5. Introduction

The basic principle involved in lasing action is the phenomenon of ***stimulated emission*** which was predicted by Einstein in 1917. Einstein argued that when an 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 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 radiation but occurs spontaneously. Further, the rate of spontaneous emission 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 depends both on the energy density of the incident radiation and also on the number of atoms in the excited state.

The description of thermodynamic equilibrium between atoms and the incident radiation led Einstein to the prediction of stimulated emission. He showed that both spontaneous and stimulated emissions are necessary to obtain Planck's radiation law.

5.1 Einstein Coefficients

Consider an atom having two states (as in Figure 5.1). Let N_1 and N_2 be the number of atoms (per unit volume) in states 1 and 2, respectively; the levels correspond to energies E_1 and E_2.

An atom in the lower energy level can absorb radiation and get excited to the level E_2. This excitation process can occur only in the presence of radiation. Such a process is called *absorption* (or ***stimulated absorption***). The rate of absorption depends on the density of radiation at the particular frequency ν corresponding to the energy separation of the two levels.

$$h\nu = E_1 - E_2$$

The absorption process depends on the energy density of radiation $u(\nu)d\nu$ at the frequency ν. The energy density is defined as the radiation energy per unit volume within the frequency interval ν and $\nu + d\nu$. The *rate of stimulated absorption* is proportional to N_1 and also to $u(\nu)$ (Figure 5.2). Thus, the number of absorption per unit time per unit volume can be written as

$$B_{12}N_1u(\nu)$$

where B_{12} is the coefficient of proportionality and is a characteristics of the energy level.

In spontaneous emission, the rate of downward transition is independent of the energy density of the radiation and depends only on the number of atoms in the higher energy level N_2 (Figure 5.3). If A_{21} represents the coefficient of proportionality, then

$$A_{21}N_2$$

would represent the *rate of spontaneous emissions* (per unit volume) to the lower energy level.

In stimulated emission, the rate of transition to the lower energy level is directly proportional to the number of atoms in the upper energy level as well as to the energy density of the radiation at the frequency ν (Figure 5.4). Thus, the *rate of stimulated emissions* would be given by

$$B_{21}N_2u(\nu)$$

with B_{21} representing the corresponding proportionality constant. The quantities A_{21}, B_{12} and B_{21} are known as known s **Einstein coefficients** and are determined by the atomic system.

At thermal equilibrium, the number of upward transitions must be equal to the number of downward transitions. Hence, the absorption and emission rates must be equal

$$B_{12}N_1u(\nu) = A_{21}N_2 + B_{21}N_2u(\nu)$$

$$u(\nu) = \frac{A_{21}}{\frac{N_1}{N_2}B_{12} - B_{21}}$$

From Maxwell Boltzmann distribution law, the population of two energy level at temperature T,

$$\frac{N_1}{N_2} = \exp\left[\frac{E_2 - E_1}{k_BT}\right] = \exp\left[\frac{h\nu}{k_BT}\right]$$

where k_B represents the Boltzmann constant. Thus,

$$u(\nu) = \frac{A_{21}}{B_{12}\exp\left[\frac{h\nu}{k_BT}\right] - B_{21}}$$

According to Planck's radiation law, the energy density of radiation is given by

$$u(\nu) = \frac{8\pi h}{c^3}\frac{\nu^3}{\exp\left[\frac{h\nu}{k_BT}\right] - 1}$$

Comparing both the equations, we obtain

$$B_{12} = B_{21} = B$$

$$\frac{A_{21}}{B} = \frac{A}{B} = \frac{8\pi h}{c^3}\nu^3$$

Notice that if presence of stimulated emission would not have been considered, we would not be able to arrive at an expression for energy density $u(\nu)$ which is similar to Planck's radiation law.

Equations written above give the relation between the *A* and *B* coefficients and are known as the ***Einstein relations***.

The first relation shows that the coefficients for both absorption and stimulated emission are numerically equal. The equality implies that the probability for an upward (absorption) transition is equal to the probability for a downward (stimulated emission) transition.

The second relation shows that the ratio of coefficients of spontaneous versus stimulated emission stimulated emission is proportional to the third power of frequency of the radiation. This is why it is difficult to achieve laser action in higher frequency ranges such as X-rays.

$$\frac{A}{Bu(\nu)} = \exp\left[\frac{h\nu}{k_BT}\right] - 1$$

Hence, at thermal equilibrium (at temperature T), for $\nu \ll k_B T/h$, the number of stimulated emissions far exceeds the number of spontaneous emissions while for $\nu \gg k_B T/h$, the nuber of spontaneous emission far exceed the number of stimulated emissions.

For normal optical sources $T \sim 10^3$K and $k_B T/h \sim 10^{13}$Hz. Since for the optical region $\nu \sim 10^{14}$Hz, we find that at optical frequencies the emission is predominantly due to the spontaneous transitions and hence the emission from usual light sources are incoherent.

5.2 Conditions for Laser Action

The name Laser is an acronym of light amplification by stimulated emission of radiation. A Laser is a device that produces an intense, concentrated and highly parallel beam of coherent light.

Consider a gas enclosed in a vessel containing free atoms having a number of energy levels, at least one of which is ***metastable***. By shinning white light into this gas many atoms can be raised, through *resonance*, from the ground state to excited states. As the electron drop back, many of them will become trapped in the metastable state. If the pumping light is intense enough, we may obtain a ***population inversion***, i.e., more electrons in the metastable state than in the ground state.

When an electron in one of these metastable states spontaneously jumps to the ground state, it emits a photon of energy $h\nu$. This is called ***fluorescent radiation***. As the photon passes by another nearby atom in the same metastable state, it can, by the principle of *resonance*, immediately stimulate that atom to radiate a photon of the exactly same frequency and return it to its ground state (see Figure 5.5). This stimulated photon has exactly the same frequency, direction and polarization as the primary photon (spatial coherence) and exactly the same phase and speed (temporal coherence).

Both of these photons may now be considered primary waves and upon passing close to other atoms in their metastable states, they stimulate them to emission in the same direction with the same phase. However, transition from the ground state to the excited state can also be stimulated, thereby absorbing the primary wave. An excess of stimulated emission therefore requires a *population inversion*. Thus, if the conditions in the gas are right, a ***chain reaction*** can be developed, resulting in high-intensity coherent radiation known as ***laser radiation***.

The stimulated emission must be collimated to produce a laser radiation. This is done by properly designing a *cavity* (known as ***resonance cavity***) in which the waves can be used over and over again. Suppose we use two flat mirrors, strictly parallel to each other and of the high reflective power, at the ends of the cavity, or tube. Into this cavity, introduce an appropriate solid, liquid or gas having metastable states in the atoms or molecules of its structure (Figure 5.6). Now excite electrons in these atoms or molecules by any *pumping* scheme and produce a population inversion.

If one or more atoms in a metastable state spontaneously radiate, those photons moving at an appreciable angle to the wall of the cavity, or tube will escape and be lost. Those emitted parallel to the axis will reflect back and forth from end to end. Their chance of stimulating emission will now depend upon a high reflectance at the end mirrors and a high population density of metastable atoms within the cavity. If both these conditions are satisfied, the build up of photons rising and falling through the cavity can be self-sustaining and the system will oscillate, or *lase*, spontaneously.

5.3 Population Inversion

If we have large number of atoms, say N_0, in thermal equilibrium, then their distribution in different energy states obeys the Maxwell-Boltzmann statistics. If we assume that at temperature T K, the instantaneous populations in energy state E_1 and E_2 are N_1 and N_2, respectively, then

$$N_1 = \exp\left[\frac{-E_1}{k_B T}\right] \qquad \text{and} \qquad N_2 = \exp\left[\frac{-E_2}{k_B T}\right]$$

Thus, the relative population

$$\frac{N_1}{N_2} = \exp\left[\frac{E_2 - E_1}{k_B T}\right]$$

The equation indicates that $N_2 \ll N_1$ at equilibrium (because $E_2 > E_1$). It means that the number of atoms in the higher energy states is less than the number of atoms in the lower energy states as shown in Figure 5.7. Under such circumstances, the probability of stimulated emission is much less than the probability of spontaneous emission. But since in spontaneous emission, the photon emitted from various atoms have random direction and random phase, a source of light emits incoherent radiation.

On the other hand, in stimulated emission, the radiation is completely coherent and amplified. Therefore, the basic requirement of a laser is to have predominantly stimulated emission. For it, two conditions must be satisfied:

(i) The higher energy state should have a longer mean life time i.e., it should be a metastable state.
(ii) The number of atoms in the higher energy state E_2 must be greater than that in E_1 i.e.; $E_2 > E_1$ but $N_2 > N_1$, as shown in Figure 5.8.

This condition is quite unnatural, because for any equilibrium state $N_2 \ll N_1$. If anyhow, by some means a large number of atoms are made available in the higher energy state, stimulated emission is promoted. *The situation in which the number of atoms in the higher energy state is greater than at in the lower energy state is called* ***population inversion***.

5.4 Ruby Laser – A Pulsed Mode Laser

The first successful laser, developed by Maiman in 1960, used a single crystal of synthetic pink ruby as its resonance cavity. The ruby is primarily a transparent crystal of *corundum* (alumina, Al_2O_3) doped with approximately 0.05 % of trivalent chromium ions (Cr^{3+}) in the form Cr_2O_3, the chromium providing its pink colour. The aluminium and oxygen atoms of the corundum are inert; the chromium ions are the active ingredients.

A ruby crystal, cylindrical in shape, is cut some 10 cm or so long having about 5 mm diameter and the ends polished flat and parallel. In a typical ruby laser one end is completely silvered to highly reflective (about 96%), and the other end is close to half-silvered (about 50%).

To greatly increase the electron population in the metastable states, very intense light sources, as well as light gathering systems, have been developed. In the arrangement used by Maiman (as shown in Figure 5.9), a high-intensity helical xenon flash lamp surrounding the ruby rod

provides adequate pumping light, whenever activated by the power supply, to produce a population inversion.

Another more effective arrangement is shown in Figure 5.10. By placing a strong pulsed light source at one focus of a cylindrical reflector of elliptical cross section and the ruby rod at the other focus, high efficiency can be realised.

A number of other pumping light sources of energy have been developed and used successfully. A set of condensers can be discharged through the lamp for high intensity pulsed operation.

The main characteristics of the energy levels (Figure 5.11) of the chromium ion lies in the fact that the bands labelled E_1 and E_2 have a lifetime (average time an atom spends in an excited state before making a transition to a lower energy state) of $\leq 10^{-9}$sec whereas the state marked M has a lifetime of $\sim 3 \times 10^{-3}$sec. A state of such a long lifetime is termed as *metastable state*.

The chromium ion in its ground state can absorb a photon (whose wavelength is around 6600Å) and make a transition to one of the states in the band E_1; it could also absorb a photon of wavelength around 4000Å and make a transition to one of the states in the band E_2. In either case, it immediately makes a non-radiative transition (in a time $\leq 10^{-9}$sec) to the metastable state M. Also since the state M has a very long life, the number of atoms in this state keeps increasing and one may achieve population inversion between states M and G. Thus, we may have large number of atoms in state M than in G. Once population inversion is achieved, the atoms jump back from the metastable state M to the ground level G, emitting visible red light corresponds to a wavelength of 6943Å. The light amplification can take place, within the two reflecting ends of the ruby rod forming a cavity.

By pumping from a strong surrounding xenon light source, a large part of the stored energy is converted into a coherent beam. Coherent waves travelling in opposite directions in the ruby rod setup standing waves. With one end only partially reflecting, part of the internal light is transmitted as an emerging beam of a wavelength of 6943Å.

5.5 He-Ne Laser – A Continuous Mode Laser

The first successful gas laser was put into operation by Ali Javan and his co-worker in 1961 at Bell Telephone Laboratory in USA. The Helium-Neon laser is most inexpensive, usually stable and emits continuously, therefore widely used in optics and physics laboratories the world over.

It is composed of a glass discharge tube nearly 1m long (as shown in Figure 5.12) and contains helium and neon at a pressure of approximately 1 torr (1 torr = 1mm of Hg pressure) and 0.1 torr, respectively. The highly reflecting mirrors (one is highly while the other is partially, so that energy may be come out of the cavity) at the ends are made parallel to a high degree of accuracy.

When an electric discharge is passed through the gas, the electrons travelling down the glass tube collide with the He atoms and excite them to the levels marked F_2 and F_3. These levels are metastable, i.e. He atoms excited to these states stay in these levels for a sufficiently long time before losing energy through collisions. Through these collisions, the Ne atoms are excited to the levels marked E_4 and E_6 which have nearly the same energy as the levels F_2 and F_3 of He. Thus, when He atoms in levels F_2 and F_3 collide with unexcited Ne atom, they raise them to the levels E_4 and E_6, respectively. This results in a substantial population of the levels E_4 and E_6. The population in these levels happens to be much more than those in the lower levels E_3 and E_5.

Thus, a state of population inversion is achieved and any spontaneously emitted photon can trigger laser action in any of the three transitions, shown in Figure 5.13. The transitions from E_6 to E_5, E_4 to E_3 and E_6 to E_3 result in the emission of wave having wavelengths 33926Å (3.39μm), 11523Å (1.15μm) and 6328Å, respectively. Bouncing back and forth between the end mirrors, these waves will stimulate emission of the same wavelength from the other excited Ne atoms, and the initial wave with the stimulated wave will travel parallel to the axis. The laser transitions corresponding to the first two wavelengths are in the near-infrared region. The third transition at 6328Å corresponds to the red light of the He-Ne gas laser is the most intense amplified wavelength in the visible region.

The Ne atoms then drop down from the lower laser levels to the levels E_2 through spontaneous emission (~6000Å). From the level E_2, the Ne atoms are brought back to the ground state through collisions with the walls of the narrow tube.

Actually there are a large number of levels grouped around E_2, E_3, E_4, E_5 and E_6. Only those levels are shown in the Figure 5.13 which corresponds to the important laser transitions.

5.6 Characteristics of Laser

The most important features of a laser beam are

(i) directionality
(ii) high intensity
(iii) high degree of coherence, and
(iv) extraordinary mono-chromaticity

5.6.1 Directionality

The common light sources emit light in all directions. In case of a laser, the active material is in a cylindrical resonant cavity. Any light travelling in a direction other than parallel to the cavity axis is eliminated and only the light that is travelling parallel to the axis emerges from the cavity and becomes the laser beam. Hence, the light is emitted by a laser only in one direction. The directionality of a laser is expressed in terms of *beam divergence*.

Light from a laser diverges very little. Up to a certain distance, the beam shows little spreading and remains essentially a bundle of parallel light rays. The distance from the laser over which the light rays remain parallel is known as *Rayleigh range*. The laser beam diverges beyond the Rayleigh range as shown in Figure 5.14.

There are two parameters which cause beam divergence. They are

(i) the size of beam waist, and
(ii) diffraction

The divergence angle is measured from the centre of the beam to the edge of the beam, where the edge is defined as the location in the beam where the intensity decreases to $1/e$ of that at the centre. Twice the angle of divergence is known as the *full angle beam divergence*.

The *beam divergence due to the size of beam waist* (Figure 5.15) is given by

$$\theta = \frac{4\lambda}{\pi d_0}$$

where d_0 is the diameter of the beam waist. The beam divergence is inversely proportional to the diameter of the beam waist d_0. Thus, divergence is large for a beam of small waist.

The *beam divergence due to diffraction* is determined from Rayleigh's criterion

$$\theta = 1.22\frac{\lambda}{D}$$

where *D* is the diameter of the laser's aperture.

In case of gas laser, the diffraction divergence is about twice as large as the beam waist divergence. A typical value of divergence for a He-Ne laser is 10^{-3} radian. It means that the diameter of the laser beam increases by about 1 mm for every meter it travels.

5.6.2 Intensity

The power output of a laser may vary from a few milli-watts to a few kilo-watts. But this energy is concentrated in a beam of very small cross-section. The intensity of a laser beam is approximately given by

$$I = \left(\frac{10}{\lambda}\right)^2 P$$

where *P* is the power radiated by the laser. In case of 1mW He-Ne laser, $\lambda = 6328 \times 10^{-10}$m and

$$I = \left(\frac{10}{6328 \times 10^{-10}}\right)^2 1 \times 10^{-3} = 2.5 \times 10^{11}\ \text{W/m}^2$$

To obtain light of same intensity from an ordinary tungsten bulb, it would have to be raised to a temperature of 4.6×10^6 K. The normal operating temperature of such bulb is about 2000 K.

5.6.3 Coherence

Light waves are said to be *coherent* if they are in phase with each other. For example, if they maintain crest-to-crest and trough-to-trough correspondence, as in Figure 5.16. Two things are necessary for light waves to be coherent. First, they must start with the same phase at the same position. Second, their frequencies must be same otherwise they will drift out of phase because the crest of the higher frequency will arrive ahead of the crests of the lower frequency wave.

The light that emerges from any common light sources (such as tungsten bulb, sodium or mercury lamp etc.) is a mess of short waves which combine with each other in an unsystematic manner. The resultant light is *incoherent* and the wave front varies from point to point and changes from instant to instant.

On the other hand, the light from a laser is a resultant of a large number of identical photons which are in phase and is therefore, exhibits a *high degree of coherence*. There are two classes of coherence, namely *temporal coherence* and *spatial coherence*.

(a) Temporal coherence refers to the constancy and predictability of phase as a function of time when the waves travel along the same path at slightly different times.

Let us consider a single wave propagating along *x*-direction. Let us note the electric field of light wave at any point in space at two different time t_1 and t_2, as in Figure 5.17. Let the phase

difference between the field E_1 at t_1 and the field E_2 at t_2 be $\emptyset_1$. Let us again note the electric fields at later times t_3 and t_4, where $(t_4 - t_3) = (t_2 - t_1)$. Let the phase difference be now $\emptyset_2$. If $\emptyset_2 = \emptyset_1$, and it is true for any time interval of same duration, then the wave is said to be ***temporally coherent***. If phase difference $\emptyset_2 \neq \emptyset_1$, and changes from interval to interval and in an irregular fashion, then the wave is said to the *incoherent*.

Temporal coherence is characterised by two parameters, namely ***coherence length***, l_{coh} and ***coherence time***, t_{coh}. The coherence length and coherence time measure how long light waves remain in phase as they travel in space.

$$l_{coh} = ct_{coh}$$

where c is the speed of light. It can be expressed in terms of frequency as $t_{coh} = 1/\Delta\nu$. Therefore

$$l_{coh} = \frac{c}{\Delta\nu}$$

where $\Delta\nu$ is the *line width* of the source. A strictly monochromatic wave ($\Delta\nu = 0$) is an ideal harmonic wave of infinite extension, and of infinite coherence length. The broader the line width, $\Delta\nu$, the shorter is the wave packet and its coherence length, as shown in Figure 5.18. So, *the monochromaticity of a light beam is a measure of its temporal coherence*.

The ***coherence length*** is a very useful measure of temporal coherence because it tells us how far apart two points along the light beam can be, and remain coherent with each other. It depends on the central wavelength λ and the bandwidth $\Delta\lambda$ of the wave packet. It is given by,

$$l_{coh} = \frac{\lambda^2}{2\Delta\lambda}$$

Fluorescent tube lights emit visible light of wavelengths in the range; say 4000Å to 7000Å, with an average wavelength of 5500Å. The coherence length

$$l_{coh} = \frac{(5500)^2}{2 \times 3000} = 5040\text{Å}$$

Light from a sodium lamp which is the traditional monochromatic source has two visible lines 5890Å and 5896Å, therefore have a coherence length of about 0.3 mm.

$$l_{coh} = \frac{(5893)^2}{2 \times 6} = 0.29 \text{ mm}$$

A He-Ne laser having red light at 6328Å and bandwidth of about 2×10^{-5}Å has a coherence length of about 100 m.

$$l_{coh} = \frac{(6328)^2}{2 \times 2 \times 10^{-5}} \approx 100 \text{ m}$$

(b) Spatial coherence refers to the phase relationship between waves travelling side by side at the same time but at some distance from one another.

Let us consider two identical waves travelling along the same direction but are at a distance from each other. Let us compare their phases at some time, say t_1, as in Figure 5.19. The

electric field at P_1 is E_1 and at P_2 is E_2. The phase difference between the two electric vectors is zero. Let us consider the same two waves at some other time t_2. Now E_1 at P_1 and E_2 at P_2 are different than what they were at t_1. However, the phase difference between them is still zero. If the phase difference between the two electric vectors remains zero for all times, then the two waves are said to have *spatial coherence*.

Light waves from a point source, producing ideally spherical wave fronts, maintain spatial coherence, therefore, points P_1 and P_2 have the same phase (Figure 5.20). Extended source produces wave fronts, far from ideal. Thus, P_1 and P_2 don't have the same phase (Figure 5.21), leading to spatial incoherence.

Light emerging from a laser is both temporally and spatially coherent to a high degree.

5.6.4 Monochromaticity

If light coming from a source has only one frequency of oscillation, the light is said to be monochromatic and the source a monochromatic source. In practice, it is not possible to produce light with only one frequency. Light coming out of any source consists of a band of frequencies closely spaced around a central frequency ν_0. The band of frequencies $\Delta\nu$ is called the linewidth or bandwidth (as shown in Figure 5.22).

The light from conventional sources has large linewidth of the order of 10^{10} Hz or more. On the other hand, light from lasers is more monochromatic, having linewidth of the order of 100 Hz. The linewidth of mirror cavity is given by

$$\Delta\nu = \frac{c}{2\pi L}\left(\frac{1-R}{\sqrt{R}}\right)$$

Where L is the length of the cavity and R is the reflectance of the output mirror.

5.7 Applications of Laser

Since the advent of the laser, it is used in almost every field (next to the computer,) and brings revolutionary changes in our lives. They are used in fundamental research, applied in entertainment electronics, industrial electronics, communications, mechanical working, metrology, surveying, surgery and related medical fields, information processing and even in warfare. One of the most significant uses of the laser has been in the production of ***holograms***. Here is the brief list of some important area where laser is being extensively in use.

1. **In mechanical industry:** For drilling, cutting, welding, heat treating on heavy metals etc.
2. **In electronic industry:** For scribing substrates, soldering leads, trimming thick or thin film, photolithography of semiconductor wafers, etc.
3. **In nuclear energy:** For isotope separation, nuclear fusion, thermonuclear reactions etc.
4. **In medicine:** In eye, brain, spinal, oviduct surgery. Ulcer and cancer treatment, angioplasty, DNA analysis, genetic engineering etc.
5. **In defence:** Mainly in searching and ranging targets, guiding and destroying weapons, etc.
6. **In survey:** Measuring distance, level grading, alignment, pipe laying, tunnel boring, etc.
7. **In environmental study:** LIDAR (light detection and ranging), measurement of the concentrations of various atmospheric pollutants, particulate matter, etc.
8. **In consumer electronics industry:** Super market scanners, compact discs, optical data storage, optical communications, optical computer, holography etc.