LASER

Dr. Tessy P. T
Assistant Professor
Department of Humanities & Applied Science
VESIT, Chembur

JESSY

LASER

Syllabus: Laser: Spontaneous emission and stimulated emission; metastable state, population inversion, types of pumping, Resonant cavity, Einstein's equation Helium Neon laser; Nd:YAG laser, semiconductor laser, Applications of Laser – Holography
(No numericals)

LASER: Light Amplification by Stimulated Emission of Radiation is the acronym of LASER

Laser is a highly directional, monochromatic coherent light source. Laser can be explained by the theory of interaction of light with medium from the point of view of quantum mechanics.

Let us consider a material medium, which is composed of identical atoms with many energy levels. For simplicity, let us consider atoms of material medium under consideration be characterized by only two energy levels E_1 and E_2. Let N_1 and N_2 be the populations (no: of atoms per unit volume) of ground state E_1 and excited state E_2 respectively. Under normal conditions $N_1 > N_2$. Let light radiations be incident on the material.

The incident light can be considered as a stream of photons. Let each photon carry an energy

$$E = E_2 - E_1 = h\nu$$

$\rho(\nu) \rightarrow$ Photon density.

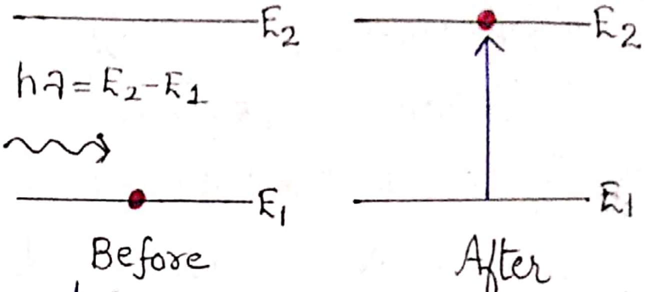
When light (Photons) travels through the medium, three different process are possible: ① absorption ② spontaneous emission & ③ stimulated emission.

②

1. Absorption

$$\boxed{A + h\nu \rightarrow A^*}$$

$A \rightarrow$ atom in lower state
$A^* \rightarrow$ Excited atom



If a photon of energy $(E_2 - E_1)$ is incident on the atom, it imparts its energy to the atom and disappears. When an atom in the ground state absorb adequate energy, it jumps to the excited state. Such a transition is called absorption transition. As the absorption process is induced by a photon it is also called induced absorption.

The probability that an absorption transition occurs is proportional to photon density $\rho(v)$

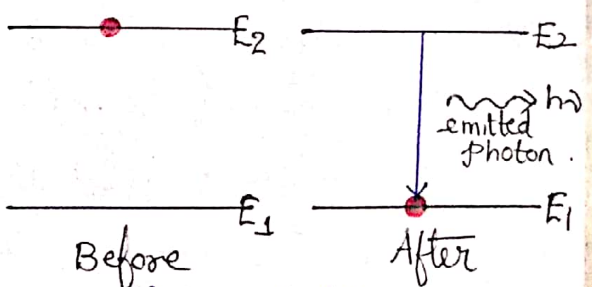
$$P_{12} \propto \rho(v)$$
$$P_{12} = B_{12}\, \rho(v)$$

B_{12} is constant of proportionality known as Einstein coefficient for induced absorption.
Number of absorption transition during time Δt is

$$= N_1 \; P_{12}\, \Delta t$$
$$= N_1 \; B_{12}\, \rho_{(v)}\, \Delta t$$

2. Spontaneous Emission

$$\boxed{A^* \rightarrow A + h\nu}$$



An excited state is normally unstable. The lifetime of an atom in an excited state is very short about 10^{-8} seconds. Hence an atom in the excited state returns to the ground state

spontaneously by releasing a photon of energy $h\nu$ $(= E_2 - E_1)$
The emission of photon occurs on its own.
It is NOT in anyway induced or stimulated by any radiation. Hence it is called spontaneous emission.

The probability of spontaneous transition is

$(P_{21})_{spon} = A_{21}$ where $A_{21} \rightarrow$ Einstein coefficient for spontaneous emission

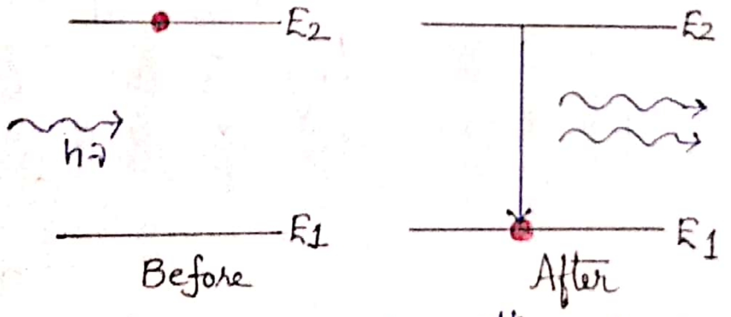
No: of spontaneous transition during the time Δt $\Big\}$ $N_{sp} = N_2 A_{21} \Delta t$

The instant of spontaneous transition, direction of emission of photon, the phase of photon etc are random. Therefore the light generated by the medium will be incoherent.

(note: The light from the conventional sources originates in spontaneous emission)

3) Stimulated Emission

$$\boxed{A^* + h\nu \rightarrow A + 2h\nu}$$



Stimulated emission occurs in the presence of external radiation. If an atom in the excited state interacts with a photon having energy $h\nu = E_2 - E_1$, then the photon induces the excited atom to make a downward transition well before the atom can make a spontaneous transition.

The interaction of incident photon with excited atom causes the excited atom to make transition to ground state by releasing the energy in the form of a photon. This emitted photon is in phase with the incident photon. That is in stimulated emission multiplication of photon takes place. These photons are travel in same direction in same phase and hence the light generated is coherent in nature. The stimulated emission is a forced emission by an external agency and therefore it is also called induced emission.

The probability of stimulated transition $(P_{21})_{stimulated}$ is proportional to photon density $\rho(\nu)$.

$$(P_{21})_{stimulated} \propto \rho(\nu)$$

$$\therefore (P_{21})_{stimulated} = B_{21}\,\rho(\nu)$$

where $B_{21} \rightarrow$ Einstein coefficient for stimulated emission

The no: of stimulated transition during Δt time is

$$N_{sti} = N_2 (P_{21})_{sti}\,\Delta t$$
$$= N_2 B_{21}\,\rho(\nu)\,\Delta t$$

Outstanding feature of stimulated emission is

Multiplication of photons

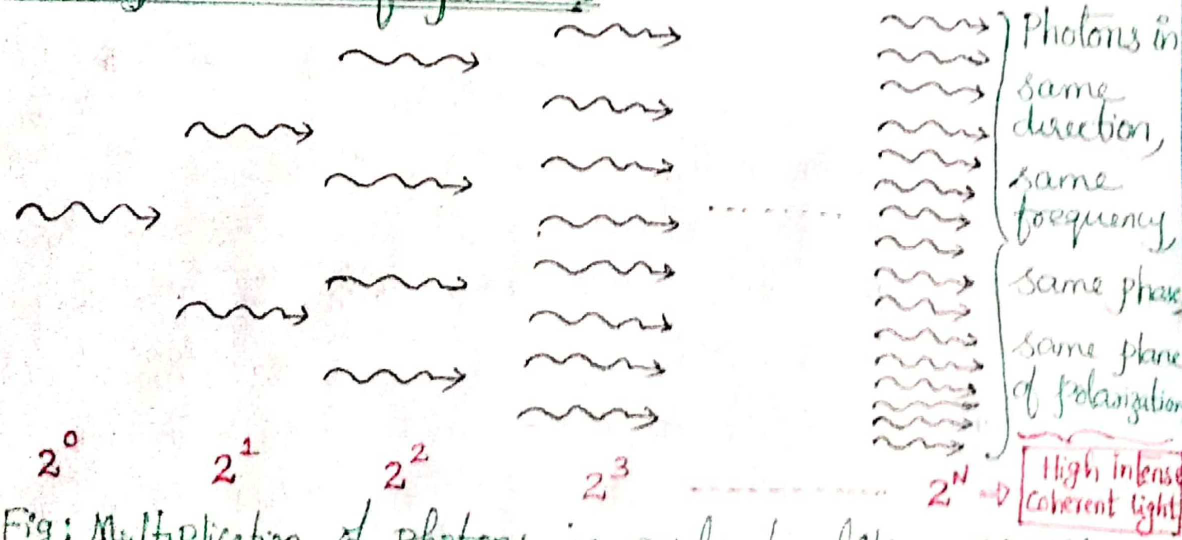


Fig: Multiplication of photons in avalanche like manner.

All the coherent waves constructively interfere and the net intensity of light will be $\boxed{I_{tot} = N^2 I}$ $N \rightarrow$ No: of atoms radiating light

An enormously high intense light is produced

Differentiate between spontaneous & Stimulated Emission

Spontaneous Emission	Stimulated Emission
Spontaneous emission is a random and uncontrolled process	Stimulated emission is NOT a random process & it is controlled process
Photons are emitted in random direction, not in phase with each other & with different frequencies.	Photons emitted in this process travel in same direction, all in same phase & with same frequency (equal amount of energy)
Light produced in this process is incoherent, not monochromatic and non directional	Light produced in this process is coherent, monochromatic and directional
Multiplication of photons does not take place. Hence there is no amplification of light due to spontaneous emission	Multiplication of photons (2^N photons) takes place. Due to this Light amplification occurs in stimulated emission
The net intensity of generated light is $I_T = NI$ $N \rightarrow$ no: of atoms emitting photon $I \rightarrow$ Intensity of each photon	All photons in same phase, interfere constructively produce intensity $I_T = N^2 I$
Light produced is unpolarized (Plane of polarization of the photons are oriented randomly)	Light produced is polarized (plane of polarization are identical for all photons)

(6)

Einstein's coefficients & their relations

The three Einstein coefficients are

(i) $A_{21} \rightarrow$ related to spontaneous emission

(ii) $B_{12} \rightarrow$ related to induced absorption

(iii) $B_{21} \rightarrow$ related to stimulated emission

In thermal equilibrium, the number of transition from E_1 to E_2 is equal to the no: of transition from E_2 to E_1

Absorption probability = Emission Probability (spontaneous + stimulated)

$$N_1 P_{12} = N_2 P_{21}$$

$$N_1 B_{12} \rho(\nu) = \underbrace{N_2 A_{21}}_{\text{(spontaneous)}} + \underbrace{N_2 B_{21} \rho(\nu)}_{\text{(stimulated)}}$$

$$\rho(\nu)\left[N_1 B_{12} - N_2 B_{21}\right] = N_2 A_{21}$$

where $\rho(\nu) \rightarrow$ Photon density

$$\rho(\nu) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

By dividing both numerator and denominator by $N_2 B_{12}$

$$\rho(\nu) = \frac{A_{21}/B_{12}}{\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}}}$$

By Maxwell-Boltzmann distribution law

$$N_1 = e^{-E_1/KT}$$

$$N_2 = e^{-E_2/KT}$$

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

$$= e^{h\nu/KT}$$

$K \rightarrow$ Boltzmann constant

$$\rho(\nu) = \frac{A_{21}}{B_{12}}\left[\frac{1}{e^{h\nu/KT} - \frac{B_{21}}{B_{12}}}\right]$$

This relation can be compared with Planck's radiation Law

$$\rho(\nu) = \left(\frac{8\pi h \nu^3 \mu^3}{c^3}\right)\left(\frac{1}{e^{h\nu/KT} - 1}\right)$$

$\mu \rightarrow$ ref. index of medium

$c \rightarrow$ velocity of light

Because to maintain thermal equilibrium system must release electromagnetic radiation. This radiation is identical with blackbody radiation and consistent with Planck's law

By comparison we get

$$\boxed{\frac{A_{21}}{B_{12}} = \frac{8\pi h \nu^3 \mu^3}{c^3}} \quad \text{and} \quad \frac{B_{21}}{B_{12}} = 1$$

Einstein's relations

$$\therefore B_{12} = B_{21} = \frac{c^3}{8\pi h \nu^3 \mu^3} A_{21} \quad \text{or} \quad \boxed{B_{12} = B_{21}}$$

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(i) The Einstein relation shows that the coefficients of both absorption and stimulated emission are numerically equal (ii) The ratio of coefficient of spontaneous versus stimulated is proportional to third power of frequency of radiation.

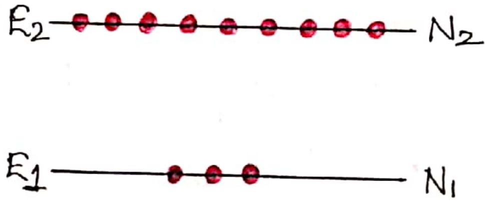
Requirements for LASER

Population Inversion

When the material is in thermal equilibrium condition, the population N_2 at the excited level is smaller than population N_1 at ground level. The stimulated emission dominates over the spontaneous emission and absorption if $N_2 \gg N_1$. ie, number of atoms in excited state exceeds that in lower energy state

Population inversion is the condition of the material in which population of the upper energy level N_2 far exceeds the population of the lower energy level N_1

That is, $\boxed{N_2 >> N_1}$



In this condition, population distribution between the levels E_1 and E_2 is inverted and hence it is known as inverted state. The process of producing population inversion is called pumping.

Pumping

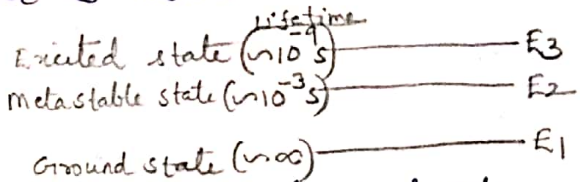
For achieving and maintaining the condition of population inversion, the method used for raising atoms from lower energy level to upper energy level is called pumping. The various techniques of pumping are.

① optical pumping ② Electrical discharge and ③ direct conversion.

① Optical Pumping:– In optical pumping, a light source such as a flash discharge tube is used to achieve population inversion. This method is used in solid state lasers.

② Electrical discharge:– In electrical pumping, an electric field is used to create ionization of the medium and raises atoms to the excited state. It is used in gas lasers

③ Direct Conversion:– In direct pumping a direct conversion of electrical energy into light energy takes place. This method is used in semiconductor lasers.



Metastable State

The excited state atoms have short lifetime of nanoseconds (10^{-9} s). Then eventhough the pumping agent continuously raises the atoms to the excited level, they undergo spontaneous transition rapidly to lower energy level. In order to establish population inversion, the excited atoms required to wait at the upper energy level till large number of atoms accumulate at that level. Therefore, a third type of energy state called metastable state is required. A metastable state atoms have lifetime of the order of 10^{-6} to 10^{-3} s. This is 10^3 to 10^6 times the lifetimes of ordinary excited level. Therefore, the metastable allows the accumulation of a large number of excited atoms at that level. There by population inversion is achieved between metastable state and lower level, which leads to stimulated emission for laser action.

Metastable state can be readily achieved by adding impurity in the material. For example: He is useful in He–Ne laser, Nd is useful in Nd–Yag laser.

COMPONENTS OF LASER

1). **Active Medium**

An active medium is the material in which the laser action takes place. This medium, when excited reaches the state of population inversion and promotes stimulated emission leading to light amplification.

2) **The pump** (explained earlier)

3). **Resonant Cavity : Optical Resonator**

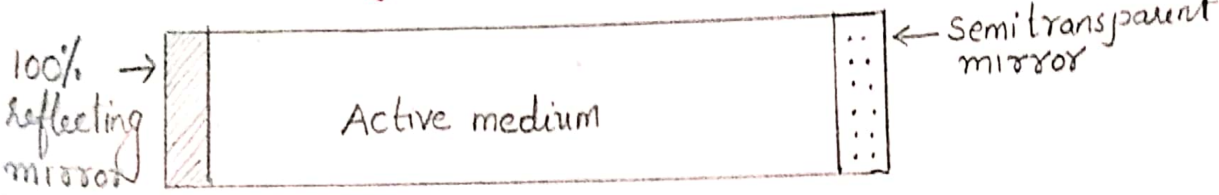


Fig: Optical resonator

A pair of optically plane parallel mirrors, enclosing laser medium in between them is known as optical resonant cavity. One of these mirrors is 100% reflecting and the other is partially reflecting.

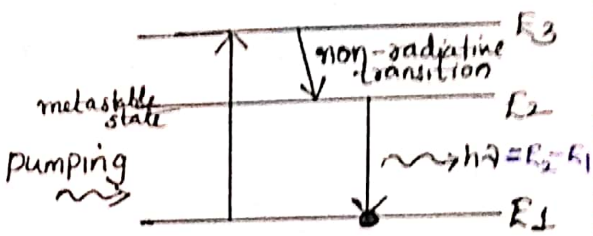
The primary function of optical resonator is to provide positive feedback of photons into the medium, so that stimulated emission is sustained for the laser action to take place.

Two Level, Three Level & Four Level Laser System

1) Two level system

In a two level system, there are only two energy levels – a lower energy level E_1 and excited level E_2. The atom from ground level E_1 excited to higher level E_2 by pumping. Then from excited state it may undergo transition to lower state.

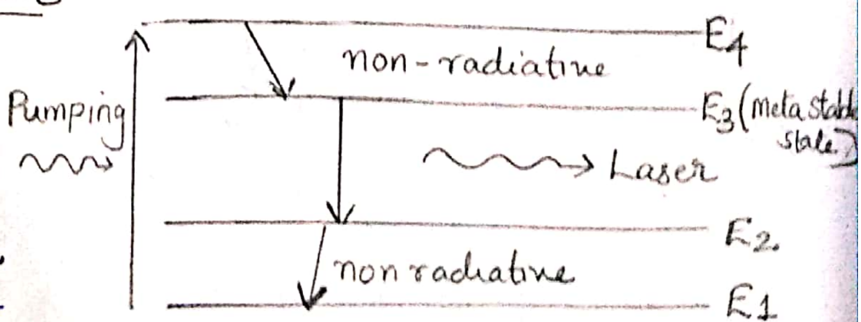
2) Three level system



In a three level laser system, three energy level E_1, E_2, E_3 are involved.

An atomic system in the lowest energy state E_1 will be excited to highest level E_3 by pumping. From this state E_3, the system decays fast to level E_2 through some non-radiative process. The state E_2 has a long life time and it acts as metastable state. The transition from E_3 to E_2 is very fast, most of the atoms from E_3 will decay to level E_2 and E_2 become more populated. Hence population inversion is achieved between levels E_2 and E_1 ~~are~~ and laser radiations are emitted between these levels.

3 Four Level system



In a four level laser system, there are four energy levels E_1, E_2, E_3 & E_4. E_1 is ground state and others are excited states. Atoms in level E_1 are excited to level E_4 by pumping. From E_4 they decay very rapidly to E_3 through non radiative transitions.

E_3 is a metastable state having long life time. This level E_3 forms the upper laser level and E_2, the lower laser level. The population inversion is achieved between E_3 and E_2 and so lasing action takes place between these levels.

The lower laser level E_2 have only a short life time so the atoms from E_2 make transition E_1, ready for being pumped up to E_4

Laser Beam characteristics.

Comparison between Laser and Ordinary Light

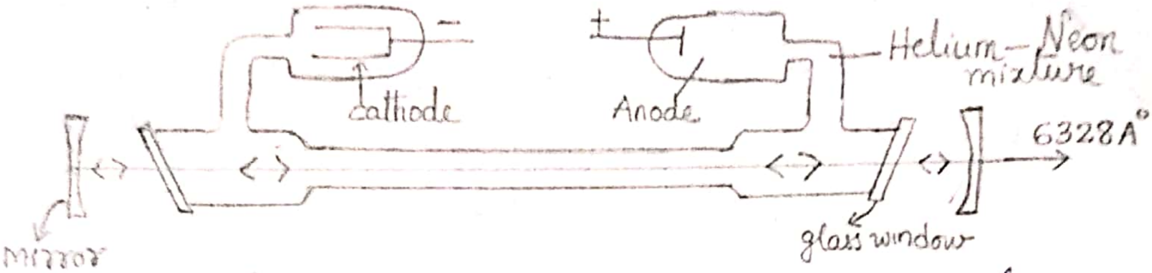
LASER	ORDINARY LIGHT
It is highly monochromatic	It is polychromatic
It is highly coherent	It is not coherent
Laser light is highly directional	It is not directional
Divergence of light is negligible	Divergence is very high.
Intensity is tremendously large and constant with distance	Intensity is low and decreases rapidly with distance.
Stimulated emission is responsible for it	Spontaneous emission is responsible for it.

Types of Lasers

Laser are divided into deffferent types. Some of the important types on the basis of materials used are

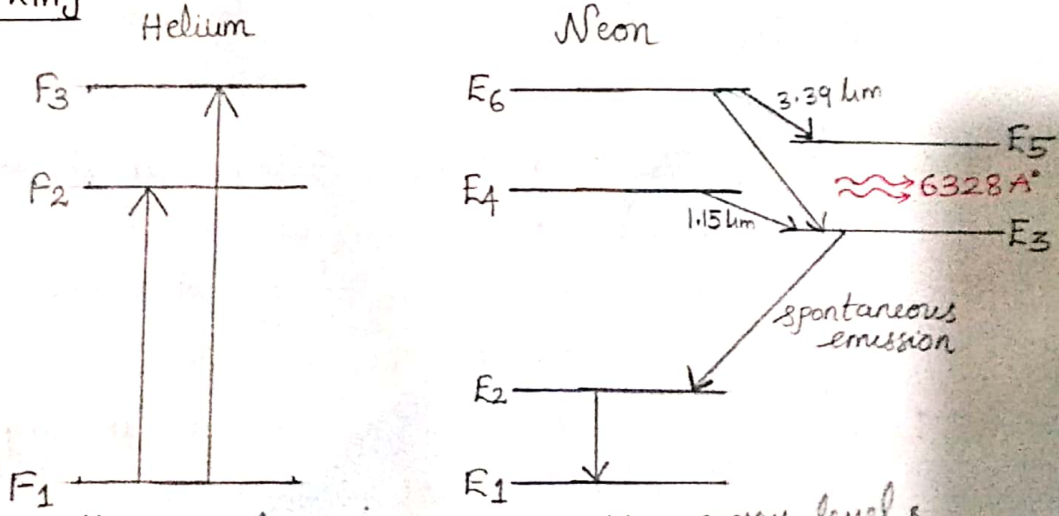
1. Solid state lasers : e.g: Ruby laser, Nd:YAG Laser etc.
2. Gas Laser : e.g: Helium Neon Laser, CO_2 laser etc.
3. Semiconductor diode laser : e.g: GaAs laser, InP laser etc.

Helium - Neon Laser



The He-Ne laser was the first gas laser, which was invented in 1961. The He-Ne laser consists of a long and narrow discharge tube filled with a mixture of helium and neon gases in the ratio 10:1. Electrical discharge method is used for producing population inversion in gas lasers. Electrodes are provided in the discharge tube to produce discharge in the gas. They are connected to a high voltage power supply. The tube is sealed by inclined windows at its two ends. On the axis of tube, two mirrors are arranged, one is a perflector at one end and the other is partial reflector at the other end (optical resonator)

Working



He energy levels

Ne energy levels

Pumping mechanism:- When the power is switched on, a high voltage is applied across the gas mixture. It ionizes the gas. The electrons and ions produced are accelerated towards the anode and cathode respectively. They

(13) collide with He & Ne atoms and excite them to higher energy state. The accelerated electrons ~~collie~~ excite He atoms more readily as they are lighter and greater in number than Ne.

F_1, F_2, F_3 represent the energy states of He atom & $E_1, E_2 \cdots E_6$ ~~rep~~ those of Neon atoms. The He atoms are excited by electrons to the energy levels F_2 and F_3 from F_1. These levels F_2 and F_3 have long life time.

The excited states E_4 and E_6 of Neon and the states F_2 and F_3 of Helium have approximately the same energy values. When He atoms in levels F_2 and F_3 collide with Ne atoms in the level E_1, resonant transfer of energy takes place. This causes excitation of Ne atoms to level E_4 and E_6. At the same time, colliding Helium atoms get deexcited to ground level.

The discharge through the gas mixture continuously increases the Neon excited energy level E_4 & E_6. Thus a state of population inversion between E_4 or E_6 and the lower levels E_3 and E_5 of Neon is achieved. Hence lasing action takes place and the various transitions are

(i) $E_6 \rightarrow E_5$: giving radiations of 3.39 μm in the infrared region, which are not visible.

(ii) $E_6 \rightarrow E_3$: giving radiations of 632 A° wavelength in visible region, red in colour

(iii) $E_4 \rightarrow E_3$: giving radiations of 1.15 μm in infrared region which are not visible

The Ne atoms in the level E_3 drops down to E_2 level spontaneously. E_2 is also a metastable state. This will reduce the population inversion between E_6 and E_3. Hence it is necessary that the Ne atoms accumulate at level E_2 are brought to ground state

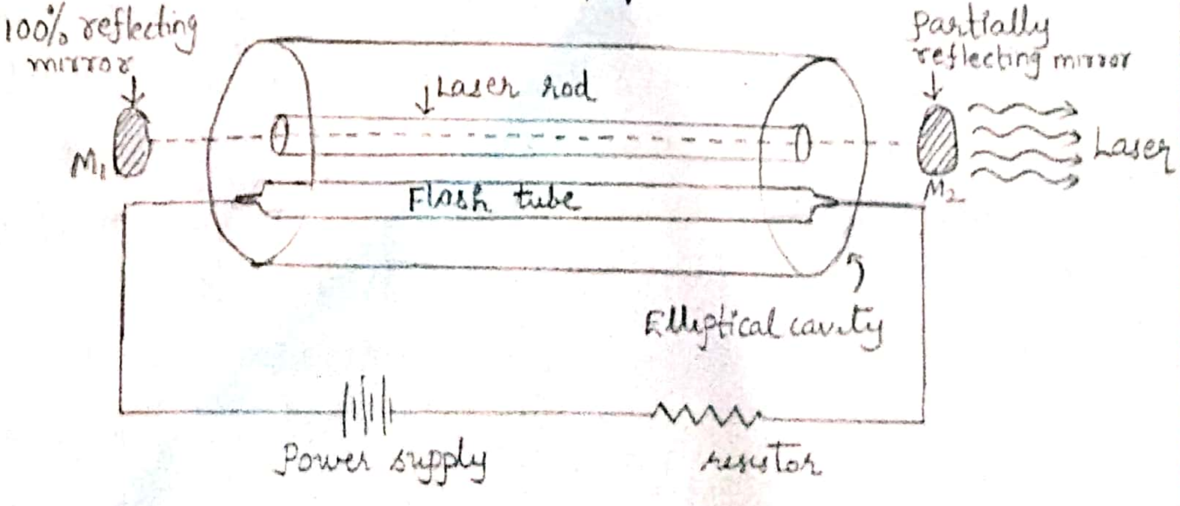
E_1 quickly. The only way of bringing the atoms to the ground state is through collisions. If a narrow tube is used, the Ne atoms in the level E_2 will collide with the walls of the tube and will get de-excited to the level E_1

FEATURES

* Its output is continuous
* It gives highly monochromatic red colour, which is highly stable
* NO need for any cooling arrangement
* Low efficiency and low power output

Nd:YAG LASER

Nd:YAG Laser is a solid state laser based on four level system. The YAG is an abbreviation for Yttrium aluminium garnet ($Y_3Al_5O_2$). YAG (Y^{3+} ions) is doped with Neodymium ions (Nd^{3+}). The YAG acts as the host crystal. Whereas Nd^{3+} ions are the activators, which take part in lasing action.



The system consists of an elliptical cylindrical cavity that has laser rod along one of its focus line and a flash lamp (for pumping) along the other focus line.

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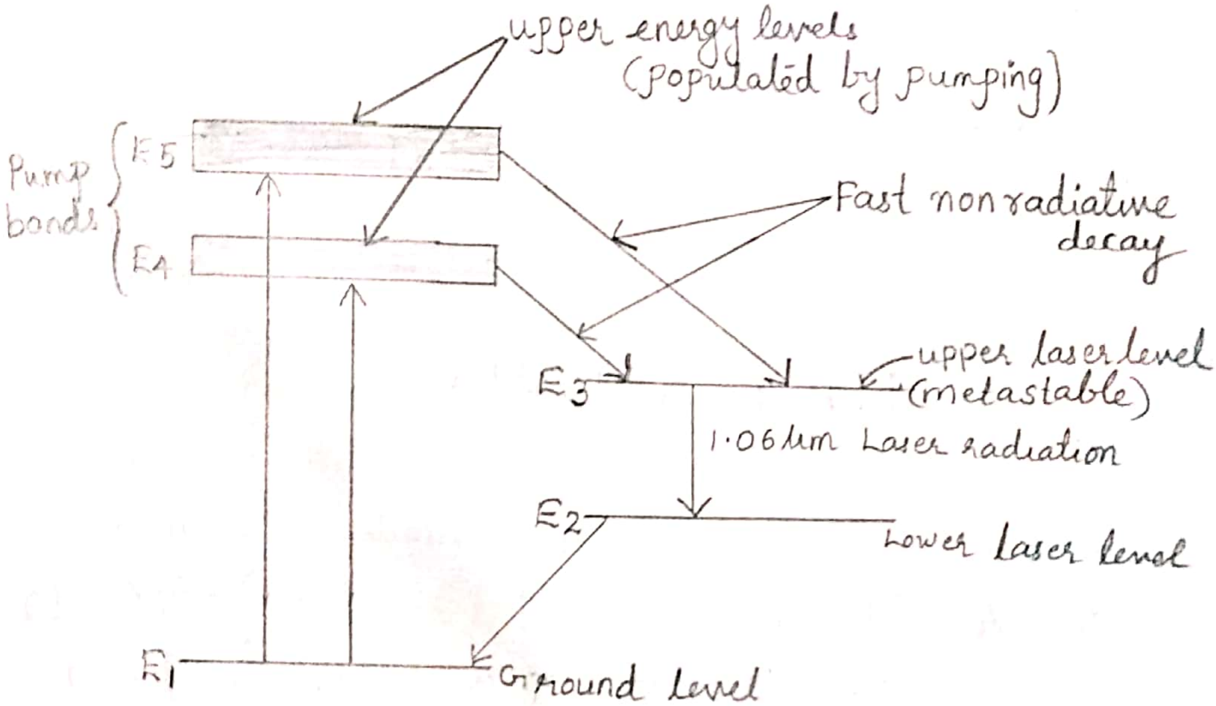
The two ends of the laser rod covered with polished and silvered reflecting surfaces which forms the optical resonator. The laser rod is 10cm long and 12mm in diameter. The light leaving one focus of the ellipse will pass through the other focus after after reflection from the silvered surface of the reflector. Thus the entire flash lamp radiation gets focused on the laser rod.



When the flash lamp is switched on, the Nd^{3+} ions are excited to upper energy bands E_4 and E_5 from ground state. These ions make a transition from these energy levels to level E_3 by non-radiative transition. E_3 is a metastable state. The metastable level E_3 is the upper laser level, while E_2 forms lower laser level. E_3 states ~~is~~ gets rapidly populated and population inversion takes place between E_3 and E_2. Thus with the help of pumping and resonant cavity a continuous laser of 1.06μm (10,600 Å) wavelength in infrared region is given out between E_3 and E_2.

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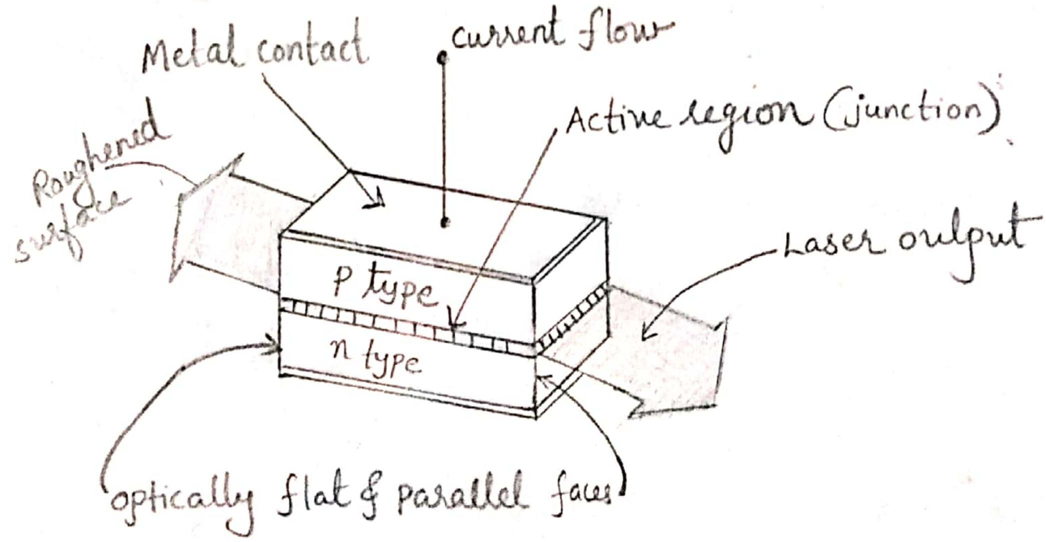
Semiconductor Diode Laser

Semiconductor diode laser is formed by a heavily doped p-n junction diode, which emits coherent light when it is forward biased. These lasers are made using direct bandgap semiconductors. Gallium Arsenide (GaAs) diode is an example of semiconductor diode laser. It has many special characteristics like (1) Extremely small in size and low cost (2) Due to direct conversion of electrical energy into light energy it is very efficient. The basic principle of light emission from a semiconductor laser is the recombination of electrons & holes at a p-n junction when a current is passed through the diode

The wavelength of light $\Rightarrow \lambda = \frac{hc}{E_g}$

E_g is the energy gap (separation between conduction and valence band)



A heavily doped diode is used for semiconductor diode laser. The top and bottom faces are metallized and metal contacts are provided to pass current through diode. The front and rear end faces are polished parallel to each other and

17 perpendicular to the junction in order to create a resonator cavity. The thin junction here act as the active region.

There are two types of semiconductor lasers: homojunction semiconductor lasers & heterojunction semiconductor lasers.

Homojunction laser:- A simple diode laser, which makes use of same semiconductor material on both sides of the junction. eg: Gallium Arsenide (GaAs) laser.

Heterojunction laser:- Is a diode laser which makes use of different semiconductor materials on the two sides of the junction. eg: A junction laser having GaAs on one side and GaAlAs on other side.

Pumping Mechanism

When the junction is forward biased, electrons and holes are injected into the junction region in high concentrations. i.e charge carriers are pumped by dc voltage source. When the diode current reaches a threshold value, the carrier concentration in the junction will rise to a very high value.

Population Inversion

Due to forward bias, the active region contains a large concentration of electrons within the conduction band and simultaneously a large number of holes within the valence band. Thus, the upper energy levels in the active region are having a high electron population while the lower energy levels in the same region are ~~active~~ vacant. Thereby, the condition of population inversion is achieved in the narrow active region.

Lasing

The recombination acts of electron-hole pair lead to spontaneous emission of photons. The spontaneous photons propagating in the junction plane stimulate the conduction electrons to jump into the vacant sites of valence band. This produces coherent radiation by lasing action.

The wavelength of Laser depends on the band gap energy E_g of the material

$$E_g = h\nu = \frac{hc}{\lambda}$$

$\therefore$ wavelength of Laser beam $\lambda = \frac{hc}{E_g}$

GaAs laser emits wavelength of 9000 A° which is in the infrared region. GaAsP laser emits laser of wavelength 6500 A° in the visible red region.

Applications of Laser

HOLOGRAPHY

A photograph is a two dimensional record of a three dimensional object. Here three dimensional character of the object is lost. In ordinary photography only the distribution of intensity, i.e distribution of square of amplitude is recorded in the plane of the photograph.

Holography means complete recording. A hologram is the three dimensional record of a three dimensional object or scene. In this method, both amplitude and phase components of light wave are recorded on a photographic plate. Holography required an intense coherent light source.

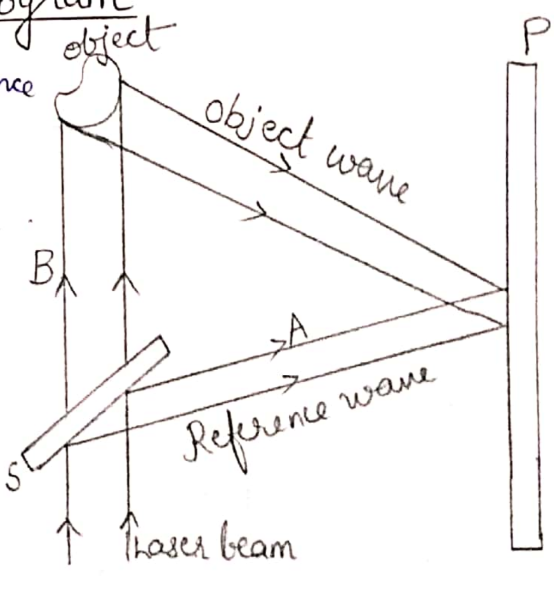
Principle of Holography

The basic principle of holography can be explained in two steps (i) Recording of hologram and (ii) Reconstructing the image.

(i) Recording of the Hologram

Holography is a interference based technique.

A laser beam is divided by a beam splitter S' into two beams namely a reference beam (A) and an object beam (B)

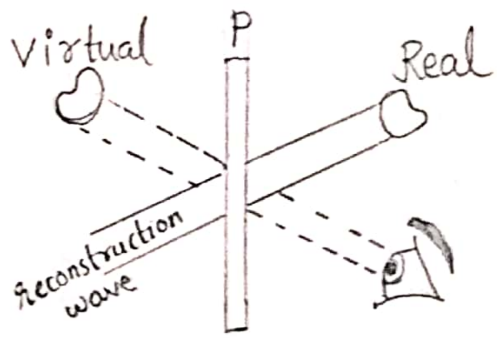


The transmitted beam B falls on the object whose hologram is to be prepared. A part of the light scattered by the object falls on a photographic
(object beam)

plate P. This scattered beam from the object is object beam. The reflected beam 'A' which is called the reference beam also falls on the photographic plate. The superposition of these two beams produces an interference pattern which is recorded on the plate. The photographic plate is developed. The developed plate i.e, the resulting photograph is known as hologram. The hologram does not contain a distinct image of the object, but carries a record of both the intensity and relative phase of light wave at each point.

(ii) Reconstruction of the image

For reconstruction of the image, the hologram is illuminated by a laser beam identical with the one used in recording. This laser beam is called a read out wave or reconstruction wave. It interacts with the interference pattern on the plate. Two images are produced due to diffracted waves. One of them appears at position originally occupied by the object. This image is virtual. The other image is real, which is formed infront of the hologram. The virtual image which is seen by looking through the hologram appears in complete three dimensional form. The perspective of the picture changes by moving the position of the eyes.



21. Distinguish between photograph and Hologram

Photography	Holography
Two dimensional recording of the object	Three dimensional recording of the object
uses ordinary light	Uses laser light for recording
Amplitude recording is done	Both amplitude and phase recording is done
The negative resembles the object	The hologram is an interference pattern that does not resemble object
Photograph reading is not encoded	Hologram reading is encoded with the wavelength of light used for recording it

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Stay Safe
Study Well

Regards
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