WAVE OPTICS

chapter-5 LASERs

Ques. - Discuss Einstien's Theory of matter radiation interaction

Sol. - When an atom is in excited state there are two types of emissions of radiation and absorption of radiation-

① **Spontaneous Emission** - An atom in excited state remains only for about 10^{-8} sec, then it comes on its own to lower energy state by emitting a photon or radiation. This process is called as spontaneous emission. These radiations are incoherent.

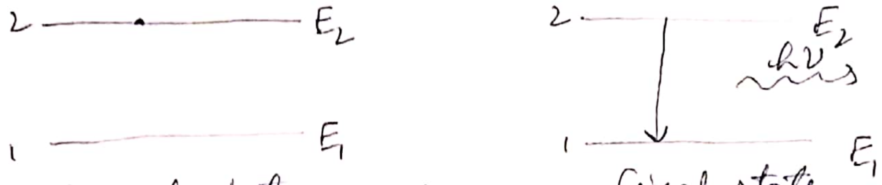

Fig - Spontaneous emission

The probability of spontaneous emission $2 \to 1$ depends only on the properties of states 1 and 2. According to Einstein the probable rate of spontaneous emission is given as

$$(P_{21})_{spontaneous} = A_{21} \qquad \text{—— ①}$$

A_{21} is called Einstein's coefficient of spontaneous emission

② **Stimulated or Induced Emission** → If an atom is in excited state then an incident photon of correct energy may cause the atom to jump to lower energy state emitting an additional photon of same frequency. This phenomenon is called stimulated emission of radiation. These two photons are coherent and travel in same directio[n]

The probability of stimulated emission from energy state E_2 to energy state E_1 depends on the energy density of incident radiation as well as on properties of two energy states and is given as

$$(P_{21})_{stimulated} = B_{21}\, u(\nu) \quad \text{— (2)}$$

$u(\nu)$ – Energy density

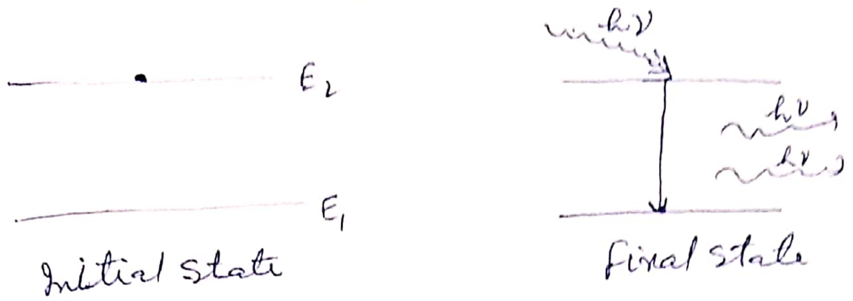

Fig. – Stimulated emission

where, B_{21} is Einstein's coefficient of stimulated emission of radiation.

The total probability of emission transition $2 \rightarrow 1$ is the sum of spontaneous and stimulated emission probabilities. i.e.

$$P_{21} = A_{21} + B_{21}\, u(\nu) \quad \text{— (3)}$$

(3) <u>Absorption of Radiation</u> – When energy is given to an atom in ground state it goes to higher energy state (excited state). This process is called absorption of radiation.

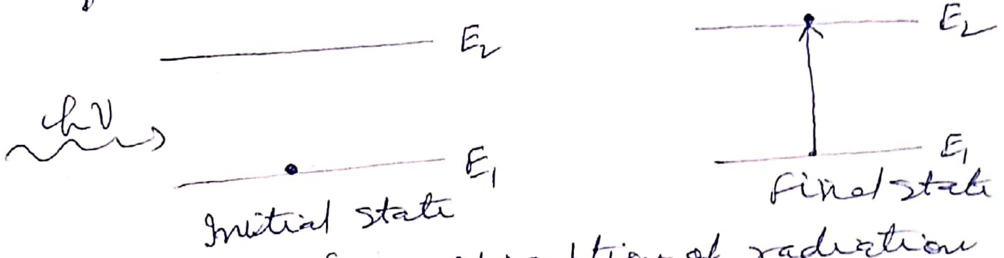

Fig. Absorption of radiation

The, frequency of absorbed radiation

$$\nu = \frac{E_2 - E_1}{h} \quad \text{— (4)}$$

where, $h \rightarrow$ Planck's constant.

E_1 & E_2 $\rightarrow$ Energies of electron in initial & final state.

- Absorption is stimulated or induced process.

The probability of transition $1 \to 2$ depends on the properties of states 1 and 2 and energy density of radiation of freq. ν incident on atom.

$$P_{12} = B_{12} U(\nu) \quad \text{——— (5)}$$

$U(\nu) \to$ Energy density.

B_{12} is called Einstein's coefficient of absorption of radiation.

Ques. - Establish relationship between Einstein's A and B coefficients.

Sol. - Let, N_1 and N_2 be the number of atoms in energy states 1 and 2 respectively at temperature T at any instant. ν be the frequency and $U(\nu)$ be the energy density of radiation.

Rate of absorption in state 1 may be given as

$$N_1 P_{12} = N_1 B_{12} U(\nu) \quad \text{——— (1)}$$

and, rate of emission (spontaneous + stimulated) in state 2 may be given as -

$$N_2 (P_{21})_{spontaneous} + N_2 (P_{21})_{stimulated} = N_2 A_{21} + N_2 B_{21} U(\nu)$$

$$= N_2 [A_{21} + B_{21} U(\nu)] \quad \text{——— (2)}$$

For, equilibrium rate of absorption & emission must be equal.

$$\therefore N_1 P_{12} = N_2 [(P_{21})_{spont.} + (P_{21})_{stimulated}]$$

$$N_1 B_{12} U(\nu) = N_2 [A_{21} + B_{21} U(\nu)].$$

$$\text{or,} \quad U(\nu)[N_1 B_{12} - N_2 B_{21}] = N_2 A_{21}$$

$$\text{or.} \quad U(\nu) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

$$U(\nu) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right) - 1} \quad \text{——— (3)}$$

According to Baltzman's statistics. —

$$N_1 = N_0 e^{-E_1/KT} \quad \text{and,} \quad N_2 = N_0 e^{-E_2/KT}$$

where, $N_0 \rightarrow$ total number of atoms present

$K \rightarrow$ Baltzman's constant.

$$\therefore \frac{N_2}{N_1} = \frac{e^{-E_2/KT}}{e^{-E_1/KT}} = e^{-(E_2-E_1)/KT}$$

But, $E_2 - E_1 = h\nu$

$$\therefore \frac{N_2}{N_1} = e^{-h\nu/KT}$$

$$\text{or,} \quad \frac{N_1}{N_2} = e^{h\nu/KT} \quad \text{——— (4)}$$

From eqns (3) and (4) we get,

$$u(\nu) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{e^{h\nu/KT}\left(\frac{B_{12}}{B_{21}}\right) - 1} \quad \text{——— (5)}$$

Planck's radiation formular is -

$$u(\nu) = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{h\nu/KT} - 1} \quad \text{——— (6)}$$

Comparing eqns (5) & (6) we get,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \text{——— (7)}$$

$$\text{and} \quad \frac{B_{12}}{B_{21}} = 1 \quad \text{——— (8)}$$

(i) from eqn (8) $\boxed{B_{12} = B_{21}}$

The probability of stimulated emission is same as that of absorption

(ii) From eqn (7) $\frac{A_{21}}{B_{21}} \propto \nu^3$ i.e. probability of spontaneous emission dominates over induced emission more and more as the energy difference between two states increases.

Ques. - What do you mean of LASER. Discuss principle of LASER action.

OR

Discuss light amplification by population inversion.

Sol. - LASER is abbreviated form of Light Amplification by Stimulated Emission of Radiation.

LASER (1960) is a device by virtue of which we can produce high intense, coherent, monochromatic, highly directional and parallel beam of light. All the LASERs comprise of three basic components ① Active medium ② Excitation source/pump. ③ reflecting mirrors/Resonator.

Action of LASER → for laser action following three steps are required.

① The number of atoms in higher energy state must be greater than that in lower energy state. - Under ordinary condition most of the atoms are in ground state or lower energy state. The establishment of situation in which number of atoms in higher energy state is greater than that in lower energy state is called the population inversion. The process of creating population inversion is called pumping.

② The energy density of stimulated radiation must be large. - This condition makes

$$(P_{21})_{stimulated} > (P_{21})_{spontaneous}$$

when the condition of population inversion is achieved, the incident photon stimulates only one atom to emit a photon. The number of identical coherent photons grow from one to two. These two coherent photons result in four coherent photons and so on. These coherent photons travel in same direction and we get high intense and directional beam of radiation. This process is called LASER. i.e., light amplification by stimulated emission of radiation

③ Optical Pumping - In optical pumping the process involved three energy levels. Optical pumping is a process of creating population inversion.

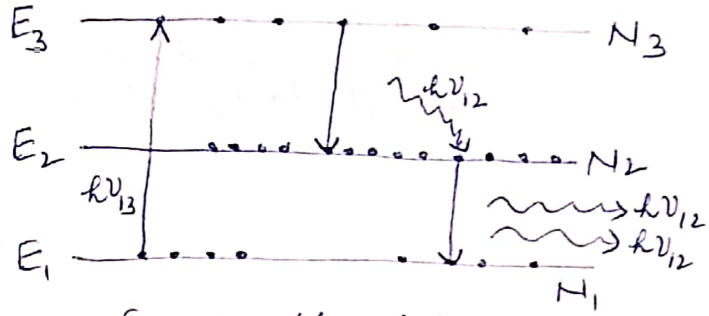

Fig. - optical pumping

Atoms are excited from lowest energy level E_1 to highest energy level E_3 by absorption of radiation of energy $h\nu_{13}$. Some excited atoms immediately drops to an intermediate energy level E_2, called metastable state. In this transition $E_3 \rightarrow E_2$ atoms don't radiate any energy. and in metastable state atoms can stay for a longer time. In this way population N_2 of atoms in energy state E_2 become higher than the population N_1 of of atoms in energy state E_1 (ground level). By radiations of energy $h\nu_{12}$, the induced emission takes place $E_2 \rightarrow E_1$ and we get laser frequency ν_{12}.

$$\nu_{12} < \nu_{13}$$

Thus we see that for LASER operation minimum three energy level system is needed. A two energy level system is not suitable for LASER action

Ques. - Discuss the properties of LASER beam.

Ans. - LASER beam is highly intense, monochromatic, coherent, directional and parallel in nature.

1. High Directionality → A LASER source emits radiation only in one direction. The directionality of a Laser beam is explained in terms of divergence angle of beam.

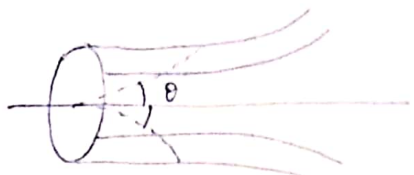

fig - Directionality of Laser beam

When a light beam of wavelength(λ) from a plane wavefront comes out of an aperture of diameter d, then the beam propagates as a parallel beam through a certain distance called Rayleigh range given $\frac{d^2}{\lambda}$, after that it begins to diverge due to diffraction effects. The spread θ of beam on one side is given by

$$\theta = \beta \frac{\lambda}{d} \qquad \beta \text{ is a constant.}$$

A LASER beam spreads only 0.01 mm for every 1 m propagation.

2. High Intensity → The intensity of light at any point is defined as the energy passing normally per unit area per second. The LASER beam is a narrow beam so its whole energy is concentrated in a very small region. 1 Watt LASER source is more intense than an ordinary 100 Watt ordinary source of light.

For an area of 1 cm^2 the number of photon from a hot source of light at 1000 K is about 10^{12} while for LASER the number of photon is 10^{16} for same area.

(3) High Monochromaticity → Light from an ordinary source of light is never monochromatic but has a frequency

range of mega hertz while LASER beam is extraordinarily monochromatic.

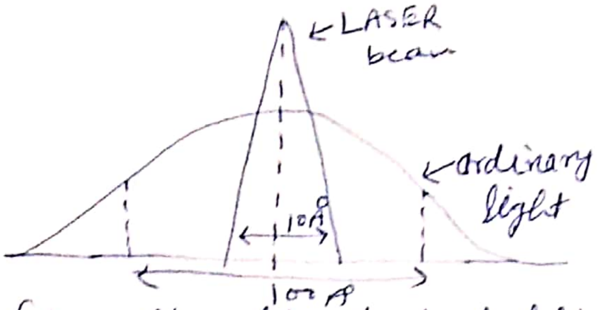

Fig. - Spreading of spectral line

If $\Delta\nu$ is frequency spread of a spectral line of frequency ν_0 then the degree of non-monochromaticity is defined as

$$\epsilon = \frac{\Delta\nu}{\nu_0}$$

For a LASER source $\epsilon \approx 10^{-12}$

For an ordinary light source $\epsilon \approx 10^{-5}$

4. Highly Coherent → The coherence is the most important characteristic of a LASER beam. There are two types of coherence.

(a) Temporal coherence - The average time interval for which the field remains sinusoidal is known as temporal coherence. The distance L for which the field remains sinusoidal is called coherence length, and is given by

$$L = \tau c$$

where, c → speed of light.

(b) Spatial Coherence - The spatial coherence is the phase relationship between the radiation fields at different points in space.

Ques. - Explain Ruby LASER.

Ans. - It consists of three parts (1960)-

(i) The working substance in the form of a rod of ruby crystal.

(ii) Resonant cavity.

(iii) optical pumping system.

Rube is a crystal of Aluminium oxide (Al_2O_3) with some Al atoms replaced by chromium (Cr) atoms.

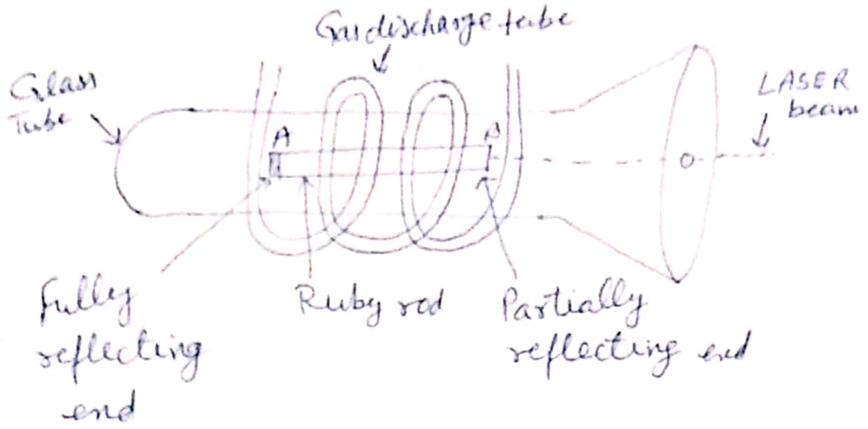

Fig. 1

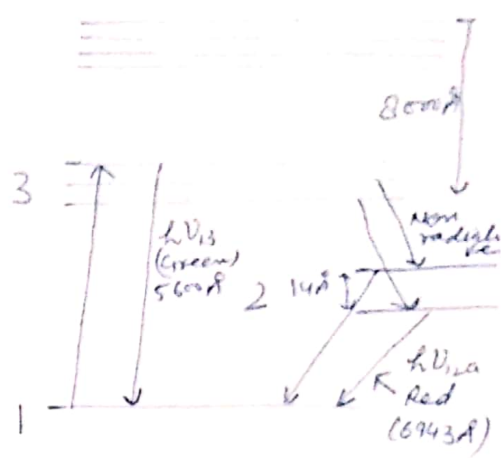

Fig. 2

Rube LASER is a pulsed Laser. It consists of a Ruby rod of nearly 10 cm. in length and 0.8 cm in diameter. Flat end faces A and B are made strictly parallel, plane and silvered so that end face A becomes fully reflecting and end face B partially reflecting.

The ruby rod is arranged along the axis of helical xenon flash tube so that coils of tube surround the rod. The energy diagram corresponding to operating principle is shown in figure. When light from tube is made to fall upon the ruby rod the chromium atom absorbs the green component ≈ 5600 Å ~~avg~~ and get excited from energy level 1 to energy level 3. The Cr atom has a double energy level 2 with a difference of ≈ 14 Å. From energy level 3 some excited atoms return to ground state 1 while other move to level 2. The probability of transition 3 to 2 is much higher than that from 3 to 1. As a result the energy level 2 becomes more populated than 1.

such a system with population inversion is not a stable one because one spontaneous transition may cause an induced transition resulting in two photons.

The level 2 in ruby LASER is actually a doublet of seperation 14 Å. The spontaneous transition would give two weak lines at 6943 Å and 6929 Å each of width nearly 6 Å. But under the lasting condition the line 6943 Å dominates over other line.

Ques - Explain He-Ne LASER.

Sol. - He-Ne LASER (1961) - This is a gaseous LASER

It consists of -

1. Working substance in the form of He & Ne gas mixture in the ratio of 7:1
2. A resonant cavity of quartz tube
3. An exciting source for creating a discharge in tube.

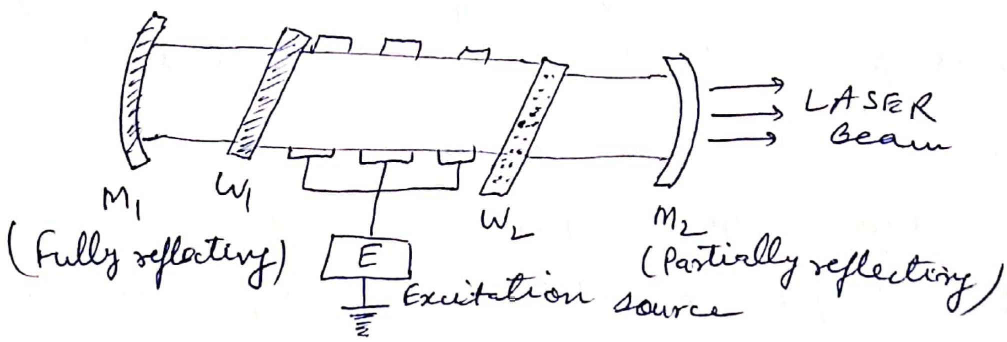

fig. - He-Ne LASER

The working of He-Ne Laser is based on the fact that Energy levels of Ne are very close to metastable state of He. He-Ne gas LASERs can operate into three distinct spectral regions in the red 6328 Å, in near infrared about 1.15 μm and in the infrared at 3.39 μm.

The partial energy level diagram of He-Ne Laser is shown in following diagram

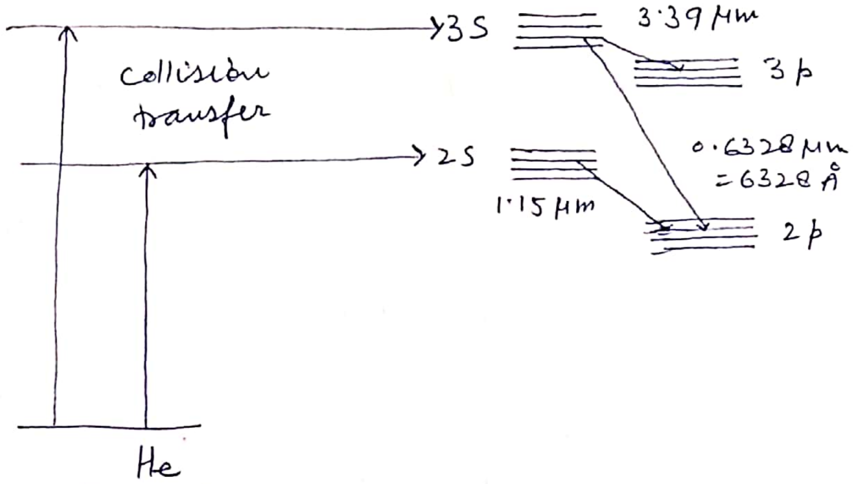

Fig.- Partial energy level of He-Ne gas LASER.

When electromagnetic energy is injected into tube through metal bands by means of a radio frequency high voltage source, He atoms get excited to metastable state. Excited He atoms collide with unexcited Ne atoms and after transferring energy return to ground state.

When population inversion has occurred in Ne atom they return to lower energy states emitting the photons. Photons emitted bounce back and forth between polished mirrors. Thus photons get multiplied and a powerful coherent parallel LASER beam emerges from partially reflecting end of tube.

Ques.- Discuss Neodymium (Nd): YAG LASER.

Ans.- Neodymium: YAG (Nd: YAG) Laser is a four level laser system. This is a solid state LASER.
Nd stands for Neodymium (rare earth element) and YAG stands for Yttrium Aluminium Garnet ($Y_3Al_5O_{12}$).

Nd:YAG LASER consists of three important elements (i) Active medium (ii) energy source or excitation source (iii) optical resonator.

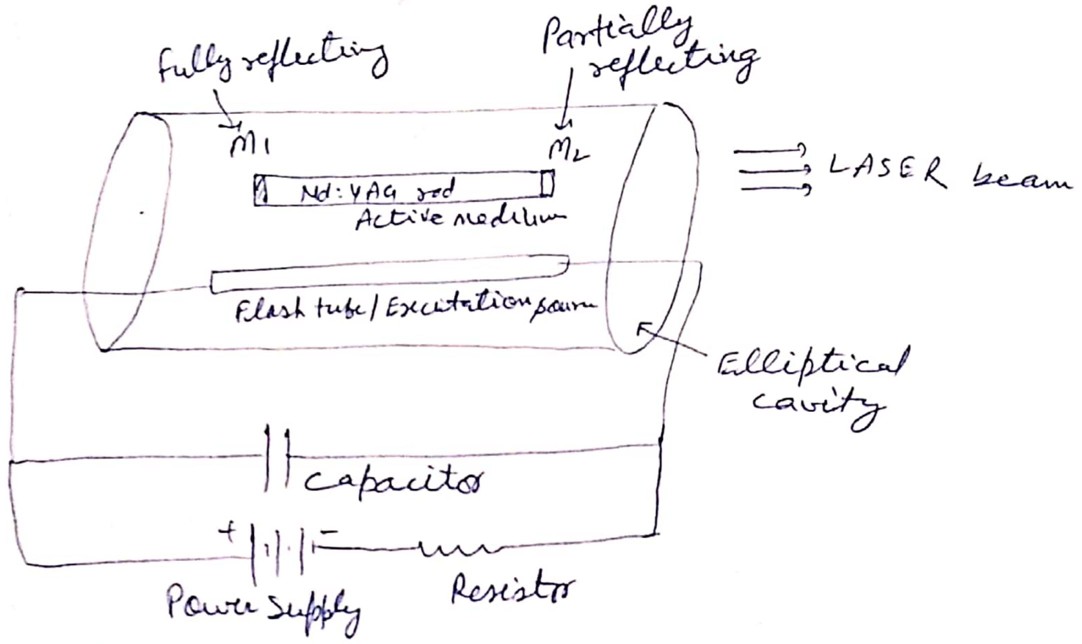

Fig -- Nd:YAG LASER

Active medium of LASER medium of the Nd:YAG laser is made up of a synthetic crystalline material (YAG) dopped with a chemical element Nd. The active medium is cut into a cylindrical rod. The ends of cylindrical rod are highly polished and they are made optically flat and parallel. A small amount of Y_3^{+++} ions is replaced by Nd^{+++} ions in the active region.

To achieve population inversion light energy source such as flash tube or laser diodes are used as energy source / excitation source. The cylindrical rod of Nd:YAG and pumping source (Flash tube) are placed inside a elliptical cavity.

The optical resonator is formed by using two external reflecting mirrors. One mirror M_1 is fully (100%) reflecting while other mirror M_2 is partially reflecting. following figure shows energy level diagram of Nd:YAG laser.

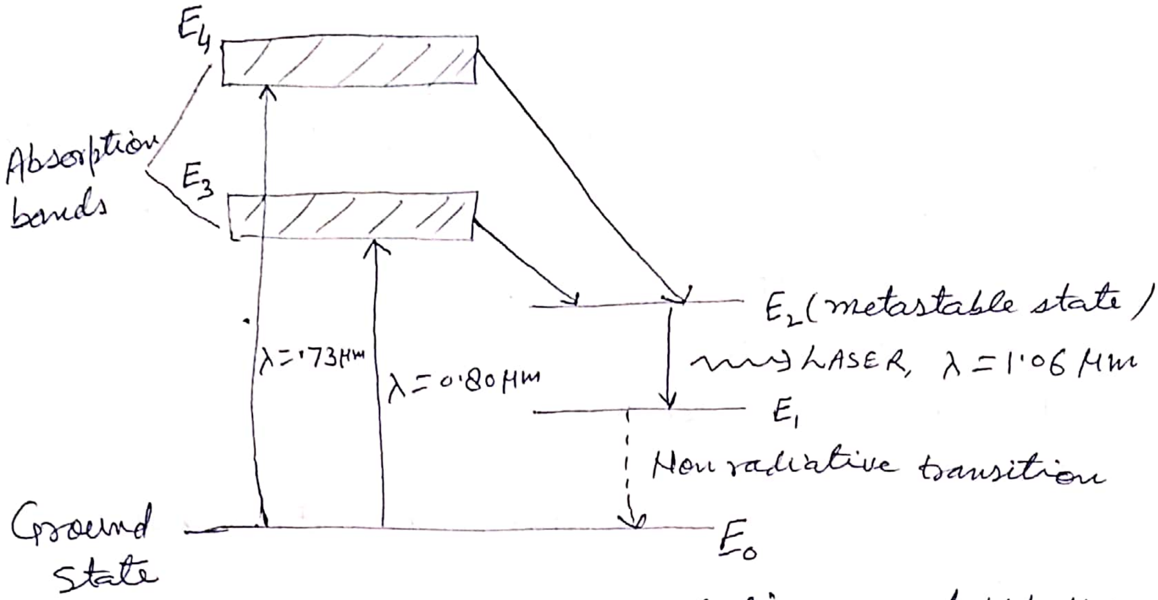

Fig. - Energy level diagram of Nd: YAG LASER.

When the flash tube is switched on then by absorption of light of wavelength 0.73 μm and 0.80 μm the Nd^{+++} ions are excited from Ground state E_0 to higher levels E_3 & E_4. These excited ions make a transition from level E_3 & E_4 to level E_2.. E_2 is a metastable state. Hence, in this level E_2 population inversion takes place.. An ion makes a spontaneous transition from E_2 to E_1 emitting a photon of energy $h\nu$. This photon causes a chain of stimulated photons between levels E_2 & E_1. These photons bounce back and forth between mirrors M_1 and M_2. After some time due to resonance of these photons we get a high intense and parallel LASER beam of wavelength 1.06 μm from partial reflector. The power output is approximately 70 Watt.

Ques. - Discuss CO_2 LASER.

Ans. - Carbon di oxide (CO_2) LASER is a gaseous LASER. CO_2 Lasers (1964) are the highest power continuous wave LASERs. This is four level molecular LASER. In CO_2 Laser light takes place within the molecules of carbon di oxide rather than within the atoms of pure gas.

construction of CO_2 gas LASER - The CO_2 gas LASER can be constructed in the number of different configurations. Five important configuration of CO_2 Laser constructions are-

1. Sealed tube design.
2. Coaxial flow design
3. Fast axial flow design
4. Transverse flow design
5. Transeverse Excitation at Atmospheric (TEA) design.

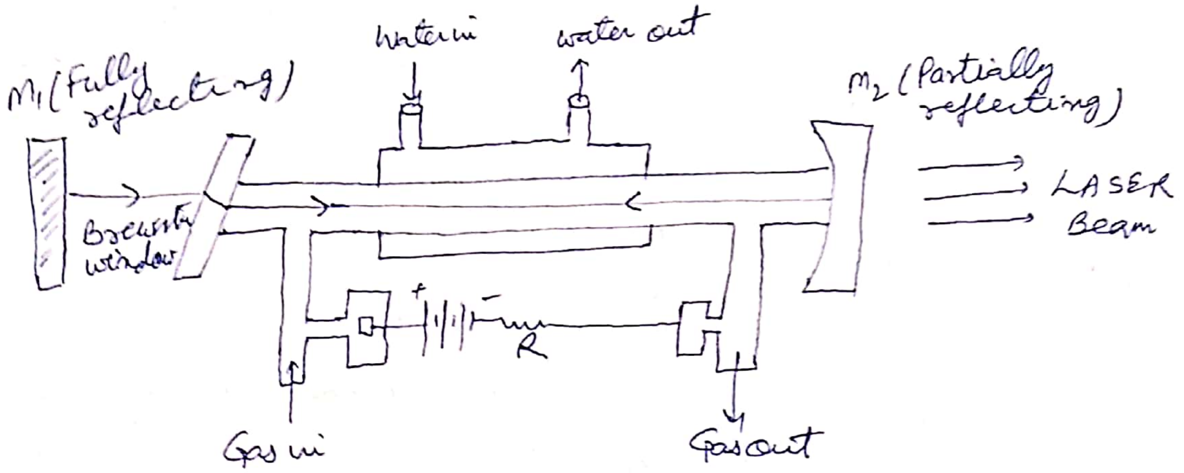

Fig. - A schematic of typical CO_2 LASER.

Function of CO_2 LASER - The CO_2 LASER uses a mixture of Helium, Nitrogen and Carbon di oxide as the active medium. In this mixture He & N_2 work in concert with the CO_2 to produce lasing effect. Here, N_2 gas acts as a buffer gas as He did in He-Ne laser. The N_2 gas absorbs the pumping energy from the current flow in the gas and transfer the energy through collisions to the CO_2 molecule. So the CO_2 molecules reach their excited meta stable state and when they drop from this excited level then lasing occurs.

A high DC voltage causes an electric discharge to pass through the tube. Discharge breaks down CO_2 molecules to O and CO.

Following figure shows energy level diagram of CO_2 Laser

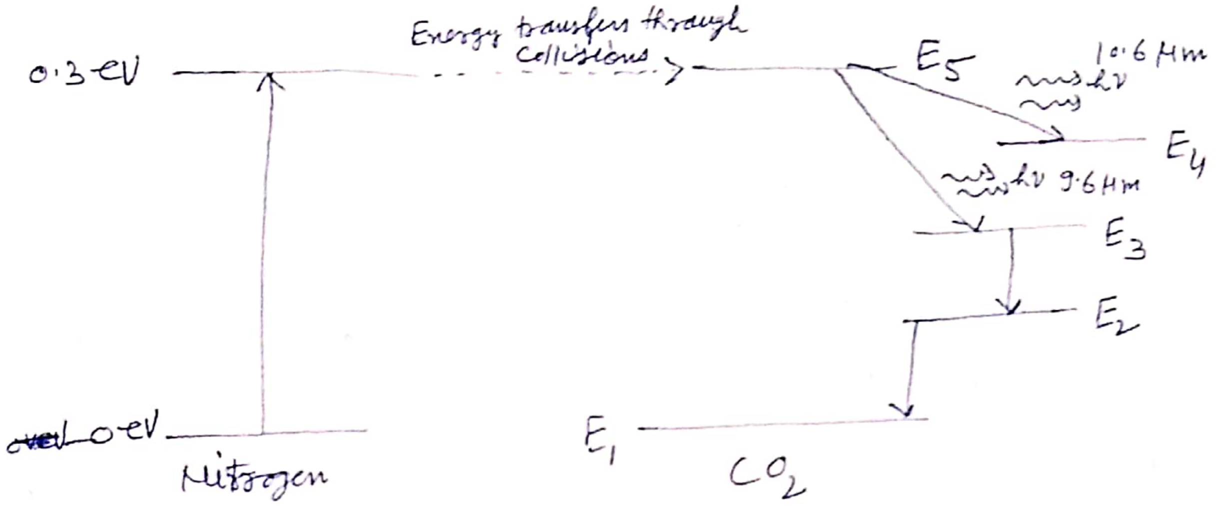

Fig. - Energy levels of CO_2 & N_2 molecules and transitions

In CO_2 Laser N_2 plays same role as He in He-Ne Laser. Lowest vibrational levels of N_2 have nearly same energy as asymmetric mode of CO_2. Readily transfer of energy of N_2 to CO_2 molecules takes place through resonant collisions. CO_2 molecules get excited to E_5 level. Population inversion takes place between E_5 & E_4 levels and E_5 & E_3 levels. Levels E_3 & E_4 act as metastable state. CO_2 molecules at E_4 & E_3 levels drop to level E_2 through inelastic collision with He atoms. He atoms help to depopulate level E_2 through collisions. But level E_2 is very close to ground state hence tends to populate by thermal excitations. Therefore, it is necessary to keep the temperature of CO_2 low. In CO_2 lasers, N_2 helps to increase population of upper laser level where as. He depopulates the lower laser level. In CO_2 laser high power levels are obtained ranges from few watts to 15000 watts. The CO_2 lasers are more versatile lasers

Ques. - Discuss Dye Lasers.

Ans. - Dye Lasers (1966) - The Dye laser is a liquid laser. Liquid Lasers are those lasers which use liquid as an active medium. In dye laser active medium is an organic dyes, which is carbon based, soluble stain that is often fluorescent, such as dye in highlighter pen. The dye is mixed with a compatible solvent, allowing the molecules to diffuse evenly throughout the liquid. Generally we use rhodamine 6G, rhodamine B and sodium fluorescein as an active medium which causes to produce laser light.

The dye lasers produce output whose wavelengths are in visible, ultraviolet and near far infrared region. which usually depending on the dye used. Wavelength range vary from 390 nm to 1000 nm. The output power of dye laser can be considered to start from 1 watt with no theortical upword limit. The out put beam diameter is typically 0.5 mm and the beam divergence is from 0.8 to 2.0 milli radians.

We know that the active medium used in a dye laser i.e. dye is dissolved in a solvent such as water, alcohol or ethylene glycol. The organic dye such a rhodamine B has the chemical formula $C_{28}H_{31}$. It is therefore very difficult to determine the element that actually lases. For this reason we simply say that organic dye will lase. Rhodamine B produces wavelengths in the 590 nm to 660 nm range. However the amount of amplification varies across the range of frequencies with maximum output at about 618 nm.

organic dye molecules have two sets of excited states

(i) singlet states, S_0, S_1, S_2

(ii) triplet states, T_1 & T_2

Transition from singlet states to triplet states is not allowed. Following figure shows the schematic energy level diagram of an organic dye molecule

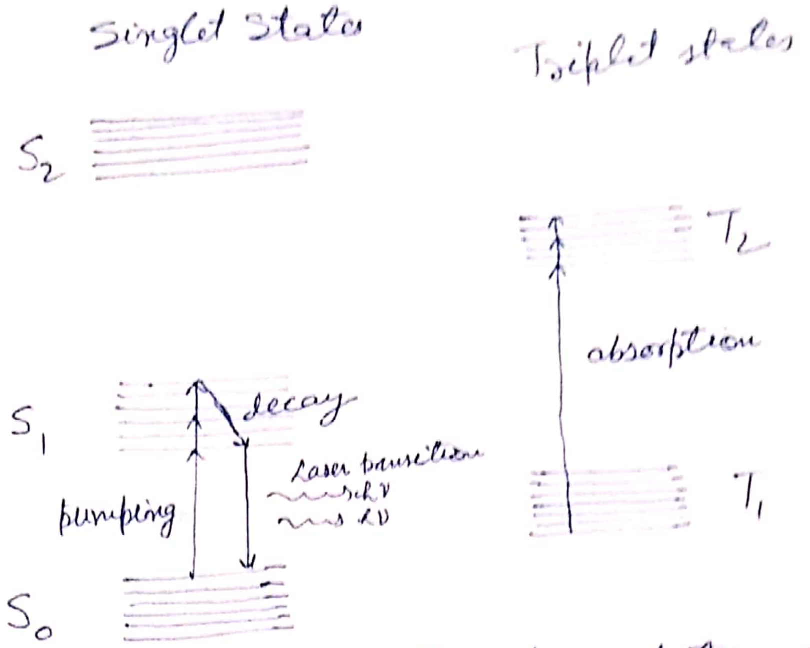

Fig. - Schematic representation of the energy levels of an organic dye molecule.

optical pumping excites dye molecules from lowest vibrational level of ground state S_0 to one of upper vibrational level of excited state S_1. The excited molecule undergo non radiative transition to the lower vibrational level of S_1. The laser transitions can be to various levels within a range defined by vibrationally excited sublevels on the ground state.

Dye lasers are mostly used as a research tool in medical applications.

Ques - What are the applications of LASERs.

Ans - Applications of LASER.

1. LASERs are used to produce highly coherent sources of light.
2. Due to Narrow band width of Laser beam it is used in communication systems and computers.
3. Lasers are used in space, remote sensing, spectroscopy and holography
4. Lasers are used in material processing eg. cutting, drilling, welding, marking, heat treating etc.
5. Lasers are used in graphic arts in high-end printing & copying
6. Lasers have wide applications in the field of medicine and surgery eg. - in treatment of brain tumors, removing of kidney stones, for remedy of eye defects, glaucoma, treatment of skin cancer, in removing to tatoos etc.
7. In Military & Defence - due to high energy content of Laser beam lasers are being used as a harmful weapons, for ranging, anti-missile shield, laser detonators instruments, spying etc.
8. A high energy pulsed YAG laser has even been used in rocket propulsion experiments.
9. Lasers are used for semiconductor fabrication eg. wafer cutting and IC trimming.
10. Lasers are used in removal of unwanted hairs & spots.