Laser is an acronym for 'Light Amplification by stimulated Emission of Radiation'. It is a photonic device which uses a quantum mechanical effect stimulated emission to generate a very collimated, monochromatic and coherent beam of light. The first working laser was made by Theodore H Maiman in 1960 at Hughes Research Laboratory. The second working laser, Helium-Neon (He-Ne) laser, which is the first gas laser was developed by Ali Javan and his associates in 1961. With the development of semiconductor technology, semiconductor lasers as small as a grain of salt was fabricated. The light beam produced by most laser is pencil thin and maintains it size and direction over very large distances.

Characteristics of laser light

Laser light has several special quantities which distinguish them from other light sources. The most striking features of laser light are its

a) high degree of coherence

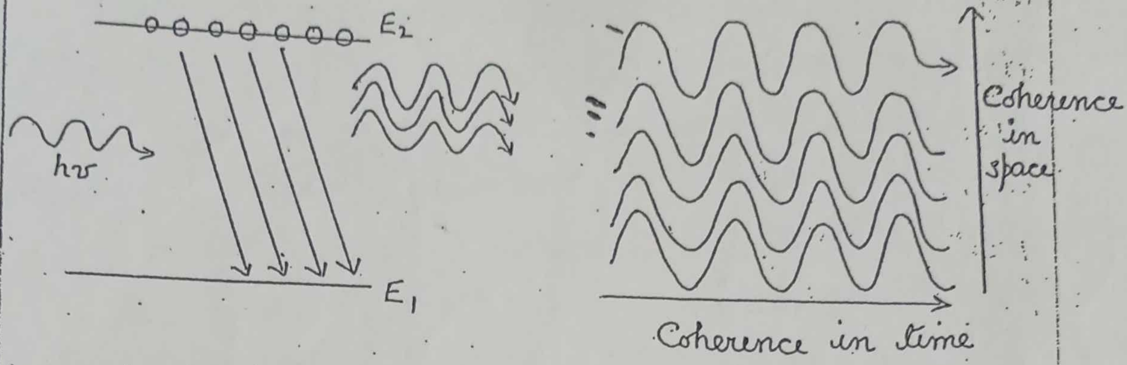
b) high intensity

c) extraordinary monochromaticity

d) unidirectionality [highly collimated or less divergent]

Coherence

Coherence is one of the unique properties of laser light. It arises from the stimulated emission process which provides the amplification. Since a common stimulus triggers the emission events which provide the amplified light, all the emitted photons bear a constant phase relationship with each other in both time and phase. The light is said to be coherent, both in terms of temporal and spatial coherence.



Monochromatic

Light from a laser typically comes from one atomic transition with a single precise wavelength. So the laser light has a single spectral colour and is almost the purest monochromatic light available.

Collimated

The light from a typical laser emerges in an extremely thin beam with very litte divergence. Or the laser beam is highly collimated. The high degree of collimation arises from the fact that the cavity of the laser has very nearly parallel front and back mirrors which constrain the final laser beam to a path which is perpendicular to the mirrors.

Intensity

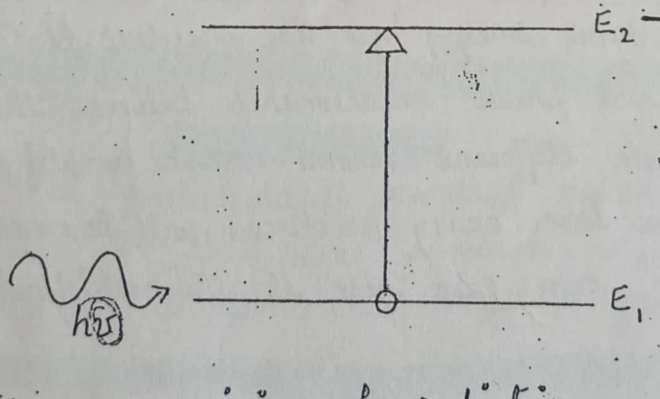
The light from a conventional source streams out more or less uniformly in all directions. The intensity decreases rapidly with distance as it spreads out in the form of plane waves. The laser emit light into a narrow beam which propagates in the form of plane waves. The light bounces back and forth between the mirrors many times in order to gain intensity by the stimulated emission of more photons at the same wavelength. As the energy is concentrated, both spatially and spectially in a very small region, its intensity would be tremendously high.

<u>Interaction of radiation with matter</u>

In order to know how an amplifying medium amplifies light, we should known the quantum processes that take place in a material when exposed to radiation. A material medium is composed of atoms, which can move from one energy state to another when it receives or releases an amount of energy which is equal to the difference in energy between those two states. Let a monochromatic radiation of frequency ν is incident on the medium. If the energy $h\nu = E_2 - E_1$, the interaction of radiation with atoms leads to three distinct processes.

1. <u>Stimulated absorption of radiation</u>

When a photon having energy $h\nu$ $(= E_2 - E_1)$ is incident on the atom, the energy is absorbed by the atom in the ground state E_1 and jump to the excited state E_2. This transition is known as stimulated or induced absorption of photon.

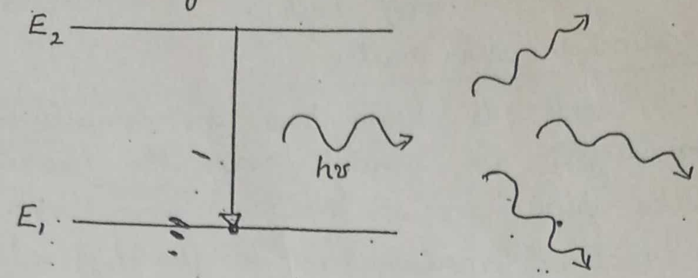


$h\nu = E_2 - E_1$

$E_2 = E_1 + h\nu$

2. <u>Spontaneous emission of radiation</u>

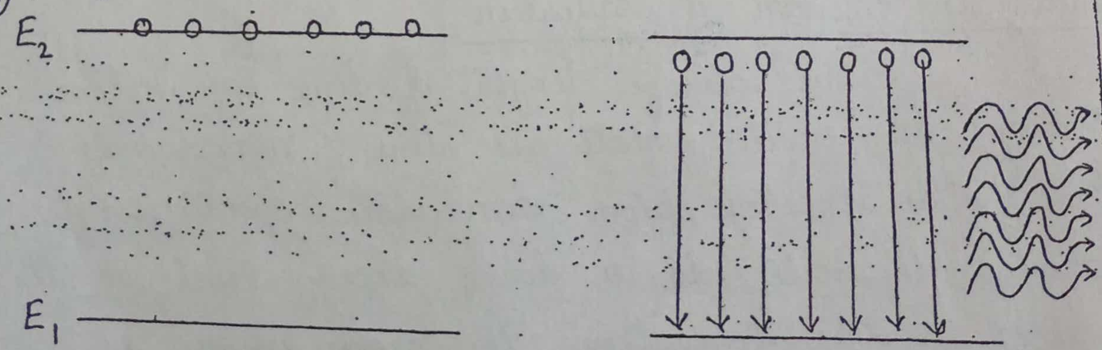
The average length of time an atom can stays in excited state is tens of nanoseconds (10^{-8} secs). The excited atom can then spontaneously (randomly) de-excite to a lower energy level on its own. During this transition, the excess energy is released as a photon of $h\nu = E_2 - E_1$. This kind of process by which photons are emitted without any external force is called spontaneous emission.



The emitted photons can move in any random direction and there does not exist any relation between the photon emitted from different atoms. So the radeation coming out will be incoherent.

3. Stimulated emission of radiation

Stimulated emission is a very uncommon quantum process in nature but it is crucial for the formation of LASER action. In stimulated emission, atoms in an upper energy level can be triggered or stimulated in phase by an incoming photon of a specific energy. The incident photon must have an energy corresponding to the energy difference between the upper and lower states. The atom in the higher energy level de-excites with the consequent release of photons of the same energy as the incident photon. There exists a fixed phase relationship between the photons emitted from different atoms in the amplifying medium and the laser beam produced will be coherent. Stimulated emission can give rise to the amplification of light.



The stimulated photons have unique properties

1) the emitted photon is in phase with the incident photon.

2 The emitted photon has the same wavelength as the incident photon

3 The emitted photon travels in the same direction as incident photon.

Einstein's co-efficients (A, B)

Under thermal equilibrium, the population N_1 and N_2 in the lower and upper energy levels respectively must remain constant. The condition is that the number of transition from E_2 to E_1 must be equal to the transition from E_1 to E_2.

The number of ~~photon~~ atoms absorbing photons per second per unit volume = The number of atoms emitting photons per second per unit volume.

The rate of absorption transition is given by

$$R_{ab} = B_{12}\,\rho(\nu)\,N_1 \qquad \text{--- (1)}$$

where N_1 is the population of atoms at E_1, $\rho(\nu)$ the energy density of the incident beam and B_{12} is the constant of proportionality known as the Einstein coefficient for induced absorption. Equation (1) indicates the probability of occurence of an induced transition from level 1 to 2.

The rate of spontaneous transition is given by

$$R_{sp} = A_{21} N_2 \qquad \text{--- (2)}$$

A_{21} is the proportionality constant called the Einstein coefficient for spontaneous emission. A_{21} represents the probability of a spontaneous transition from level 2 to 1.

The rate of stimulated emission of photons is

$$R_{st} = B_{21}\,\rho(\nu)\,N_2 \qquad \text{--- (3)}$$

B_{21} is the Einstein coefficient for stimulated emission and represents the probability for induced transition from level 2 to 1.

Equating equation (1) with (2) & (3)

$$R_{ab} = R_{sp} + R_{st}$$

$$B_{12}\,\rho(\nu)\,N_1 = B_{21}\,\rho(\nu)\,N_2 + A_{21} N_2$$

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

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

By dividing both the numerator and denominator on the right side by $B_{12}N_2$

$$\rho(\nu) = \frac{A_{21}/B_{12}}{N_1/N_2 - B_{21}/B_{12}} \quad \text{--- (4)}$$

At thermal equilibrium, the population at the energy levels with the help of Boltzmann law

$$N_1 = N_0 e^{-E_1/kT} \quad \& \quad N_2 = N_0 e^{-E_2/kT}$$

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

But $E_2 - E_1 = h\nu$

$$\frac{N_1}{N_2} = e^{h\nu/kT}$$

$$\therefore \rho(\nu) = \frac{A_{21}}{B_{12}}\left[\frac{1}{e^{h\nu/kT} - B_{21}/B_{12}}\right] \quad \text{--- (5)}$$

To maintain thermal equilibrium, the system must release energy in the form of electromagnetic radiation. It is required that the radiation must be identical with the black body radiation and be consistent with Planck's radiation law. According to Planck's law

$$\rho(\nu) = \frac{8\pi h\mu^3\nu^3}{c^3}\left[\frac{1}{e^{h\nu/kT} - 1}\right] \quad \text{--- (6)}$$

Energy density $\rho(\nu)$ given by eqn. (5) will be consistent with Planck's law (6) only if

$$\frac{A_{21}}{B_{12}} = \frac{8\pi h\nu^3\mu^3}{c^3} \quad \text{--- (7)}$$

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

Equations (7) and (8) are known as Einsteins relations.

Since $B_{21} = B_{12}$

$$\frac{A_{21}}{B_{12}} = \frac{A_{21}}{B_{21}} = \frac{8\pi h\mu^3\nu^3}{c^3}$$

ie the ratio of spontaneous verses stimulated emission is proportional to the third power of frequency of the radiation. This is why it is difficult to achieve laser action in higher frequency ranges such as X-rays.

Condition for stimulated emission to dominate absorption

The presence of a large number of photons will lead to more absorption rather than stimulated emission. Three conditions are to be satisfied to make stimulated emission exceeds absorption. ~~are~~ They are

1. the number of atoms in the excited state should be greater than that at the lower energy level.
2. the ratio B_{21}/A_{21} should be large, and
3. a very high radiation density should be present in the medium.

A medium amplifies light only when these three conditions are fulfilled. To achieve high percentage of stimulated emissions

1. an artificial situation known as population inversion is to be created in the medium...
2. a larger value of B_{21}/A_{21} is achieved by choosing a metastable energy level as the higher level.
3. $\rho(\nu)$ is made larger by enclosing the emitted radiation in an optical resonant cavity formed by two parallel mirrors.

Population Inversion

When the material is in thermal equilibrium the population ratio is governed by the Boltzmann distribution law according to the equation

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/kT} \qquad \text{——— (1)}$$

which means that the population N_2 at the excited level E_2 will be far smaller than the population N_1 at the level E_1. This condition is called normal condition or thermal equilibrium.

To achieve a high percentage of stimulated emission, a majority of atom should be at the higher energy level than at the lower level. ie. the population ratio N_2/N_1 should increase momentarily without change in temperature. Population inversion is the non-equilibrium condition of the material in which population of upper level exceeds that of the lower level.

ie $N_2 >> N_1$

According to equation ① N_2 can exceed N_1 only if the temperature were negative. So the state of population inversion is also refrred to as a negative temperature state. It does not mean that we can achieve temperature below absolute zero. It is only a non-equilibrium condition and population inversion is attained at normal temperature.

Active medium

In a medium consisting of different species of atoms, only a small fraction of atoms of a particular type have energy level system suitable for achieving population inversion. Those atoms which cause laser action are called active centers. The rest of the medium acts as host and support active centers and ~~are~~ called active medium. An active medium is a medium which when excited reaches the state of population inversion and promotes stimulated emissions leading to light amplification.

Pumping

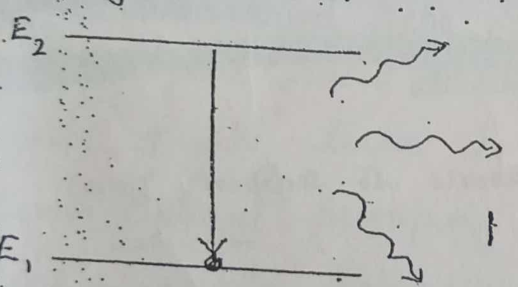
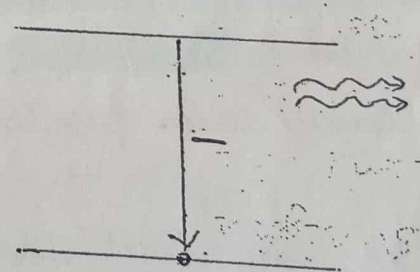
For achieving and maintaining the condition of population inversion, the atoms in the lower energy level have to raise continuously to the upper energy level. A large amount of input energy has to be supplied to the system to momentarily increase N_2 to a value comparable to N_1. Pumping is the process of supplying energy to the laser medium.

There are a number of techniques for pumping a collection of atoms to an inverted state.

What is Laser ?

LASER stands for Light Amplification by Stimulated Emission of Radiation. It is a photonic device used to produce high intense, highly coherent, monochromatic and well collimated beam of light.

Differentiate between spontaneous and stimulated emission.

Spontaneous Emission	Stimulated Emission
It is a natural transition in which the atom is de-excited to the lower energy level after spending $\sim 10^{-8}s$ in the higher energy level.	It is a quantum process in which the atoms in the higher energy level are triggered by an incoming photon of specific energy
The emitted photon can move in any random direction. 	The incident photon and the emitted photon will move in the same direction. 
The photons emitted are not in phase and the radiation coming out is incoherent.	The photons emitted are in phase and the radiation produced will be coherent.
The rate of spontaneous emission depends only on the number of atoms in the energy level	The rate of stimulated emission depends only on the number of atoms in the energy level as well as the energy density of the incident radiation.

What do you understand by a metastable state ?

Normally an atom in the excited state comes back to the ground state within a very short time of about $10^{-8}s$ by the emission of a photon. The average time for which an atom remains in an excited state is known as its mean life. Energy states having mean life of more than 10^{-3} sec are known as metastable states.

4. What is population inversion? How is it achieved?

In thermal equilibrium, the number of atoms in the higher energy state is less than the number of atoms in the lower energy state. According to Maxwell-Boltzmann distribution law

$$N_1 = N_0 e^{-E_1/kT} \quad \& \quad N_2 = N_0 e^{-E_2/kT}$$

As $E_2 > E_1$, $N_2 < N_1$. In order to have laser action, the no. of atoms in the higher energy state E_2 must be greater than that in E_1. The establishment of a situation in which the number of atoms in the higher energy level is greater than that in the lower energy level is called population inversion. The procedure adopted to achieve population inversion is called ~~optical~~ pumping.

5. Is two level laser possible? Give reasons to support your answer.

No, two level laser is not possible because it is difficult to achieve population inversion. According to Einstein relation, the probability for stimulated absorption and stimulated emission is exactly the same. The lifetime of an excited state is about $10^{-8}s$ and the atoms drop back down to the ground state as fast as they are pumped to the higher energy level. Thus the upward transitions would be accomplished by premature downward stimulated transitions and the population in higher level would not accumulate to the required extent. Thus with two level system, population inversion cannot be achieved.

6. What are the essential conditions for lasing actions?

Laser is produced by stimulated emission of radiation. To start the laser action the probability of stimulated emission should be more compared to spontaneous emission. To achieve higher probability of stimulated emission the following conditions must be satisfied

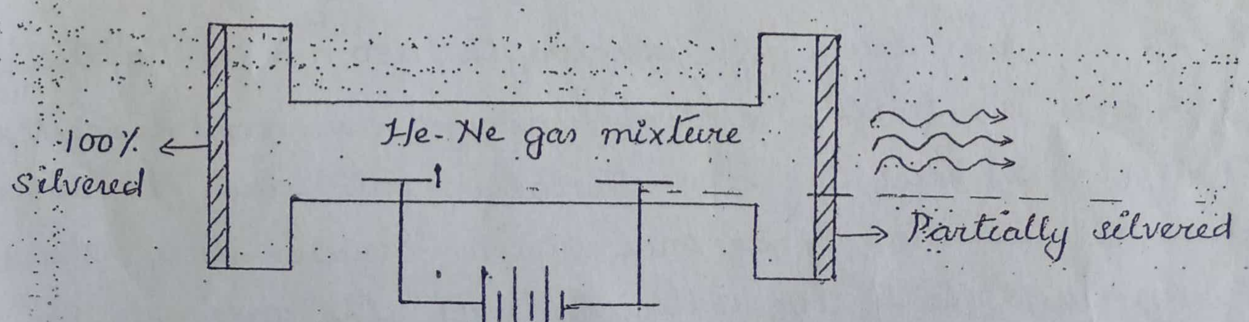
1. The higher energy state should have a longer mean life ie it should be a metastable state.
2. The number of atoms in the higher energy state must be greater than that in the lower energy state.

7. What is the role of He in He-Ne laser?

Helium helps in the excitation of neon atoms. The metastable states of helium atom are almost identical with two energy states of neon atom. He absorbs energy from the electrons generated by electric discharge and then that energy is transferred to neon atom.

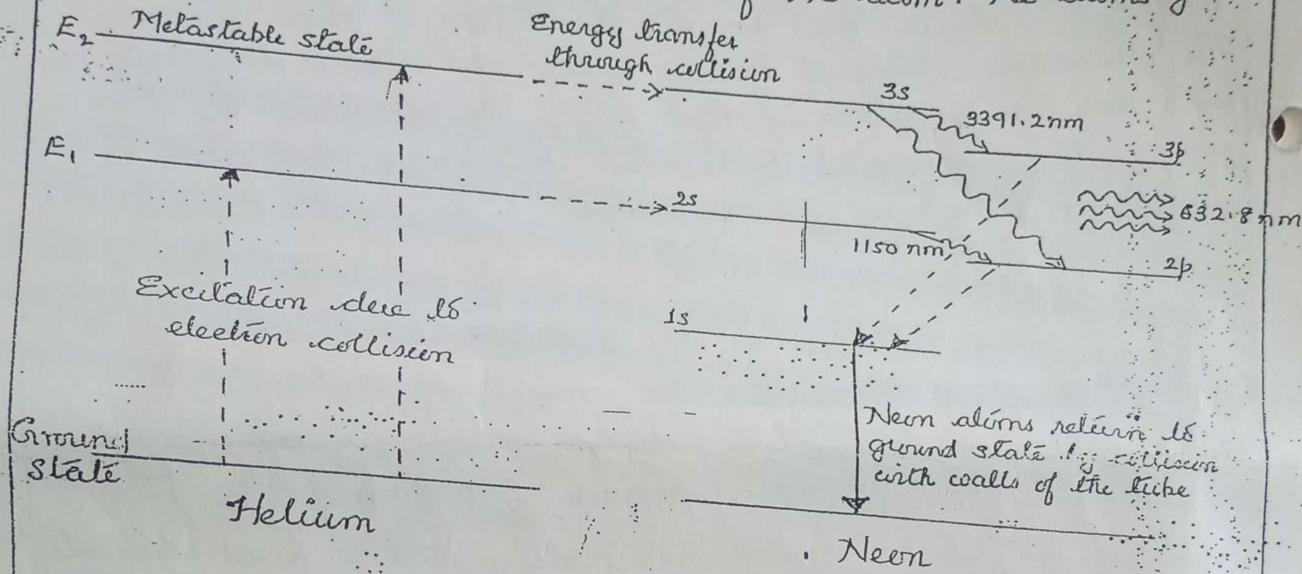
He-Ne laser

He-Ne laser is the first gas laser built in 1961 by Ali Javan and W. Bennett. It consists of a long and narrow discharge tube filled with a mixture of He and Ne gases in the ratio 10:1 and pressure of 0.1 mm of Hg. The length of the tube is approximately 0.5m and diameter 1.5cm. Optical pumping is carried out using electrical discharge. The tube is fitted with two electrodes across which high voltage dc is applied. Two mirrors are fitted at the ends of the tube; one is fully silvered and other is partially silvered and this combination acts as a resonant cavity.



(12)

<u>Working</u>: When a discharge is passed through the gaseous mixture, electrons are accelerated down the tube. These accelerated electrons collide with He atoms and excited them to higher energy levels. E_1 and E_2 are metastable states and He atoms stay there for a relatively long time. Due to collision between He and Ne atoms, the excited He atoms transfer energy to Ne atom as Ne have two identical energy state as that of He atom. Ne atoms get



accumulated in these two excited states and causes population inversion. Once the population inversion is established, three laser transitions take place.

1. 3s to 2p : Laser beam of red colour of wavelength 632.8nm is produced

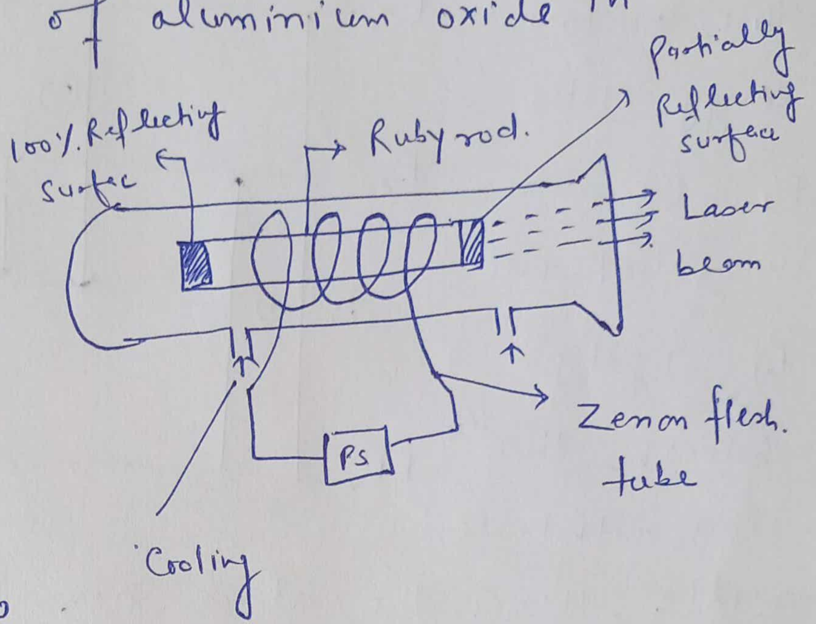
2. 3s to 3p : Laser beam of wavelength 3391.2nm in the far infrared region is produced

3. 2s to 2p : Infrared Laser beam of wavelength 1150 nm is produced

From 3p and 2p levels, Ne atoms undergo downward transition to 1s level. 1s level is a metastable state and Ne atoms may accumulate ~~at~~ this level once <u>again</u>; however they return to the ground state by colliding with the walls of the tube.

Ruby Laser :- Simon was the first to use ruby crystal for obtaining laser beam.

Ruby is a crystal of aluminium oxide in which some chromium atoms take the place of some aluminium atoms. (0.5% Cr^{3+}) is present.

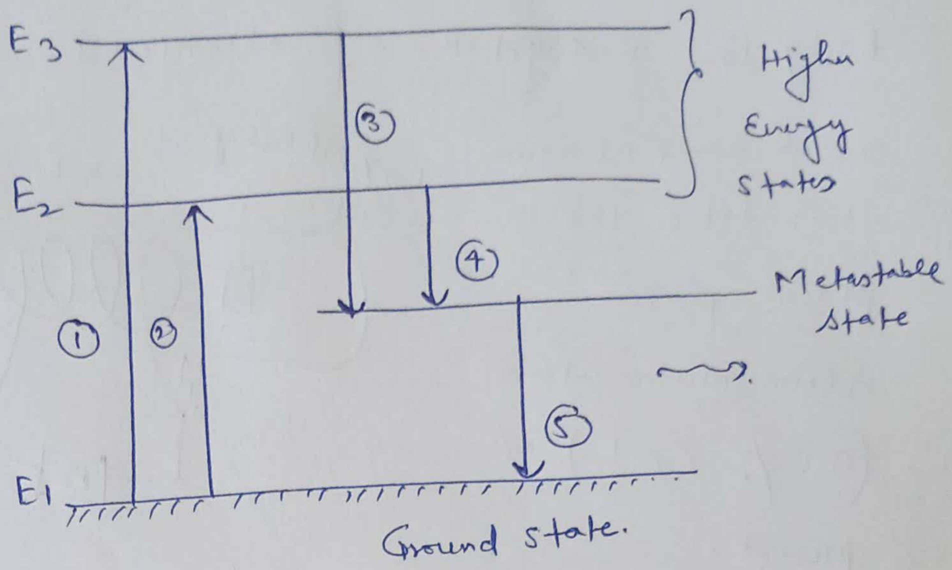


- wavelength 6943 A°
- Solid state Laser
- 3-Levels Laser

A helical Zenon flash tube is wrapped on the ruby rod, which produces pumping light which shifts the chromium ions to high energy levels. When Power supply on, Zenon flash operates for few ms which provides several thousand Joules energy. only one part of this is used in pumping the Cr^{3+} ions, remaining energy heat up the apparatus, so a cooling system is also arranged. In output laser beam we get the principal wavelength of 6943 A° which lie in the visible part of the spectrum. The time of output pulse is 300 μs. This laser is very intense (~10,000 W)

Explanation (working)

In Chromium ion there are two energy states E_2 & E_3 above the ground state E_1. Slightly below E_2 there is a metastable



state, Hence the atoms can remain in the state for long time.

When the flash of light falls on ruby laser the chromium ions absorb green and yellow light and get excited and shift to the higher energy states E_2 and E_3. The excited ions after giving some energy to the crystal come back to metastable state as shown by (3) & (4)

When an excited atom returns from metastable state to ground state E_1 it emits red photon of red colour as shown by (5)

That photon travels parallel to ruby rod get reflected again and again by ends of the rod. During this photon collide with any other excited atom and emits the photon of the same freq. by stimulated emission. This photon travels ‖ to the axis of ruby rod and get reflected again and again. This process is continues and this beam gets enlarged so that a part of this beam is refracted by the partial reflecting surface and come out of the rod.

Coherence :-

The laser beam is coherent, with the waves of all exactly in phase with one another.

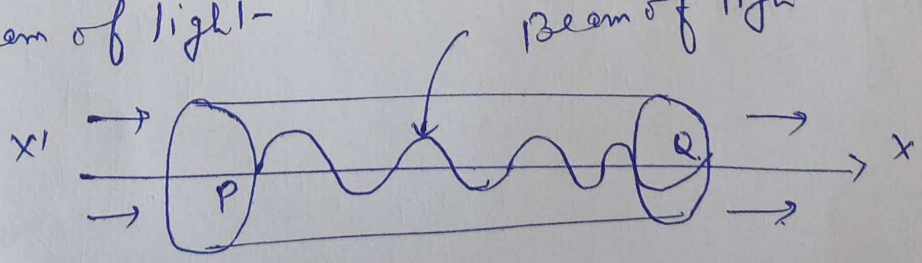
It is of two types -

(a) Temporal or Time Coherence

(b) Spatial or space coherence.

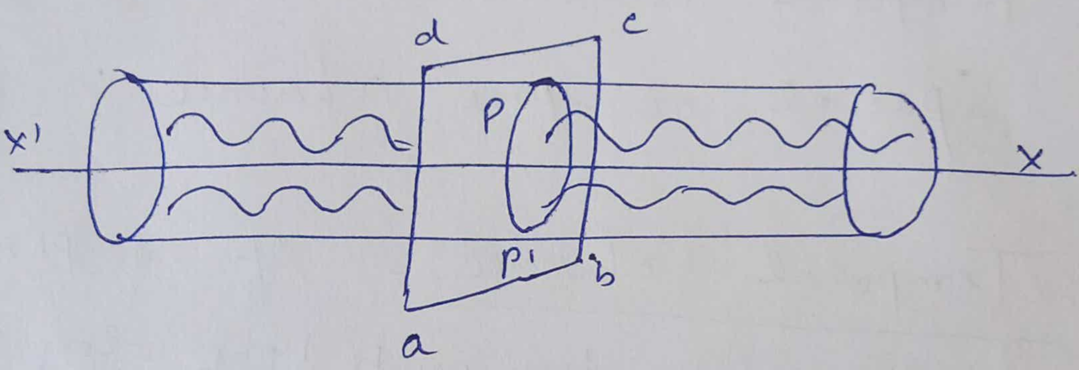
(a) Temporal Coherence :- If the phase difference of waves crossing the two points lying along the direction of propagation of the beam is time dependent, then a beam of light is said to possess temporal or time coherence. This coherence is also known as longitudinal coherence

In fig. a beam of light travelling along X' X



P and Q are the two points lying on this time. The beam is said to possess temporal coherence if the phase diff. of waves crossing P and Q at any instant is always constant.

Spatial Coherence :- A laser beam is said to possess spatial coherence, if the phase difference of the waves crossing the two points lying on a plane ⊥ to the direction of propogation of the beam is time dependent. This coherence is also called as transversed or lateral Coherence. It is a measure of the minimum separation across the wave. from where two waves remain coherent.



In fig. a beam of light travelling along the line X'X. abcd is a plane ⊥ to X'X. The beam is said to possess spatial coherence, if the ~~plane~~ phase difference of the waves crossing P and P' at any instant is always coherent.