LASER AND ITS APPLICATION

Lecture-2

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Contents:

Optical resonator:

An optical resonator can have different configuration. A resonator for a laser device consists of two mirrors. These mirrors may be plane or spherical. The diffraction losses are low in a confocal configuration of the optical resonator which consists of two identical concave mirror separated by a distance equal to their radius of curvature.

The radiation field inside the resonator generates a standing wave configuration with a node at each mirror. Let L be the length between the two mirrors. In case of resonance the cavity contains the integral multiple of half wavelength

i.e. $L = m\lambda/2$ m=0,1,2,3......................

$\lambda = 2L/m$ m is called as axial mode

$\nu_m = c/n\lambda$

Here c/n –velocity of the light in active medium.

c - velocity of light in vacuum

n-refractive index of the medium.

If ν_m is the frequency of the mth mode

$$\nu_m = \frac{cm}{2Ln} \qquad \text{.....................(1)}$$

Here c is the velocity of light in vacuum and n is the refractive index active medium.

Now the frequency separation between two consecutive mode is

$$\Delta\vartheta = \vartheta(\mathrm{m}+1) - \vartheta\mathrm{m}$$

$$= \frac{c}{2Ln} \qquad \text{..(2)}$$

These resonant modes of the cavity are narrower in frequency than the bandwidth of a single spontaneous emission line

So several resonant cavity modes may lie within the width of a single emission line.

The cavity selects and amplify Only certain narrow bands from emission line. This is the origin of extreme quasi-mono chromaticity of laser light.

The resonant mode of a resonator is not a sharp line but has a small finite frequency spread . This spread is related to various losses (scattering, absorption, diffraction etc.) associated with the mode of the cavity.

***Q* factor or quality factor:**

It is defined as the ratio of the initial energy stored in the resonator to the energy lost in one radian of the cycle of oscillation. Q factor is alternatively defined as the ratio of a resonator's centre frequency to its bandwidth when subject to an oscillating driving force. It is a dimensionless parameter.

$$Q = 2\pi \times \frac{\text{Maximum energy stored per cycle in the mode}}{\text{Energy dessipated per cycle in the mode}}$$

$$= \frac{f}{\Delta f}$$

$$= \frac{\omega}{\Delta \omega}$$

Here $\Delta\omega$ is the line width. Thus a high Q cavity has low loss and narrow width of a mode.

where $\omega = 2\pi f$ is the angular resonant frequency here f is the resonant frequency. Δf is the **resonance width** or full width at half maximum of resonant frequency and $\Delta\omega$ is the angular half-power bandwidth.

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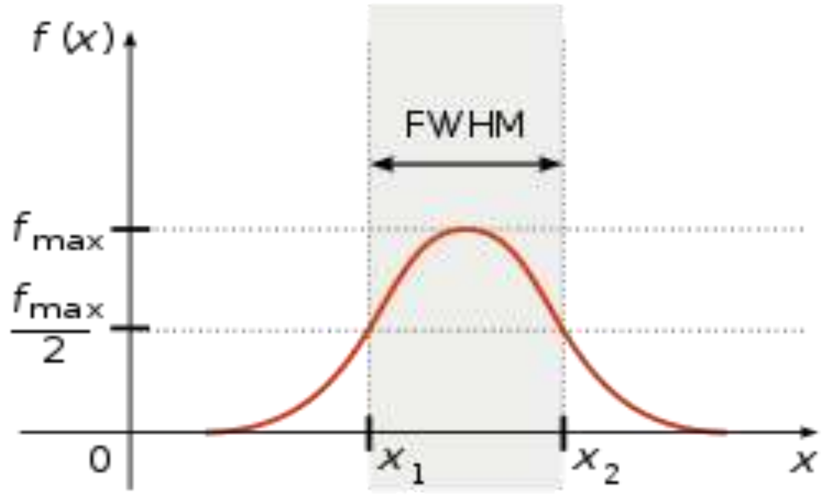

FWHM—Full Width at Half Maximum

Emission and absorption of radiation by matter:

According to Bohr's atom model, when an atom makes transition from an upper energy state E_2 to lower energy state E_1 and emits a radiation of frequency √ then we can write,

E_2-E_1=h√ ....(1)

On the other hand, if an atom absorbed a particular amount of energy of the radiation incident on it, which is equal to the energy difference of the two levels E_1 and E_2 then it makes transition from E_1 to E_2. Then the radiation is called as absorption radiation.

Einstein postulated that there are two types of emission

a) spontaneous emission

b)stimulated emission.

Spontaneous emission:

When an atom in ground state absorbs an incident photon it becomes excited and goes to the higher energy state.

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A atom thus excited can stay there for a maximum time of about 10^{-8} second. Within this time it dropped back to the ground state by emitting a photon spontaneously.

The emitted radiation in this case has got random phase and so incoherent and can be emitted in all possible directions from different atoms in the system. This type of emission is known as spontaneous emission.

Stimulated emission :

Let us consider an atom excited to the state E_2 from state E_1 by absorbing a photon of energy hν such that

$$E_2 - E_1 = h\nu$$

Now if another photon of energy hν impinge upon the excited atom ,it stimulates the atom to come down to the lower state along with the emission of the absorbed photon. In this case, the direction of the emitted photon is same as that of the incident photon and also the phases of the two photons are exactly same and so they are coherent. Such emission is called as stimulated emission.

Thus in a stimulated emission the radiation is coherent but in spontaneous emission the radiation is non-coherent.

Population inversion :

Normally the number of atoms in the ground state is much larger than the number of atoms in the excited state. During spontaneous emission the atoms which are raised to the excited state automatically come down to the lower energy state within the time period of 10^{-8}sec with spontaneous emission radiation.

If by any means we can increase the numbers of atoms in the excited state than the ground state, then that state is called as population inversion state. Population inversion is an essential condition for laser emission.

:Method of creating population inversion in a LASER:

The population inversion can be achieved by---

1. Optical pumping
2. by electrical discharge
3. by chemical method.

Let us consider some independent atoms which can exist only in two energy states E1 and E2. Let N_1 and N_2 be the number of atoms per unit volume in the state E1 and E2 respectively. Applying Boltzmann distribution law ,under thermal equilibrium state we can write

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/KT} \quad \text{.........................(1)}$$

where K is Boltzmann's constant and T is absolute temperature and $E_2 > E_1$.

This shows that the population of higher energy state is lower than the population of lower energy state. The above equation shows that at room temperature, for transition of visible light the number of atoms N_2 is negligible in comparison to the number of atoms in state N_1.

Now if a photon of energy E_2-E_1=hν approaches a system it is absorbed by the atoms in state 1 and the atoms get excited to the state 2. But to get stimulated emission there must be population inversion.

Equation (1) shows that when temperature T is made infinitely high then N_2 becomes equal to N_1. So to get population inversion the temperature T of equation (1) must be negative.

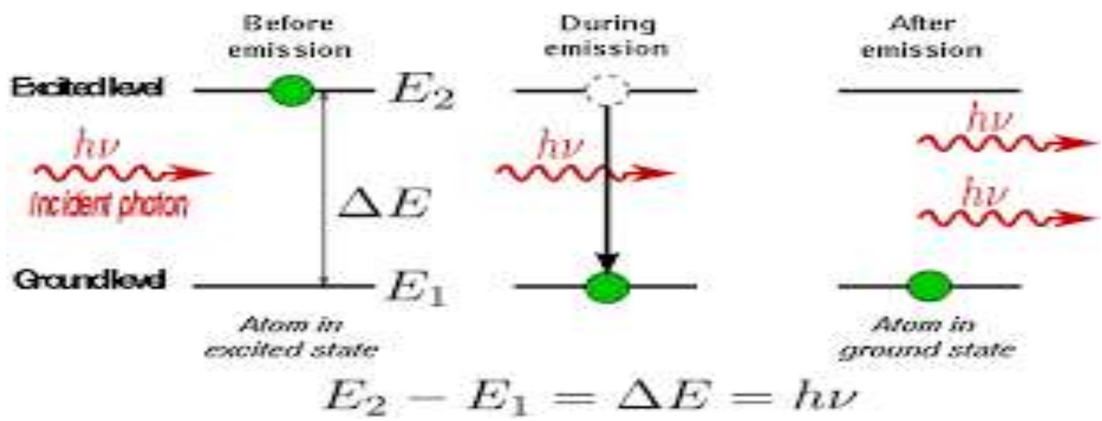
For this reason the state of population inversion is misleadingly called as negative temperature. In fact, population inversion can be achieved at normal temperature and Boltzmann law is not applicable here.

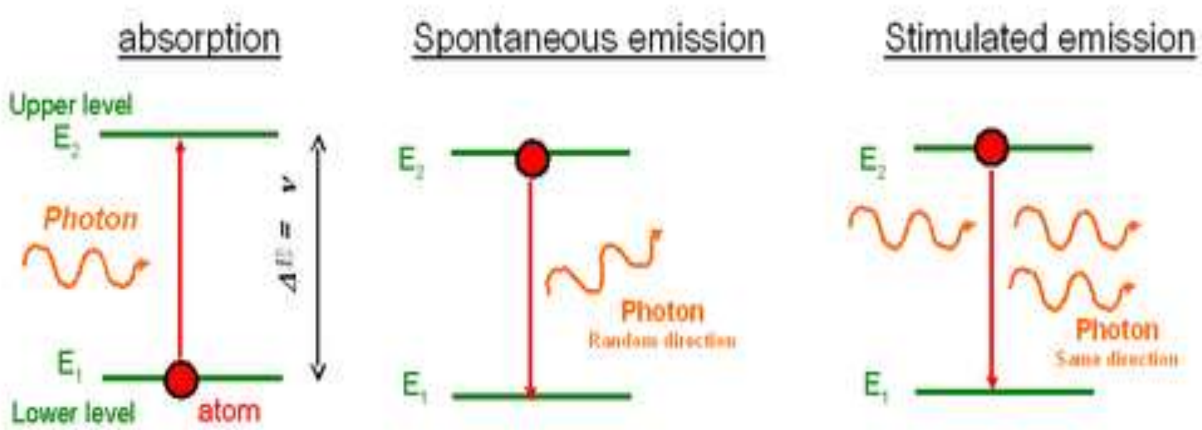
Metastable state :

The metastable states are certain levels of some atoms where the excited electrons with the absorbed photons can stay for a much longer duration of time, which is equal to about 3×10^{-5}second.

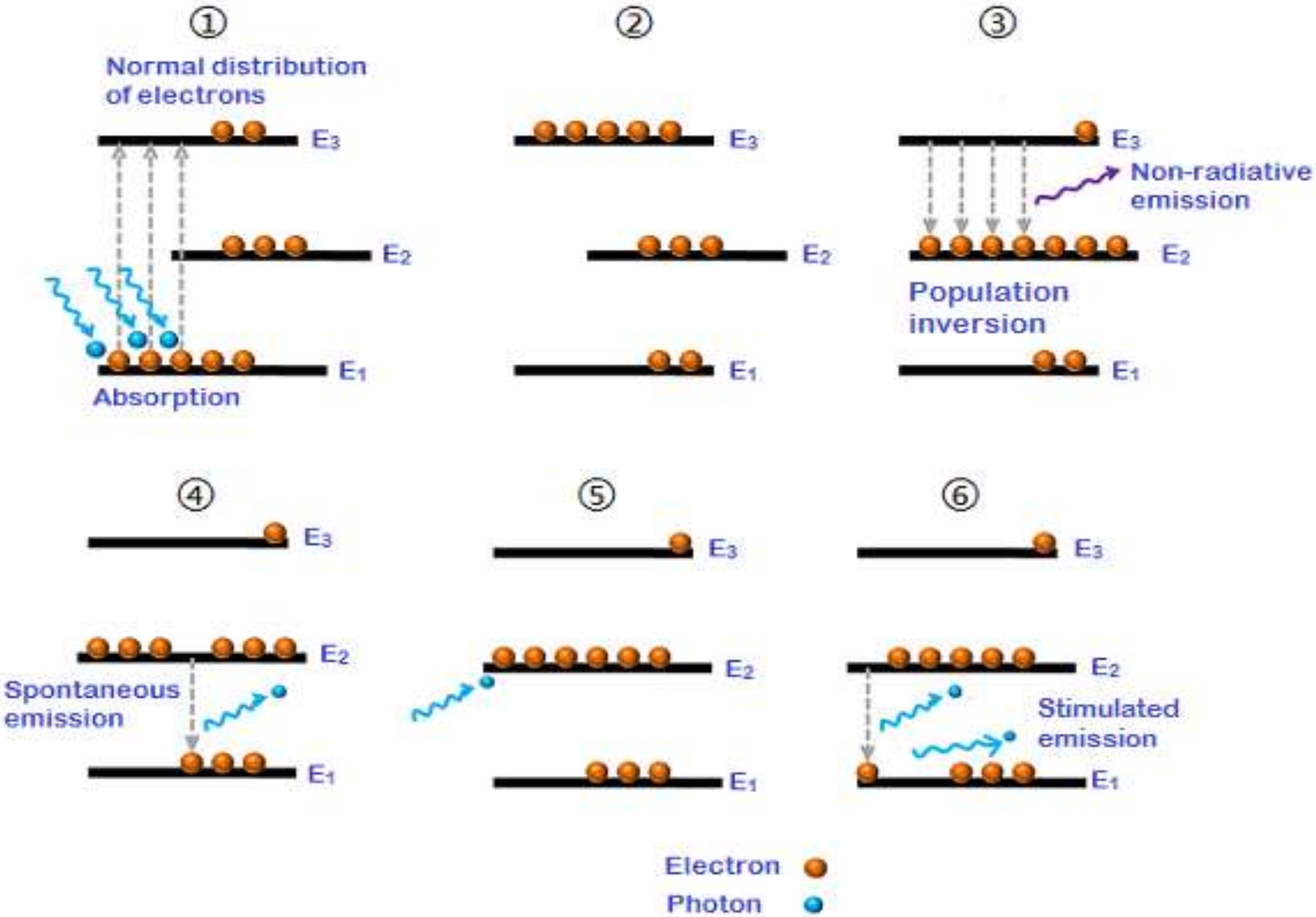
An electron which is raised to the excited state can dropped down to the meta stable state by non-radiating transition i.e. by vibrational energy transfer within the structure of the substance and can stay there for a longer duration of time.

Due to this energy transfer the substance generally get heated and the electrons are trapped there in the meta stable state .


Before emission
During emission
After emission
Excited level
Ground level
E_2
E_1
$h\nu$
incident photon
ΔE
Atom in excited state
Atom in ground state
$E_2 - E_1 = \Delta E = h\nu$


absorption
Spontaneous emission
Stimulated emission
Upper level
E_2
Photon
E_1
Lower level
atom
$\Delta E = h\nu$
Photon
Random direction
Photon
Same direction

Population inversion in 3-level laser



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When the irradiation is continued, number of atoms in the excited state increase. In this way we can get population inversion.

If a photons of appropriate energy which is equal to $E= E_2-E_1$, collide these atoms in the metastable state then we get extremely intense monochromatic, coherent laser beam.

Principle of laser:

When an atom in ground state E_1 absorbs an incident photon it becomes excited and goes to the higher energy state E_2. An atom thus excited can stay there for a maximum time of about 10^{-8} second. Within this time it dropped back to the ground state by emitting a photon spontaneously. This type of emission is known as spontaneous emission.

But if a photon of the energy hɣ which is equal to E_2-E_1, as that of the difference of the two energy levels of the atom, strikes the atom in excited state, the emission of the absorbed atom can be stimulated.

The impinging photon along with the stimulated emitted photon moves in same direction and are exactly in the same phase with each other. Hence they are coherent. After that the excited atom comes down to the ground state. Such emission is called as stimulated emission.

In an ordinary system, most of the atoms remain in the ground state. So when photons of appropriate energy impinge upon the atoms both spontaneous and stimulated emission are present, but spontaneous emission predominates.

In laser a situation is created artificially such that the stimulated emission is increased millions of times over spontaneous emission and the light thus emitted are made to travel in a given direction .

To obtain such a condition it is essential that the number of excited atoms in the metastable state must exceed millions of time over the numbers of atoms in the ground state so that probability of encounter of the photons with the atoms in the excited state are greatly increased.

This condition is known as population inversion. This is the most essential condition for the laser action.

Einstein coefficients :

Einstein coefficients are mathematical quantities which are the measure of the probability of absorption or emission of light by an atom or molecule.

The Einstein *A* coefficient is related to the rate of spontaneous emission of light.

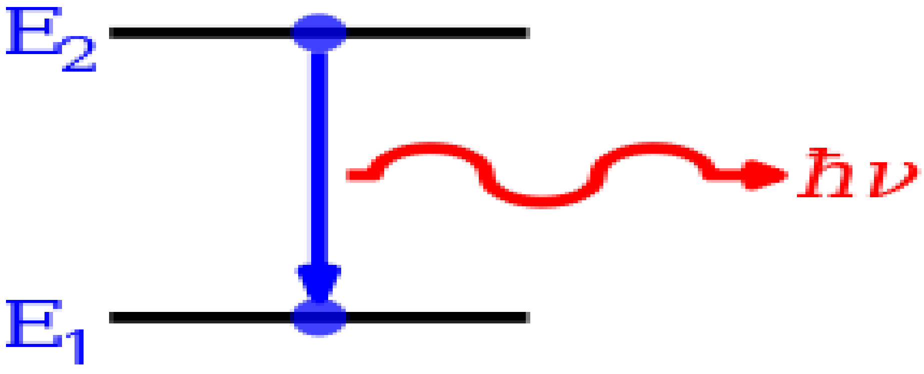
Einstein *B* coefficients is related to the absorption and stimulated emission of light.

Spontaneous emission:

It is the process by which an electron spontaneously decays from a higher energy level to a lower one.

The probability per unit time per unit volume that an electron can decay spontaneously from state 2 to state1, emitting a photon of energy $E_2 - E_1 = h\nu$ is denoted by Einstein coefficient A_{21}. Therefore Probability for spontaneous decay is A21.N2

Here N2 is the no. of atoms in state 2 per unit volume



Spontaneous emission

Probability for spontaneous decay is A21.N2

here N2 is the no. of atoms in state 2 per unit volume

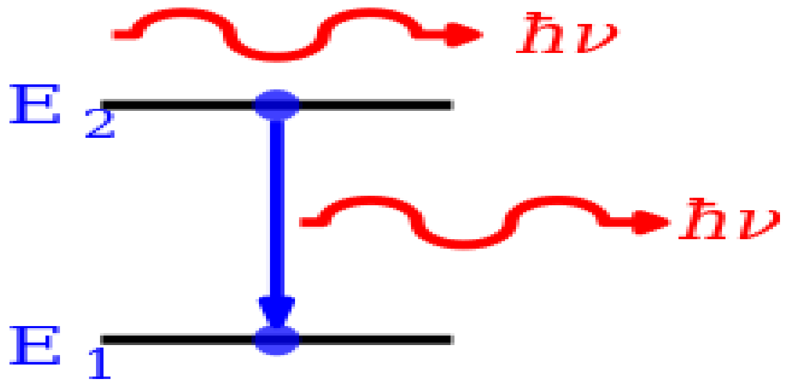
Let N_1 and N_2 be the number density of atoms in state 1 and state 2 in thermal equilibrium respectively.

Then the number of transition per unit time per unit volume due to spontaneous emission from state 2 to state 1 will be **$A_{21}.N_2$** .

Stimulated emission:

When a photon of energy $h\nu = E_2 - E_1$ interacts with the atom in upper state 2, then we get stimulated emission. The number of such transition depends on the number of atom in state 2 and the number of incident photons i.e radiation energy density $U\nu$. So number of stimulated transition per unit time per unit volume is $N_2B_{21}U\nu$.

Where B21 is Einstein B coefficient which is the probability of radiation induced transition from state 2 to state 1



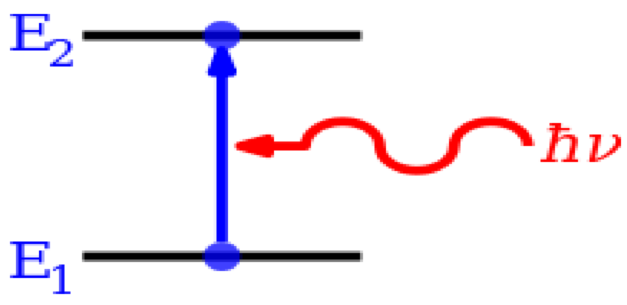
Stimulated emission

Probability for stimulated decay from state 2 to state 1 is $N_2B_{21}\ U\nu$.

Stimulated absorption :

When a photon of energy an energy $hv = E_2 - E_1$ interacts with the atoms in lower state 1 and excited the atoms from lower state to higher state then the number of such transitions per unit volume per unit time will be $N_1B_{12}U\nu$.

where B_{12} is the probability of the stimulated absorption.



Stimulated absorption

In thermal equilibrium net downward transitions must be equal to net upward transitions.

$$A_{21}.N_2 + N_2B_{21}\, U\nu = N_1B_{12}U\nu$$

$$U\nu = \frac{A21}{B21} \cdot \frac{1}{\frac{N1}{N2}\frac{B12}{B21} - 1}$$

Considering the radiation to be similar to Plank's black body radiation and applying Boltzmann's distribution law (considering the degeneracy of each level to be unity) we can show that

$$U\nu = \frac{8\pi h\gamma^3}{c^3} \cdot \frac{1}{e^{h\gamma/KT} - 1}$$

Since $N_2/N_1 = e^{-h\gamma/KT}$

And $B_{12}=B_{21}$

probability of stimulated emission = probability of stimulated absorption

Therefore $$\frac{A21}{B21} = \frac{8\pi h\gamma^3}{c^3}$$

This is known as Einstein's relation.

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