Basic Laser Principles

Lasers are devices that produce intense beams of light which are *monochromatic*, *coherent*, and *highly collimated*. The wavelength (color) of laser light is extremely pure (monochromatic) when compared to other sources of light, and all of the photons (energy) that make up the laser beam have a fixed phase relationship (coherence) with respect to one another. Light from a laser typically has very low divergence. It can travel over great distances or can be focused to a very small spot with a brightness which exceeds that of the sun. Because of these properties, lasers are used in a wide variety of applications in all walks of life.

The basic operating principles of the laser were put forth by Charles Townes and Arthur Schalow from the Bell Telephone Laboratories in 1958, and the first actual laser, based on a pink ruby crystal, was demonstrated in 1960 by Theodor Maiman at Hughes Research Laboratories. Since that time, literally thousands of lasers have been invented (including the edible "Jello" laser), but only a much smaller number have found practical applications in scientific, industrial, commercial, and military applications. The helium neon laser (the first continuous-wave laser), the semiconductor diode laser, and air-cooled ion lasers have found broad OEM application. In recent years the use of diode-pumped solid-state (DPSS) lasers in OEM applications has been growing rapidly.

The term "laser" is an acronym for (L)ight (A)mplification by (S)timulated (E)mission of (R)adiation. To understand the laser, one needs to understand the meaning of these terms. The term "light" is generally accepted to be electromagnetic radiation ranging from 1 nm to 1000 μm in wavelength. The visible spectrum (what we see) ranges from approximately 400 to 700 nm. The wavelength range from 700 nm to 10 μm is considered the near infrared (NIR), and anything beyond that is the far infrared (FIR). Conversely, 200 to 400 nm is called ultraviolet (UV); below 200 nm is the deep ultraviolet (DUV).

To understand stimulated emission, we start with the Bohr atom.

THE BOHR ATOM

In 1915, Neils Bohr proposed a model of the atom that explained a wide variety of phenomena that were puzzling scientists in the late 19th century. This simple model became the basis for the field of quantum mechanics and, although not fully accurate by today's understanding, still is useful for demonstrating laser principles.

In Bohr's model, shown in figure 36.1, electrons orbit the nucleus of an atom. Unlike earlier "planetary" models, the Bohr atom has a limited number of fixed orbits that are available to the electrons. Under the right circumstances an electron can go from its ground state (lowest-energy orbit) to a higher (excited) state, or it can decay from a higher state to a lower state, but it cannot remain between these states. The allowed energy states are called "quantum" states and are referred to by the principal "quantum numbers" 1, 2, 3, etc. The quantum states are represented by an energy-level diagram.

For an electron to jump to a higher quantum state, the atom must receive energy from the outside world. This can happen through a variety of mechanisms such as inelastic or semielastic collisions with other atoms and absorption of energy in the form of electromagnetic radiation (e.g., light). Likewise, when an electron drops from a higher state to a lower state, the atom must give off energy, either as kinetic activity (nonradiative transitions) or as electromagnetic radiation (radiative transitions). For the remainder of this discussion we will consider only radiative transitions.

PHOTONS AND ENERGY

In the 1600s and 1700s, early in the modern study of light, there was a great controversy about light's nature. Some thought that light was made up of particles, while others thought that it was made up of waves. Both concepts explained some of the behavior of light, but not all. It was finally determined that light is made up of particles called "photons" which exhibit both particle-like and wave-like properties. Each photon has an intrinsic energy determined by the equation

$$E = h\nu \tag{36.1}$$

where ν is the frequency of the light and h is Planck's constant. Since, for a wave, the frequency and wavelength are related by the equation

$$\lambda\nu = c \tag{36.2}$$

where λ is the wavelength of the light and c is the speed of light in a vacuum, equation 36.1 can be rewritten as

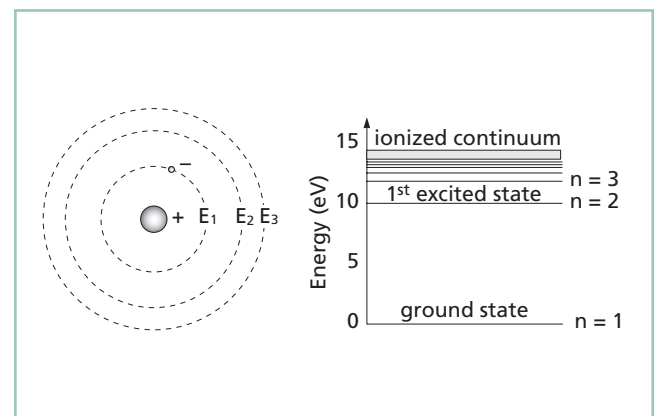$$E = \frac{hc}{\lambda}. \tag{36.3}$$

Figure 36.1   **The Bohr atom and a simple energy-level diagram**

It is evident from this equation that the longer the wavelength of the light, the lower the energy of the photon; consequently, ultraviolet light is much more "energetic" than infrared light.

Returning to the Bohr atom: for an atom to absorb light (i.e., for the light energy to cause an electron to move from a lower energy state E_n to a higher energy state E_m), the energy of a single photon must equal, almost exactly, the energy difference between the two states. Too much energy or too little energy and the photon will not be absorbed. Consequently, the wavelength of that photon must be

$$\lambda = \frac{hc}{\Delta E}$$

where   (36.4)

$$\Delta E = E_m - E_n.$$

Likewise, when an electron decays to a lower energy level in a radiative transition, the photon of light given off by the atom must also have an energy equal to the energy difference between the two states.

SPONTANEOUS AND STIMULATED EMISSION

In general, when an electron is in an excited energy state, it must eventually decay to a lower level, giving off a photon of radiation. This event is called "spontaneous emission," and the photon is emitted in a random direction and a random phase. The average time it takes for the electron to decay is called the time constant for spontaneous emission, and is represented by τ.

On the other hand, if an electron is in energy state E_2, and its decay path is to E_1, but, before it has a chance to spontaneously decay, a photon happens to pass by whose energy is approximately $E_2 - E_1$, there is a probability that the passing photon will cause the electron to decay in such a manner that a photon is emitted at exactly the same wavelength, in exactly the same direction, and with exactly the same phase as the passing photon. This process is called "stimulated emission." Absorption, spontaneous emission, and stimulated emission are illustrated in figure 36.2.

Now consider the group of atoms shown in figure 36.3: all begin in exactly the same excited state, and most are effectively within the stimulation range of a passing photon. We also will assume that τ is very long, and that the probability for stimulated emission is 100 percent. The incoming (stimulating) photon interacts with the first atom, causing stimulated emission of a coherent photon; these two photons then interact with the next two atoms in line, and the result is four coherent photons, on down the line. At the end of the process, we will have eleven coherent photons, all with identical phases and all traveling in the same direction. In other words, the initial photon has been "amplified" by a factor of eleven. Note that the energy to put these atoms in excited states is provided externally by some energy source which is usually referred to as the "pump" source.
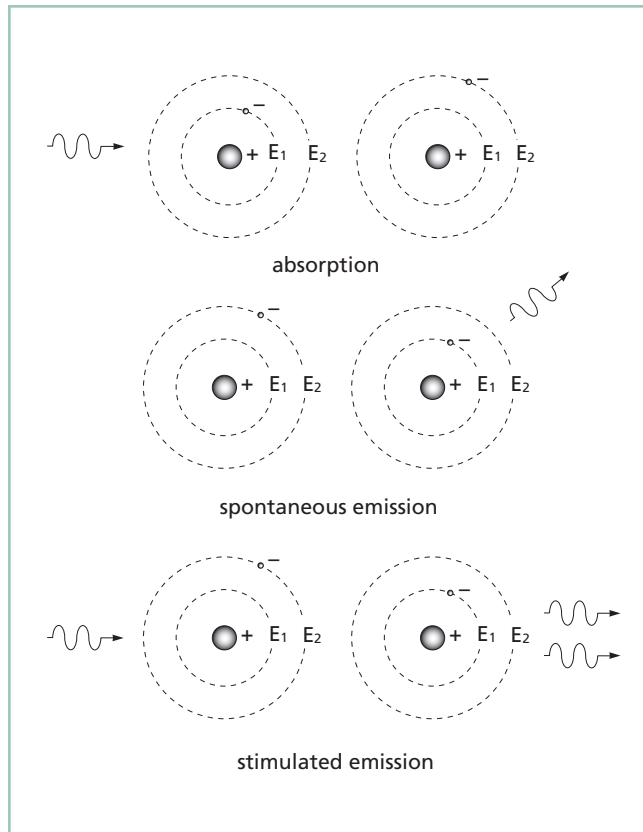
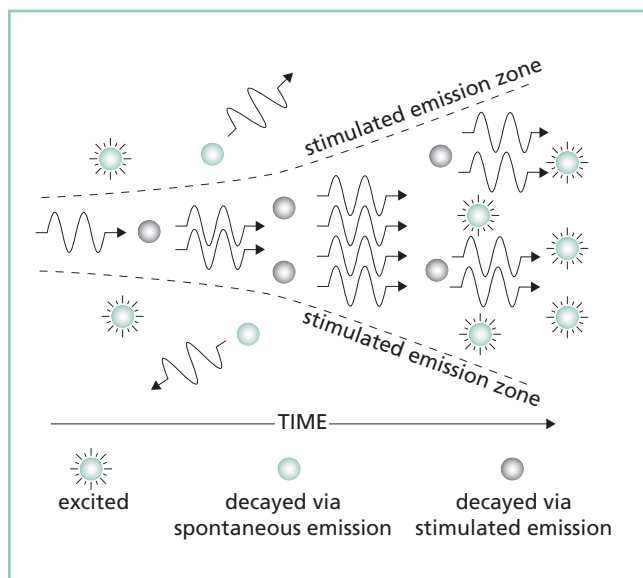Figure 36.2   **Spontaneous and stimulated emission**

Figure 36.3   **Amplification by stimulated emission**

Of course, in any real population of atoms, the probability for stimulated emission is quite small. Furthermore, not all of the atoms are usually in an excited state; in fact, the opposite is true. Boltzmann's principle, a fundamental law of thermodynamics, states that, when a collection of atoms is at thermal equilibrium, the relative population of any two energy levels is given by

$$\frac{N_2}{N_1} = \exp\left(-\frac{E_2 - E_1}{kT}\right) \qquad (36.5)$$

where N_2 and N_1 are the populations of the upper and lower energy states, respectively, T is the equilibrium temperature, and k is Boltzmann's constant. Substituting $h\nu$ for $E_2 - E_1$ yields

$$\Delta N \equiv N_1 - N_2 = \left(1 - e^{-h\nu/kT}\right)N_1. \qquad (36.6)$$

For a normal population of atoms, there will always be more atoms in the lower energy levels than in the upper ones. Since the probability for an individual atom to absorb a photon is the same as the probability for an excited atom to emit a photon via stimulated emission, the collection of real atoms will be a net absorber, not a net emitter, and amplification will not be possible. Consequently, to make a laser, we have to create a "population inversion."

POPULATION INVERSION

Atomic energy states are much more complex than indicated by the description above. There are many more energy levels, and each one has its own time constants for decay. The four-level energy diagram shown in figure 36.4 is representative of some real lasers.

The electron is pumped (excited) into an upper level E_4 by some mechanism (for example, a collision with another atom or absorption of high-energy radiation). It then decays to E_3, then to E_2, and finally to the ground state E_1. Let us assume that the time it takes to decay from E_2 to E_1 is much longer than the time it takes to decay from E_2 to E_1. In a large population of such atoms, at equilibrium and with a continuous pumping process, a population inversion will occur between the E_3 and E_2 energy states, and a photon entering the population will be amplified coherently.

THE RESONATOR

Although with a population inversion we have the ability to amplify a signal via stimulated emission, the overall single-pass gain is quite small, and most of the excited atoms in the population emit spontaneously and do not contribute to the overall output. To turn this system into a laser, we need a positive feedback mechanism that will cause the majority of the atoms in the population to contribute to the coherent output. This is the resonator, a system of mirrors that reflects undesirable (off-axis) photons out of the system and reflects the desirable (on-axis) photons back into the excited population where they can continue to be amplified.
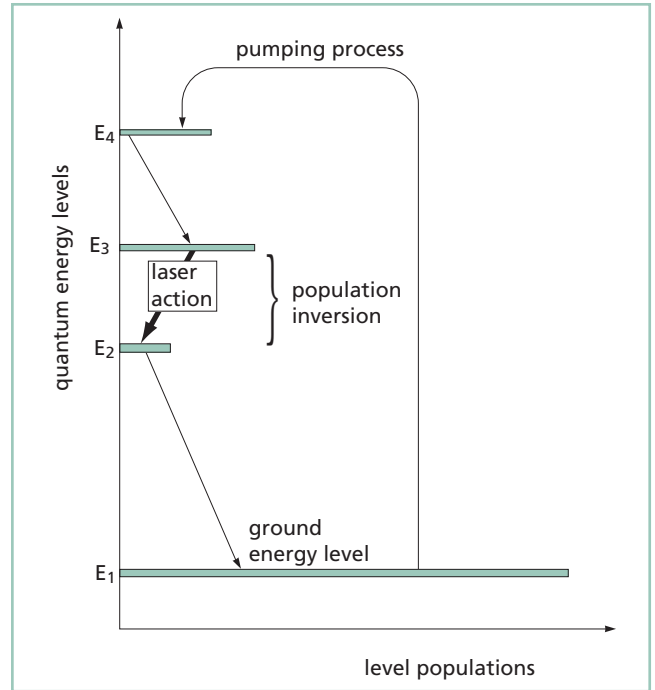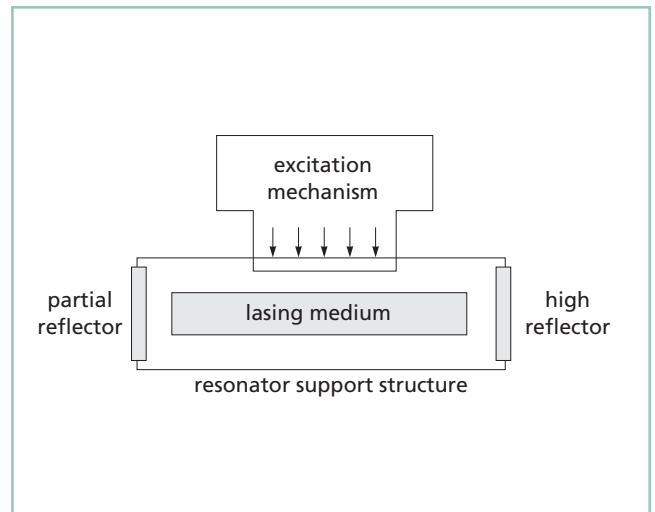

Figure 36.4 **A four-level laser pumping system**

Figure 36.5 **Schematic diagram of a basic laser**

Now consider the laser system shown in figure 36.5. The lasing medium is pumped continuously to create a population inversion at the lasing wavelength. As the excited atoms start to decay, they emit photons spontaneously in all directions. Some of the photons travel along the axis of the lasing medium, but most of the photons are directed out the sides. The photons traveling along the axis

have an opportunity to stimulate atoms they encounter to emit photons, but the ones radiating out the sides do not. Furthermore, the photons traveling parallel to the axis will be reflected back into the lasing medium and given the opportunity to stimulate more excited atoms. As the on-axis photons are reflected back and forth interacting with more and more atoms, spontaneous emission decreases, stimulated emission along the axis predominates, and we have a laser.

Finally, to get the light out of the system, one of the mirrors is has a partially transmitting coating that couples out a small percentage of the circulating photons. The amount of coupling depends on the characteristics of the laser system and varies from a fraction of a percent for helium neon lasers to 50 percent or more for high-power lasers.

Practical Optical Coatings

In the design of a real-world laser, the optical resonator is often the most critical component, and, particularly for low-gain lasers, the most critical components of the resonator are the mirrors themselves. The difference between a perfect mirror coating (the optimum transmission and reflection with no scatter or absorption losses) and a real-world coating, capable of being produced in volume, can mean a 50-percent (or greater) drop in output power from the theoretical maximum. Consider the 543-nm green helium neon laser line. It was first observed in the laboratory in 1970, but, owing to its extremely low gain, the mirror fabrication and coating technology of the day was incapable of producing a sufficiently loss-free mirror that was also durable. Not until the late 1990s had the mirror coating technology improved sufficiently that these lasers could be offered commercially in large volumes.

The critical factors for a mirror, other than transmission and reflection, are scatter, absorption, stress, surface figure, and damage resistance. Coatings with low damage thresholds can degrade over time and cause output power to drop significantly. Coatings with too much mechanical stress not only can cause significant power loss, but can also induce stress birefringence, which can result in altered polarization and phase relationships. The optical designer must take great care when selecting the materials for the coating layers and the substrate to ensure that the mechanical, optical, and environmental characteristics are suitable for the application.

The equipment used for both substrate polishing and optical coating is a critical factor in the end result. Coating scatter is a major contributor to power loss. Scatter arises primarily from imperfections and inclusions in the coating, but also from minute imperfections in the substrate. Over the last few years, the availability of "super-polished" mirror substrates has led to significant gains in laser performance. Likewise, ion-beam sputtering and next-generation ion-assisted ion deposition has increased the packing density of laser coatings, thereby reducing absorption, increasing damage thresholds, and enabling the use of new and exotic coating materials.