18PYB101J MODULE-5

LECTURE 1 & 2

- **LASERS INTRODUCTION**
- **BASIC PRINCIPLE,**
- **EINSTEIN’S THEORY**
- **POPULATION INVERSION, LASER LEVEL**
- **TYPES AND CHARACTERISTICS OF LASER**

Lasers

A Brief History of Lasers

Laser is the acronym of Light Amplification by stimulated emission of Radiation. Laser is light of special properties.

- In 1704, Newton characterized light as a stream of particles. Maxwell’s electromagnetic theory explained light as rapid vibrations of EM field due to the oscillation of charged particles.

- It was until Plank introduced the ***"quantum"*** concept in 1900 when this was explained. Thus energy is not continuous, it is discrete and can only be the multiples of a small unit.

- Einstein proposed the concept of ***"photon",*** we can say light is composed of individual particles called photons which posses a discrete amount of energy or quanta.

- Einstein also predicted in 1917 that when there exist the population inversion between the upper and lower energy levels among the atom systems, it was possible to realize amplified stimulated radiation, i.e., laser light.

- Many people tried to find methods for amplified stimulated emission, but it was not realized until 1960, about half a century after Einstein's prediction.

- When we know the principles of laser, this won't be too big a surprise. But the wide and continuously expanding applications of lasers are indeed miracles.

Basic Principle

Absorption

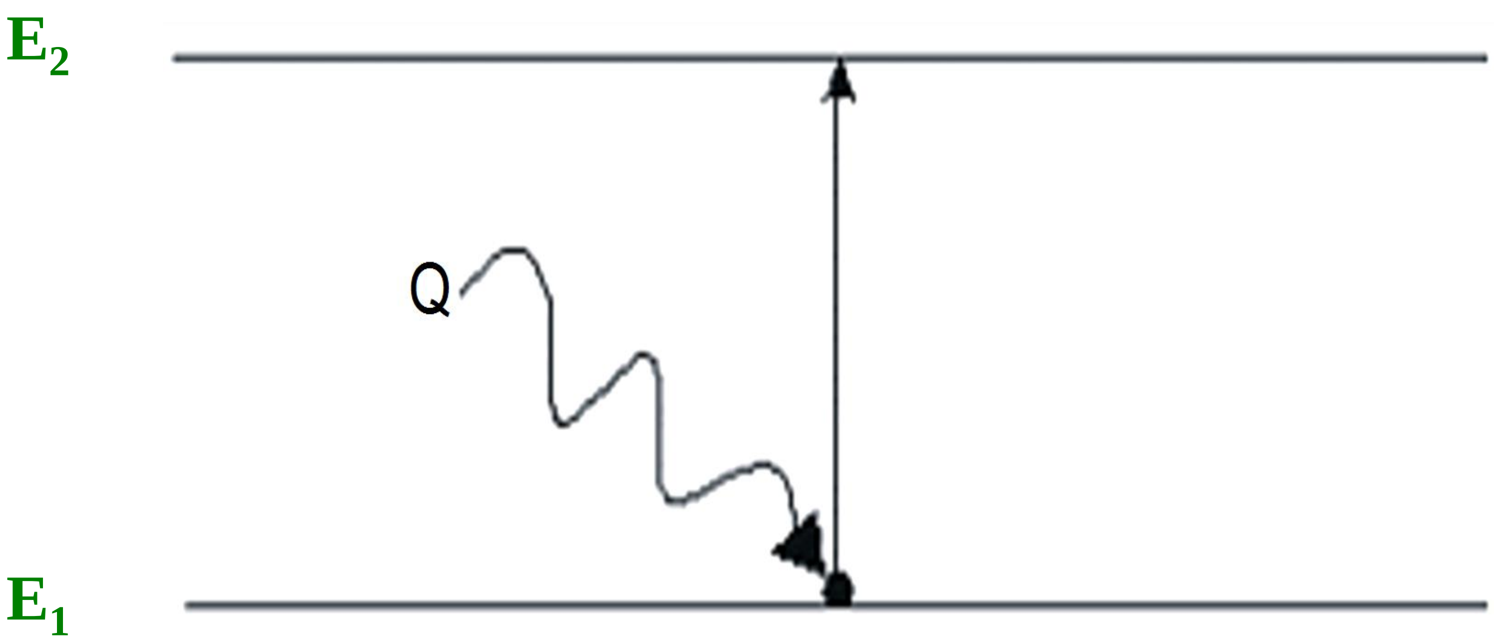
i. A system containing two energy levels namely the ground state and the excited state.

ii. The number of atoms in the ground state is more than the number of atoms in the excited state.

iii. For an atom to move from the ground state to the excited state it should absorb energy at least equal to the difference between the two energy levels.

iv. If E_1 is the energy of atoms in the ground state and E_2 the energy of atoms in the excited state.

v. The energy required for excitation should be greater than or equal to $E_2 – E_1$.



Absorption process

The process of raising the atoms from the ground state to the excited state is known as absorption.

The number of atoms, per unit volume undergoing absorption will be proportional to N_1, the number of atoms per unit volume in the ground state and *Q*, the energy density of the incident radiation.

The number of atoms undergoing absorption per unit volume per unit time can be expressed as

$$N_{ab} = B_{12} N_1 Q \qquad (1)$$

B12 is called the proportionality constant, which depends on the energy levels $\boldsymbol{E_1}$ and $\boldsymbol{E_2}$.

Emissions

An atom after absorbing energy goes to the excited state and does not stay there indefinitely.

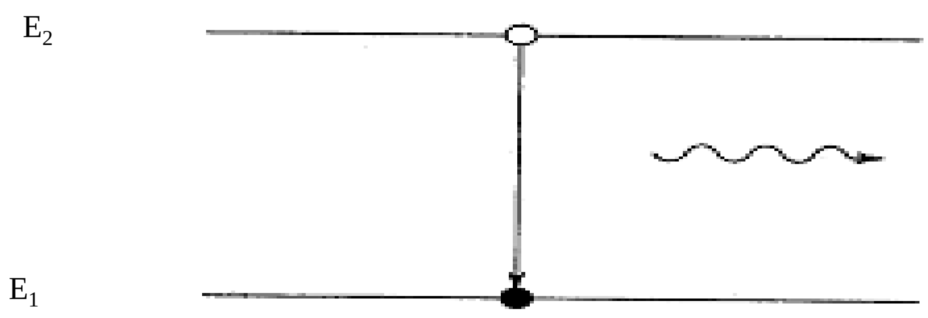
They make transition to the ground state E_1.

Spontaneous Emission

- The spontaneous emission does not require any external energy.

- After its lifetime from the excited state atom goes back to the ground state.

- The average lifetime of carriers in the excited state is 10^{-8} sec, thus they go back to the ground state by emitting energy.



The number of atoms making spontaneous emission per unit volume per unit time can be expressed as

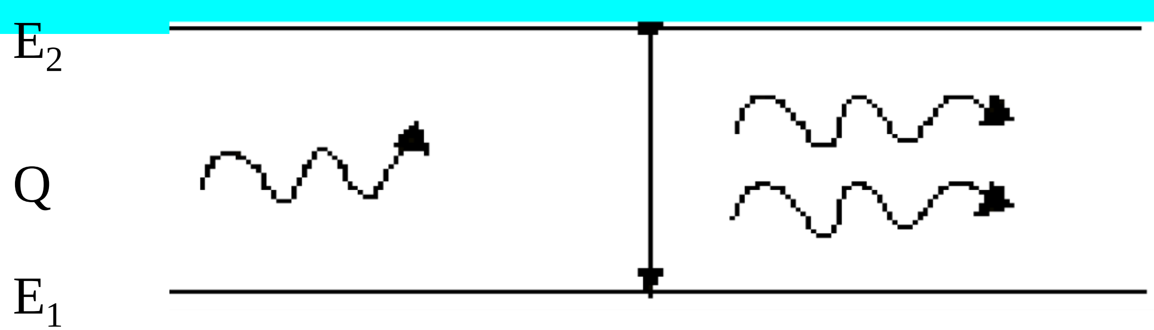
$$N_{sp} = A_{21} N_2 \qquad (2)$$

A_{21} is proportionality constant, which depends on the energy levels.

Stimulated emission

- The atom in the excited state is given an external energy and is forced to go to the ground state.

- The atom in the excited state is not allowed to stay for its lifetime.



Stimulated emission

The number of transitions per unit volume per unit time can be expressed as

$$N_{st} = B_{21} N_2 Q \quad (3)$$

B_{21} is a constant, which depends on the energy levels. A_{21}, B_{12} and B_{21} are called as Einstein's coefficients.

Einstein’s theory of spontaneous and stimulated emission

At thermal equilibrium, the number of upward transition should be equal to the number of downward transitions per unit volume per unit time.

$$B_{12}N_1Q = A_{21}N_2 + B_{21}N_2Q \qquad (4)$$

(or)

$$Q = \frac{A_{21}}{\left(\frac{N_1}{N_2}\right)B_{12} - B_{21}} \qquad (5)$$

From Boltzmann's distribution law, at a given temperature *T*, the ratio of the population of two levels is given by

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/kT} \qquad (6)$$

(or) $$\frac{N_1}{N_2} = e^{h\nu/kT} \quad (7)$$

where k is Boltzmann constant. Substituting the value of N_1/N_2 in this Eqn

$$Q = \frac{A_{21}}{\left(\frac{N_1}{N_2}\right)B_{12} - B_{21}}$$ we get,

$$Q = \frac{A_{21}}{B_{12}e^{h\nu/kT} - B_{21}} \quad (8)$$

According to Planck's black body radiation theory, we have

$$Q = \frac{8\pi hc}{\lambda^5} \frac{1}{(e^{h\nu/kT} - 1)} \qquad (9)$$

Here c is the velocity of light.

If $B_{12} = B_{21} = B$, Eqn (8) can be expressed as

$$Q = \frac{A_{21}}{B_{21}(e^{h\nu/kT} - 1)} \qquad (10)$$

Comparing the above Eqns we get

$$\frac{A_{21}}{B_{21}} = \frac{8\pi hc}{\lambda^5} \qquad (11)$$

This eqn gives the ratio between spontaneous and stimulated coefficients. *A* and *B* are called Einstein's coefficients.

Population inversion-Negative temperature condition

❖Boltzmann distribution law specifies what fraction of atoms are found in any particular energy state for any given equilibrium temperature

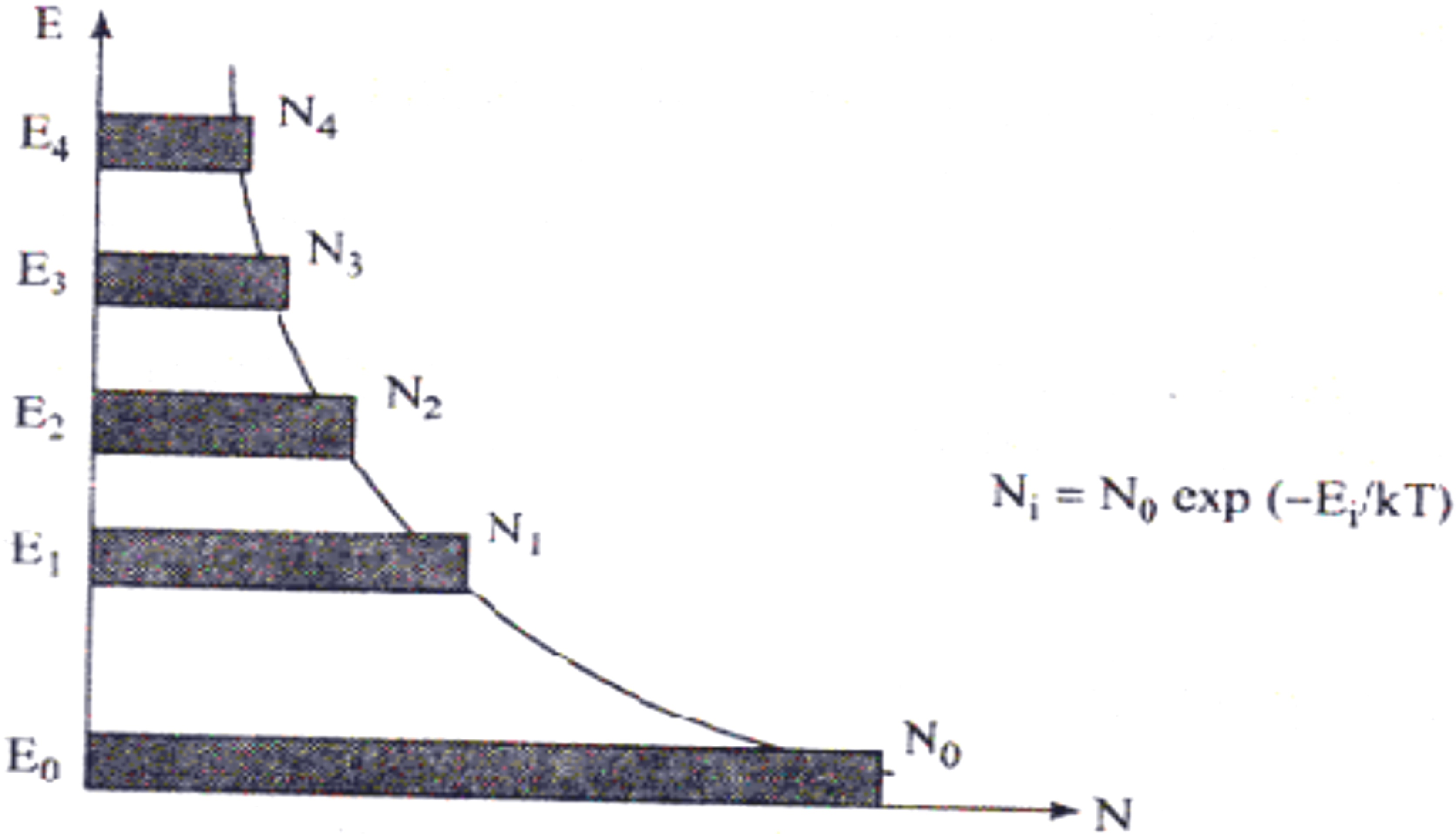
❖If N_0 is the number of atoms in the ground state, N_1 is the number of atoms in the excited state of energy E_2 measured relative to the ground state, then (ignoring degeneracy)

$$\frac{N_i}{N_o} = \exp\left(\frac{-E_i}{kT}\right)$$

where T is the absolute temperature in degree kelvin, and $k = 1.38 \times 10^{-23}$ K (Boltzmann constant)

Boltzmann distribution is graphically represented in fig

- For laser action, $N_1 > N_0$ (i.e., absorption <stimulated emission)
- The establishment of $N_1 > N_0$ is known as population inversion.



Boltzmann distribution for several energy levels

- The population inversion condition required for light amplification is a non-equilibrium distribution of atoms among the various energy levels of the atomic system.
- i.e., a *negative temperature condition* which establishes $N_1 > N_0$ is known as population inversion.

Threshold population inversion

For a medium to amplify an incident radiation, one must create a state of population inversion in the medium.

- Such a medium will behave as an amplifier for those frequencies, which will fall within its line width. In order to generate radiation this amplifying medium is placed in an optical resonator, which consists of a pair of mirrors facing each other.

- Radiation, which bounces back and forth between the mirrors, is amplified by the amplifying medium and also suffers losses due to the scattering by the medium, diffraction due to finite mirror sizes etc.

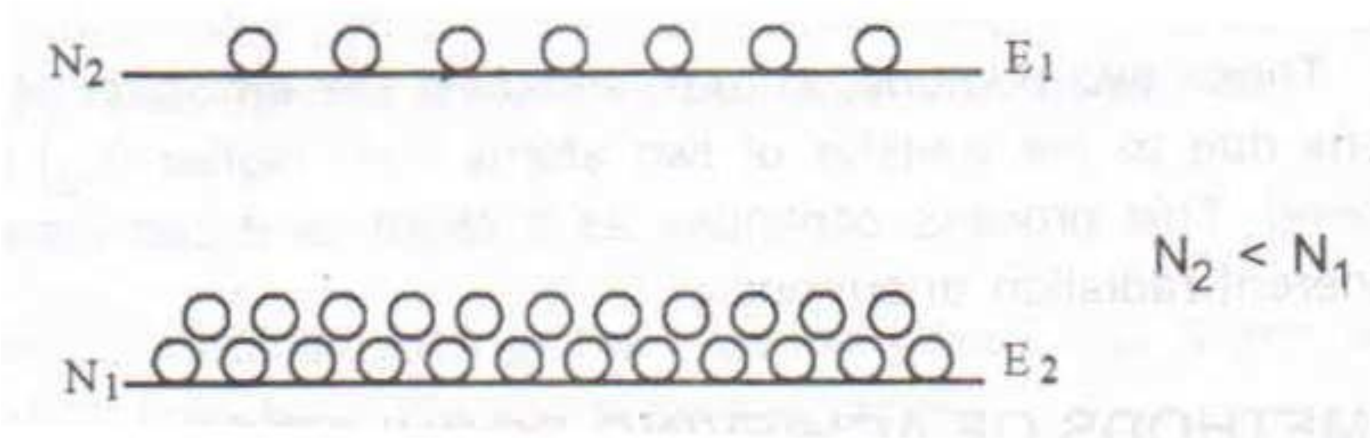
If the oscillation has to be sustained in the cavity then the losses must be exactly compensated by the gain.

Thus a minimum population inversion density is required to overcome the losses and this is called the *threshold population inversion*.

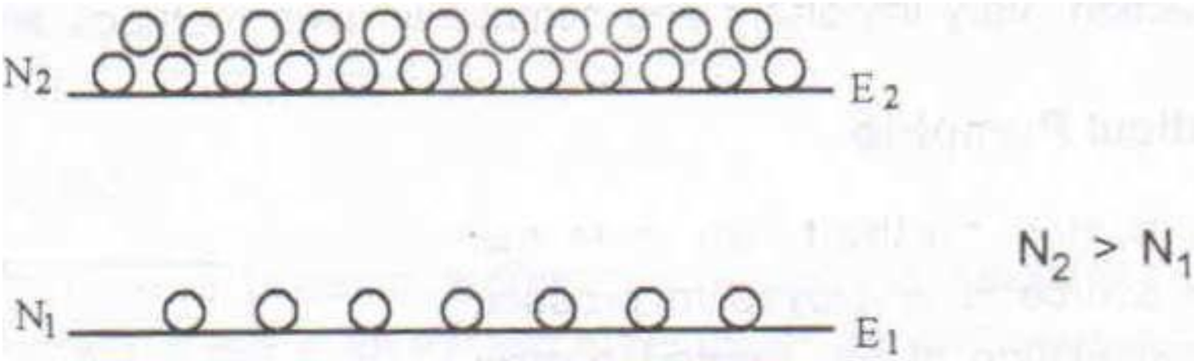
Two level laser system

- For a system involving two energy levels, by direct pumping the higher level cannot be made more populated than the lower level
- Two level laser system is impossible

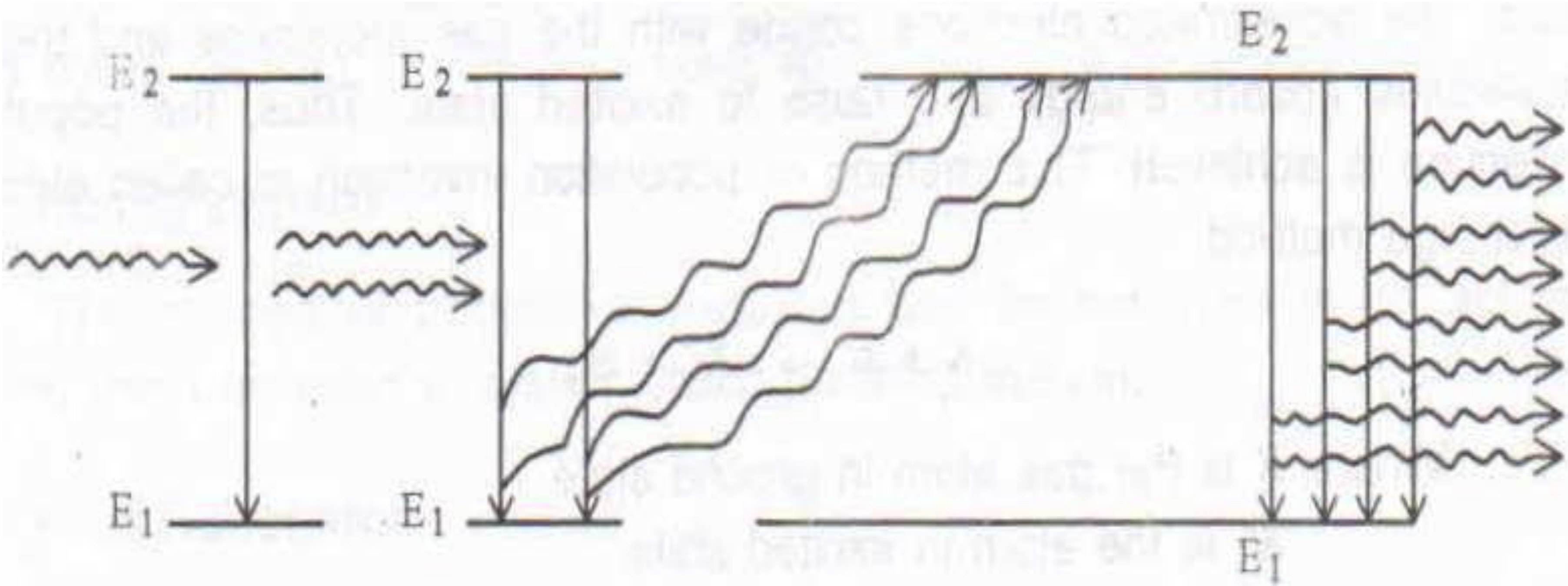
Normal population



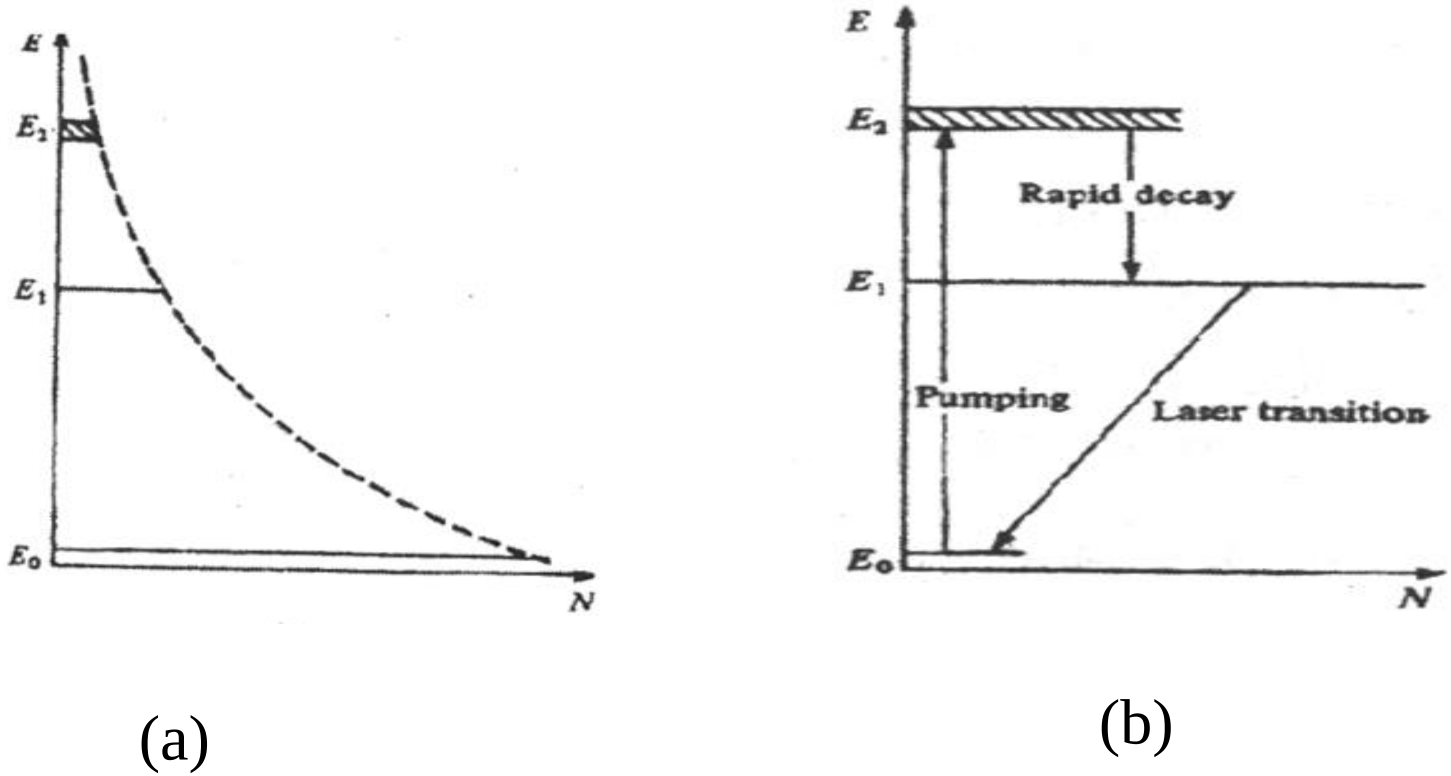
Population Inversion



Laser Action



Three level laser system



Population of the energy levels by pumping in a three level system (a) Boltzmann distribution before pumping and (b) distribution after pumping and the transitions involved.

✓If the collection of atoms is intensely pumped, a large number of atoms are excited through stimulated absorption to the highest energy level E_2.

✓If the level E_2 has very short lifetime, the atoms delay fast to level E_1.

✓If the level E_1 has relatively longer life time (a state known as *meta stable)* atoms tend to accumulate at $E_{1.}$

✓With intense pumping from E_0 to E_2, because of rapid decay to E_1, it is possible to bring in non-equilibrium distribution of atom (i.e., E_1 is more populated than E_0)

- Laser transition takes place between level E_1 (called upper laser level) and level E_0 (called lower laser level).
- Since ground level E_0, happens to be lower laser level, more than one-half of the ground state atoms must be pumped to the upper state to achieve population inversion ($N_1 > N_0$).

✓Therefore, three level pumping schemes generally require very high pumping powers.

✓If pumping continues when the condition ($N_1 > N_0$) is reached, stimulated emission rate exceeds stimulated absorption rate.

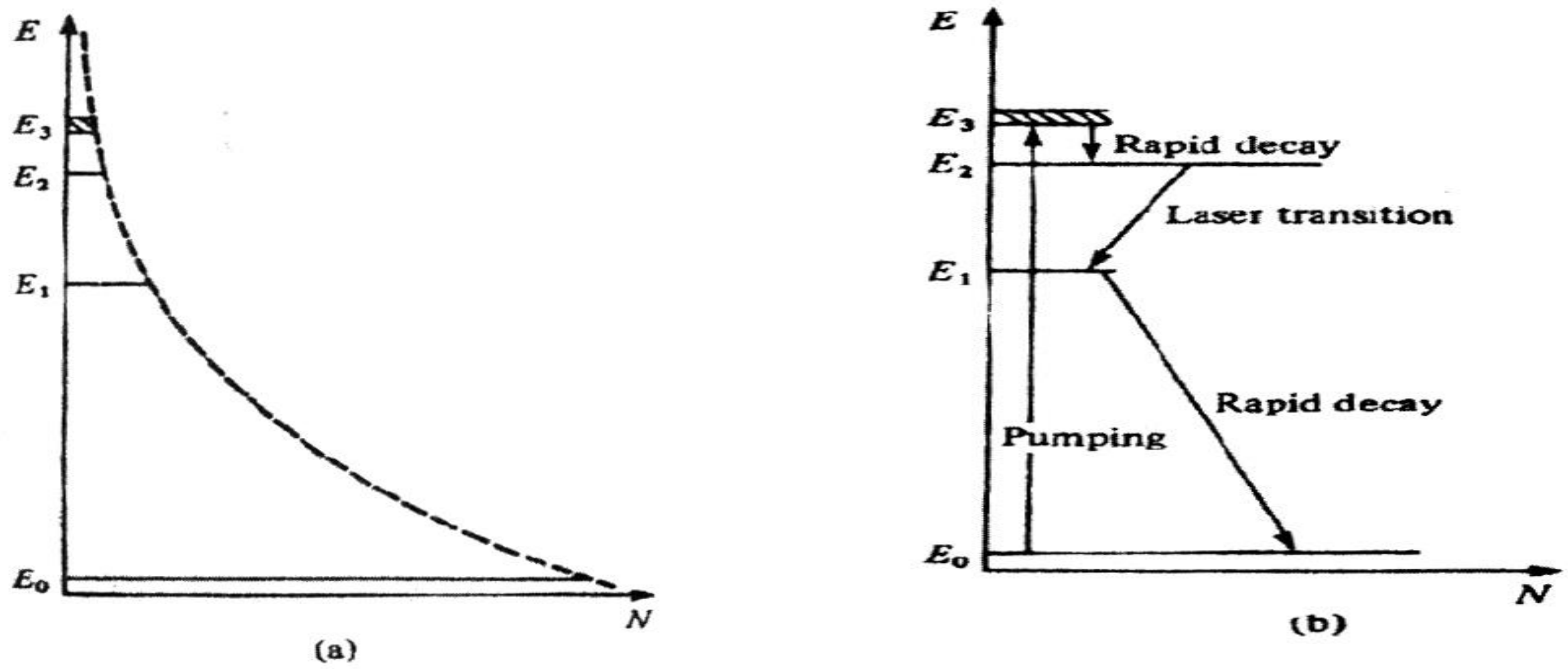
✓This immediately depopulates the upper laser level and hence populate the lower laser level.

✓Hence it is not possible to continually maintain the upper laser level more populated than the lower laser level.

✓This scheme is suitable for only pulsed mode.

✓Ruby laser is an example for three level laser scheme

Four level laser system



Population of the energy levels by pumping in a four level system (a) Boltzmann distribution before pumping and (b) distribution after pumping and the transitions involved.

•In four level scheme, on pumping, the atoms are lifted from the ground state to the highest of the four levels involved in the process.

•From this level, the atoms decay to the metastable state E_2 and the population of this state grows rapidly.

•If the life times of the (E_3 -> E_2) and the (E_1->E_0) is short, a population inversion on the (E_2 -> E_1) transition can be achieved and maintained with moderate pumping.

•Since ground level is not the lower laser level, there is no need to pump more than one-half of the population to the higher level.

•In this scheme E_1 is the lower laser level and it is relatively easier to maintain population inversion between levels E_2 and E_1 continuously with moderate pumping and continuous wave (CW) output.

•For this to happen (E_1-> E_0) transition must be very fast.

•If this transition is relatively slow, even four level laser will work in pulsed mode.

•He-Ne laser is an example for a four level laser scheme.

Laser action summary

Step 1 : Choose a proper lasing medium

Step 2 : Establish population inversion by suitable pumping

Step 3 : Stimulated emission takes place

Step 4 : Positive feed back (optical resonator)

Step 5 : Amplification of light

Characteristics of laser

(i) Directionality

- The directionality of a laser beam is expressed in terms of the full angle beam divergence which is twice the angle that the outer edge of the beam makes with the axis of the beam.

- The outer edge of the beam is defined as a point at which the strength of the beam has dropped to 1/e times its value at the centre.

- At d_1 and d_2 distances from the laser window, if the diameter of the spots are measured to be a_1 and a_2 respectively, then the angle of divergence (in degrees) can be expressed as

$$\phi = \frac{(a_2 - a_1)}{2(d_2 - d_1)}$$

- For a typical laser, the beam divergence is about 1 milli radian.

(ii) Monochromaticity

- The degree of monochromaticity is expressed in terms of line width (spectral width)
- The line width is the frequency spread $\Delta\nu$ of a spectral line
- The frequency spread $\Delta\nu$ is related to the wavelength spread $\Delta\nu$ as

$$\Delta\lambda = -(c/\nu^2)\,\Delta\,\nu$$

- The three most important mechanisms which give rise to the spectral broadening (frequency spread) are Doppler broadening, Collision broadening and natural broadening .

(1) Doppler broadening

The atoms which emit radiation are not at rest at the time of emission and depending on their velocities and the direction of motion, the frequency of the emitted radiation changes slightly and this broadening is called Doppler broadening.

(2) Collision broadening

If the atoms undergo collision at the time of emitting radiation there will be change in the phase of the emitted radiation resulting in frequency shift and is known as collision broadening.

(3) Natural broadening

In solid materials, an atomic electron emitting energy in the form of a photons leads to an exponential damping of the amplitude of the wave train and the phenomenon is called natural broadening.

Coherence

The purity of the spectral line is expressed in terms of coherence Coherence is expressed in terms of *ordering of light field.*

(1) temporal coherence and (2) spatial coherence

(i) Temporal coherence

Temporal coherence refers to correlation in phase at a given point in a space over a length of time.

i.e, if the phase difference between the two light fields $E_1(x,y,z,t_1)$ and $E_2(x,y,z,t_2)$, is constant, the wave is said to have temporal coherence.

The maximum length of the wave train on which any two points can be correlated is called coherent length.

$$\text{Coherent time} = \frac{\text{coherent lentth}}{\text{velocity of light}}$$

The high degree of temporal coherence arises from the lasers monochromaticity.

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(ii) Spatial coherence

- Spatial coherence refers to correlation in phase at different points at the same time.

- i.e, if the phase difference between the two light fields

- $E_1(x_1,y_1,z_1,t)$ and $E_2(x_2,y_2,z_2,t)$ is constant, the wave is said to have spatial coherence.

- The high degree of spatial coherence results, since the wave fronts in a laser beam are in effect similar to those emanating from a single point source.

(4) Intensity or Brightness

- When two photons each of amplitude ‘a’ are in phase with each other, then by young’s principle of superposition the resultant amplitude is ‘2a’ and the intensity is proportional to $(2a)^2$ i.e, $4a^2$.
- In laser, many number of photons (say n) are in phase with each other, the amplitude of the resultant wave becomes ‘na’ and hence the intensity is proportional to n^2a^2.
- Thus due to coherent addition of amplitude and negligible divergence, the intensity increases enormously.
- i.e., 1mw He-Ne laser can be shown to be 100 times brighter than the sun.

Difference between spontaneous emission and stimulated emission

Property	Spontaneous emission (ordinary light)	Stimulated emission (laser light)
Stimuli	Not required	Required
Monochromaticity	Less	High
Directionality	Less	High
Intensity	Less	High
Coherence	Less	High

What fraction of sodium atom is in the first excited state in a sodium vapour lamp at a temperature of 250°C.

$$T = 250 + 273 = 523\ K$$

$$K = 1.38 \times 10\text{-}23\ J/K$$

$$\lambda = 5900 \times 10^{-10} m$$

$$N_2/N_1 = e^{-(E_2 -- E_1)/kT} = e^{-h\nu/kT}$$

$$\nu = C/\lambda$$

$$N_2/N_1 = 5.364 \times 10^{-21}$$

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A He-Ne laser emits light at a wavelength of 632.8nm and has an output power of 3 mw. How many photons are emitted in each minute by this laser when operating?

$$\lambda = 6328 \times 10^{-10} \text{m} \qquad P = 3\text{mw} = 3 \times 10^{-3}\ \text{w}$$

$$\nu = c/\lambda = 4.74 \times 1014 \text{ Hz}$$

$$E = h\nu = 3.14 \times 10\text{-}19 \text{ J}$$

$$\text{Photons /minute} = n \times 60$$

5.7324 x 1010 photons / minute.

For a He-Ne laser at 1 m and 2 m distances from the laser the output beam spot diameters are 4mm and 6mm respectively , calculate the divergence.

$$d1 = 1m$$

$$d2 = 2m$$

$$a_1 = 4mm = 4 \times 10^{-3} m$$

$$a_2 = 6mm = 6 \times 10^{-3} m$$

$$\Phi = a_2 - a_1 / 2(d_2 - d_1)$$

$$\Phi = (6-4) \times 10^{-3} / 2(2-1)$$

$$\phi = 10^{-3} \text{ radian} = 1 \text{ milli radian}$$

Find the relative population of the two states in Nd:YAG laser that produces a light beam of wavelength 1.06μm at 300K.

$$\frac{N_2}{N_1} = e^{-(E_2 - E_1)/kT} = e^{-h\nu/kT} = \mathbf{2.39 \times 10^{-20}}$$