

LASER (Part I)

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Lasers

"Light Amplification by Stimulated Emission of Radiation"
 Laser is a source of high degree of coherence. The laser source will be 'n' times more intense than an ordinary source.

In ordinary source $I = I_1 + I_2 + I_3 + \dots + I_n = nI$

But, In laser source the resultant amplitude at a point is the algebraic sum of the individual disturbances (amplitude). Laser source is spatially coherent i.e. disturbances are in phase, so we get

$$A = A_1 + A_2 + \dots + A_n = nA_1$$

$$I \propto A^2 \Rightarrow I = n^2 A_1^2 = n(nI_1) \text{ [where } I_1 \propto A_1^2]$$

[where n are the number of atoms taking part in the emission]

Absorption, spontaneous and stimulated Emission of Radiation and Einstein Coefficients -

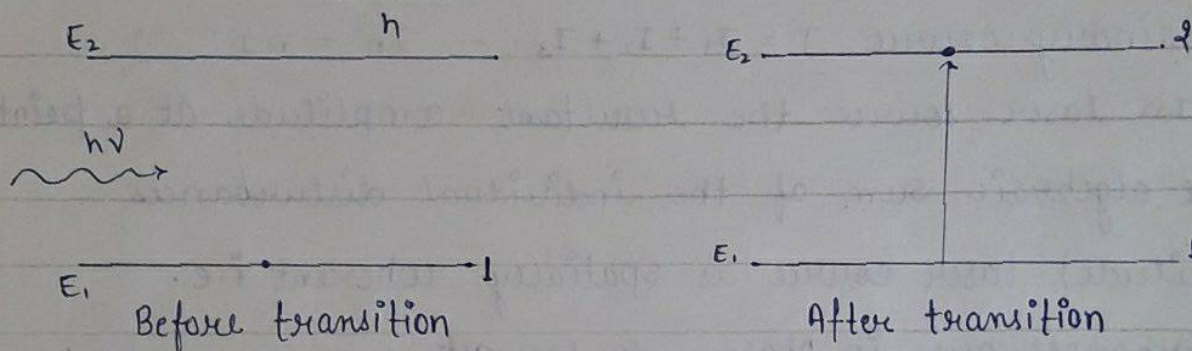
The transition of Energy (atom) in a system can occur in two ways. In one way, the atom can absorb energy and go to higher energy level (or become excited). In another way, it can also come back to the lower energy level by release energy (emission or deexcitation). Thus the transfer of energy can take place by either absorption or emission.

Emission or deexcitation of atom can occur by spontaneous or stimulated emission. ⁽²⁾

Absorption - Let us consider two energy levels in a part atom.

The lower energy level is denoted by 1 and upper level by 2. If the atom is initially in state 1, it can be raised to state 2 by absorbing a photon of light, whose frequency is

$$\nu = \frac{E_2 - E_1}{h} \quad \text{--- (1)}$$



Here E_1 and E_2 are energies of the levels 1 and 2 respectively and h is plank's constant. This process is known as absorption. The probability of such a transition depends on the two energy levels under considerations. It also depends on the number of photons incident on the system or on the energy density of incident radiations.

$$\text{Thus } P_{12} \propto U(\nu) \Rightarrow P_{12} = B_{12} U(\nu) \quad \text{--- (2)}$$

where P_{12} is the probability of absorption, $U(\nu)$ is the energy density. The rate of absorption will be given by

$$R_{12} = N_1 B_{12} U(\nu) \quad \text{--- (3)}$$

Where N_1 = number of atoms in lower energy level

R_{12} = number of atoms going from state 1 to state 2 by absorbing a photon.

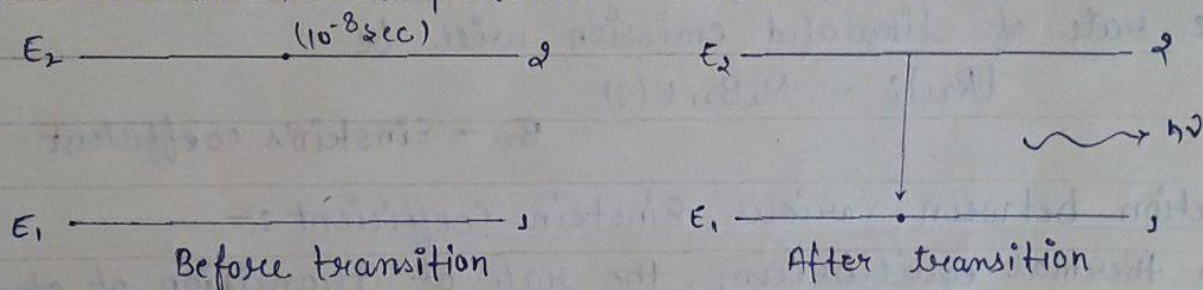
B_{12} = Einstein's Co-efficient of absorption

(3)

Spontaneous Emission: - The atom present in the excited state has a small life time (mean life $\sim 10^{-8}$ sec).

So it can spontaneously drop (Jump) from state 2 to state 1 by emitting a photon of frequency $\nu = \frac{E_2 - E_1}{h}$. This is called spontaneous emission.

Probability of such a process depends on the two energy levels under consideration. It is independent of the presence of any photon present in the system. Therefore, any of electron can jump to lower state randomly and the photons emitted are never be in phase. So, spontaneous emission provides incoherent photons. $(P_{21})_s = A_{21}$ — (4)



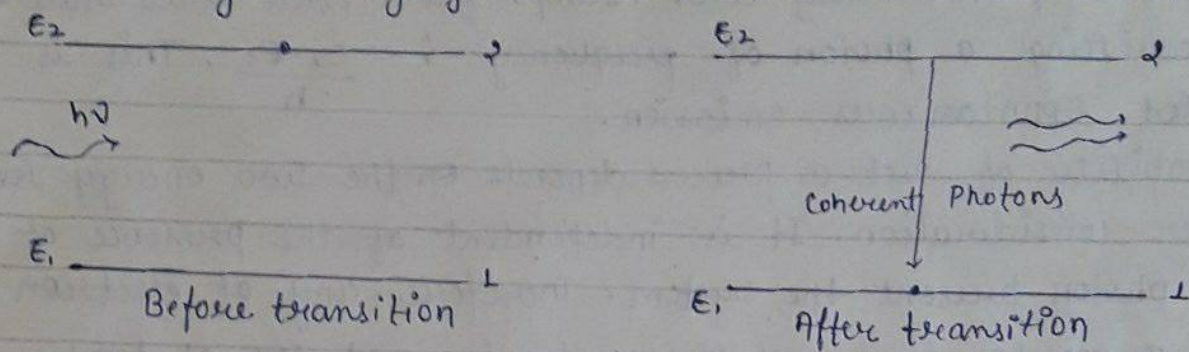
The rate of spontaneous emission will be

$$(R_{21})_s \propto N_2 \Rightarrow (R_{21})_s = A_{21}N_2 \text{ — (5)}$$

A_{21} is Einstein's co-efficient of spontaneous emission and N_2 are the number of atoms in excited state.

Stimulated Emission: - Einstein proposed that if a photon of appropriate frequency is present, it is not essential that it may always be absorbed. It can also interact with an atom in the excited state and induce that atom to emit a new photon. Such a process of emission is known as induced or stimulated emission. In this type of emission is, that the phase, direction, polarization, energy of emitted photon is same

as that of incident photon. It means, both photons are completely coherent with each other. Thus, this type of emission is to get a highly coherent beam i.e. laser beam (light). (4)



The probability of stimulated emission will thus be proportional to the energy density $U(\nu)$. Thus $(P_{21})_i = B_{21}U(\nu)$ — (5)

The rate of stimulated emission will be

$$(R_{21})_i = N_2 B_{21} U(\nu)$$

$B_{21} \rightarrow$ Einstein's coefficient

Relation between Various Einstein Coefficient :-

In thermal equilibrium, the rate of transition of atom by absorption of radiation is equal to the rate of transition by emission of radiation.

$$R_{\text{stimulate absorption}} = R_{\text{sp. emission}} + R_{\text{stimulated emission}}$$

using Eqⁿ $N_1 B_{12} U(\nu) = A_{21} N_2 + N_2 B_{21} U(\nu)$

$$U(\nu) = \frac{A_{21} N_2}{[B_{12} N_1 - B_{21} N_2]} = \frac{A_{21} N_2}{B_{21} N_2 \left[\frac{B_{12} N_1}{B_{21} N_2} - 1 \right]} \quad \text{--- (A)}$$

According to Maxwell-Boltzmann law, the population density in n^{th} energy level having an energy E_n at tempⁿ. T is given by $N_n \propto e^{-E_n/KT}$.

then $\frac{N_1}{N_2} = \frac{e^{-E_1/KT}}{e^{-E_2/KT}} = e^{(E_2 - E_1)/KT} = e^{h\nu/KT}$ — (B)

from (A)
$$U(\nu) = \frac{A_{21}}{B_{21} \left[\frac{B_{12}}{B_{21}} (e^{h\nu/KT}) - 1 \right]} \quad \text{--- (C)}$$

Now according to plank law for the distribution of radiation energy, the energy density at frequency ν is given by
$$U(\nu) = \frac{8\pi h \nu^3}{c^3 [e^{h\nu/KT} - 1]} \quad \text{--- (D)}$$

Compare (C) & (D)
$$\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3} \times \frac{B_{12}}{B_{21}} \cdot \frac{B_{12}}{B_{21}} = 1$$

Principle of laser :- We know that, in thermal equilibrium the rate of stimulated absorption is equal to total rate of both stimulated emission and spontaneous emission, but whenever an external photon is incident upon the system, the equilibrium gets disturbed.

Also we know that - $B_{12} = B_{21}$

Thus for laser action the following condition should be satisfied :

- ① The rate of transition of spontaneous emissions should be negligible as compared to the stimulated emission.

That is $R_{\text{spontaneous}} \ll R_{\text{stimulated}}$

- ② The rate of transition due to total emission should be greater than the rate of transition due to absorption.
(The emission rate should be larger than the absorption rate)

These conditions can be achieved by using following steps :-

- (i) Normal conditions of thermal equilibrium, the number of atoms in higher energy state i.e. N_2 is considerably

Smaller than the number of atoms in lower energy state N_1 , because $E_1 < E_2$ so $N_1 > N_2$. Therefore, there is very little stimulated emission compared with the absorption. If by some means, a larger number of atoms are made available in the higher energy state as compared to lower energy state, stimulated emission can be enhanced (first condition of laser). The situation, in which the number of atoms in the higher energy state exceeds with that in the lower energy state is known as population inversion.

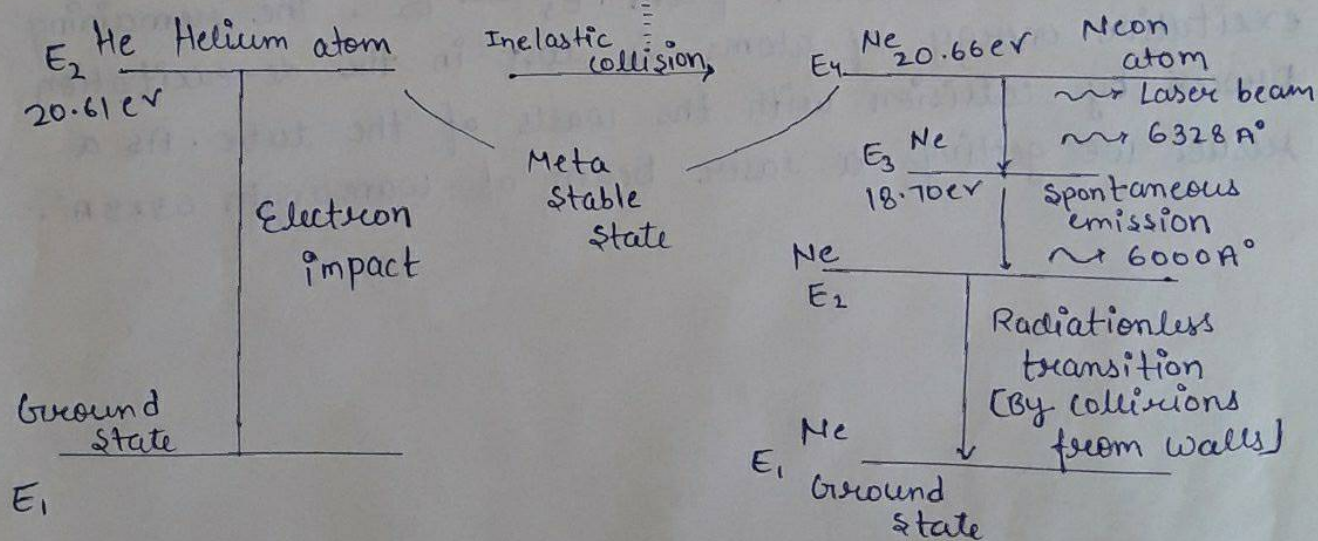
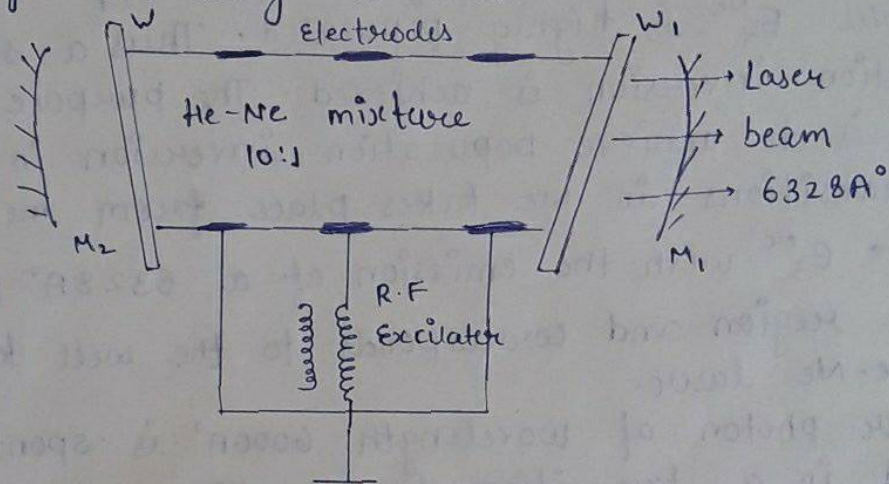
② The method adopted to achieve population inversion is called pumping. (Raising the molecules to higher energy state is called pumping and this can be done in many ways. (i) optical pumping (ii) electron-impact (iii) chemical pumping (iv) Gas dynamic pumping (v) In elastic atom-atom collision.

Conditions for laser action (Three condition) :—

(A) $N_2 > N_1$ (B) The density of incident radiations should be larger (C) $A_{21} / B_{21} \ll 1$

Helium-Neon Laser:— The He-Ne laser uses a mixture of helium and neon in the ratio of 10:1, kept in a narrow pyrex glass tube with an internal diameter of 2 mm and length of about 40 cm. The helium gas is filled at a pressure of 1 torr and neon at a pressure of about 0.1 torr. The gas system is enclosed between the pair of mirrors. The windows are cemented at Brewster angle at the end of discharge tube. The reflectors M_1, M_2 are two dielectric coated spherical mirrors having a

high reflectivity at $6328\text{\AA}$ one mirror acts a perfect reflector and the other is partly transparent for the emergence of laser light. Pumping is achieved by an electric discharge produced in the gas by means of electrodes placed outside the tube connected to a source of high frequency alternating current.



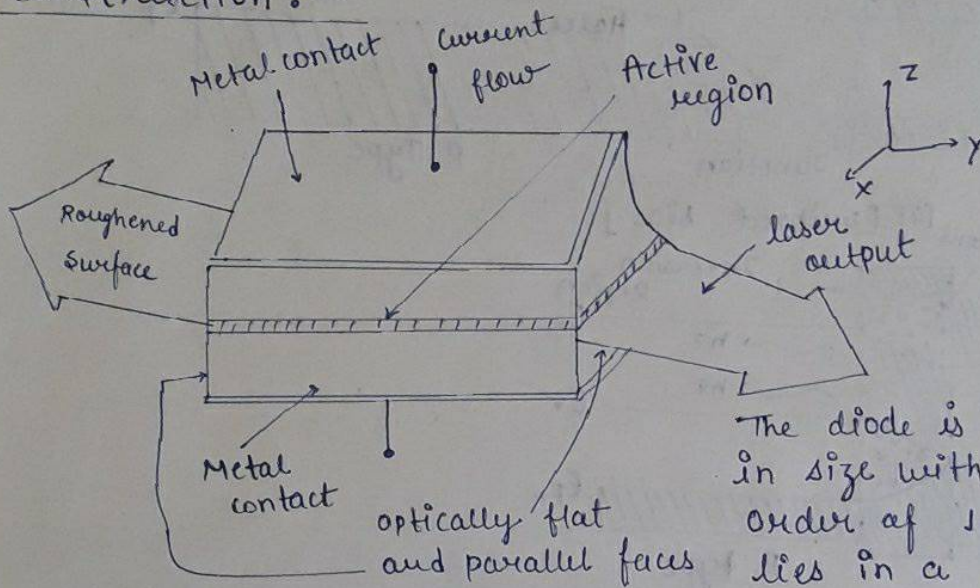
Working:- When an electric discharge is passed through the gas, the electrons travelling down the tube collide with helium atoms and excite them to E_2^{He} level. This level is meta stable i.e. the He atom excited to this state stays in this level for a sufficiently long time, before losing energy through collision. Some of the excited

He atoms transfer their energy to ground state Ne atom⁽⁸⁾ in collision, with the additional energy being provided by the kinetic energy of the ~~down~~ atom. Thus, when He atoms in level E_2^{He} collide with unexcited Ne atoms, they raise them to the level E_4^{Ne} respectively (the levels E_2^{He} and E_4^{Ne} are of ~~the~~ nearly same energy). As a result the level E_4^{Ne} is highly populated. Thus a state of population inversion is achieved. The purpose of the He atoms is to achieve population inversion in the Ne atoms. The transitions in Ne takes place from metastable levels $E_4^{\text{Ne}} \rightarrow E_3^{\text{Ne}}$ with the emission of a $6328\text{\AA}$ photon in the visible region and corresponds to the well known red light of He-Ne laser.

Another photon of wavelength $6000\text{\AA}$ is spontaneously emitted in a transition from $E_3^{\text{Ne}} \rightarrow E_2^{\text{Ne}}$. The remaining excitation energy of atoms is lost in the de-excitation process by collision with the walls of the tube. As a result we getting a laser beam of wavelength $6328\text{\AA}$.

Semiconductor Diode Laser:- A semiconductor diode laser is a specially fabricated pn-junction device ⁽⁹⁾ that emits coherent light when it is forward biased.

Construction:-



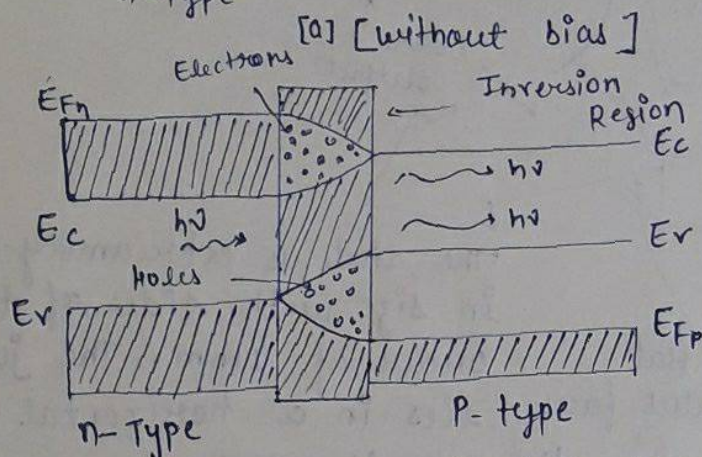
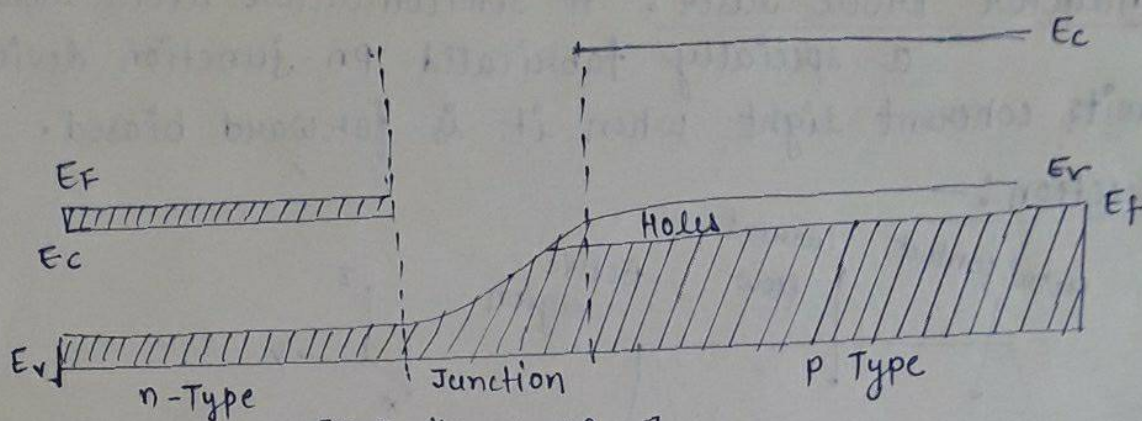
The diode is extremely small in size with sides of the order of 1mm. The junction lies in a horizontal plane through the centre.

The top and bottom faces are metallized and ohmic contact are provided to pass current through the diode.

The front and rear faces are polished parallel to each other and perpendicular to the plane of the junction.

The other two opposite faces are roughened to prevent lasing action in that direction. The active region consist of a layer of about $1\mu\text{m}$ thickness.

Working:- A simple way of achieving population inversion in a semiconductor is to use it in the form of a heavily doped pn Junction and to forward bias the junction. From fig(a) with very high doping on n-side the donor levels as well as a portion of the conduction band are occupied by electrons and the fermi level lies within the conduction band.



(b) [Heavily doped PN Junction forward biased above threshold value]

* The energy of the highest occupied state at absolute zero temp^t is called fermi energy.

Similarly, on the heavily doped p-side the acceptor levels are unoccupied and holes exist in the valence band and the fermi level lies within the valence band. At thermal equilibrium, the fermi level is uniform across junction as shown in fig (a).

When a forward bias is applied to the junction, the energy levels shift and the new distribution as shown in fig (b) will be taken up. Electrons and holes are injected into the depletion region which as a result decreases in width. The injected electrons and holes appear in high concentrations in this transition region. At low forward current level, the electron hole recombinations cause spontaneous

emission of photon and the Junction acts as LED. (11)

The bandwidth of the emitted light will be larger. As the current is increased, the intensity of light increase linearly. When the current reaches a threshold value the carrier concentration in the depletion region ~~will~~ will reach very high values. The upper levels in the depletion region are having high population density of electrons while the lower levels in the same regions are vacant. This is the state of population inversion. The narrow region where the state of population inversion is achieved is called inversion region or active region. Thus the forward bias (current) plays the role of pumping agent in semiconductor diode laser. The photons that propagate in the junction plane induce the conduction electrons to jump into the vacant states of valence band. The stimulated electron-hole recombinations cause emission of coherent radiation of very narrow band width. At room temp^r, GaAs laser emits light at a wavelength of $9000 \text{ \AA}^\circ$ in IR region & $6500 \text{ \AA}^\circ$ in the visible red region.