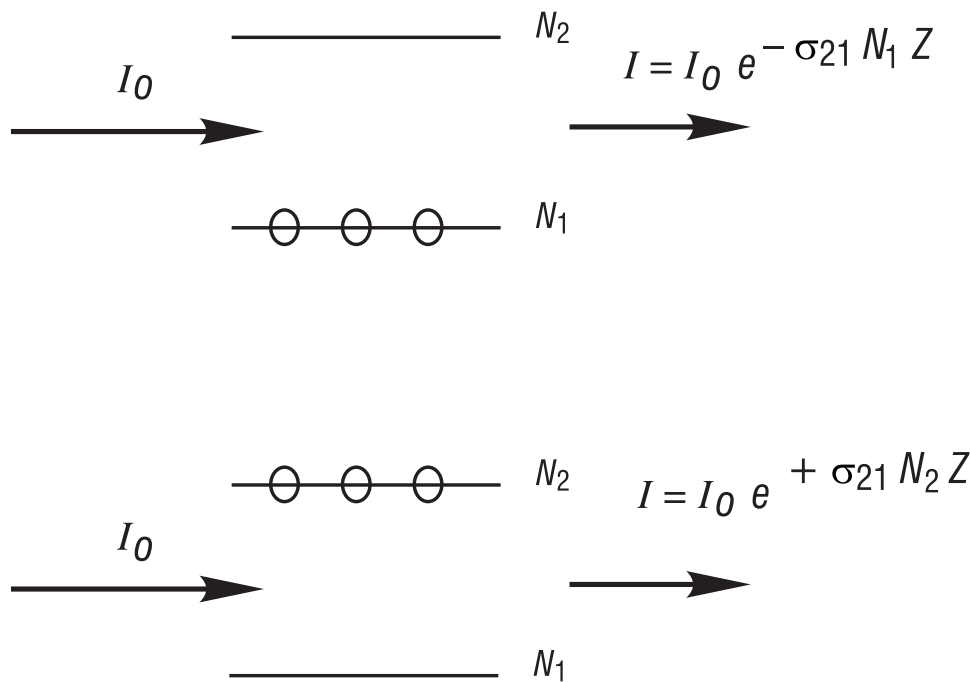
Now, if population is allowed to be in both level 1 and level 2, both absorption and stimulated emission will occur within the medium and therefore Equations 5-4 and 5-5 must be combined to give

$$I = I_0 e^{+\sigma_{21} (N_2 - N_1) L} \quad (5-6)$$

as indicated in Figure 5-6. Hence, if more population exists in level 2 than in level 1,  $N_2$  will be greater than  $N_1$  and the exponent of Equation 5-6 will be positive. The beam will grow and emerge from the medium with a greater intensity than when it entered. In other words, for amplification or gain to occur, the condition must be

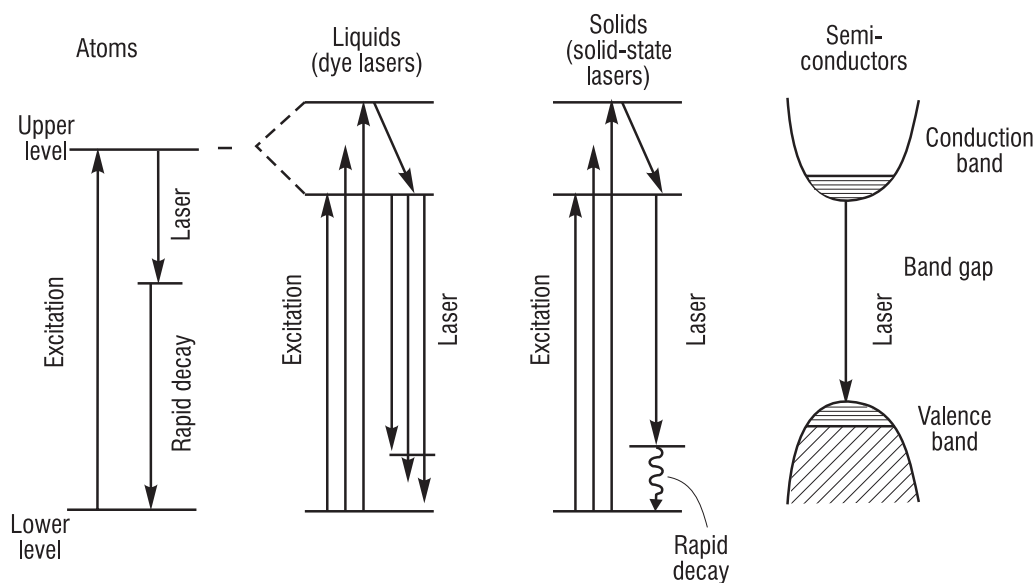
$$\frac{N_2}{N_1} > 1 \quad (5-7)$$

Having  $N_2$  be larger than  $N_1$  is known as having a *population inversion*, which is not a normal, naturally occurring relationship. This would be the equivalent of having a mountain in which there is more dirt at higher levels than at lower levels. The mountain would taper inward toward the bottom rather than outward, which is generally an unstable situation. The only way to maintain such an “inversion” is to continually transfer or “pump” more dirt up to higher levels by a conveyor belt or some other process. The equivalent transfer to higher levels, or “pumping” is also required in lasers to maintain the population inversion of level 2 with respect to level 1 such that amplification can be produced.



**Figure 5-6** Absorption and stimulated emission effects combined in a laser gain medium

**Population inversions in gases**—Inversions in gases are generally produced by applying a voltage across a gas discharge tube that consists of a long, narrow glass or ceramic tube serving to confine the gain medium, with electrodes installed at each end of the tube. In its simplified form the electrodes, which are essentially electrical feedthroughs, are attached to each end of the tube to allow a voltage to be applied across the length of the tube. The tube is then filled with a low-pressure gas or gas mixture that includes the species that will serve as the gain medium. The applied voltage produces an electric field within the laser tube that accelerates the electrons within the gas. Those electrons collide with the gas atoms and excite the atoms to excited energy levels, some of which serve as upper laser levels. Lower-lying levels, those to which higher-lying levels can transition, typically decay to the ground state faster than the higher-lying levels, thereby establishing a population inversion between some of the higher and lower levels as indicated in Figure 5-7. This inversion can be envisioned by considering that, if the lower levels drain out faster than the upper levels, there will be less population left in those lower levels than in the higher-lying levels. The laser light then occurs when the higher-lying levels decay to the lower levels while radiating photons at the wavelengths corresponding to the energy separation between the levels. In many instances the excitation is a two-step process in which the electrons first excite a long-lived or metastable (storage) level or they ionize the atom, leaving an ion of that species and another electron. In either case, that level then transfers its stored energy to the upper laser level via a subsequent collision with the laser species. The laser transitions in gaseous laser media typically occur at relatively precise, discrete wavelengths that correspond to the energy difference of inherently narrow energy levels.



**Figure 5-7** Inversion processes in gases, liquids, solids, and semiconductors

**Population inversions in liquids**—Most excited energy levels in liquids decay so rapidly due to collisions with the surrounding nearby atoms or molecules that they can't stay around long enough to participate in a lasing process. There are some molecules however, namely organic dye molecules, that do have a sufficiently long lifetime in an upper energy level (of the order of 1–5 nsec) so they can participate in the laser process by being excited to an upper laser level. These molecules also have the ability to radiate the energy from that level rather than lose the energy due to decay by collisions. Those molecules are the dyes that are used to color cloth and other objects that we use in our everyday life. When dissolved in a solvent such as alcohol or water, they can be concentrated in sufficient quantity to be used as a laser gain medium. In these dissolved dye solutions, electrons *cannot* be made to flow in the form of an electrical current within the liquid as they can in gases. Therefore the pumping of the upper laser levels must be carried out by optical means such as a flashlamp or another laser as shown in Figure 5-7. When the light is applied to the dye solution, it is absorbed at certain wavelengths by the dye as described by Equation 5-4a, placing the dye molecules in highly excited upper laser levels. A population inversion is then produced between those levels and a very broad range of lower-lying energy levels, thereby allowing the possibility for a *wide range of laser wavelengths* to be produced within the gain medium. Those lower levels are not initially pumped by the light and therefore are sufficiently empty to produce the inversion. Dye lasers thus allow the possibility of wide wavelength *tunability* and have been used extensively in doing a variety of spectroscopic studies in which very specific laser wavelengths are desired.

**Population inversions in crystalline solids and glasses**—As in the case of liquids, when energy levels in solids are excited, typically by irradiating those solids with light, the levels tend to decay much more rapidly via collisions with their surrounding neighbors rather than by radiating their energy in the form of light. In a few cases, however, specific types of atoms are embedded into a transparent host material (such as a specific crystalline solid or a glass) at concentrations of up to 1 part in 100, and the atoms radiate their energy rather than decay by collisions. These specific types of atoms, such as chromium or neodymium, consist of a radiating electron surrounded by a “screen” of other electrons that protect that radiating electron

from being bombarded by collisions from neighboring atoms. The consequence is that the atoms can absorb pump light that passes through the transparent host medium and can then subsequently radiate that energy. Gemstones such as rubies fall into that category. Ruby, a desired gemstone and also the material that comprised the gain medium for the first laser, consists of chromium atoms doped into a transparent sapphire ( $Al_2O_3$ ) host crystal. The color of the ruby crystal is determined by the chromium atoms, which absorb light in the blue and green regions of the spectrum and radiate in the red.

When these types of laser crystals absorb light, the energy ends up in excited energy levels that serve as the upper laser level. These crystals have the property that the upper laser level has a very long lifetime before it decays by radiating when compared to all other types of laser gain media. The population inversion in most of these lasers occurs by the lower laser levels being rapidly depleted by collisions with the neighboring atoms (see Figure 5-7) since these levels are not screened or protected as are the upper laser levels. An exception to this is the ruby laser in which the lower laser level is the ground state. In this case the pumping power must be excessively high in order to pump more than half of the chromium atoms into the upper laser level to produce an inversion.

In these solid-state laser gain media, some of the doping atoms produce very broad excited energy levels and others have very narrow energy levels. The broad energy levels allow a broad wavelength region over which gain or amplification occurs and thus allow broad wavelength tunability of the lasers. The narrow energy levels produce lasers operating over a very narrow wavelength region or narrow bandwidth.

**Population inversions in semiconductors**—Inversions in semiconductors are produced when joining a *p*-doped semiconductor material with an *n*-doped semiconductor material in a similar way to that of producing a transistor to create a *pn* junction. The *n*-doped material contains an excess of electrons and the *p*-doped material has an excess of holes (a material with excess positive charge). When a voltage is applied across the junction, with the positive voltage on the *p* side, the electrons are pulled through the junction toward the positive electrode and the holes are attracted to the negative side, producing an electrical current flow across the junction. The electrons and holes meet within the junction and are attracted to each other because of opposite charges. When they meet, they recombine and emit radiation and also can produce a population inversion. This inversion occurs between energy levels located above and below the semiconductor bandgap (see Figure 5-7), the gap in energy below which the material is transparent. This energy typically corresponds to a wavelength in the infrared, and hence most semiconductors radiate in the infrared and are not transparent in the visible spectral region like glass is. However, semiconductor lasers are under development to operate in the green and blue regions of the spectrum. At very low currents, a population inversion does not occur even though recombination radiation is emitted. In fact, such nonlaser-like emission is the source of radiation from a light-emitting diode (LED). In comparison, to produce a population inversion, a very high current density is applied within the junction region. However, this high current density leads to excessive heat deposition in the material; therefore a significant part of the development of semiconductor lasers involves how to remove the heat, or to make smaller junctions so that less current is required. The material and its corresponding energy bandgap determine the laser wavelength.

Equation 5-6 describes the way in which a beam is amplified if a population inversion exists between two energy levels such as 1 and 2, as described above. An inversion is a necessary

condition for making a laser but not a sufficient condition. The exponential factor in Equation 5-6 must be high enough for the beam to grow and develop into the kind of narrow beam that is expected from a laser. For example, if the exponent turns out to have a value of only 0.00001, there will be no noticeable beam growth even though Equation 5-7 might be satisfied. The exponent of Equation 5-6 consists of a cross section  $\sigma_{21}$  that is characteristic of a specific material and also a specific radiative transition in that material. It is referred to as a cross section because it has dimensions of length<sup>2</sup> or area, as we mentioned earlier. Table 5-1 lists cross sections for some of the laser transitions described in this course. The population difference  $N_2 - N_1$ , which is sometimes expressed as  $\Delta N_{21}$ , is a value determined by the power available from the pumping source. Values of  $\Delta N_{21}$  are also shown in Table 5-1. Such pumping processes are described in the next section. The other factor that affects gain is the length of the gain medium. If  $\sigma_{21}$  and  $\Delta N_{21}$  are not quite sufficient, the length  $L$  of the gain medium can be increased to increase the exponent of Equation 5-6. We will show later that the amplifier length  $L$  can be *effectively* increased by putting mirrors around it such that the beam will pass back and forth through it many times during the beam's growth process.

Table 5-1

Type of Laser	$\lambda_{21}(\text{nm})$	$\Delta\nu_{21}(\text{Hz})$	$\sigma_{21}(\text{cm}^2)$	$\Delta N_{21}(\text{cm}^{-3})$	$g_{21}(\text{cm}^{-1})$	$I_{\text{sat}}(\text{W}/\text{cm}^2)$
HeNe	632.8	$2 \times 10^9$	$3 \times 10^{-13}$	$7 \times 10^9$	$2 \times 10^{-3}$	6.2
Argon	488.0	$2 \times 10^9$	$2.5 \times 10^{-12}$	$1 \times 10^{15}$	$5 \times 10^{-3}$	16.3
HeCd	441.6	$2 \times 10^9$	$9 \times 10^{-14}$	$4 \times 10^{12}$	$3 \times 10^{-3}$	7.1
Copper Vapor	510.5	$2 \times 10^9$	$8 \times 10^{-14}$	$6 \times 10^{13}$	$5 \times 10^{-2}$	9.0
CO <sub>2</sub>	10,600	$6 \times 10^7$	$3 \times 10^{-18}$	$5 \times 10^{15}$	$8 \times 10^{-3}$	$1.6 \times 10^{-2}$
Excimer	248.0	$1 \times 10^{13}$	$2.6 \times 10^{-16}$	$1 \times 10^{16}$	$2.6 \times 10^{-2}$	$3.4 \times 10^5$
Dye (Rh6-G)	577	$5 \times 10^{13}$	$2 \times 10^{-16}$	$2 \times 10^{18}$	2.4	$3.4 \times 10^9$
Ruby	694.3	$3 \times 10^{11}$	$2.5 \times 10^{-20}$	$4 \times 10^{19}$	1.0	$3.8 \times 10^7$
Nd:YAG	1064.1	$1.2 \times 10^{11}$	$6.5 \times 10^{-19}$	$3 \times 10^{19}$	2.0	$1.2 \times 10^7$
Ti:Al <sub>2</sub> O <sub>3</sub>	760	$1.5 \times 10^{14}$	$3.4 \times 10^{-19}$	$3 \times 10^{18}$	1.0	$2.0 \times 10^9$
Semiconductor	800	$1 \times 10^{14}$	$1 \times 10^{-15}$	$1 \times 10^{18}$	$10^3$	$2.5 \times 10^9$

It is useful to describe the product of  $\sigma_{21}$  and  $\Delta N_{21}$  as the small-signal-gain coefficient  $g_{21}$  or

$$g_{21} = \sigma_{21} \Delta N_{21} \quad (5-8)$$

Hence, Equation 5-6 can be rewritten as

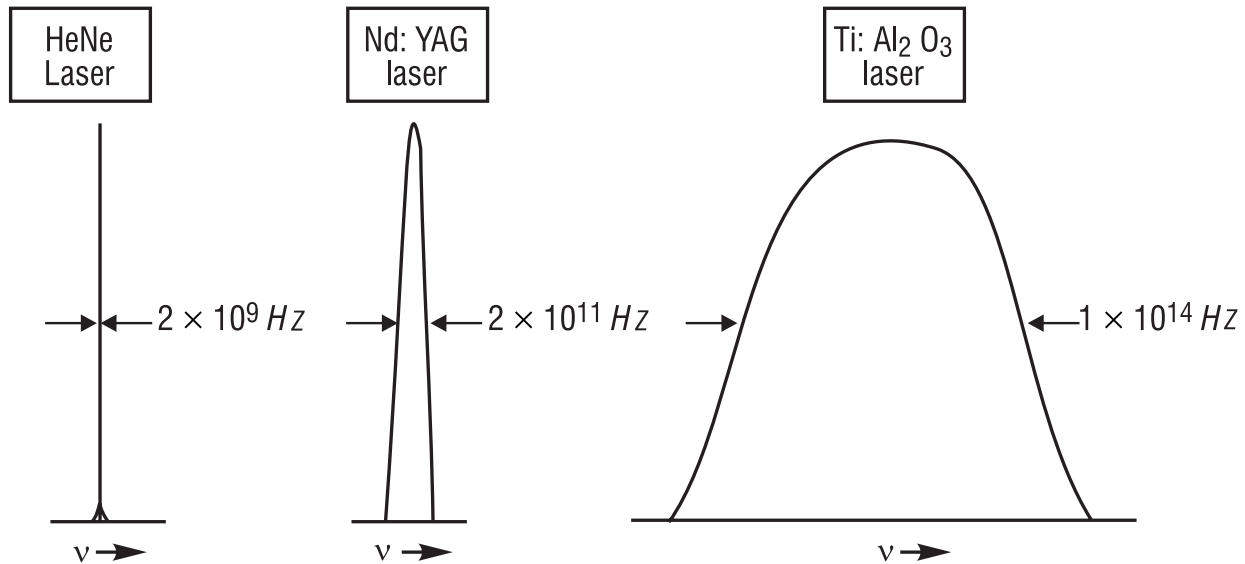
$$I = I_0 e^{g_{21} L} \quad (5-9)$$

By considering the units of both  $\sigma_{21}$  (length<sup>2</sup>) and  $\Delta N_{21}$  (1/length<sup>3</sup>) we can see that  $g_{21}$  has the units of 1/length. Hence, if  $\sigma_{21}$  is given in units of cm<sup>2</sup> and  $\Delta N_{21}$  is given in units of (1/cm<sup>3</sup>),  $g_{21}$  will be given in (1/cm), more commonly expressed as cm<sup>-1</sup>. Values of the cross sections  $\sigma_{21}$  and  $\Delta N_{21}$ , and the small-signal gain  $g_{21}$ , are listed in Table 5-1 for some of the lasers described in this module.

**Bandwidth of laser gain medium**—The bandwidth of the laser gain medium determines the range of wavelengths over which amplification can occur for any specific laser. This bandwidth is expressed in either a wavelength range  $\Delta\lambda_G$  or a frequency range  $\Delta\nu_G$ . These two expressions are related by

$$\Delta\lambda_G = \frac{\lambda^2}{c} \Delta\nu_G \quad (5-10)$$

in which  $\lambda$  is the laser wavelength and  $c$  is the speed of light. The bandwidth of the gain medium is usually determined by the bandwidth over which the spontaneous emission occurs for a given laser transition. This bandwidth is determined by specific properties of the energy levels involved in the transitions, such as their lifetimes, how the atoms interact with other atoms, how closely the atoms are arranged, etc. Typically, atomic gas lasers have bandwidths of the order of 1 GHz ( $10^9$  Hz). Molecular lasers have bandwidths that are sometimes a factor of 10 to 10,000 larger than that due to the closeness in wavelength of several molecular transitions that overlap in frequency. Solid-state lasers can have relatively narrow bandwidths of the order of 100 GHz in cases such as the Nd:YAG laser, or very wide bandwidths, of the order of 100 THz ( $10^{14}$  Hz) in the case of the titanium sapphire laser. Semiconductor lasers have bandwidths typically of  $10^{13}$  Hz. Comparisons of the laser gain bandwidths for the HeNe, Nd:YAG, and Ti:Al<sub>2</sub>O<sub>3</sub> lasers are shown in Figure 5-8. These various bandwidths are not the bandwidths of the laser beam that emerges from the amplifier but do indicate the range over which amplification can occur. Laser mirror cavity properties primarily determine the bandwidth of the emerging laser beam, as will be described later under laser beam properties.



**Figure 5-8** Laser gain bandwidths for the HeNe, Nd:YAG, and Ti:Al<sub>2</sub>O<sub>3</sub> lasers

## B. Laser pumping sources

Laser pumping sources are the means by which energy is transferred into the laser gain medium to produce the required population inversion  $\Delta N_{21}$ . These pumping sources generally consist of either electrons flowing within the medium or light being absorbed by the medium.

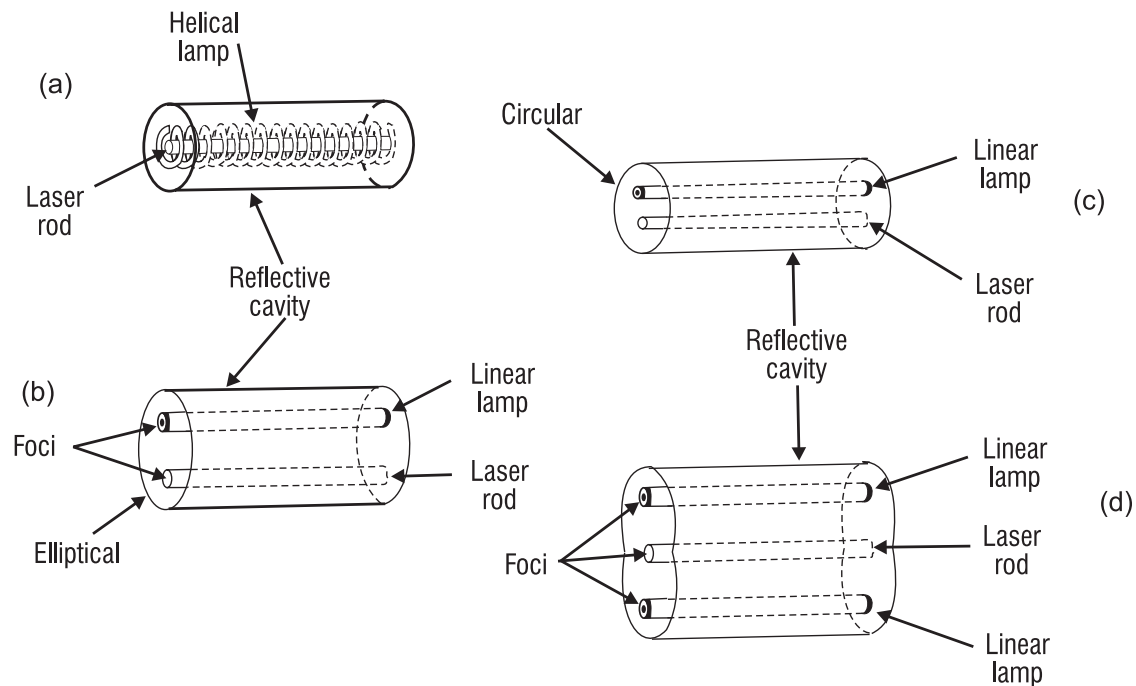
**Electron pumping**—Electron pumping is used primarily in gaseous or semiconductor gain media. In gases, many electrons are produced when a few initial electrons within the gain medium are accelerated by an electric field within the medium and these many electrons then collide with neutral atoms, exciting those atoms to higher-lying energy levels and even ionizing some of the atoms (removing an electron). The freed electrons are also accelerated, producing an avalanche of electrons and therefore an electrical current within the medium. The electrons lose their energy by transferring it to the atoms during the collision process. Some of the lasers operate on a pulsed basis, applying a large amount of current for a short period of time. Others operate on a continuous (*cw*) basis, using a much smaller but continuous current.

In semiconductors, the electrons flow through the semiconducting material by applying a voltage across the *pn* junction with the positive voltage on the side of the *p*-type material. This leads to recombination radiation when the electrons combine with the holes in the junction. The heat loading of the semiconductor limits the current.

**Optical pumping**—Optical pumping of lasers generally applies to the pumping of liquid (dye) lasers and to dielectric solid-state lasers and is provided by either flashlamps or other lasers.

The most common types of flashlamps used for pumping lasers are narrow, cylindrical quartz tubes with metal electrodes mounted on the ends, filled with a gaseous species such as xenon that serves as the radiating material within the lamp. A voltage is applied across the electrodes of the flashlamp and current flows through the gas, populating excited levels of the atoms within the gas that radiate and produce intense light emission. The process is similar to that of electron excitation of lasers described above except that a population inversion is not produced and the radiating material of the lamp radiates via spontaneous emission, rather than by stimulated emission as in the case of a laser gain medium. The pumping wavelength of the flashlamp is determined by the gaseous medium inserted within the flashlamp tube. Xenon is the most common species because of both its radiating efficiency and its emission of a broad spectrum of wavelengths from which to choose in matching the lamp emission to the pumping absorption bands of the laser.

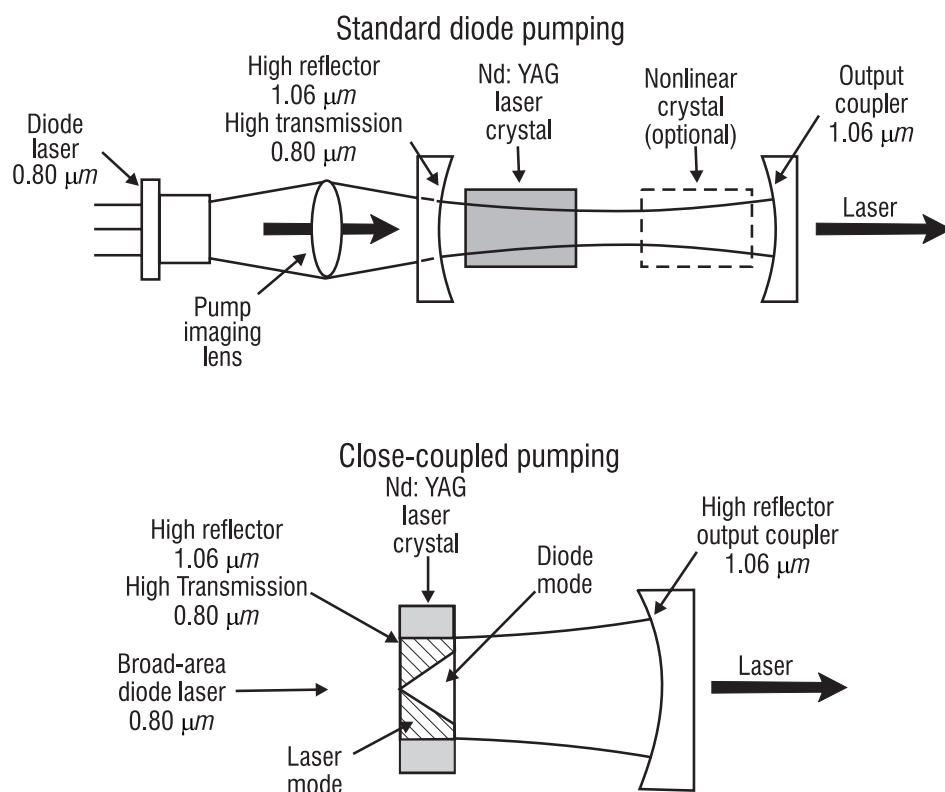
Examples of flashlamp configurations for pumping lasers are shown in Figure 5-9. Figure 5-9a shows the flashlamp in the form of a helix wrapped around the laser rod. Figures 5-9b and 5-9c show the flashlamp inserted into an elliptically-shaped or circularly-shaped elongated laser cavity. In Figure 5-9b the flashlamp is located at one focus of the ellipse and the laser rod to be pumped at the other focus of the ellipse. Figure 5-9d shows two flashlamps used in a double elliptical cavity, one of the most favorable arrangements, with the laser rod in the center. Sometimes the laser mirrors are coated onto the ends of the laser rod and sometimes they are mounted externally to the rod, along the longitudinal axis of the cavity.



**Figure 5-9** Flashlamp configurations for pumping lasers

Laser pumping is used in cases in which the pumping energy must be concentrated into a relatively small volume or for a very short time, or if the pumping wavelength must be provided over a fairly narrow-wavelength bandwidth. Pumping lasers include the argon ion or doubled Nd:YAG cw lasers for pumping titanium-sapphire lasers, excimer lasers for pumping dye lasers, and gallium arsenide semiconductor lasers for pumping Nd:YAG lasers. In most cases the laser is focused to a relatively small gain region, a line focus for dye lasers and a spot focus for the other lasers. Two examples of diode pumping of Nd:YAG lasers are shown in Figure 5-10.





**Figure 5-10** Examples of laser diode pumping of Nd:YAG lasers

### C. Laser beam properties

Laser beam properties such as direction and divergence of the beam, the beam profile, and the wavelength and frequency characteristics of the laser within the wavelength region of the laser gain bandwidth are determined largely by the laser mirrors. The factors determining those properties include mirror curvature, surface quality, and reflectivity as well as separation and location, assuming that the structure holding the mirrors is a secure, vibration-free structure. The unique electromagnetic wave properties produced by the mirrors are referred to as modes. Before discussing these mirror properties, we must consider the shape of the gain medium and the beam growth to the point of beam saturation.

**Shape of gain medium**—The goal of constructing a laser is to capture most of the spontaneous emission that is normally emitted in all directions within the gain medium and redirect it into a single direction. This is done with the assistance of the gain or amplification that can be initiated within the medium. It is desirable to have the gain medium be of an elongated shape so that the gain, which is length dependent, will operate primarily in that one elongated direction. Hence, most laser gain media are long, narrow devices with mirrors located at the ends.

**Growth of beam and saturation**—If significant gain is provided along the length of the gain medium, the spontaneous emission emitted in the elongated direction will grow at a rate dependent upon the amount of gain available as it moves through the length of the medium. The emission that starts at one end and transits to the other end will have grown by a factor of between 0.02 (2%) and 10 (1,000%) in a single pass, depending upon the type of laser.

However, even the high factor-of-10 growth available in some lasers is not sufficient to produce a powerful unidirectional laser beam in one pass. Hence, mirrors are placed at both ends of the medium, forming a cavity to redirect the beam back and forth through the amplifier and thereby allow the beam to continue to grow until a point of beam saturation is achieved. At somewhere between 2 passes (dye lasers) and 500 passes (HeNe lasers), the beam will have become so intense within the laser cavity that there won't be sufficient atoms in the upper laser level within the gain medium to accommodate all of the impinging photons. This is the condition of beam saturation, and the intensity of the beam is known as the saturation intensity. Values of saturation intensity for a variety of lasers are given in Table 5-1.

The condition of saturation occurs when the exponent of Equation 5-6 ( $\sigma_{21}\Delta N_{21}L$ ) reaches a value of approximately 12. In this saturation, the length  $L$  is the effective length of many passes through the amplifier so we will define that length as  $L_T$ . Hence, we have the condition to reach saturation as ( $\sigma_{21}\Delta N_{21}L_T \cong 12$ ) or ( $g_{21}L_T \cong 12$ ). At that point the beam will have grown by a factor of approximately  $e^{12} = 1.6 \times 10^5$  according to Equation 5-6. When it reaches that intensity it will settle down to a stable value (as long as the pumping continues) in which the conversion from pump power to laser photons reaches an equilibrium balance. In the case of the HeNe laser described above, that requires 500 passes through the amplifier. If the amplifier length is 20 cm, the effective length in Equation 5-6 is  $500 \times 20$  cm or 100 m. Hence, the beam travels through 100 m of amplifier length before it reaches saturation. If more pump power is applied, above the value where the saturation intensity is reached, more laser power will be produced and will be available through the output mirror of the laser.

The condition for a population inversion and thus amplification within the amplifier was given by Equation 5-7 ( $N_2/N_1 > 1$ ). However, even though gain might exist within the amplifier, the laser still might not develop a beam if the gain is not sufficiently high to overcome losses within the laser cavity. The laser mirrors won't have 100% reflectivity and there might be additional losses such as scattering and reflective losses at windows and other optical elements placed within the cavity. Hence, a simple expression is used to determine the threshold condition for a laser beam to develop, based upon the laser cavity characteristics. For a laser in which the amplifier length has a value of  $L$  and the mirrors have identical reflectivities  $R$ , with no other losses in the cavity, the threshold condition for the gain coefficient  $g$  is given as

$$g = \frac{1}{2L} \ln \frac{1}{R^2} \quad (5-11)$$

which has dimensions of 1/length. Any value of  $g$  higher than that given by Equation 5-11 will produce a laser beam within the cavity. For a more complex laser cavity in which the mirrors have different reflectivities  $R_1$  and  $R_2$ , and  $a_1$  and  $a_2$  represent other losses within the cavity (beyond the amplifier), the expression for the threshold gain  $g$  is given as

$$g = \frac{1}{2L} \ln \left[ \frac{1}{R_1 R_2 (1-a_1)(1-a_2)} \right] + \alpha \quad (5-12)$$

The term  $\alpha$  represents a potential absorption loss within the amplifier itself, which is present in only a few types of lasers. It is a distributed loss expressed in the same units as  $g$  or (1/length). For example, in solid-state lasers it is termed excited state absorption.

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**Example 1**

Consider a HeNe laser in which the mirror reflectivities might be  $R_1 = 0.999$  (99.9%) and  $R_2 = 0.990$  (99%) and the cavity losses are  $a_1 = a_2 = 0.002$  (0.2%) and  $\alpha = 0$ . For that situation calculate the gain per pass that would be necessary to operate the laser at threshold.

Using Equation 5-12 for the gain coefficient, we can obtain

$$g = \frac{1}{2 \times 20} \ln \left[ \frac{1}{(0.999)(0.990)(1 - 0.002)(1 - 0.002)} \right] = 0.00038/\text{cm} = 0.038\%/\text{cm}$$

Hence the increase over a 20-cm-length amplifier would be

$$gL = 20 \text{ cm} \times (0.00038)/\text{cm} = 0.0076 \text{ or } 0.76\% \text{ per pass.}$$


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The useful power from the laser is obtained by locating a partially transmitting “output” mirror at one end of the amplifier so that part of the beam “leaks out” of the mirror cavity as shown in Figure 5-1. The initial gain in the amplifier must be greater than the loss of the transmitting mirror (plus other mirror and cavity losses) or the beam will not develop as described in Equations 5-8 and 5-9. A simple expression for the optimum mirror transmission  $T_{opt}$  in terms of the small-signal-gain coefficient  $g$ , the actual amplifier length  $L$ , and the absorption loss  $a$  (averaged over a single pass from one mirror to the other) can be expressed as

$$T_{opt} = (gL a)^{1/2} - a \quad (5-13)$$

---

**Example 2**

For the HeNe laser given in Example 1, assume that the gain is 10 times the threshold value or  $g = 10 \times 0.00038 = 0.0038$  and  $L = 20$  cm. Also assume that the absorption loss  $a$  is an average of  $a_1$  and  $a_2$  as defined above, or  $a = 1/2(a_1 + a_2) = 0.002$ . Compute the optimum mirror transmission for that situation.

Using Equation 5-13 we have for  $T_{opt}$

$$T_{opt} = [(0.0038)(20)(0.002)]^{1/2} - (0.002) = 1.04\%$$

A mirror reflectivity of 98.96% or approximately 99% would be the appropriate reflectivity of the output mirror. This was in fact the transmission used in Example 1 for  $R_2$ .

---

The laser beam output intensity  $I_{max}$  emitted from the output mirror can also be estimated in terms of the saturation intensity  $I_{sat}$ ,  $T_{opt}$ , and the average absorption per pass  $a$  in the following expression

$$I_{max} = \left( \frac{T_{opt}^2}{2a} \right) I_{sat} \quad (5-14)$$

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**Example 3**

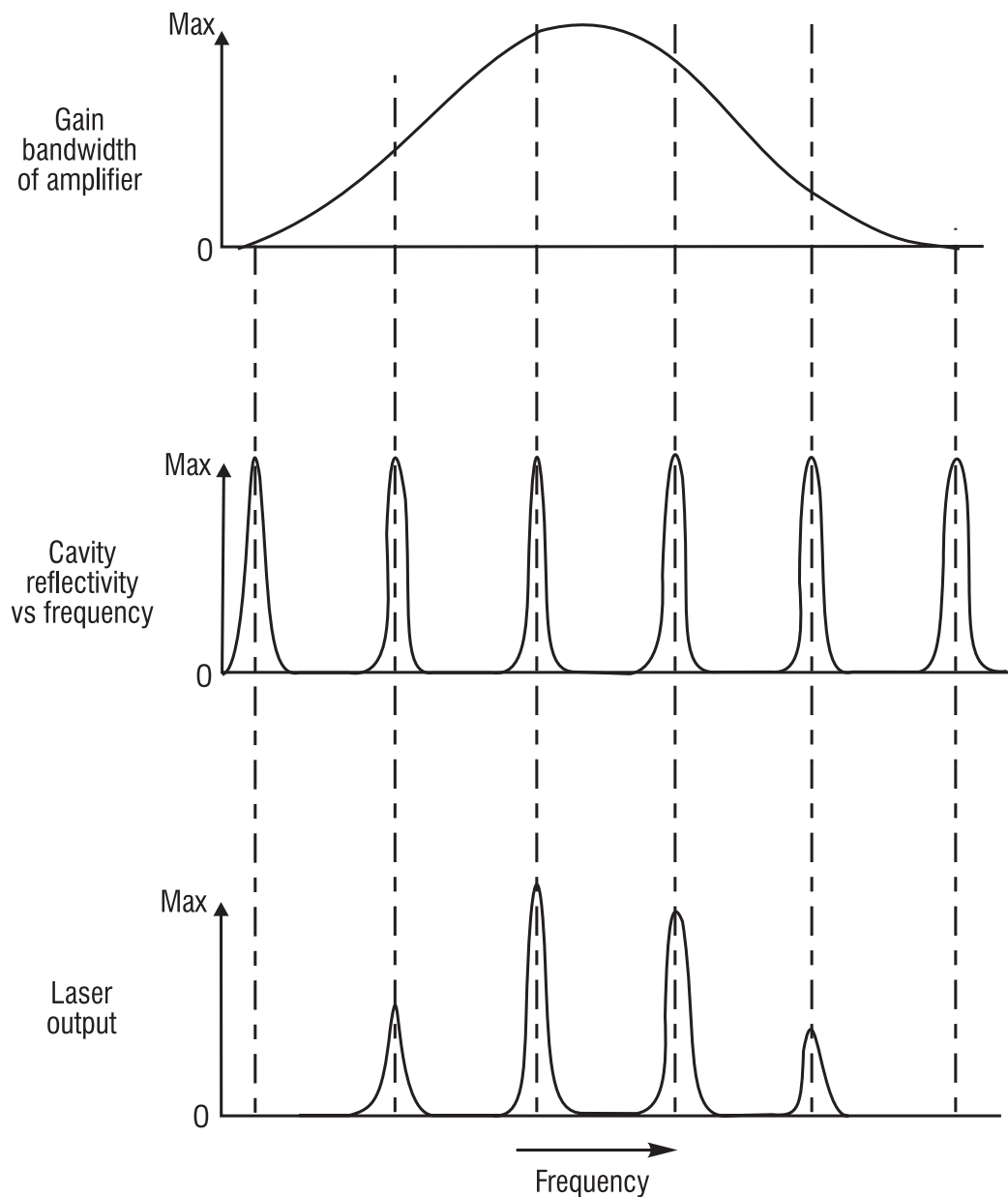
For the HeNe example given above, estimate the power output from the laser. Using Equation 5-14 and the conditions described in the example above,  $T_{opt} = 0.0104$ ,  $a = 0.002$ , as well as the value of the saturation intensity from Table 5-1 of  $I_{sa} = 6.2 \text{ W/cm}^2$ , we find that the maximum output power is  $I_{max} = 167 \text{ mW}$ . This is on the high end of the power spectrum for a HeNe laser.

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**Longitudinal cavity modes**—When the beam is developing within the mirror cavity, traveling back and forth, certain wavelengths within the gain bandwidth of the laser tend to be more enhanced than others. These are wavelengths (or frequencies) in which the light beam in the cavity forms a *standing wave*. Such an effect occurs when an exact number of half-wavelengths of the light fit within the separation distance between the mirrors. Typically there will be several hundred thousand wave peaks for each standing wave that occurs within the cavity. Hence, each standing wave must have a wavelength such that an integral number of oscillating waves fits in the space separating the mirrors. If more than one standing wave is present, each standing wave (longitudinal mode) will be separated in frequency from the next one by a fixed exact amount that depends upon the laser cavity length  $d$ . That frequency separation  $\Delta\nu$  between longitudinal modes can be obtained by dividing the speed of light  $c$  by twice the cavity length or

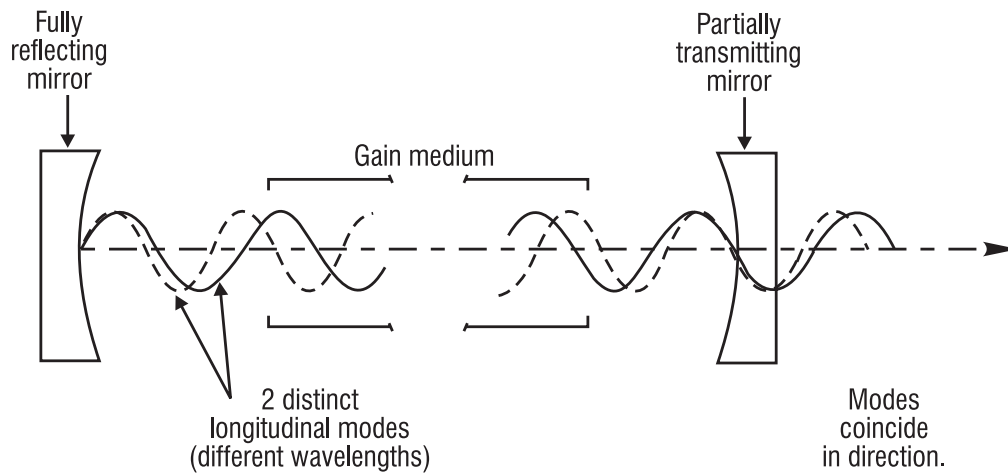
$$\Delta\nu = \frac{c}{2d} \quad (5-15)$$

In Figure 5-11, several of these modes are shown occurring within the frequency bandwidth of a typical gas laser. Typically, the separation in frequency is of the order of 500 MHz ( $5 \times 10^8 \text{ Hz}$ ) whereas the laser frequency itself is of the order of 500,000,000,000,000 Hz ( $5 \times 10^{14} \text{ Hz}$ ). For example, two of these discrete standing waves might have frequencies of 500,000,000,000,000 Hz and 500,000,500,000,000 Hz, separated in frequency by 500 MHz.



**Figure 5-11** Several longitudinal modes are shown occurring within the gain bandwidth of a typical gas laser.

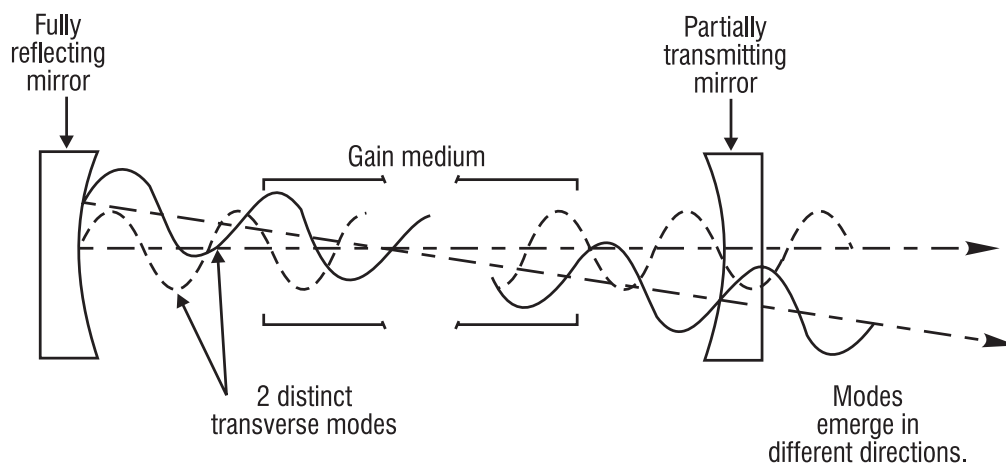
Each discrete standing wave is referred to as a longitudinal mode associated with the laser cavity. Figure 5-12 shows two such modes within a cavity. There will always be at least one longitudinal mode and there could be many more, depending on the frequency or wavelength bandwidth of the laser gain medium. If more than one longitudinal mode is being generated, they will be indistinguishable unless a spectrum analyzer is used to analyze the beam. They all travel in the same direction, and their color will be indistinguishable because their wavelengths (frequencies) are so similar, as indicated above.



**Figure 5-12** Two distinct longitudinal modes operating simultaneously in the same laser cavity

The frequency width of a single longitudinal mode can be very narrow, typically in the range of  $10^6$  to  $10^8$  Hz, determined by the mirror reflectivity (higher-reflecting mirrors produce narrower bandwidths) and by the cavity stability (free of vibrations).

**Transverse modes**—The presence of more than one longitudinal mode involves many light beams traveling exactly the same path through the amplifier but differing in wavelength depending upon the total number of wave cycles that fit between the mirrors. Contrary to this, different transverse modes involve slightly different optical paths through the amplifier and thus have slightly different directions when they emerge from the laser as shown in Figure 5-13. Because of the different optical path lengths, they also have slightly different frequencies. Each of these stable modes evolves because the light traveling that particular pathway recurs exactly from one round trip of the beam to the next, therefore developing into a steady beam. Each transverse mode traveling over its unique path might also consist of several longitudinal modes separated in frequency according to Equation 5-15.



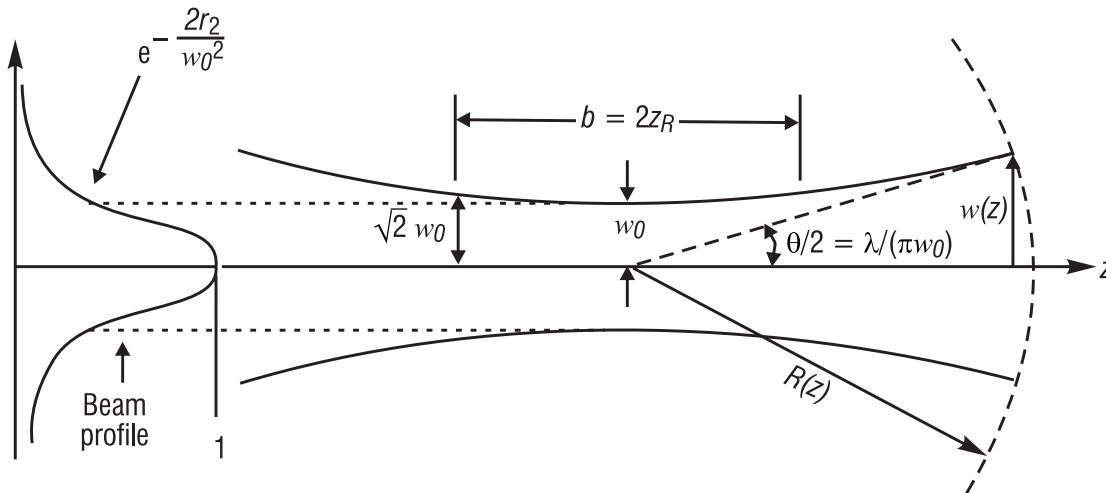
**Figure 5-13** Two transverse modes occurring simultaneously within a laser cavity. The on-axis mode is the  $TEM_{00}$  mode. The angled mode is actually rotationally symmetric and would produce a doughnut spot on the wall.

The lowest-order transverse mode, known as the  $TEM_{00}$  mode, travels down the central axis of the laser gain medium. Higher-order modes have slightly diverging beams as shown in Figure 5-13. The  $TEM_{11}$  mode, for example, if it were the only mode present, would appear as a doughnut-shaped beam when projected onto a screen. Complex patterns can be present if several transverse modes are operating. In most cases, closely located transverse modes differ in frequency by a smaller value than do adjacent longitudinal modes that follow the same path through the amplifier.

The  $TEM_{00}$  mode has a beam-intensity profile in the direction transverse to the direction of propagation that is described by a Gaussian function as given by the following expression.

$$I = I_0 e^{-\frac{2r^2}{w^2}} \quad (5-16)$$

where  $I_0$  is the intensity on the beam axis at any location,  $r$  is the perpendicular distance from the beam axis, and  $w$  is defined as the beam waist. This beam profile is shown on the left side of Figure 5-14. The beam waist, varying along the axis of the laser, is defined such that the intensity has fallen to  $1/e^2$  of the intensity on axis. It turns out that 86.5% of the energy is contained within the beam radius in which  $r = w$ . The  $TEM_{00}$  mode is often the desired mode because it propagates with the least beam divergence and can be focused to the tightest spot. It can generally be obtained by placing an adjustable aperture within the laser cavity and decreasing the aperture diameter until only the  $TEM_{00}$  mode remains.



**Figure 5-14** A diagram showing some of the parameters of a Gaussian laser beam ( $TEM_{00}$  mode)

Gaussian beams have a minimum beam waist  $w_0$  that usually occurs somewhere between the laser mirrors. The beam then gradually expands from that location. If the laser mirrors have the same radius of curvature, the minimum beam waist occurs exactly halfway between the mirrors. If the minimum beam waist is known, the beam waist  $w(z)$  at any distance  $z$  from where the minimum occurs can be determined from the following equation (provided the beam does not interact with any type of optical element that would change the beam in any way).

$$w(z) = w_0 \left[ 1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2 \right]^{1/2} \quad (5-17)$$

where  $\lambda$  is the wavelength of the beam. This is diagrammed in Figure 5-14. The expanding beam has a curved wavefront with a radius of curvature  $R(z)$  given by

$$R(z) = z \left[ 1 + \left( \frac{\pi w_0^2}{\lambda z} \right)^2 \right] \quad (5-18)$$

The beam angular spread  $\Theta$  in radians at distances well beyond the laser mirrors can be expressed as

$$\Theta = \frac{2\lambda}{\pi w_0} \quad (5-19)$$

as shown in Figure 5-14. This angular divergence  $\Theta$  can be approximately determined by measuring the beam diameter at a known distance from the laser (by projecting the beam onto a screen) and then finding the ratio of the beam radius (half the diameter) to the distance from the laser. From Equation 5-19, it can be seen that a larger  $w_0$  and/or a shorter wavelength  $\lambda$  gives a smaller angular beam divergence.

Also shown in Figure 5-14 is the value of  $z = z_R$  such that

$$z_R = \frac{\pi w_0^2}{\lambda} \quad (5-20)$$

This value  $z_R$  is referred to as the Rayleigh range and is considered the depth of focus for a Gaussian beam. Twice the value of  $z_R$  or  $b = 2 z_R$  is known as the confocal parameter. At a distance  $z_R$  in either direction from the location of the minimum beam waist  $w_0$ , the value of the beam waist has increased to  $\sqrt{2} w_0$  as shown in Figure 5-15. When a confocal laser cavity is set up (as described later) the *diameter* of the beam at the mirrors will thus have the value of  $2\sqrt{2} w_0$ .

For laser cavities in which the mirrors have the same radii of curvature, the expression for  $w_0$  can be given as

$$w_0 = \left\{ \frac{\lambda}{2\pi} [d(2R-d)]^{1/2} \right\}^{1/2} \quad (5-21)$$

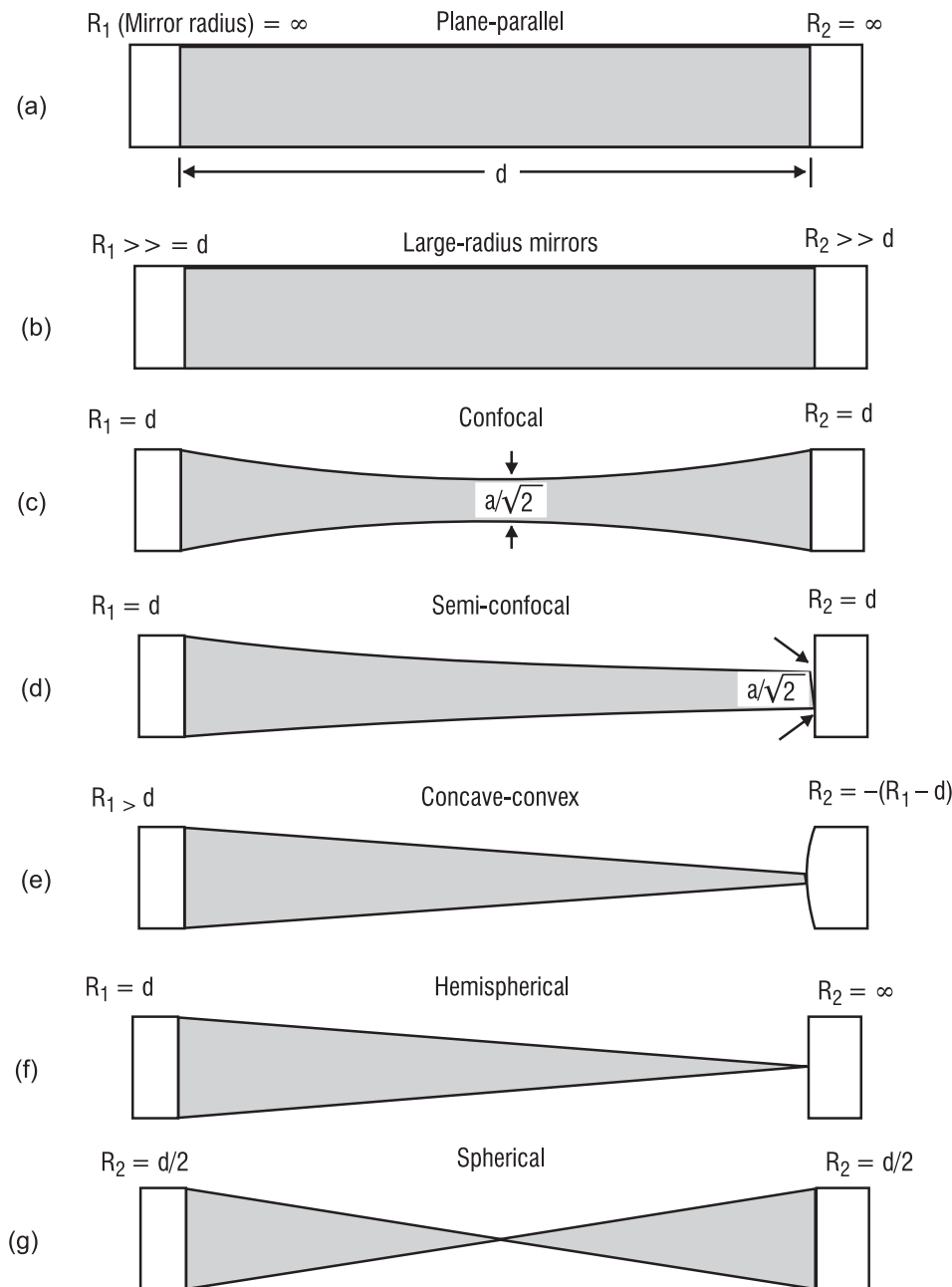
If the radius of curvature is equal to the separation between mirrors, or  $R = d$ , the cavity is known as a confocal resonator. For this case the expression for  $w_0$  then simplifies even further to



$$w_0 = \left( \frac{\lambda d}{2\pi} \right)^{1/2} \quad (5-22)$$

Another very common laser cavity arrangement is known as the semi-confocal resonator cavity. This case uses a curved mirror and a flat mirror (infinite radius of curvature) with the mirror separation being *half* the radius of curvature. This, in effect, is one-half of the confocal resonator as described above because it folds half of the resonator back on itself by using a flat mirror at the halfway location. This is a common resonator to obtain a parallel beam at the output of the laser, if the output mirror is the flat mirror.

**Stable laser cavities or resonators**—A variety of laser mirror arrangements might be considered in constructing a laser cavity, as shown in Figure 5-15. In that figure, the mirror radii of curvature are defined in terms of the separation distance  $d$  between the mirrors. However, not all of these cavities allow for stable laser operation. Such stability is obtained if the laser beam is reflected back toward the axis of the amplifier rather than sending the beam in a diverging direction after each mirror reflection. Of those cavities shown, the stable ones are the large-radius mirrors (Figure 5-15b), the confocal cavity (Figure 5-15c), the semi-confocal cavity (Figure 5-15d), and the concave-convex cavity of Figure 5-15e.



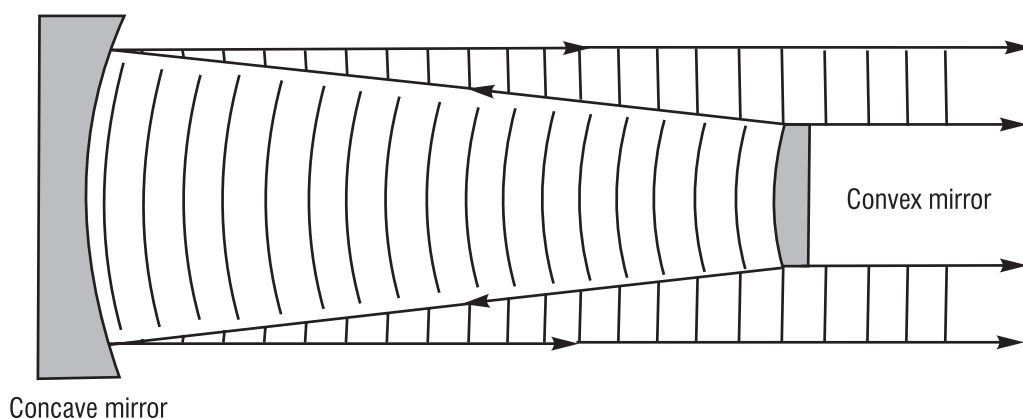
**Figure 5-15** Various possible laser cavity configurations

With curved mirrors, a general way of defining a stable cavity is with one of the two following arrangements:

- (1) Both mirrors are concave. Either the center of curvature of each mirror lies beyond the other mirror or the center of curvature of each mirror lies between the other mirror and the center of curvature of the other mirror.
- (2) One mirror is convex and one is concave. The center of curvature of the concave mirror lies between the convex mirror and the center of curvature of the convex mirror.

A common cavity arrangement used to obtain the smallest output-beam diameter from the laser is the semi-confocal cavity as shown in Figure 5-15d. It consists of one curved and one flat mirror, with the flat mirror used as the output mirror. This is the equivalent of taking a stable cavity having two equal radii-of-curvature mirrors and replacing one of the curved mirrors with a flat mirror located at the halfway point between the two curved mirrors. For this arrangement the minimum beam waist  $w_0$  occurs at the flat mirror.

**Unstable resonators**—A laser operating in the TEM<sub>00</sub> mode typically has an inherently very narrow beam within the laser cavity. It thus cannot take advantage of a relatively wide gain region that might be available within the laser amplifier. Accessing the wide gain region could contribute significantly more energy to the laser output beam than is possible in the TEM<sub>00</sub> mode. A special type of resonator cavity, referred to as an *unstable resonator*, has been developed to take advantage of such wide gain regions. A diagram of such a resonator is shown in Figure 5-16 with the gain region located between the concave and convex mirrors and having a transverse dimension the size of the diameter of the larger (concave) mirror. Such a



**Figure 5-16** *Diagram of an unstable resonator*

resonator operates on a pulsed basis and requires a laser with a very high gain medium of the order of a factor of 10 or more per pass. In this resonator arrangement, the beam develops initially on the longitudinal axis between the two mirrors and then expands toward the convex mirror, reflecting and then further expanding to the larger concave mirror, and then passes out of the cavity in a straight line past the smaller (convex) mirror. The beam emerges from the laser in the shape of a doughnut, the center of the beam being obscured by the smaller mirror. The observed laser beam shape just beyond the mirror has the expected hole in the middle, however, farther away from the laser the hole fills in and a relatively high-quality, nearly Gaussian shaped beam evolves. This resonator configuration can produce significant amounts of pulsed energy that is extracted from the entire laser gain medium with a reasonably good beam quality.

**Q-switching**—Q-switching is a technique to produce short-duration high-energy laser pulses. It is achieved by pumping the laser gain medium with no cavity in place and then rapidly switching the mirror cavity into the system, thereby producing a giant pulse. Normally when a laser is “turned on” and pumping of the gain medium begins, as soon as the gain exceeds the mirror losses, laser energy begins to be extracted from the medium and an equilibrium balance is achieved with the expected power output from the laser. However, if the mirrors are not in

place at the ends of the gain medium, energy is not extracted and the medium will continue to accumulate population in the upper laser level for the duration of the lifetime of the level. Some laser gain media have upper laser levels with relatively long storage lifetimes before the electrons decay spontaneously to lower levels. These gain media are typically the solid-state lasers with storage times significantly longer than a microsecond, whereas most laser gain media have upper-level lifetimes of the order of one tenth to one thousandth of a microsecond. The longer storage lifetimes allow a very large population to build up in such levels when the laser medium is pumped with no mirrors present. In actual implementation of this process, the mirrors are situated at the appropriate locations in the cavity but an additional “shutter” is located between one of the mirrors and the end of the gain medium. This shutter can be an electro-optic shutter such as a Pockels cell or a Kerr cell, an acousto-optic shutter, or a saturable absorber. Opening the shutter, in effect, switches the mirrors into position for lasing to begin.

**Mode locking**—It is possible in a laser that has a very wide gain bandwidth to obtain thousands of longitudinal modes operating simultaneously. If those modes are all locked in phase so that they all oscillate upward or downward together, they will combine in a way that produces a chain of very short pulses separated in time by  $\Delta t_{sep}$ . This is the time it takes for a pulse to travel round trip within the cavity or

$$\Delta t_{sep} = \frac{1}{\Delta \nu} = \frac{2d}{c} \quad (5-23)$$

where  $\Delta \nu$  is from Equation 5-15. This separation time is typically of the order of 10–20 nsec.

The duration of the ultrashort pulse  $\Delta t_p$  generated in such a process is given by the inverse of the frequency bandwidth spanned by all of the longitudinal modes. If  $N$  is the number of modes operating, the frequency bandwidth over which the modes are generated is just  $N\Delta \nu$ . Hence,  $\Delta t_p$  can be expressed as

$$\Delta t_p = \frac{1}{N\Delta \nu} \quad (5-24)$$

The maximum possible gain bandwidth  $N\Delta \nu$  is the full gain bandwidth of the laser transition. Lasers with very wide gain bandwidths  $\Delta \nu_{21}$ , such as dye lasers and  $\text{Ti:Al}_2\text{O}_3$  lasers (see Table 5-1), can produce the shortest pulses, light pulses as short as 5 femtoseconds (0.000000000000005 second or  $5 \times 10^{-15}$  sec) have been produced with this technique. While producing such short pulses is quite difficult, it is relatively easy nowadays to produce 100-fsec-duration pulses.

Ultrashort pulses, using mode-locking techniques, can be produced only if the laser is operating continuously (cw) or quasi cw (stable for periods of at least several cavity round-trip times as given by Equation 5-23). The principal method of locking the longitudinal modes in phase is to place a shutter within the laser cavity near one mirror. This shutter is opened when the short pulse arrives, allowing it to pass through to the mirror and back toward the amplifier, and then quickly closes until the next arrival of that pulse, when the shutter again opens. The shutter can be either an active shutter, such as an acousto-optic device driven with RF power, or a passive nonlinear optical shutter that opens when an intense pulse arrives. The active shutter is controlled with external electronics, whereas a passive shutter operates nonlinearly in a passive way, by rapidly opening for a high-intensity pulse but remaining closed for a low-intensity

pulse. This prevents the formation and growth of weaker pulses that could effectively compete with the original short pulse, and thereby lengthen it beyond its desired duration.

## II. LASER PROPERTIES RELATED TO APPLICATIONS

Most of the properties described below are interrelated. Often, in carrying out a specific laser design to provide one of these properties, many of the others will also be obtained with no extra effort. Nevertheless, each effect will be described separately, since only one of the properties is typically sought for a specific application.

### A. Collimation

*Collimated light* is light in which all of the light rays or waves are traveling in a specific direction and hence they are all parallel to each other. Lasers produce the most collimated light of any type of light source. Such collimated light is used for reference beams in construction, leveling and grading land, alignment of pipe such as sewer pipe, and sending light over long distances without suffering significant divergence, and in laser pointers. Producing the most collimated light, in other words the least divergent light, is determined by the cavity mirror properties including the radii of curvature of the mirrors and the separation between mirrors as indicated in Equations 5-17, 5-18, and 5-19. For the smallest beam divergence,  $w_0$  must be large, as you can see from Equation 5-19. Also, the rays of the laser beam are the most parallel when the beam is at the location of the minimum beam waist  $w_0$  as described in Equations 5-17, 5-20, and 5-21. This parallelism of the beam can be realized by using a semi-confocal resonator arrangement for the laser cavity as shown in Figure 5-15d and described after Equation 5-21, with the flat mirror as the output mirror.

### B. Monochromaticity

*Monochromaticity* refers to how pure in color (frequency or wavelength) the laser beam is or, in other words, how narrow the laser beam frequency bandwidth is. Note that this is essentially  $N\Delta\nu$  as described above in the mode-locking discussion if the laser is lasing with more than one longitudinal mode. If the laser is operating in a single longitudinal mode, as most solid-state and semiconductor lasers do, the actual laser linewidth can be significantly narrower, the width of a single longitudinal mode beam. For most applications requiring a single narrow wavelength, most lasers would normally provide a sufficiently narrow frequency output bandwidth, of the order of  $10^9$ – $10^{11}$  Hz. This would represent a bandwidth that is less than 0.1% of the frequency or wavelength of the beam itself (or even smaller in most instances). However, in some applications, such as in remote sensing or in establishing a new frequency standard, a much narrower linewidth is required. Linewidths of the order of 1 MHz ( $10^6$  Hz) or less can be obtained by operating with a single longitudinal and single transverse mode ( $\text{TEM}_{00}$ ). The narrowing is enhanced by choosing highly reflecting mirrors, constructing a very stable mirror cavity in conjunction with the amplifier by eliminating vibrations of the mirrors and other cavity elements, and providing temperature stability.

## C. Coherence

*Coherence* refers to the how much *in step* or *in phase* various portions of a single laser beam are. The closeness in phase of various portions of the laser frequency bandwidth is referred to as temporal or longitudinal coherence. The closeness in phase of different spatial portions of the beam after the beam has propagated a certain distance is referred to as spatial or transverse coherence. This phased relationship determines how readily the various portions of the beam can interfere with each other, after the beam has propagated a specific distance, to produce such effects as diffraction (bending) of light and related applications such as holography. Typically, applications involve dividing the beam into two or more beams that travel different lengths or pathways and are then recombined. When they are recombined they will interfere with each other, producing the desired effect if those parts are still in phase (coherent); if they are no longer in phase, the effect will not occur. The coherence length is used to describe the beam propagation distance over which the beams stay in phase.

For longitudinal or temporal coherence, the coherence length  $\ell_c$  is related to the wavelength  $\lambda$  and the total frequency bandwidth of the laser  $\Delta\nu_L$  by

$$\ell_c = \frac{\lambda^2}{\Delta\lambda} \quad (5-25)$$

Note:  $\Delta\lambda$  is the actual bandwidth of the laser beam given in wavelength units.

For transverse or spatial coherence, the transverse coherence length  $\ell_t$  is related to the laser wavelength  $\lambda$ , the laser source diameter at its origin  $s$ , and the distance  $r$  the beam has propagated from its origin, by the following relationship.

$$\ell_t = \frac{r\lambda}{s} \quad (5-26)$$

## D. Intensity and Radiance

Intensity or irradiance is the power of the laser beam divided by the cross-sectional area of the beam. It is thus typically given in watts per square centimeter ( $\text{W}/\text{cm}^2$ ). It is a measure of the amount of energy that can be applied to a specific region within a given amount of time. It is one of the two most important parameters in using the laser for materials processing applications such as welding, cutting, heat treating, ablating, and drilling, or for laser surgery. The other important parameter is the laser wavelength, since the amount of absorption of all materials, including biological materials, is dependent upon the wavelength of the light. In some instances a deep penetration of the beam is desired, for example in doing processes that must be carried out quickly. In that situation, a laser wavelength in which the material has a relatively low absorption would be selected. Other applications might require a shallow penetration in order to control the quality of the edge to be left after the process is completed, such as in some surgical processes or in drilling very small holes. Thus, a wavelength region of high absorption would be chosen for the laser. A general rule is that absorption is very high for most materials at ultraviolet wavelengths and decreasing at longer wavelengths. However, this does not hold true for all materials or for all wavelengths. Many materials have high absorption peaks at specific

wavelengths that could occur anywhere in the spectrum, so one must be careful to obtain the absorption versus wavelength curves for the desired material before choosing the specific laser.

In all instances where high beam intensity is desired, the availability of the laser with sufficient intensity at that wavelength must be considered. Not all wavelengths with such intensity are possible. There are, however, lasers such as the CO<sub>2</sub> laser in the middle infrared (10.6  $\mu\text{m}$ ); the Q-switched Nd:YAG laser in the near infrared (1.06  $\mu\text{m}$ ) and frequency-doubled Nd:YAG to the green (530 nm); the copper vapor laser in the green (510 nm) and yellow (578 nm); and the ultraviolet excimer lasers including the XeF laser (351 nm), XeCl laser (308 nm), KrF laser (at 248 nm), ArF laser (193 nm), and F<sub>2</sub> laser (157 nm). For various aspects of materials processing, the beam must have an intensity in the range of  $10^8$ – $10^9$  W/cm<sup>2</sup>.

*Radiance* is a parameter that includes the beam intensity (W/cm<sup>2</sup>) and takes into account the beam divergence angle. The divergence angle is generally given in steradians (see Equation 5-2 and Figure 5-2), which is a three-dimensional angular measurement as opposed to the term degrees, which describes angular spread in only two dimensions (in a plane). As noted in Figure 5-2a, a complete sphere contains  $4\pi$  steradians. Hence, radiance is given in units of watts per unit area per unit solid angle or (W/cm<sup>2</sup>-sr). Laser beam divergence is usually given in milliradians (mr) because of the very low divergence of most lasers. The approximate beam divergence in radians can be obtained by measuring the laser beam diameter at a specific, relatively long distance from the laser and dividing it by the square of the distance to where the measurement is made. To obtain the beam divergence in steradians, Equation 5-1 can be used.

Radiance becomes useful when a beam must be propagated over a reasonable distance before it is used or where the divergence can affect the focusing ability of the beam. Since most materials applications do not involve the tightest focusing possible for a given beam, intensity is usually the more important parameter.

## E. Focusability

Many applications of lasers involve their ability to be focused to a very small spot size. Perhaps one of the most demanding applications is in focusing the small diode laser in a compact disk player. To store as much information as possible on each disk, that information must be included in the smallest grooves possible on the disk. The width of the grooves is determined by the ability of a laser beam to access a single groove without overlapping into adjacent grooves. Hence, the diameter of the spot size to which the laser beam can be focused becomes a very important parameter.

The smallest diameter that can be obtained with a focused laser, assuming that a single TEM<sub>00</sub> mode can be obtained from the laser, is approximately the dimension of the wavelength of the laser and is given by the following expression.

$$d_{\min} \cong \frac{4 \lambda (f/\#)}{\pi} \quad (5-27)$$

in which the  $f/\#$  is the focal length of the lens used for the focusing divided by the useful diameter of the lens, the same notation as on camera lenses (see Module 1-3, *Basic Geometrical Optics*). If the laser beam is less than the actual lens diameter, the beam diameter is used instead of the lens diameter in determining the  $f/\#$ . In other words, a laser operating in the visible

spectral region with a wavelength of the order of 500 nm could be focused to a size of less than one hundredth the width of a human hair! The effective  $f/\#$  focusing lens (ratio of focal length to laser beam diameter intercepted by the lens) must be of the order of unity to obtain such a small focus. Most lasers, however, can be focused relatively easily to spot diameters of the order of 0.1–0.2 mm. Extra care must be taken in terms of beam quality (mode quality) and lens focal length to obtain smaller spot diameters.

### III. EXAMPLES OF COMMON LASERS

#### A. HeNe

The helium-neon laser (HeNe) was the first gas laser. The most widely used laser wavelength is the red wavelength (632.8 nm) with a cw power output ranging from 1 to 100 mW and laser lengths varying from 10 to 100 cm. HeNe lasers can also be operated at the 543.5-nm green wavelength and several infrared wavelengths. Initiation of a relatively low electrical current through a low-pressure gas discharge tube containing a mixture of helium and neon gases produces the population inversion. With this gas mixture, helium metastable atoms are first excited by electron collisions with helium ground-state atoms. This energy is then transferred to the desired neon excited energy levels, thereby producing the required population inversion with lower-lying helium energy levels.

#### B. Argon ion and Krypton ion

The argon ion laser and the krypton ion laser provide a wide range of visible and ultraviolet laser wavelengths. They produce cw output at wavelengths ranging from 275 to 686 nm and powers of up to tens of watts. Running a dc current through a long, narrow-bore plasma discharge tube filled with a low-pressure (0.1 torr) argon or krypton gas produces the population inversion. The argon atoms must be ionized to the first through third ionization stages to reach the appropriate energy levels for laser action. As a result, these lasers are relatively inefficient but still extremely useful for certain applications because of their short wavelengths.

#### C. HeCd

The helium cadmium laser (HeCd) operates continuously (cw) in the blue (441.6 nm) and ultraviolet (354 and 325 nm) portions of the spectrum with powers ranging from 20 to 200 mW and laser lengths of 40–100 cm. The population inversion in the amplifier region is produced by heating metallic cadmium to a vaporized state in a narrow-bore quartz discharge tube, mixing it with helium gas, and running an electrical discharge current of up to 100 mA through the tube. The excitation mechanisms include *Penning ionization* (helium metastable atoms colliding with neutral Cd atoms and exchanging energy), electron collisional ionization, and photoionization from strong, short-wavelength radiation originating within the helium atoms. The laser uses an effect known as *cataphoresis* to transport the cadmium atoms through the discharge and thereby provide the necessary uniform cadmium distribution within the gain region.



## D. Copper vapor

The pulsed copper vapor laser (CVL) provides high average powers of up to 100 W at green (510 nm) and yellow (578 nm) wavelengths at very high repetition rates of up to 40 kHz and pulse durations of 10–50 nsec. The copper is heated within the laser gain region to temperatures of up to 1600°C in 2–10-cm-diameter ceramic tubes typically of 100–150 cm in length. The lasers are self-heated such that most of the energy provided by the discharge current provides heat to bring the plasma tube to the necessary temperature. Excitation occurs by electrons colliding with neutral copper atoms to excite them to the relevant laser-related energy levels.

## E. CO<sub>2</sub>

The carbon dioxide laser (CO<sub>2</sub>), operating primarily in the middle infrared spectral region around 10.6  $\mu\text{m}$ , is one of the world's most powerful lasers, producing cw powers of over 100 kW and pulsed energies of up to 10 kJ. It is also available in smaller versions with powers of up to 100 W from lasers the size of a shoe box. These lasers operate in a gas discharge in mixtures of helium, nitrogen, and CO<sub>2</sub> gases. Electron collisions with the nitrogen molecules within the discharge produce metastable energy levels. The energy contained in those levels is subsequently transferred by collisions to the CO<sub>2</sub> molecule, where the population inversion is produced. This is one of the most efficient lasers, with conversion of input electrical power to laser output power of up to 30%.

## F. Excimer

Excimer lasers consist of mixtures of noble gas atoms such as argon, krypton, and xenon with reactive gases such as fluorine or chlorine operating in a special type of high-pressure gaseous discharge. They are therefore also known as rare gas-halide lasers. The actual laser species is an excited-state molecule containing a combination of the two types of atoms, such as ArF, KrF, XeF, and XeCl. The term excimer results from a contraction of the words “excited state dimer,” which indicates the excited-state nature of the lasing molecule. The lasers operate primarily in the ultraviolet spectral region with wavelengths at 193 nm (ArF), 248 nm (KrF), 308 nm (XeCl), and 351 nm (XeF). The laser output consists of 10–50-nsec pulses typically of 0.2 to 1 J/pulse at repetition rates of up to 1 kHz. These lasers are relatively efficient (1–5%) and are of a size that can fit on a desktop. The excitation occurs with electrons within the discharge colliding with and ionizing the rare gas atoms while at the same time dissociating the halide molecules into either F or Cl atoms to form negative halogen ions F<sup>−</sup> and Cl<sup>−</sup>. The negative halogen ions and positive rare gas ions readily combine in an excited state to form the laser species since they are of opposite charge and hence attract each other.

## G. Organic dye

Dye lasers have the advantage of wide tunability in wavelength. When changing from one dye to another, the total wavelength region that can be covered ranges from 320 to 1500 nm. The gain medium for dye lasers consists of a solvent such as alcohol or water within which an organic dye is dissolved in a typical concentration of 1 part in ten thousand. If a diffraction grating or prism is used to replace one of the laser mirrors, the grating can be rotated to tune the laser wavelength over the spectrum of the dye. Each dye has a tunable gain bandwidth of

approximately 30–40 nm with a linewidth as narrow as 10 GHz or less. Dye lasers are available in either pulsed (up to 50–100 mJ/pulse) or cw (up to a few W) in tabletop systems that are pumped either by flashlamps or by other lasers such as frequency-doubled or -tripled YAG lasers or argon ion lasers. Most dye lasers are arranged to have the dye mixture circulated by a mechanical pump into the gain region from a much larger reservoir because the dyes degrade at a slow rate due to the excitation (optical pumping) process. Dye lasers, with their broad gain spectrum, are particularly attractive for producing ultrashort light pulses by a mode-locking process as described earlier. The shortest pulses ever generated are 5 thousandths of a trillionth of a second ( $5 \times 10^{-15}$  sec).

## H. Ruby

The ruby laser, which lases at the extreme red end of the visible spectrum at 694 nm, was the very first laser demonstrated. It consists of a crystalline sapphire ( $\text{Al}_2\text{O}_3$ ) host material into which chromium atoms (the lasing species) are infused (doped) at a concentration of up to 0.05% by weight. The energy-level arrangement of the ruby laser, with the ground state as the lower laser energy level, makes for a very ineffective pumping process, in which very large amounts of pump light are required before gain is achieved. Therefore, this laser is not as efficient as other solid-state lasers and is not used much anymore.

## I. Nd:YAG and Nd:glass

Neodymium is a very effective laser species when doped into either yttrium-aluminum-garnet (YAG) or glass host materials. The primary laser wavelength is at 1.06  $\mu\text{m}$  for YAG and 1.05  $\mu\text{m}$  for glass. The lasers are optically pumped either by flashlamps or by other lasers (especially GaAs semiconductor diode lasers). YAG is a very attractive host material for Nd because it has a high thermal conductivity and is a robust material, and hence the laser can produce high average-power output without having the crystal break. The Nd:YAG laser produces cw powers of up to 250 W and pulsed energies of up to 1 J/pulse.

## J. Ti:Al<sub>2</sub>O<sub>3</sub>

Another class of solid-state lasers is the broad-bandwidth, tunable lasers. The most well-known and used laser in this category is the titanium-sapphire laser, Ti:  $\text{Al}_2\text{O}_3$ , consisting of titanium atoms doped into a sapphire ( $\text{Al}_2\text{O}_3$ ) host at a concentration of up to 0.1% by weight. This laser operates over a wavelength ranging from 660 nm to 1,180 nm (1.08  $\mu\text{m}$ ), which gives it a gain bandwidth of 520 nm, the largest of any laser except perhaps the free-electron laser (a laser generated by an oscillating beam of high-energy electrons). This large bandwidth allows for large tunability as well as very short pulse production via mode-locking. It is also the one solid-state laser that has a much shorter upper-level lifetime than most other solid-state lasers, just under 4  $\mu\text{sec}$ , which makes it difficult to pump with flashlamps and also difficult to Q-switch. Hence, this laser is typically pumped with other lasers such as the argon ion laser or the doubled Nd:YAG laser.

Ti:Al<sub>2</sub>O<sub>3</sub> lasers are used in infrared spectroscopy of semiconductors, laser radar, rangefinders, and remote sensing and in medical applications such as photodynamic therapy. They are also

used to produce short pulses of X rays by focusing high-intensity pulses onto a solid target from which a tiny, high-temperature, high-density plasma is produced that radiates large quantities of X rays.

Other lasers in this broadband, tunable category include the alexandrite laser operating at 700 nm to 820 nm and the chrome-doped LiSAF laser, operating at 780 nm to 1010 nm.

### K. Erbium fiber

Fiber lasers were first operated in Nd-doped glass fibers, but the fiber laser of major current interest is the erbium-doped fiber laser operating at 1.4 to 1.6  $\mu\text{m}$ . This fiber laser can be spliced into a normal transmitting optical fiber, and, when optically pumped with a semiconductor laser at either 980 nm or 1.48  $\mu\text{m}$ , it provides amplification to a communication signal that is being transmitted through the fiber. The pump light is fed into the fiber line—with a beam-combining device—thereby merging with the signal. This laser amplifier is especially useful in undersea optical fiber cables transmitting phone and data information between continents. More recently, it has also been used in local area networks and other shorter-distance communication applications. Several of these amplifiers must be installed equally spaced within a fiber when transmitting a message from America to Europe, for example. The amplifier bandwidth allows for a technique referred to as WDM (wavelength division multiplexing), which involves sending many separate signal beams at slightly different wavelengths through the same fiber, each of which is amplified by the single erbium-doped fiber amplifier. Hence, the data volume is increased significantly without having to install more fiber communication lines.

### L. Semiconductor lasers (solid state)

Semiconductor lasers are small, very efficient lasers with dimensions of less than a millimeter (see semiconductor gain media). The wavelengths of commercial lasers range from approximately 600 nm in the red to 1.6  $\mu\text{m}$  in the near infrared. Lasers in the blue and green are also under advanced development, but very few are available commercially. These lasers consist of small semiconductor crystals grown such that they can be cleaved in short segments of approximately 0.5 mm in length. The cleaving is done in a direction perpendicular to the laser axis, leaving a surface (facet) at each end of the gain medium that serves as a mirror. No reflective coatings are generally required; the cleaved surface itself serves to provide a reflectivity of the order of 35% or more from each of the two mirror surfaces, which is ample due to the very high gain or amplification present in the laser. Because of the short separation between mirrors, it is generally possible to obtain laser operation on only one longitudinal mode. Also, because of the short cavity length, the laser operates in a highly multi-transverse-mode output with a high angular divergence beam. To obtain single  $\text{TEM}_{00}$ -mode operation, it is necessary to coat the two end facets of the laser with an antireflection coating at the laser wavelength. Then an external mirror cavity can be installed with the appropriate mirror radii and reflectivity, as well as a suitable aperture on axis to restrict beam spread.

Semiconductor lasers are mass produced by depositing various layers of *p*- and *n*-doped material, insulating material, and metal contact layers by lithographic techniques. The most common semiconductor lasers are heterostructure lasers in which additional layers of different materials of similar electronic configurations are grown adjacent to the *pn* junction. This helps

confine the electrical current flow to the junction region in the direction perpendicular to the layers, thus minimizing the required current, energy deposition, and heat loading in the devices. The laser mode in the transverse direction is controlled either by (1) gain guiding, in which the gain is produced over a specific narrow lateral extent determined by fabrication techniques, or by (2) index guiding, in which the index of refraction in the transverse direction is varied to provide total internal reflection of the guided mode. Quantum-well lasers are semiconductor lasers that have a very thin gain region in the direction perpendicular to the layers, of the order of 5–10 nm. The laser gain bandwidth is significantly reduced due to a quantum effect. The gain coefficient remains the same, but the volume over which the energy deposition occurs is confined to an even smaller region. This significantly reduces the threshold current without significantly sacrificing laser output power. Because of their low threshold current and their low power consumption, quantum-well lasers are presently the most commonly used semiconductor lasers.

The largest applications of semiconductor lasers are in communication, in which the laser provides the signal, and in compact disk players, in which the laser is focused into the disk grooves and reflected to detect the digitally coded information. They are also used in high-speed printing systems and laser pointers and as pump sources for solid-state lasers (mainly Nd:YAG).

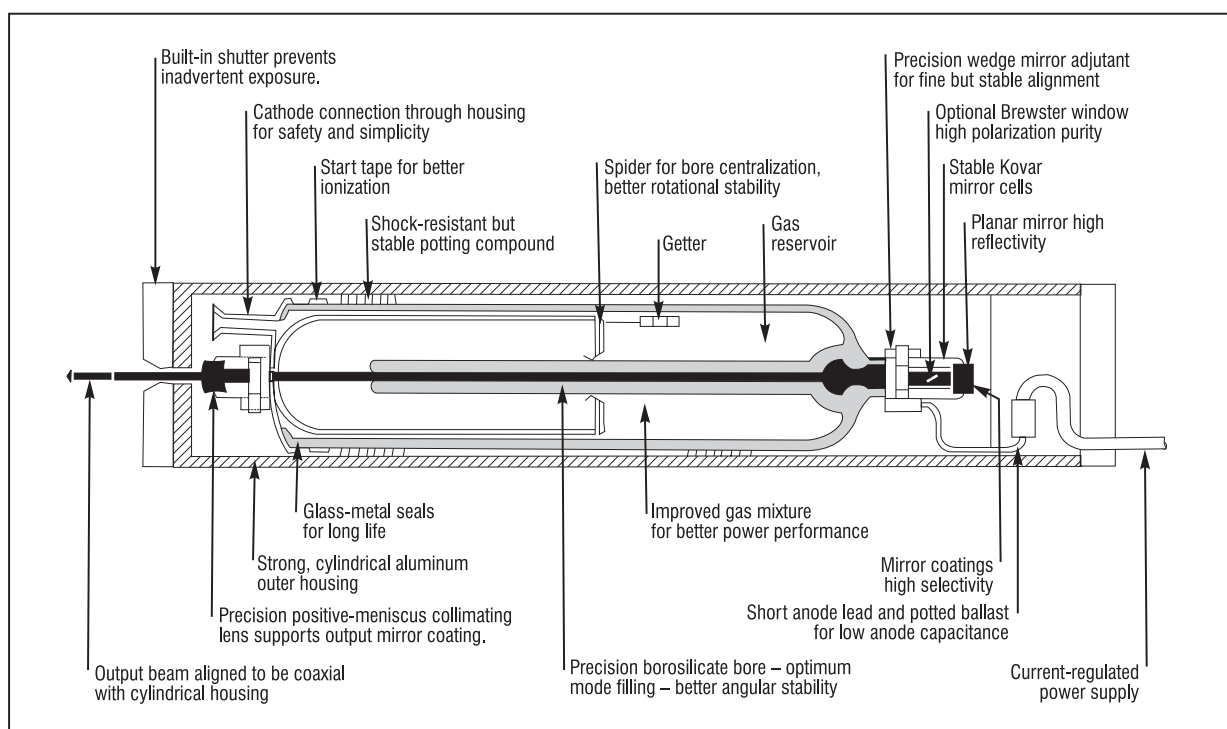
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## IV. OPERATION OF A HeNe LASER

The helium-neon laser is the most commonly used gas laser. Hence it serves as a good example in describing the detailed operation of a gas laser.

### A. Laser structure

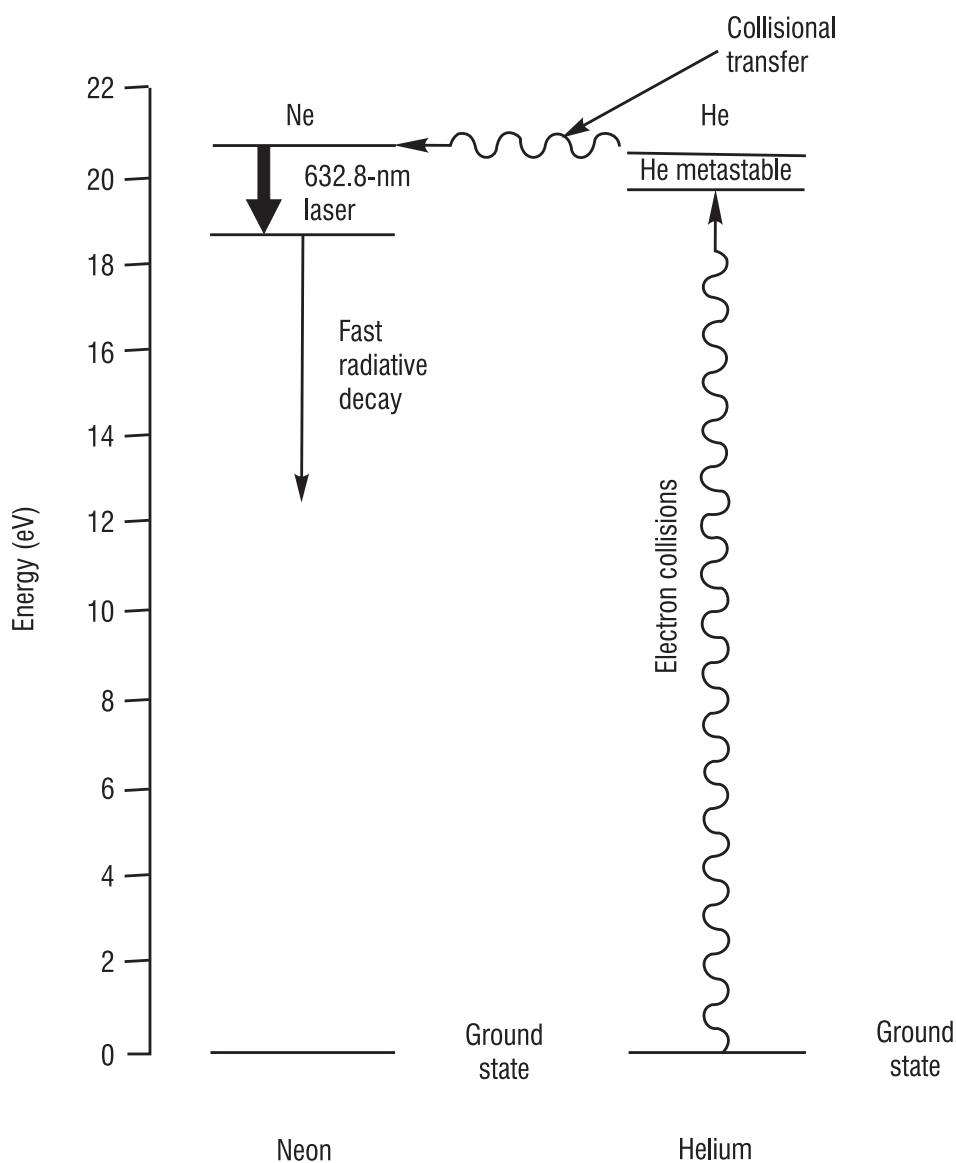
The He-Ne laser operates in a narrow-bore glass or quartz discharge tube with laser mirrors mounted at both ends of the tube. The tube can be anywhere from 10 to 100 cm in length, with most having lengths of 10–20 cm. The tube is filled with a low-pressure (2–3 torr) gas mixture of helium and neon in a ratio of approximately 5:1. At each end of the tube are electrical connections, referred to as electrodes, through which a high-voltage power supply is connected to the tube. The positive high voltage is connected to the anode electrode. The electrode at the other end of the tube, known as the cathode, is at ground potential. The anode electrode consists of a metal pin inserted through the glass so that one end extends into the gas region of the tube and the other is connected to the power supply. The cathode electrode typically consists of a cylindrical aluminum canister a few cm in diameter located inside a glass cylinder that concentrically surrounds the discharge tube, as shown in Figure 5-17. The large surface area of the canister cathode serves to minimize sputtering of the electrode material from the cathode when the discharge current is flowing in the tube. Excessive sputtering would contaminate the gas within the tube and reduce or eliminate laser operation.



**Figure 5-17** *HeNe laser diagram*

## B. Laser operation

When a voltage is applied between the electrodes, a discharge current develops within the tube with the discharge electrons flowing from the cathode toward the anode. As the discharge current develops, the tube begins to emit light in a similar fashion to that of a neon sign. The light is produced by the electrons flowing within the gas and colliding with both helium and neon atoms, “knocking” them to excited energy levels from which they can radiate light via spontaneous decay. A partial diagram of the electronic energy levels of both neutral neon and neutral helium is shown in Figure 5-18.



**Figure 5-18** Relevant energy levels in helium and neon gases indicating energy-transfer processes

This diagram shows only one of the upper laser energy levels for neon so as not to complicate the description of the excitation process. All the laser transitions in the HeNe laser originate from within the neon atom. The presence of helium serves to provide the excitation or pumping of the neon laser levels in a two-step process. In helium, there are two excited energy levels known as metastable levels, which cannot emit light and thus do not easily decay. They serve as storage reservoirs since energy is collected in these levels. The energies of these metastable levels nearly exactly coincide with some of the excited energy levels of neon. Hence, when the helium metastable levels collide in the discharge with neon atoms in their ground state, the energy from the helium metastables is transferred to the neon atoms, effectively “pumping” them directly into their upper laser-energy levels. This establishes a population inversion in the neon atoms between those levels and lower-lying neon levels, and the necessary gain or amplification process is initiated.

### C. Laser beam development

Some of the neon atoms that radiate from those higher-lying energy levels send light in the direction of the elongated bore of the discharge tube. That light is amplified as it travels down the tube as described by Equation 5-6. The light reaches a mirror and (if the mirror is appropriately aligned) is reflected back through the tube, where it is again amplified. It reaches the mirror at the other end and is again sent back through the tube to be amplified further. This process continues until a strong beam develops after about 500 passes, typically within a time of less than a millionth of a second. At that point the growth of the beam saturates, since only a finite number of atoms residing in the upper laser level can contribute to the population inversion and thus the gain or amplification within the tube. Thus, the laser beam very rapidly reaches an equilibrium situation in which the loss of a portion of the light transmitted through one of the mirrors (the output mirror) balances the energy pumped into the tube through the discharge current according to Equation 5-11 or 5-12. The light emitted from the partially transmitting mirror becomes the useful laser light. The optimum transmission can be determined by the use of Equation 5-13.

When the discharge current is turned off, the laser beam decays in approximately the same time duration as that of the buildup time (when the laser is turned on), or approximately 1  $\mu\text{sec}$ . This is due to the time required for the laser beam to leak out of the output mirror while bouncing back and forth between the mirrors with no amplification available.

### D. Longitudinal frequency modes

The laser-gain bandwidth, the frequency spectrum over which gain occurs at the laser wavelength, is approximately 2 GHz. When the discharge current is initiated and the laser beam begins reflecting back and forth between the mirrors, amplification occurs over this entire frequency width. However, certain longitudinal cavity modes develop that further refine the frequency characteristics of the beam in the form of the development of longitudinal modes. These modes typically consist of several discrete narrow-frequency beams of several to tens of MHz in width (see Figure 5-12) having equally spaced frequencies in the region of the laser wavelength of approximately 250–750 MHz (determined by the laser mirror separation). These separate longitudinal modes all travel in exactly the same direction, with their beam profile determined by the transverse or spatial mode characteristics described in the next paragraph.

### E. Transverse spatial beam modes

The laser spatial or transverse mode characteristics are determined by the amount of gain in the amplifier as well as the size and location of the restricting aperture of the laser cavity. This aperture could be the laser discharge tube itself or a smaller aperture built into the cavity to limit the lateral spatial extent of the laser beam. When the limiting aperture is sufficiently small but still allows the laser beam to develop, the beam is said to be in its lowest-order mode or “single mode.” This is a very pure mode with a Gaussian-shaped beam profile. This very smooth, rounded transverse profile is the beam profile used for very precise beam propagation as well as focusing to a small spot size. When larger apertures are used, the lateral extent of the beam profile is enlarged. The resulting beam size also expands more rapidly to a larger diameter (greater beam divergence) than does the single-mode beam. More total power is available when the laser is operating in this multimode configuration. A laser with a beam consisting of only a

single spatial mode is referred to as a single-mode laser, and that specific mode is designated as a  $TEM_{00}$  mode, using the nomenclature developed for microwave beams.

## F. Laser cavity properties

The amount of power provided by the laser is determined by the length and diameter of the discharge tube as well as the value of the discharge current. As the current is increased, more laser power is available up to a certain maximum current, depending on the discharge-tube bore diameter. Typically, the maximum current is up to a few tens of mA. The laser mirror cavity must be held very rigid to maintain the alignment of the beam within the laser gain region. If misalignment develops, the beam power will be reduced and the quality of the transverse modes will deteriorate. In small HeNe lasers the rigidity of the mirror alignment is maintained by the glass structure of the tube onto which the mirrors are cemented. In longer lasers, an external mechanical cavity is used to keep the mirrors rigid. This cavity often consists of rods made of Invar, a very sturdy metal with very low thermal expansion, that span the length of the laser and attach to the mirror mounts at each end. In longer lasers, Brewster-angle windows are attached to each end of the discharge tube so that the beam will not suffer loss or reduction in power when it passes through those windows. When Brewster-angle windows are used, the beam is automatically polarized in a single transverse direction. Consequently, if a polarizing filter is placed in the laser output beam and rotated, the beam will reach a maximum power in one location and will be reduced to essentially zero power when the filter is rotated ninety degrees with respect to the direction of maximum transmission.

## G. HeNe laser wavelengths

The most often used laser transition in neon is the red-colored laser operating at 632.8 nm. It is the easiest visible HeNe laser wavelength to produce since it has the highest gain. Additional visible wavelengths are the green laser at 543.5 nm, the yellow laser at 594 nm, and the orange laser at 612 nm. In the near infrared there are several laser transitions in the 1.15- $\mu$ m region and one at 1.523  $\mu$ m, and a strong transition at 3.39  $\mu$ m.

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# Laboratory

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This laboratory is designed to demonstrate several different aspects of the operation of a laser.

## Experiments to be carried out

- Alignment of laser mirror cavity
- Laser beam sensitivity to mirror alignment
- Operation of the laser at 632.8 nm with several different laser mirror configurations
- Single-mode and multimode (transverse or spatial mode) operation



## LASERS

- Operation of the laser in the green at 543.5 nm
- Variation of laser power with discharge current

### Equipment List

HeNe laser discharge tube with Brewster windows

Power supply with variable current capability to operate discharge tube

Stable optical rail or optical bench upon which to mount laser and related optical components

Mirror mounts with interchangeable mirror capability

Separate HeNe laser for alignment

Adjustable aperture to be placed on axis within the laser optical cavity

Rotating beam polarizer

Laser power meter

The following sets of laser mirrors with diameters of 0.5–1.0 inch:

- 2 high-reflecting laser mirrors at 632.8 nm with 1-m radius of curvature
- 1 99%-reflecting laser mirror with 1-m radius of curvature
- 1 99%-reflecting laser mirror at 632.8 nm with infinite radius of curvature (flat)
- 2 high-reflecting laser mirrors at 543.5 nm with 1-m radius of curvature

### Procedure

1. Set up alignment laser on optical rail or optical bench and turn the laser on.
2. Place HeNe laser tube on optical rail and adjust the tube to be collinear and concentric with the beam of the alignment laser.
3. Attach high-voltage connections of power supply to laser electrodes. DO NOT TURN ON AT THIS TIME!
4. Place mirror mounts at each end of laser tube with mirror centers concentric with laser tube.
5. Place aperture at one end of laser tube between tube and mirror and adjust so that aperture is concentric with laser tube.
6. Install a high-reflecting 632.8-nm, 1-m radius-of-curvature laser mirror in the mirror mount farthest from the alignment laser and adjust the reflected spot to be centered with the alignment laser output beam.
7. Install the other high-reflecting mirror at the end of the laser cavity nearer the alignment laser and adjust until reflected spot is centered with alignment laser beam.
8. Turn laser power supply ON and initiate starter pulse from power supply (laser discharge should be visible at this time).

9. Observe laser mirrors and Brewster-angle windows to see if laser beam has developed. If laser beam is apparent, install power meter at one end of laser, beyond the laser mirror, to detect output beam.
10. Adjust both the horizontal and vertical position adjusters of both laser mirror mounts while observing laser power meter, to maximize laser power output by optimizing laser mirror alignment.
11. Remove mirror from laser mirror mount located closer to the alignment laser.
12. Install 99%-reflecting 1-m radius-of-curvature 632.8-nm mirror in the laser mirror mount and adjust the reflected spot from the alignment laser to be centered on the alignment laser beam. When the reflected spot is centered, a strong beam should become apparent emerging from the 99%-mirror end of the test laser. Install the laser power meter in front of the beam and optimize the mirror alignment by observing the laser power meter.
13. When mirror alignment is optimized, place a turning mirror in front of the beam to project the beam onto a screen approximately 2 or more meters from the laser mirror, to observe the quality of the beam. While observing the beam projected on the screen, reduce the diameter of the aperture within the laser cavity until the laser beam is no longer apparent. Then slowly increase the aperture diameter until the beam just begins to appear. Note the quality of the laser spot projected upon the screen. This is the single transverse laser mode known as the  $TEM_{00}$  laser mode. It is the highest-quality laser mode available in terms of focusing and propagation capabilities.
14. Slowly increase the aperture and see the beam enlarge on the screen. This shows the development of higher-order transverse laser modes. Commercial lasers with this cavity arrangement are known as multimode lasers.
15. Remove the 99% 1-m radius-of-curvature output mirror and replace it with the flat 99%-reflecting output mirror. Adjust the alignment until the laser beam appears. Note how much smaller the output beam diameter has now become. This is the semi-confocal cavity arrangement for many small commercial lasers to give a high-quality, small-diameter beam.
16. Remove the laser mirrors and install and align the 543.5-nm mirrors as was done in (6), (7), and (9) above. Observe the green laser beam within the laser cavity. Adjust the power on the meter to produce maximum power output.
17. Reinstall the mirrors of (6) and (12) above and adjust mirrors for maximum laser output.
18. Install polarizer in front of laser output beam with power meter located beyond polarizer. Rotate polarizer and graph the power output as a function of polarizer angle, rotating the polarizer through a full 360-degree rotation. Note the two maxima and two minima. Compare the maxima and minima with the orientation of the Brewster-angle windows.

## Problem Exercises

1. You are provided with a 10-cm-long Nd:YAG laser rod to be used as a laser amplifier, with no mirrors attached at the ends of the rod. The rod is to be flashlamp-pumped in order to produce gain. You transmit a separate beam from another Nd:YAG laser through the amplifier rod and measure the emerging beam to increase by a factor of 10 from when it entered the rod. Calculate the value of  $g$  for the amplifier rod for such a situation, using Equation 5-9. If the rod is then placed within a mirror cavity and operated as a laser with the beam bouncing back and forth through the laser rod, determine how many passes the beam will have to make to reach the saturation intensity. (Hint: Remember that  $gL_T = 12$ . Hence, if we let  $L_T = ML$  where  $M$  is the number of passes and  $L$  is the length of the gain medium, we can solve for  $M$ .)
2. Estimate the beam waist of a laser at a distance of 25 cm from the output mirror. This is a HeNe laser operating at 632.8 nm with a flat mirror at the output end and a curved mirror of radius 50 cm at the other end. Separation between the two mirrors is 25 cm. How would this compare to the beam waist at the location of the curved laser mirror?
3. Murray positions a ruby laser rod halfway between two identical mirrors of 100-cm radius of curvature with a mirror separation of 20 cm. The laser is operated at 694.3-nm wavelength. It has a restrictive aperture that forces it to operate in a single transverse TEM<sub>00</sub> Gaussian mode. Murray aims the beam toward a satellite installed in a geosynchronous orbit 20,000 miles above the earth. Calculate the diameter of the beam when it reaches the satellite.
4. Lin adjusts a mode-locked titanium sapphire laser to produce very short mode-locked pulses. She measures the pulses to have a duration of 100 fsec. A distance of 200 cm separates the cavity end mirrors. From this information, determine the spacing in frequency between the longitudinal modes and estimate how many modes must be lasing to produce the 100-fsec pulses. Also determine the spacing in time between successive pulses.
5. The single-pass gain of an argon ion laser is 100% per pass such that the beam will double in intensity after passing once through the amplifier. The single-pass losses, not including the mirror-transmission losses but including scattering losses, are 0.2% per pass. If one mirror is a highly reflecting mirror and the other is used for an output mirror, determine the optimum reflectivity of the output mirror for coupling out the maximum power.
6. With the information obtained in Exercise 5, estimate the output intensity of the argon laser when using the optimum-output mirror determined above.
7. Wai-Min measures a 632.8-nm HeNe laser to have a spot diameter of 1 mm as it emerges from the laser. When the beam is propagated a certain distance away, he notices that it has expanded to a size of 1-cm diameter. He is interested in generating a hologram. Using Wai-Min's information, calculate the maximum distance the beam can propagate and still have a coherent interaction. (Hint: The outer edges of the beam, separated by the 1-cm diameter, are the portions of the beam farthest from each other. They are thus the most susceptible to becoming out of phase with each other.)
8. Eric carries out an investigation to use a pulsed ArF excimer laser operating at 193 nm for drilling 500-nm-diameter holes in ultrathin steel plates. He sets the laser up to operate in

the TEM<sub>00</sub> mode to obtain the best focus and realizes that he must order a lens for this purpose. Eric's laser beam has a transverse diameter of 2 cm, and he wants to obtain a 500-nm beam-spot size. What is the focal length of the lens that Eric needs?

9. Maria sets up a HeCd laser (operating at 441.6 nm) with two identical mirrors of 99% reflectivity and 2-m radii of curvature. What threshold gain coefficient would Maria have to achieve in the electrical discharge mixture of helium and cadmium vapor for a gain length of 30 cm? For this calculation, assume that the window losses and other scattering losses are negligible.
10. Brian sets up a laser mirror cavity to operate a carbon dioxide laser at a wavelength of 10.6  $\mu\text{m}$ . He uses two identical mirrors of 2.0-m radius of curvature. Brian is restricted to placing the mirrors 1.0 m apart and to having the mirror curvatures exactly match the beam curvature in the cavity. Determine the minimum beam waist  $w_0$  produced with this arrangement.

## Student Project

Locate a flashlight and two different types of lasers, preferably a helium-neon laser and a laser pointer (a semiconductor diode laser), each of which is designed to be eye-safe. Install the three light sources in a rigid mount and project them into a relatively long room or hallway to measure the beam divergence. Measure the beam size and compute the angular divergence  $\Delta\Omega$  in *steradians* for all three according to Equation 5-1. The helium-neon laser will most likely be operating in the TEM<sub>00</sub> mode and will thus have the smallest beam divergence. Also calculate the half-width angular divergence in *radians* by dividing the beam radius by the distance from the laser to where the spot size is measured. Knowing this angular divergence and wavelength, calculate the minimum beam waist of the HeNe laser from Equation 5-19.

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