Chapter 9

Laser and its Applications

The word 'LASER' is the abbreviation of 'Light amplification by stimulated emission of radiation'. This process can take place in atoms, ions and molecules of gases, liquids, solids and gives us pure intense beam of light. The mechanism involved in this process basically reveals the interaction between atoms or molecules and electromagnetic field. Quantum mechanical treatment is essential to explain the process of this type of interaction and thus the topic is extensively studied under quantum electronics.

The frequency of emitted radiation extends from the ultraviolet to radiofrequency region of the electromagnetic spectrum. The output power of radiation of a laser varies from a few mw to Mw. Different laser emits radiation in form of either continuous mode or pulsed mode.

9.1 Principle of Laser

The principle of laser depends on the phenomenon of stimulated transition. Sir Albert Einstein in 1917 theoretically proposed the idea that the process of stimulated emission must exist. But only in 1960, T. H. Maiman of Hughes Research Laboratories first achieved laser action at optical frequency range.

If we consider the interaction of radiation with atoms, molecules of a substance, then, for interaction to take place, the energy of interacting photon $h\nu$ must be equal to the energy difference between the two states of the atoms or molecules engaged in that interaction. There are three possibilities of transition of atoms between two energy states namely

(1) Spontaneous emissions,

(2) Stimulated absorption or induced absorption or simply absorption, and

(3) Stimulated emission.

9.1.1 Spontaneous Emissions

When the atoms of the material which has been exposed to radiation go from an excited state to a lower energy state, *spontaneous emissions* of light takes place. In this process, an atom goes from higher energy state E_2 to lower energy state E_1. The energy of the emitted photon is

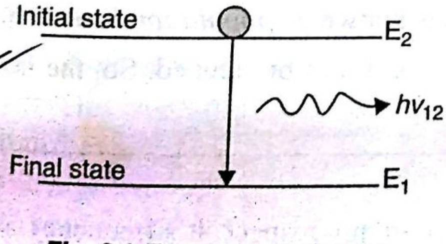

Fig. 9.1 Energy level diagram represents spontaneous emissions.

$$h\nu_{12} = E_2 - E_1$$

where ν_{12} is frequency of radiation and 'h' is Planck's constant.

In this type of emission, photons are emitted at random in all directions. There is no definite phase relationship among the different emitted photons. The emitted radiation is therefore incoherent. This type of emission depends on the type of particle and the type of transition but independent of outside circumstances.

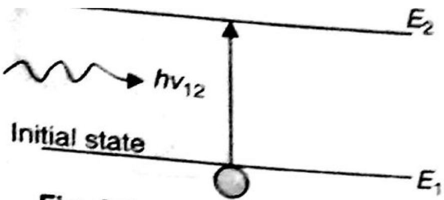

Fig. 9.2: Energy level diagram represents stimulated absorptions.

... energy $h\nu_{12}$ is incident on an atom in the energy state E_1, then the atom will undergo an upward transition to the higher energy state E_2 by the absorption of the incident photon. This transition is called transition due to absorption. It is also termed as *stimulated absorption*.

In excited state, atoms stay in higher energy state for a **short duration of time called their *life time*. The density of** photon of incident radiation decreases in this process due to **the absorption of photons.**

9.1.3 Stimulated Emission

If an atom is in higher energy state E_2, then an incident photon of energy $h\nu_{12}$ may induce **transitions from the higher energy state E_2 to the lower energy state E_1. This transition is induced or stimulated by the radiation of electromagnetic wave. It produces *stimulated emission of* radiation.**

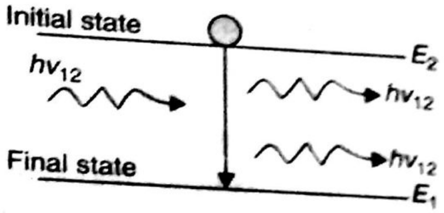

Fig. 9.3 (a): Energy level diagram represents stimulated emissions.

In this type of radiation, the emitted photons have same energy, direction and phase as those of the incident photon. So, two coherent photons are obtained at output for one incident photon due to this. These two photons can again induce stimulated emission of two more photons by interacting with two atoms in the higher energy state E_2. So, four coherent photons of same energy are obtained. This process is repeated in chain, producing a large number of coherent photons of same energy $h\nu_{12}$. The photon density increases in this process.

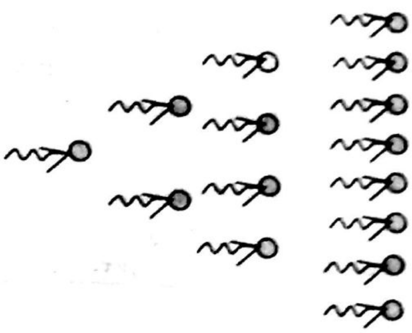

Fig. 9.4: Generation of photons in chain process.

In this way, the intensity of the beam is increased and amplification due to stimulated emission is achieved. It explains the meaning of the word --- 'laser'. At the same time, there is a possibility of transition by means of spontaneous emission. The spontaneous emission in this process is referred to as *'quantum noise'*.

The necessary condition for the laser process is that the number of atoms in the higher energy state E_2 must be sufficiently greater than that of lower energy state. Generally, the number of atoms in **the upper state E_2 is considerably less than that of in the lower energy state E_1.** So, the time rate of **induced downward transitions is much less than that of the upward transitions. To enhance the rate of stimulated emission, the number of atoms in the state E_2 must be increased over the number of atoms in the state E_1. The state of highly populated higher energy state is known as *population inversion*.**

Due to Doppler Effect and other causes, the energy levels and are broadened. So, the laser radiation has a small spread in frequency.

9.2 Basic Components of a Laser

Structurally, the three main components of any laser device are -----

(1) Active medium (gas, liquid or solid),

(2) Pumping source, and

(3) Optical resonator.

9.2.1 Active Medium

The active medium consists of a collection of atoms, molecules or ions (in solid, liquid or gaseous form) which has capability of amplifying light waves. Under normal circumstances, there are always a large number of atoms in lower energy state than that in the excited energy state. An electromagnetic wave passing through such a collection of atoms would get attenuated due to the absorption of energy of the electromagnetic wave. In this process, energy density decreases. Thus, in order to have amplification, the medium has to be kept in a state of population inversion.

Characteristics of active medium

- It should be transparent to both the stimulating radiation and the laser output which are often at totally different wavelengths.
- It should have good optical properties, i.e; it should exhibit negligible variation of refractive index, scattering and undesired absorption of stimulating radiation and laser output.
- It should accommodate the active species that helps in lasing action without changing the desired properties.
- It should have good mechanical and thermal properties, i.e; deformation or fracture should not occur during extreme working conditions.

Any system in which population inversion can be achieved is called an **active medium.** Learn this

9.2.2 Pumping Source

The pumping mechanism provides for getting a state of population inversion between a pair of energy levels of the atomic system.

The method by which a population inversion is achieved is called **pumping.**

Pumping mechanism ----- creation of population inversion

There are different mechanisms useful to pump the atoms of the active medium to higher energy states to create population inversion. These are -----

(a) Excitation with the help of photons

If the atoms are exposed to electromagnetic radiation of frequency $v = (E_2 - E_1) / h$, then there is selective absorption of this radiation due to which the atoms are raised to the excited state E_2. This method is known as *optical pumping*. The materials having very broad absorption band can absorb sufficient amount of energy from the emission spectra of flash lamp and population inversion is created. Example is ruby laser.

(b) Excitation by electrons

This method is an example of electrical pumping used in some gas lasers. Electrons are released from the atoms due to high voltage electric discharge through a gas. These electrons are then accelerated with high velocities due to the strong electric field inside the discharge tube. When they collide with the neutral gas atoms, a fraction of these atoms are raised to the excited state due to the inelastic collision between the electron and the atom, symbolically

$$M + e_{fast} \rightarrow M^* + e_{slow}$$

where. M represents the atom of the gaseous substance, e_{fast} represents electron with greater

9.4 Threshold Condition for Population Inversion

We know that light amplification occurs when population inversion is produced in the medium. Theoretically it continues with time. But in reality, this is not the actual case. The reason is the presence of different types of losses in the medium. At the time of amplification, some photons are lost due to absorption and scattering by the active medium. These are intrinsic by nature. Another kind of loss of photon is due to those photons taken out as an output of the system. Again we know that lasing action depends on the energy density of photons in the active medium. If the population inversion density is sufficiently large then these losses are compensated by the gain in the system. The population inversion density for which the gain is just equal to the loss in the system is termed as *threshold inversion density*. Different systems have different threshold values because it is related to the intrinsic properties of the system.

9.5 Einstein A, B Coefficients

Let us consider two energy states of an atomic system. Let N_1 is the number of atoms per unit volume present in the energy state E_1 and N_2 is the number of atoms per unit volume present in the energy state E_2.

If a radiation at a frequency corresponding to the energy difference $(E_2 - E_1)$ of two energy states falls on the atomic system, it can interact in three distinct ways :-

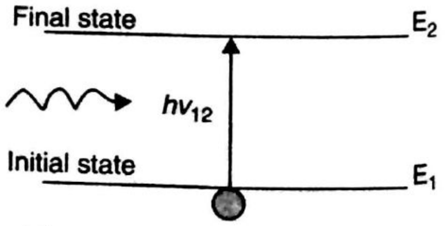

Fig. 9.10(a): Energy level diagram represents Stimulated absorptions.

(a) Upward transition by stimulated absorption

An atom in the lower energy level E_1 can absorb the incident radiation and be excited to E_2. This excitation process requires the presence of radiation. The time rate of such transitions (τ_{12}) is proportional to

(*i*) The number of atoms (N_1) present in the level E_1, i.e;

$$\tau_{12} \propto N_1$$

(*ii*) Energy density (u_ν) of the radiation at the frequency $\nu = \frac{E_2 - E_1}{h}$, i.e;

$$\tau_{12} \propto u_\nu$$

where, $$u_\nu = nh\nu,$$

n = number of photons (of frequency ν) per unit volume.

h = Planck's constant.

So, the number of atoms undergoing absorption per unit time per unit volume from energy state to energy state E_2 is

$$\tau_{12} = B_{12} N_1 u_\nu \qquad \text{... (9.2)}$$

where, B_{12} = constant of proportionality known as Einstein coefficient of stimulated absorption and depends on the energy levels E_1 and E_2.

For just reverse process, namely the deexcitation of the atoms from E_2 to E_1, Einstein proposed at an atom can make a transition from E_2 to E_1 through two distinct processes, namely

- Stimulated emission, and
- Spontaneous emission.

Downward transition by stimulated emission

In case of stimulated emission, the radiation which is incident on the atom stimulates it to emit radiation and the rate transition (τ_{21}) to the lower energy state is proportional to

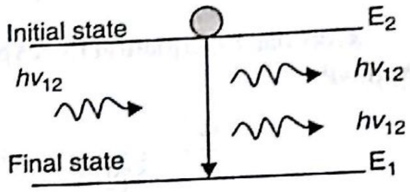

Fig. 9.10 (*b*): Energy level diagram represents stimulated emissions.

(*i*) The energy density (u_ν) at the frequency ν which is equal to $nh\nu$, i.e;

$$\tau_{21} \propto u_\nu$$

(*ii*) The number of atoms (N_2) present in the energy state , i.e;

$$\tau_{21} \propto N_2$$

It is occurred when excited atoms interact with photons before deexcitation to their lower energy states by spontaneous emission. Thus, the number of atoms undergoing stimulated emission per unit time per unit volume is given by

$$\tau_{21} = B_{21} N_2 u_\nu \qquad \text{... (9.3)}$$

where, B_{21} = constant of proportionality known as Einstein coefficient of stimulated emission and depends on the energy levels E_1 and E_2.

Downward transition by spontaneous emission

An atom which is in the upper energy level E_2 can formulate a spontaneous emission, thus the rate (V_{21}) be proportional to N_2 only, i.e;

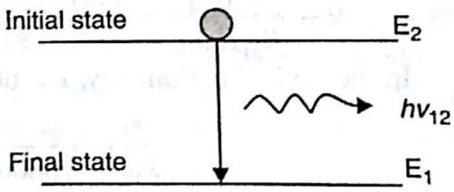

Fig. 9.10 (*c*): Energy level diagram represents spontaneous emissions.

$$V_{21} \propto N_2$$

Thus we have for the number of atoms making spontaneous emissions per unit time per unit volume is

$$V_{21} = A_{21} N_2 \qquad \text{... (9.4)}$$

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

$$\tau_{12} = \tau_{21} + V_{21}$$

or,
$$B_{12} N_1 u_\nu = A_{21} N_2 + B_{21} N_2 u_\nu$$

or,
$$u_\nu = \frac{A_{21}}{\left(N_1/N_2\right) B_{12} - B_{21}} = \frac{\left(A_{21}/B_{21}\right)}{\left(\dfrac{B_{12}}{B_{21}}\right)\left(N_1/N_2\right) - 1} \qquad \text{... (9.5)}$$

Ignoring degeneracy of energy states, the population of the energy state E_2 of a system in thermal equilibrium is given by the Boltzmann distribution law which is given by

$$\frac{N_1}{N_2} = \exp\left[(E_2 - E_1)/kT\right] = \exp\left[h\nu/kT\right] \quad \text{...(9.6)}$$

where, $E_2 - E_1 = h\nu$ and k = Boltzmann constant.

So, from equation 9.5, u_ν can be written as

$$u_\nu = \frac{(A_{21}/B_{21})}{\left(\frac{B_{12}}{B_{21}}\right)\left(N_1/N_2\right) - 1} = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left(\frac{B_{12}}{B_{21}}\right)\exp[h\nu/kT] - 1} \quad \text{... (9.7)}$$

Now from Planck's radiation formula, the energy density (u_ν) at a frequency ν is given by

$$u_\nu = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{\exp[h\nu/kT] - 1} \quad \text{... (9.8)}$$

Comparing equation the expression of energy density at frequency ν from equation 9.7 and 9.8, we have

$$\frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{\exp[h\nu/kT] - 1} = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left(\frac{B_{12}}{B_{21}}\right)\exp[h\nu/kT] - 1} \quad \text{... (9.9)}$$

Comparing both sides of equation 9.9, we can write,

$$B_{12} = B_{21} = B \text{ (say), and} \quad \text{... (9.10)}$$

$$\frac{8\pi h\nu^3}{c^3} = \frac{A_{21}}{B_{21}} \quad \text{... (9.11)}$$

These two relations are called Einstein relations. The coefficient A and B are referred to as *Einstein's A and B coefficients.*

The ratio of the number of atoms undergoing spontaneous transition to that in case of stimulated emission is

$$R = \frac{A_{21}N_2}{B_{21}N_2u_\nu} = \frac{8\pi h\nu^3}{c^3} \cdot \frac{c^3}{8\pi h\nu^3}\left[\exp(h\nu/kT) - 1\right] = \left[\exp(h\nu/kT) - 1\right] \quad \text{... (9.12)}$$

In the optical region (say, $\lambda = 6000°\ A$) at room temperature (300°K), we have

$$\frac{hc}{\lambda\, kT} = \frac{6.625 \times 10^{-34} \times 3 \times 10^8}{6000 \times 10^{-10} \times 1.380 \times 10^{-23} \times 300} = 80$$

Hence, [exp $(h\nu/kt)$ −1] is a very large number and therefore R is also a very large number. It means that spontaneous emission is predominant in optical region.

In practice, the absorption and emission processes occur simultaneously. At thermal equilibrium, stimulated emission is not a predominating process. Even for sources operating at higher temperature and lower frequency, spontaneous emission predominates.

From the above discussion, it is clear that to make R smaller, the energy density (u_ν) of interacting radiation has to be made larger. We have seen that stimulated emission and stimulated absorption rates are proportional to the number of atoms available in the higher energy and lower energy states respectively. Therefore,

$$\frac{\text{Stimulated emission transtion}}{\text{Stimulated absorption transition}} = \frac{B_{21}N_2u_\nu}{B_{12}N_1u_\nu} = \frac{N_2}{N_1} \quad [\because B_{21} = B_{12}]$$

At thermal equilibrium, $\frac{N_2}{N_1} \langle\langle 1$, so $N_2 \langle\langle N_1$.

Photons of relevant energy have more probability to interact with atoms in the lower energy state than with atoms in the excited states because N_1 is greater than N_2, and hence probability is more for stimulated absorption than that for stimulated emission. To cause a stimulated transition inside the medium, the higher energy state should be more populated than that of lower energy state. Therefore, if we create a situation in which $N_2 \gg N_1$, stimulated emission will prevail over stimulated absorption. If stimulated emission predominates, the photon density increases and light amplification by stimulated emission of radiation (LASER) occurs. Therefore, in order to achieve more stimulated emission, population of the excited state (N_2) should be made larger than the population of the lower energy state (N_1) and this condition is termed as *population inversion*. Hence, if we want to amplify a beam of light by stimulated emission then we must -------

- Create population inversion, and
- Increase the energy density of interacting medium because $R = \dfrac{A_{21}}{B_{21}u_\nu}$.

Conditions of laser action:

- ✓ Population inversion.
- ✓ The rate of stimulated emission is greater than the rate of stimulated absorption.
- ✓ There should be a metastable state and a lower energy level that decays quickly to the ground state.
- ✓ Active medium, pumping system to create population inversion and optical resonator are essential.