LASER

An atomic system is characterized by discrete energy states, and usually the atoms exist in the lowest energy state, which is normally referred to as the ground state. An atom in a lower energy state may be excited to a higher energy state through a variety of processes. One of the important processes of excitation is through collisions with other particles. The excitation can also occur through the absorption of electromagnetic radiation of proper frequencies; such a process is known as stimulated absorption or simply as absorption. On the other hand, when the atom is in the excited state, it can make a transition to a lower energy state through the emission of electromagnetic radiation; however, in contrast to the absorption process, the emission process can occur in two different ways.

(i) The first is referred to as spontaneous emission in which an atom in the excited state emits radiation even in the absence of any incident radiation. It is thus not stimulated by any incident signal but occurs spontaneously. Further, the rate of spontaneous emissions is proportional to the number of atoms in the excited state.

(ii) The second is referred to as stimulated emission, in which an incident signal of appropriate frequency triggers an atom in an excited state to emit radiation. The rate of stimulated emission (or absorption) depends both on the intensity of the external field and also on the number of atoms in the upper state. The net stimulated transition rate (stimulated absorption and stimulated emission) depends on the difference in the number of atoms in the excited and the lower states, unlike the case of spontaneous emission, which depends only on the population of the excited state.

The three main components of any laser device are the active medium, the pumping source, and the optical resonator. The active medium consists of a collection of atoms, molecules, or ions (in solid, liquid, or gaseous form), which acts as an amplifier for light waves. For amplification, the medium has to be kept in a state of population inversion, i.e., in a state in which the number of atoms in the upper energy level is greater than the number of atoms in the lower energy level. The pumping mechanism provides for obtaining such a state of population inversion between a pair of energy levels of the atomic system. When the active medium is placed inside an optical resonator, the system acts as an oscillator.

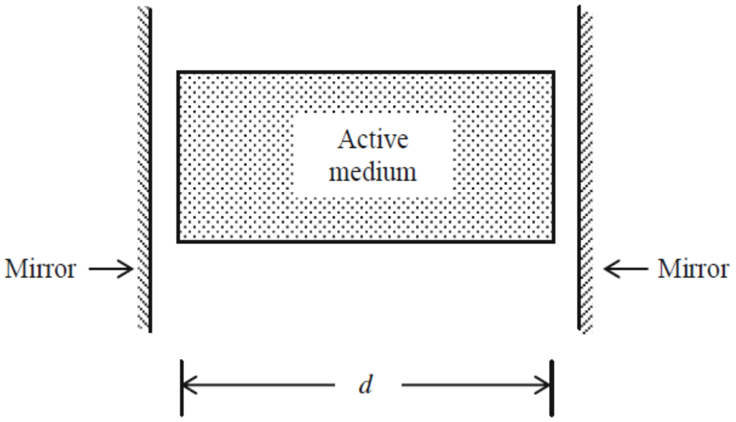
Einstein regarding the presence of both spontaneous and stimulated emissions and obtain expressions for the rate of absorption and emission using a semiclassical theory. We also consider the interaction of an atom with electromagnetic radiation over a band of frequencies and obtain the gain (or loss) coefficient as the beam propagates through the active medium.

Under normal circumstances, there is always a larger number of atoms in the lower energy state as compared to the excited energy state, and an electromagnetic wave passing through such a collection of atoms would get attenuated rather than amplified. Thus, in order to have amplification, one must have population inversion.

We will discuss the two-level, three-level, and four-level systems and obtain conditions to achieve population inversion between two states of the system. It is shown that it is not possible to achieve steady-state population inversion in a two-level system. Also in order to obtain a population inversion, the transition rates of the various levels in three-level or four-level systems must satisfy certain conditions. We also obtain the pumping powers required for obtaining population inversion in three- and four-level systems and show that it is in general much easier to obtain inversion in a four-level system as compared to a three-level system.

A medium with population inversion is capable of amplification, but if the medium is to act as an oscillator, a part of the output energy must be fed back into the system.[2] Such a feedback is brought about by placing the active medium between a pair of mirrors facing each other (see Fig. 1.1); the pair of mirrors forms what is referred to as an optical resonator.

Fig. 1.1 A plane parallel resonator consisting of a pair of plane mirrors facing each other. The active medium is placed inside the cavity. One of the mirrors is made partially transmitting to couple out the laser beam



The light emitted by ordinary sources of light, like the incandescent lamp, is spread over all directions and is usually over a large range of wavelengths. In contrast, the light from a laser could be highly monochromatic and highly directional. Because of the presence of the optical cavity, only certain frequencies can oscillate in the cavity. In addition, when the laser is oscillating in steady state the losses are exactly compensated by the gain provided by the medium and the wave coming out of the laser can be represented as a nearly continuous wave. The ultimate monochromaticity is determined by the spontaneous emissions occurring inside the cavity because the radiation coming out of the spontaneous emissions is incoherent.

Lasers can provide us with sources having extreme properties in terms of energy, pulse width, wavelength, etc., and thus help in research in understanding the basic concept of space and matter. Research and development continues unabated to develop lasers with shorter wavelengths, shorter pulses, higher energies etc.

Linac Coherent Light Source is the world's first hard X-ray free-electron laser, located at the SLAC National Accelerator Laboratory in California. Recently the laser produced its first hard X-ray laser pulses of unprecedented energy and ultrashort duration with wavelengths shorter than the size of molecules. Such lasers are expected to enable frontier research into studies on chemical processes and to perhaps understanding ultimately the processes leading to life.

Attosecond (as) is a duration lasting 10^{-18} s, a thousand times shorter than a femtosecond and a million times shorter than a nanosecond. In fact the orbital period of an electron in the ground state of the hydrogen atom is just 152 as. The shortest laser pulses that have been produced are only 80 as long. Attosecond science is still in its infancy and with further development attosecond science should help us understand various molecular processes, electron transition between energy levels, etc.

The world's most powerful laser was recently unveiled in the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in California. The NIF has 192 separate laser beams all converging simultaneously on a single target, the size of a pencil eraser. The laser delivers 1.1 MJ of energy into the target; such a high concentration of energy can generate temperatures of more than 100 million degrees and pressures more than 100 billion times earth's atmospheric pressure. These conditions are similar to those in the stars and the cores of giant planets.

The extreme laser infrastructure being designed and realized in France is expected to generate peak powers of more than a petawatt (10^{15} W) with pulse widths lasting a few tens of attoseconds. The expectations are to be able to generate exawatt (10^{18}) lasers. This is expected to make it possible to study phenomena occurring near black holes, to change the refractive index of vacuum, etc. (Gerstner 2007).

Einstein Coefficients and Light Amplification

4.1 Introduction

In this chapter we discuss interaction of radiation and atoms and obtain the relationship between absorption and emission processes. We show that for light amplification a state of population inversion should be created in the atomic system. We also obtain an expression for the gain coefficient of the system. This is followed by a discussion of two-level, three-level, and four-level systems using the rate equation approach. Finally a discussion of various mechanisms leading to broadening of spectral lines is discussed.

4.2 The Einstein Coefficients

We consider two levels of an atomic system as shown in Fig. 4.1 and let N_1 and N_2 be the number of atoms per unit volume present in the energy levels E_1 and E_2, respectively. The atomic system can interact with electromagnetic radiation in three distinct ways:

(a) An atom in the lower energy level E_1 can absorb the incident radiation at a frequency $\omega = (E_2 - E_1)/\hbar$ and be excited to E_2; this excitation process requires the presence of radiation. The rate at which absorption takes place from level 1 to level 2 will be proportional to the number of atoms present in the level E_1 and also to the energy density of the radiation at the frequency $\omega = (E_2 - E_1)/\hbar$. Thus if $u(\omega)\mathrm{d}\omega$ represents the radiation energy per unit volume between ω and $\omega + \mathrm{d}\omega$ then we may write the number of atoms undergoing absorptions per unit time per unit volume from level 1 to level 2 as

$$\Gamma_{12} = B_{12} u(\omega) N_1 \tag{4.1}$$

where B_{12} *is a constant of proportionality and depends on the energy levels* E_1 and E_2. Notice here that $u(\omega)$ has the units of energy density per frequency interval.

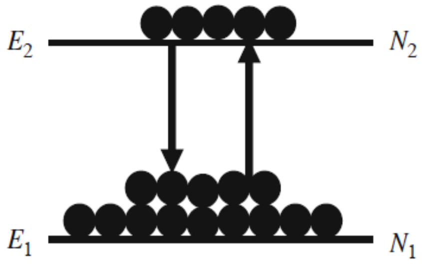


Fig. 4.1 Two states of an atom with energies E_1 and E_2 with corresponding population densities of N_1 and N_2, respectively

(b) For the reverse process, namely the deexcitation of the atom from E_2 to E_1, Einstein postulated that an atom can make a transition from E_2 to E_1 through two distinct processes, namely *stimulated emission* and *spontaneous emission*. In the case of stimulated emission, the radiation which is incident on the atom stimulates it to emit radiation and the rate of transition to the lower energy level is proportional to the energy density of radiation at the frequency ω. Thus, the number of stimulated emissions per unit time per unit volume will be

$$\Gamma_{21} = B_{21} u(\omega) N_2 \tag{4.2}$$

where B_{21} is the coefficient of proportionality and depends on the energy levels.

(c) An atom which is in the upper energy level E_2 can also make a spontaneous emission; this rate will be proportional to N_2 only and thus we have for the number atoms making spontaneous emissions per unit time per unit volume

$$U_{21} = A_{21} N_2 \tag{4.3}$$

At thermal equilibrium between the atomic system and the radiation field, the number of upward transitions must be equal to the number of downward transitions. Hence, at thermal equilibrium

$$N_1 B_{12} u(\omega) = N_2 A_{21} + N_2 B_{21} u(\omega)$$

or

$$u(\omega) = \frac{A_{21}}{(N_1/N_2) B_{12} - B_{21}} \tag{4.4}$$

Using Boltzmann's law, the ratio of the equilibrium populations of levels 1 and 2 at temperature T is

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/k_B T} = e^{\hbar\omega/k_B T} \tag{4.5}$$

where $k_{\mathrm{B}}(= 1.38 \times 10^{-23}\,\mathrm{J/K})$ is the Boltzmann's constant. Hence

$$u(\omega) = \frac{A_{21}}{B_{12} e^{\hbar\omega/k_{\mathrm{B}} T} - B_{21}} \tag{4.6}$$

Now according to Planck's law, the radiation energy density per unit frequency interval is given by (see Appendix F)

$$u(\omega) = \frac{\hbar\omega^3 n_0^3}{\pi^2 c^3} \frac{1}{e^{\hbar\omega/k_{\mathrm{B}} T} - 1} \tag{4.7}$$

where c is the velocity of light in free space and n_0 is the refractive index of the medium.

Comparing Eqs. (4.6) and (4.7), we obtain

$$B_{12} = B_{21} = B \tag{4.8}$$

and

$$\frac{A_{21}}{B_{21}} = \frac{\hbar\omega^3 n_0^3}{\pi^2 c^3} \tag{4.9}$$

Thus the stimulated emission rate per atom is the same as the absorption rate per atom and the ratio of spontaneous to stimulated emission coefficients is given by Eq. (4.9). The coefficients A and B are referred to as the Einstein A and B coefficients.

At thermal equilibrium, the ratio of the number of spontaneous to stimulated emissions is given by

$$R = \frac{A_{21} N_2}{B_{21} N_2 u(\omega)} = e^{\hbar\omega/k_{\mathrm{B}} T} - 1 \tag{4.10}$$

Thus at thermal equilibrium at a temperature T, for frequencies, $\omega >> k_{\mathrm{B}} T/\hbar$, the number of spontaneous emissions far exceeds the number of stimulated emissions.