Chapter – 5 : LASERS

Q. 1: Expand the term: 'LASER'. [Nov.-Dec. 2010 (1 Mark)]
Q. 1: State the full form of LASER. [Dec.-2008 (1 Mark)]
Ans.: Light Amplification by Stimulated Emission of Radiation.

Q. 2: Mention and explain the Properties of LASER. [Nov.-Dec. 2010 (4 Mark)]

Ans.: Properties of LASER are as follows.

1. It is highly coherent light:

When two separated beams, originating from the same source, that have travelled long distances (over several hundred kilometers) over separate paths, are recombined, they "remember" their common origin and are able to form a pattern of interference fringes. The corresponding coherence length for light originating from a light bulb is typically less than a meter.

2. It is highly directional light:

A laser beam spreads very little; it departs from parallelism only because of diffraction at the exit aperture of the laser. For example, a laser beam used to measure the distance to the moon generates a spot on the moon's surface with a diameter of only a few meters. The laser beam has an extremely small angular divergence.

3. It is highly monochromatic light:

The light from a normal monochromatic source spreads over a range of wavelength of the order 100 nm. But, the spread is of the order of 1 nm for laser. Hence, laser is highly monochromatic, i.e., it can emit light of single wavelength.

4. It can be sharply focused:

If two light beams transport the same amount of energy, the beam that can be focused to the smaller spot will have the greater intensity at the spot. For laser light the focused spot can be so small that intensity of the order of 10^{17} W/cm^2 is readily obtained. An oxyacetylene flame has an intensity of only 10^3 W/cm^2.

Q. 3: State the properties of LASER. [Dec. 2008 (1 Mark)]

Q. 3: State the characteristics of Laser. [Jan. 2011 (1 Mark)]

Q. 3: What is LASER? [March 2009(1 Mark)]

Ans.: Laser is highly directional, monochromatic, coherent and intense light.

Q. 4: Prove that the ratio of spontaneous emission and stimulated emission is proportional to the cube of frequency. [Nov.-Dec. 2010 (3 Mark)]

Q. 4: Show that the ratio of Einstein's A coefficient for spontaneous emission to that of Einstein's B coefficient for stimulated emission is given by $8\pi hf^3/c^3$. [March April 2010(6 Marks)]

Q. 4: Derive the relation between Einstein's 'A' and 'B' coefficients.
[Dec. 2008, June 2010, Jan. 2011 (5 Marks)]

Ans.:

Let us consider a system of N_0 atoms. Even at normal temperature all the N_0 atoms are not in the ground state. A very few atoms, due to thermal excitation, are in nearby excited state.

Let N_1 be the number of atoms in the ground state with energy E_1, and N_2 be the number of atoms in the excited state with energy E_2.

Let us assume that the system has been put in the bath of black body radiation at temperature T (K). The black body radiation consists of photons with continuous range of frequency. However, we shall concentrate on a single frequency f such that $E_2 - E_1 = hf$.

In the process of interaction, the photons of frequency f are absorbed by the atoms in the ground state and making transition they (atoms) acquire the excited state with energy E_2. It should be remembered that this process is statistical in nature. This means that only a certain number of atoms, determined by absorption probability, will go to the excited state.

It is assumed that probability per unit time, for absorption of the photon of frequency f, by the atoms is proportional to the energy density $\rho(f)$ of the radiation at frequency f.

If we denote the rate of absorption by R_{12}, then

$$R_{12} \propto \rho(f) N_1$$

Therefore, $R_{12} = B_{12}\, \rho(f)\, N_1$ ………… (1)

The proportionality constant B_{12} is known as Einstein's coefficient of absorption.

Normally, an atom would stay in an excited state for about 10^{-8} s and make spontaneous transition to fall back to the ground state.

In our problem, the rate of spontaneous transition (R_{12}) is proportional to the number N_2 of the atoms in the excited state.

Therefore, $R_{21}(sp) \alpha N_2$

Therefore, $R_{21}(sp) = A_{21} N_2$ ………… (2)

A_{21} is proportionality constant, the Einstein's coefficient for the spontaneous emission.

Now, we have noted earlier that to account for thermodynamic equilibrium, Einstein had proposed the stimulated emission also.

The rate of stimulated emission $R_{21}(st)$ is proportional to the energy density $\rho(f)$ of radiation corresponding to frequency f and the number N_2 of the atoms in excited state with energy, E_2.

Therefore, $R_{21}(st) \alpha \rho(f) N_2$

Therefore, $R_{21}(st) = B_{21} \rho(f) N_2$ ………… (3)

For the system to be in thermal equilibrium, the rate of upward transition must be equal to the rate of downward transition. (This is called the principle of detailed balance).

Therefore, $R_{12} = R_{21}(sp) + R_{21}(st)$ ………… (4)

Using equation (1), (2), and (3) in equation (4), we have

$$B_{12} \rho(f) N_1 = A_{21} N_2 + B_{21} \rho(f) N_2 \text{ ………… (5)}$$

Therefore, $\rho(f) [B_{12} N_1 - B_{21} N_2] = A_{21} N_2$

$$\text{Therefore, } \rho(f) = \frac{A_{21} N_2}{[B_{12} N_1 - B_{21} N_2]}$$

Dividing both numerator and denominator of right hand side of this equation by N_2 we get

$$\rho(f) = \frac{A_{21}}{[B_{12} \frac{N_1}{N_2} - B_{21}]} \text{ ………… (6)}$$

Now, according to Boltzmann's law of distribution,

$$N_1 = N_0\, e^{-E_1/kT} \text{ .... (7)}$$

and

$$N_2 = N_0\, e^{-E_2/kT} \text{ .... (8)}$$

Where, $k = 1.38 \times 10^{-23}$ J/molecule K, the Boltzmann's constant.

Using equations (7) and (8) in equation (6),

$$\rho(f) = \frac{A_{21}}{[B_{12}\, e^{(E_2 - E_1)/kT} - B_{21}]}$$

But, $E_2 - E_1 = hf$

Therefore,

$$\rho(f) = \frac{A_{21}}{[B_{12}\, e^{hf/kT} - B_{21}]}$$

$$\rho(f) = \frac{A_{21}}{B_{21}} \times \frac{A_{21}}{[\frac{B_{12}}{B_{21}}\, e^{hf/kT} - 1\,]} \text{ .... (9)}$$

Now, from Planck's theory of Black body radiation,

$$\rho(f) = \frac{8\Pi\, hf^3}{c^3} \times \frac{1}{[\, e^{hf/kT} - 1\,]} \text{ .... (10)}$$

Comparing equation (10) and (11),

$$\frac{A_{21}}{B_{21}} = \frac{8\Pi\, hf^3}{c^3} \text{ .... (11)}$$

and,

$$\frac{B_{12}}{B_{21}} = 1$$

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

We denote A_{21} by A. Then, A and B are known as Einstein's coefficients.

$$\frac{A}{B} = \frac{8\Pi\, hf^3}{c^3} \text{ .... (12)}$$

Above equations (11) and (12) shows the relation between Einstein's coefficients. From these equations it is also proved that the ratio of coefficient of spontaneous emission and stimulated emissions is proportional to the cube of frequency.

Q. 5: Write the differences between Spontaneous and Stimulated Emission.

Ans.:

The differences between Spontaneous and Stimulated Emission are as follows

Spontaneous Emission	**Stimulated Emission**
Emission takes place of its own accord without any external agency.	Emission of photon is only in the presence of external photons.
This is a random process.	This is not a random process.
Only one photon is emitted. The chain reaction does not take place.	The photons get multiplied through chain reaction.
This process can't be controlled.	It is controllable process.
Radiation is not as intense as that in stimulated emission.	More intense radiation can be obtained.
All photons do not have same frequency, same momentum and same phase.	All photons have same frequency, same momentum and phase as that of incident photon.
Photons are emitted in different directions depending on dipole moments of emitting atoms.	Photons are emitted in the same direction as that of motion of incident photon.

Q. 6: What is population inversion? [June 2010 (1 Mark)]

Ans.: Population inversion is a state of achieving more number of atoms in the excited state compared to the ground state.

Q. 7: What is the life time of charge carrier in meta-stable state? [Dec. 2008 (1 Mark)]

Ans.: The life time of charge carriers in meta-stable is about 10^{-3} second.

Q. 8: State the characteristics of laser light. Explain the terms stimulated emission, spontaneous emission, population inversion, optical resonators and active medium [Jan. 2011 (5 Marks)]

Q. 8: Explain (i) population inversion (ii) pumping (iii) optical resonator. [Jan. 2010 (3 Marks)]

Ans.:

- Characteristics:

  Laser is highly directional, monochromatic, coherent and intense light.

- Spontaneous Emission:

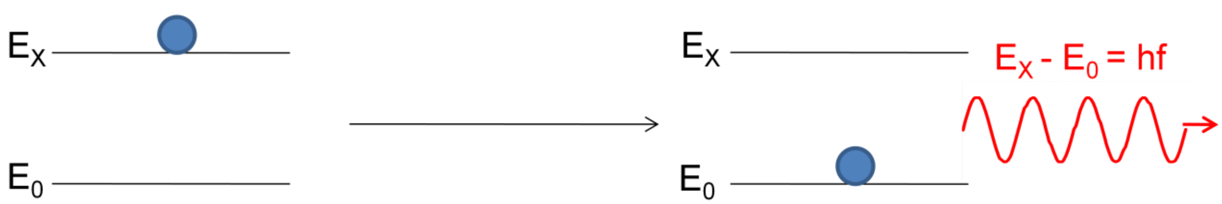


Fig.-1

Fig.-1 shows that the atom is in its excited state and no external radiation is present. It comes to this state after absorbing a photon of energy hf or by some other inelastic collision. The atom has now become an excited atom. A short time later, the atom will move itself to its ground state, emitting a photon of energy hf. We call this process spontaneous emission.

- Stimulated Emission:

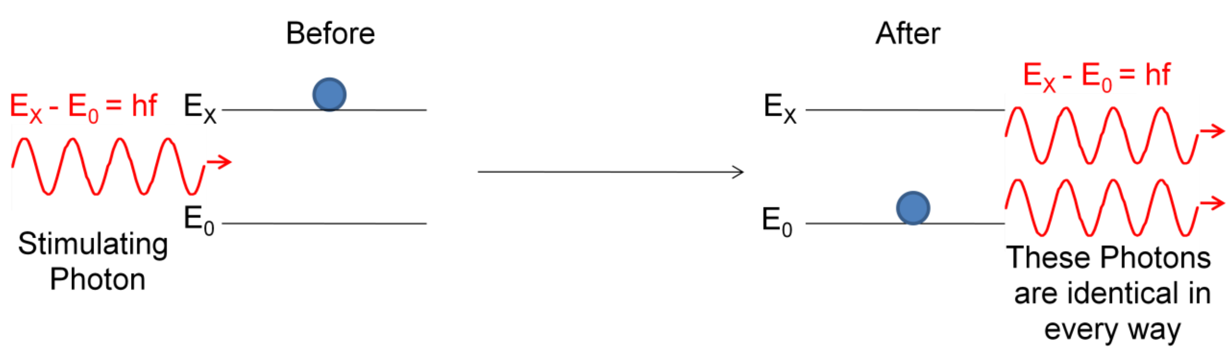


Fig.-2

In Fig.-2 the atom is in its excited state but this time a radiation with an energy $hf = E_X - E_0$ is also simultaneously present. Under these circumstances a photon of energy hf can stimulate the atom to move to its ground state, during which process the atom emits an additional photon, whose energy is also hf. We call this process stimulated emission.

- <u>Population Inversion:</u>

Population inversion is a state of achieving more number of atoms in the excited state compared to the ground state as shown in the following Fig.

Population Inversion Normal Population

- <u>Optical Resonator:</u>

It is a pair of reflecting surfaces (mirrors) of which one is a perfect reflector and the other is a partial reflector.

- <u>Active Medium:</u>

A medium in which population inversion is achieved for laser action is called active medium.

- <u>Pumping:</u>

Pumping is the mechanism of exciting atoms from the lower energy state to a higher energy state by supplying energy from an external source.

Q. 9: Distinguish between Spontaneous Emission and Stimulated Emission. [March-April 2010 (4 Marks)]

Q. 9: Briefly explain stimulated emission. [Jan. 2010 (2 Marks)]

Ans.:

- **<u>Spontaneous Emission:</u>**

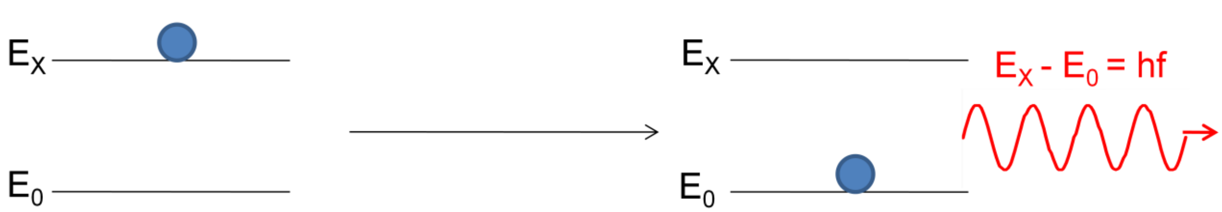


Fig.-1

Fig.-1 shows that the atom is in its excited state and no external radiation is present. It comes to this state after absorbing a photon of energy hf or by some other inelastic collision. The atom has now become an excited atom. A short time later, the atom will move itself to its ground state, emitting a photon of energy hf. We call this process spontaneous emission – spontaneous because the event was not triggered by any outside influence. The direction and phase of each of such photons is random. The light from a sodium or mercury lamp is generated in this manner.

[Normally, the mean – life of excited atoms before spontaneous emission takes place is about 10^{-8} sec. However, for some of the excited states this mean life can be as much as 10^{5} times longer. Such long-lived states are called Meta stable states.]

Stimulated Emission:

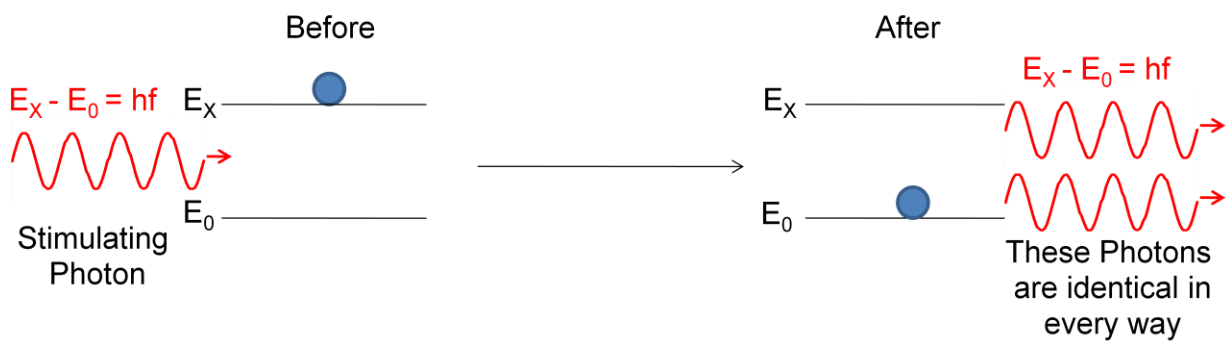
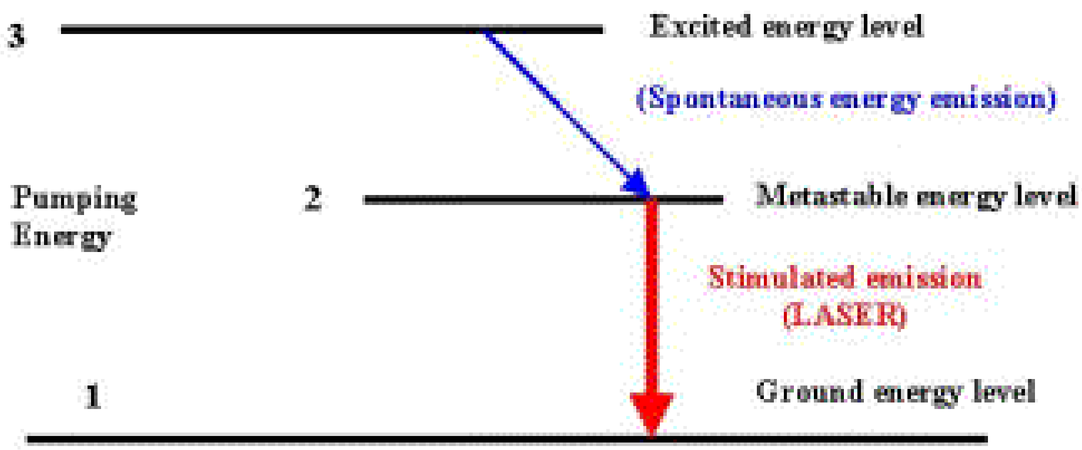


Fig.-2

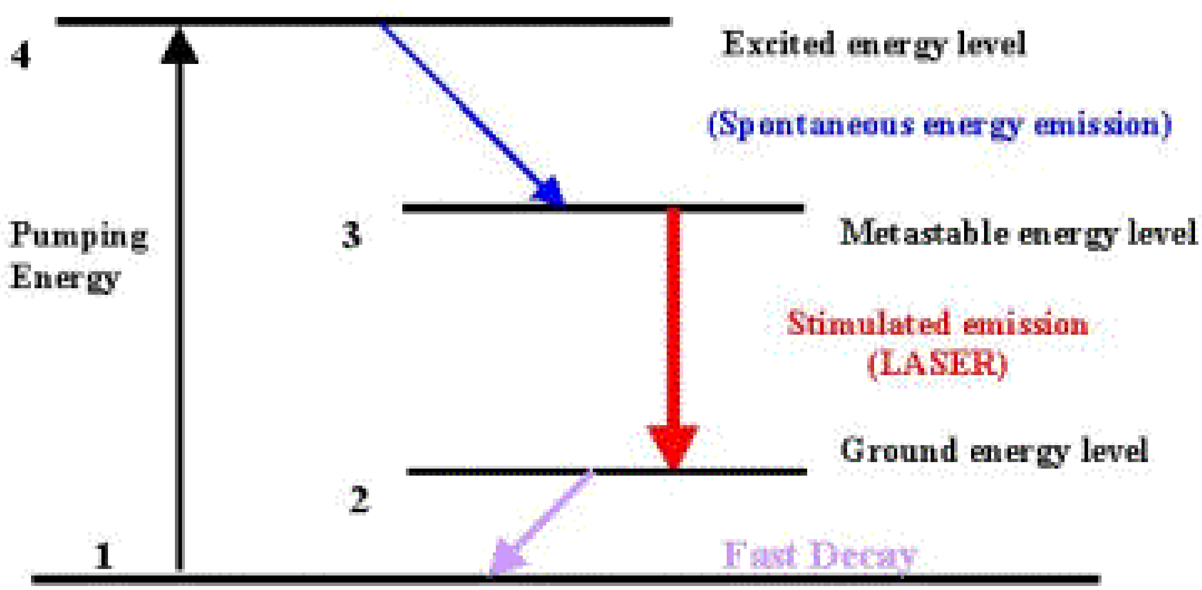
In Fig.-2 the atom is in its excited state but this time a radiation with an energy $hf = E_X - E_0$ is also simultaneously present. Under these circumstances a photon of energy hf can stimulate the atom to move to its ground state, during which process the atom emits an additional photon, whose energy is also hf. We call this process stimulated emission – stimulated because the event is triggered by the external photon. The emitted photon is in every way identical to the stimulating photon. It has the same energy, phase, polarization and direction of travel.

Q. 10: Why four level laser systems are more efficient as compared to three level lasers?

Ans.: Refer the following figures of three level and four level laser systems.



Energy States of Three – level Active Medium



Energy States of Four – level Active Medium

We know that the laser action is initiated only when the population inversion condition is achieved i.e. N2 > N1 where N1 and N2 are the population of the two levels involved in laser action. Further higher is the probability of stimulated emission as compared to absorption, if the difference N2 - N1 is large. In case of three level laser systems, the laser action is initiated only when the excited atoms in level 2 are significantly higher than the number of atoms in ground state at level 1. Since the lifetime of level 3 is of the order of nanoseconds, the excited atoms emit spontaneously and come to a metastable level 2, which has a higher lifetime. In other words, more than half of the atoms should be shifted to level 2 via level 3 to initiate laser action. This requires very strong pumping source. On the other hand, in case of four level lasers, laser action is achieved between levels 3 and 2; both of them are completely empty to start with. So if pumping were able to excite even a fraction of the total ground level atoms, these would shift to metastable level 3 via level 4, which has a short lifetime of the order of nanoseconds. This results in immediate establishment of population inversion condition and thus the laser action.

Since the number of atoms to be excited is far smaller in case of four level lasers as compared to three level lasers, the pump power requirements are much smaller too. This leads to higher efficiency in four level lasers.

Q. 11: Application of LASER in different field. [March 2009 (3 Marks)]

Q. 11: List the application of the LASER. [June 2009 (2 Marks)]

References:

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