UNIT-V Lasers

LASER Stands for Light Amplification by Stimulated Emission of Radiation.

Laser is a device which emits a powerful monochromatic, collimated beam of light. The emitted light waves are coherent in nature.

Light emerges as a narrow beam that can travel over long distances without much loss of intensity, energy and divergence. Actually, the laser amplifies the light waves.

Laser is an artifical light source having so many superior features than the conventional light sources.

Dr. T. H. Maiman invented the first laser, namely ruby laser in the year 1960. Since, then, the development of lasers has been extremely rapid with laser action demonstrated in solids, liquids, gases, semiconductors etc.

Types of Lasers

1.	Solid State laser	Ruby laser, Nd: YAG laser
2.	Gas Laser	He-Ne laser, CO_2 laser, Argon-ion laser.
3.	Liquid Laser	$SeOCl_2$ laser, Europium Chelate laser
4.	Dye Laser	Rhodamine 6G laser, Coumarin dye laser.
5.	Semiconductor Laser	GaAs laser, GaAsP Laser.

ABSORPTION AND EMISSION OF RADIATION :

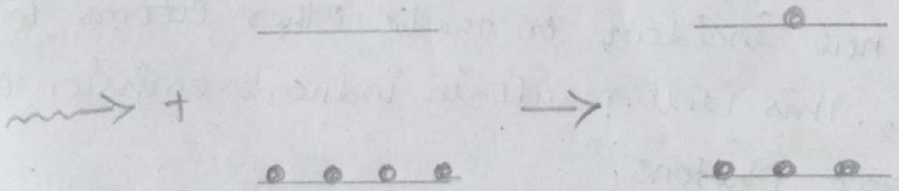
The various energy states of a molecule form a series of energy levels. If a system has number of molecules, they are distributed among the various levels as per the Boltzmann distribution law. There are three ways by which a molecule can change it's energy state.

ABSORPTION :

Consider a system of atoms or molecules having two energy levels, a ground level of energy E_1 and an excited level of energy E_2. When we allow electromagnetic radiation of frequency ν, where $h\nu = E_2 - E_1$ to interact with the system, some of the atoms or molecules absorb radiation and make transitions from state 1 to state 2. This absorption of radiation of appropriate frequency by a system is called Induced absorption.

$$\text{Atom} + \text{photon} \longrightarrow \text{Atom}^*$$

The asterisk indicates an excited state. The absorption process of a photon without this

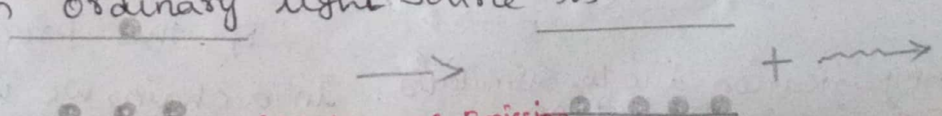


Absorption process

the influence of an external agency is called Spontaneous emission. which is represented as

$$\text{Atom}^* \longrightarrow \text{Atom} + \text{Photon}$$

Photons emitted by spontaneous emission will not be in phase and are said to be incoherent. Light from an ordinary light source is incoherent.



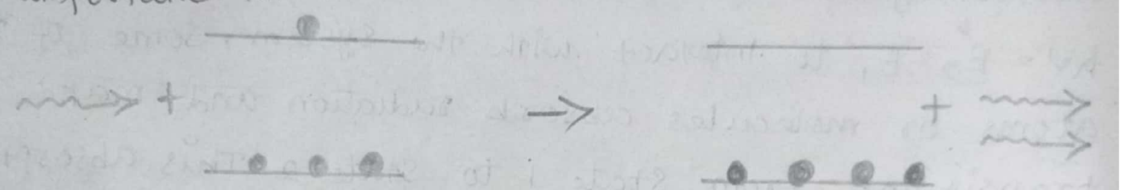
Spontaneous Emission

STIMULATED EMISSION :

In Stimulated emission or Induced emission, a molecule in the upper State may be Stimulated to release a quantum of energy $h\nu = E_2 - E_1$ by the presence of another quantum of equivalent energy $h\nu$. Symbolically,

$$Atom^* + Photon \rightarrow Atom + 2\ Photons.$$

These two photons will be in phase and will move in the same direction. That is the output will be completely coherent. The stimulated emission process suggested by Einstein in 1917 is of fundamental importance in the development of lasers.

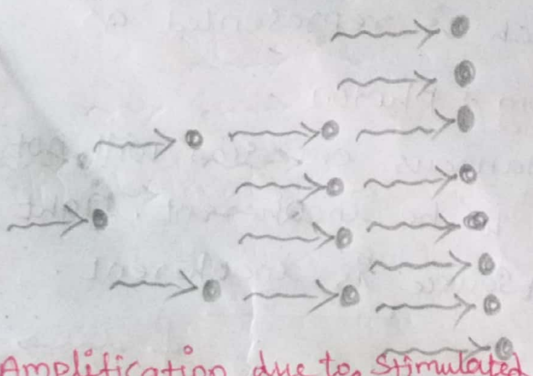


Concept of Laser :

The photon emitted during stimulated emission has the same energy, phase, frequency and direction as that of the incident photon.

Thus we have two coherent photons. These photons now incident on the two other atoms in the state E_2. This will result in induced emission of two more photons.

Now, there are four coherent photons of same energy. These four photons may induce further transitions with four other atoms in the energy state E_2. This gives stimulated emission of eight coherent photons of same energy.



If the process continues in a chain, we will ultimately

Amplification due to Stimulated emission of radiation be able to increase the intensity of coherent radiation enormously.

Stimulated emission is multiplied through a chain reaction. This multiplication of photons through Stimulated emission leads to coherent, Powerful, monochromatic, collimated beam of light. This light is known as laser light.

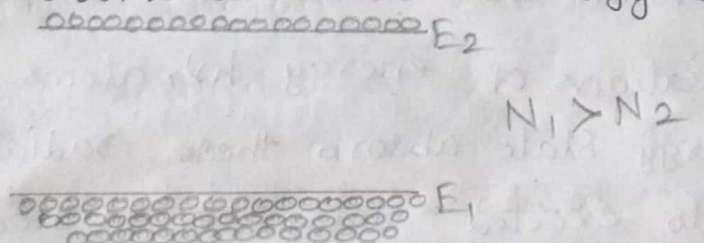
Thus for laser action, Stimulated emission is most important. This can be achieved by population inversion.

POPULATION INVERSION

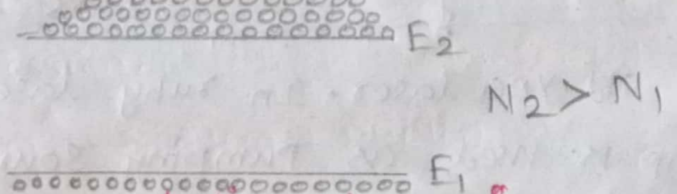
Population inversion creates a Situation in which the number of atoms in higher energy State is more than that in lower energy State.

usually at thermal equilibrium, the number of atoms N_2. the population of atoms at higher higher energy state is much lesser than the population of atoms at lower energy State N_1.

(i.e) $N_1 > N_2$



The phenomenon of making $N_2 > N_1$. the number of atoms in higher energy State is more than that the number of atoms in lower energy state is known as Population Inversion



Condition for Population Inversion:

1. There must be atleast two energy levels. $E_2 > E_1$
2. There must be a source to supply the energy of the medium.

PUMPING ACTION

The process to achieve population inversion in the medium is called Pumping action.

It is an essential requirement for producing a laser beam.

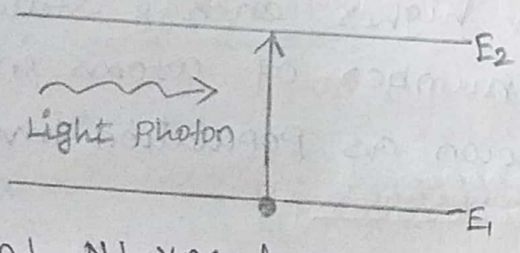
Methods for Pumping action :

The methods commonly used for pumping action are.

(i) Optical pumping (excitation by photons)
(ii) Electrical discharge method (excitation by electrons)
(iii) Direct conversion
(iv) Inelastic collision between atoms.

(i) Optical pumping :

When the atoms are exposed to light radiations of energy $h\nu$, atoms in the lower energy state absorb these radiations and they go to excited state. This method of pumping is known as optical pumping.

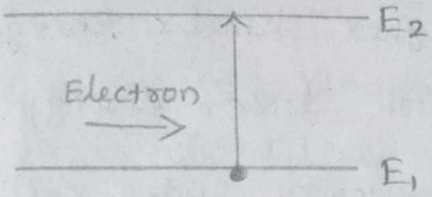


This type of pumping is used in solid state lasers like ruby laser and Nd-YAG laser. In ruby laser, xenon flash lamp is used as pumping source.

(ii) Electrical discharge method :

In this method, the electrons are produced in an electrical discharge tube. These electrons are accelerated to high velocities by a strong electrical field. Now accelerated electrons collide with the gas atoms.

By this process, energy from the electrons is transferred to gas atoms. Some atoms gain energy and they go to excited state. This results in Population inversion.



This method is known as electrical discharge method.

The energy transfer represented by the equation

$$A + e^{*} \rightarrow A^{*} + e$$

where $A \rightarrow$ Gas atom in the ground state

$A^{*} \rightarrow$ Same gas atom in the excited state

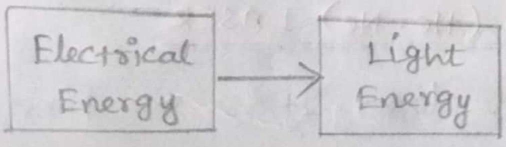
$e^{*} \rightarrow$ Electron with higher kinetic energy

$e \rightarrow$ Same electron with lesser energy.

This method of pumping is used in gas lasers like argon and CO_2 laser.

(iii) Direct Conversion :

In this method, electrical energy is applied to direct bandgap semiconductor like GaAs.



The recombination of electrons and holes take place. During the recombination process, the electrical energy is directedy converted into light energy.

This method of pumping is used in semiconductor laser.

(iv) Inelastic atom - atom collision :

In this method, a combination of two gases (say A and B) is used. The excited states of A and B nearly coincides in energy.

In the first step during the electrical discharge atoms of gas A are excited to their higher energy states A^* (metastable state) due to collision with the electrons.

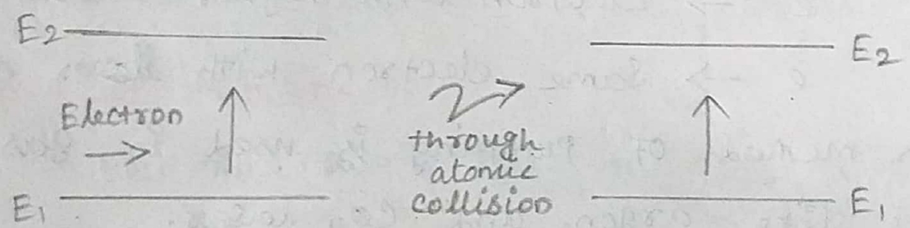
$$A + e^* \rightarrow A^* + e$$

e^* – Electron with higher kinetic energy.

e – Same electron with lesser energy.

Now A^* atoms at higher energy states collide with B atoms in lower states. Due to this inelastic collision B atoms gain energy and they are excited to a higher state B^*. Hence, A atoms lose energy and return to lower state.

$$A^* + B \rightarrow A + B^*$$



The result is population inversion in the energy states of B. This method is used in He-Ne laser.

HELIUM NEON (He-Ne) LASER

He-Ne laser is a gas laser. It is the first gas laser operated successfully by A. Javan and his co-workers of Bell telephone laboratory U.S.A in the year 1961.

Principle:

It is a four level gas laser. A mixture of helium and neon gases is used as an active medium. The population inversion is achieved by electrical discharge method.

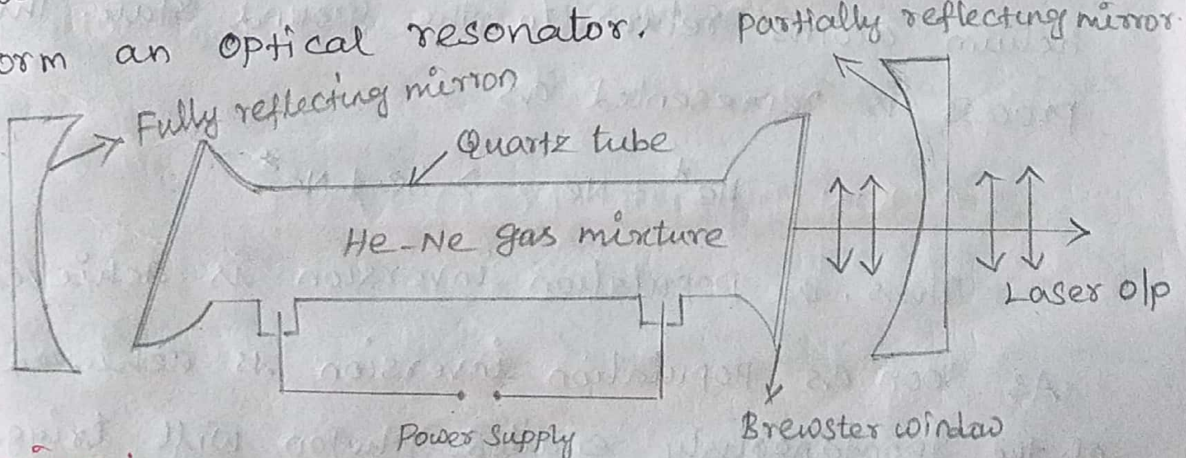
A Pair of concave mirrors facing each other is used as optical resonator to increase the strength of the out-coming laser beam.

Construction:

It consist of a long quartz discharge tube of length about 80cm and diameter 1.5cm This tube is filled with a mixture of helium and neon gases under the pressure of 1mm mercury of helium and 0.1mm mercury of neon in the ratio 10:1. This gas mixture acts as active medium.

The end faces of the discharge tube are inclined at the Polarizing angle so that the laser light emitted is Plane polarized. Such arrangement is known as Brewster window.

A fully reflecting concave mirror is placed at one end of the discharge tube and a partially reflecting concave mirror is placed at the other end. These reflecting surfaces form an optical resonator.



Working:

When the electrical discharge occurs in the gas, the electrons collide with helium atoms (He) in ground state (F_1) and excite them to metastable

State F_2 and F_3. This collision process is represented as,

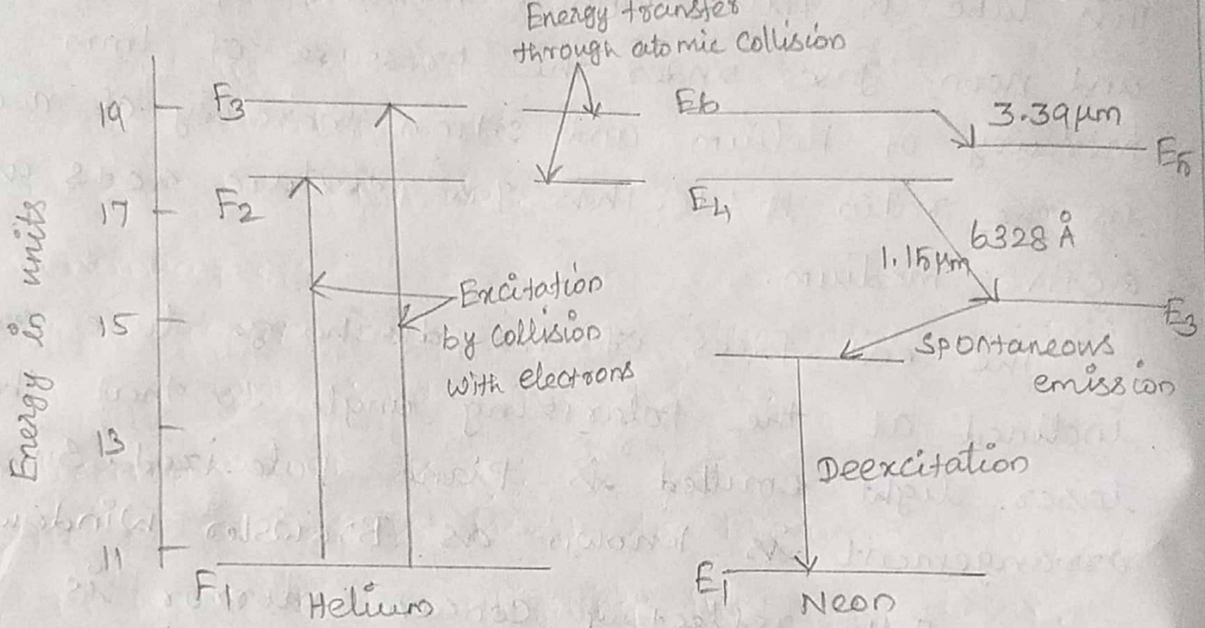
$$He + e^* \rightarrow He^* + e$$

$He \rightarrow$ Helium atom in ground state

$e^* \rightarrow$ electron with high energy

$He^* \rightarrow$ Helium atom in excited state

$e \rightarrow$ same electron with lesser energy.



Now the excited helium (He^*) collides with neon atom (Ne) in the ground state and excite them to the levels E_4 and E_6. The excited helium atoms return to the ground state. This process is represented as

$$He^* + Ne \rightarrow He + Ne^*$$

Thus, a population inversion is achieved.

As soon as population inversion is achieved, any of the spontaneously emitted photon will trigger the laser action in the tube.

Here, there are three types of transitions to produce laser beams.

(i) $E_6 \rightarrow E_3$ transition :

This transition generates a laser beam of red colour of wavelength 6328 Å in visible region.

(ii) $E_4 \rightarrow E_3$ transition :

This transition produces Infra red laser beam at a wavelength of 11500 Å (1.15 μm)

(iii) $E_6 \rightarrow E_5$ transition :

This transition produces a laser beam of wavelength 33900 Å (3.39 μm) in Infra red region.

The wavelengths in the infra-red region are suppressed in order to get a maximum output power at 6328 Å.

Characteristics :

1. Type : It is a four energy levels gas laser (3 in neon and 1 in helium)
2. Active medium : It uses the mixture of helium and neon gases as active medium.
3. Pumping method : Electrical discharge method is used for pumping action.
4. Optical resonator : A pair of concave mirrors facing each other is used as optical resonator.
5. Power output : The power output of the laser beam is 0.5 – 50 milliwatts.
6. Nature of the output : The nature of the output is continuous waves.
7. Wavelength of the output : The wavelength of the laser output is 6328 Å.
8. Frequency of the output : The frequency of the beam is about 4.7×10^{14} Hz.

Advantages :

1. He-Ne laser is the first gas laser operated in continuous wave mode.
2. It produces more directional and highly monochromatic output than solid state lasers.
3. It is capable of operating continuously without any need of cooling arrangement.
4. It has high stability of frequency.
5. The output of the laser can be tuned to certain available wavelength.
6. It is not expensive.

Disadvantages :

The output power is generally moderate when compared with solid state lasers.

Applications and uses :

1. He-Ne laser is used to produce holograms.
2. It is used for aligning the ruby laser.
3. It is used in laboratory experiments to produce interference and diffraction patterns.
4. It is used in ophthalmology.
5. It is used in optical communication without fibre for a moderate distance.

CARBON DIOXIDE (CO_2) LASER

It was the first molecular gas laser developed by Indian born American scientist Prof. C.K.N. Patel.

It is a four-level molecular gas laser. In CO_2 molecular gas laser, transition takes place between the vibrational states of carbon dioxide molecules. It is a very efficient laser.

Energy States of CO_2 Molecules :

A Carbon dioxide molecule has a Carbon atom at the Centre with two Oxygen atoms attached, one at each sides. Such a molecule exhibits three independent modes of Vibrations. They are,

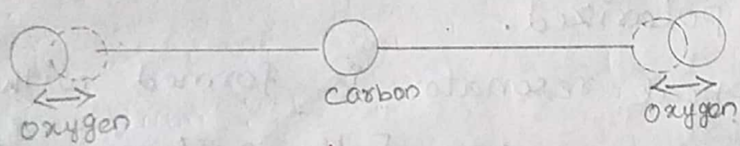
(a) Symmetric Stretching mode

(b) Bending mode

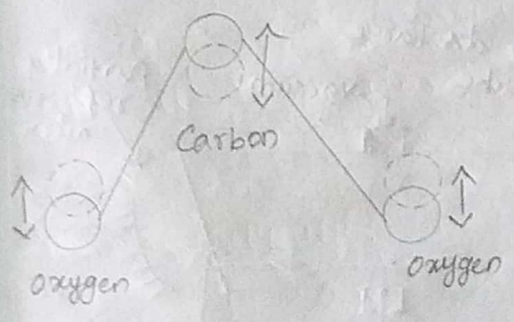
(c) Asymmetric Stretching mode.

(a) Symmetric Stretching mode :

In this mode of vibration, carbon atoms is at rest and both oxygen atoms vibrate simultaneously along the axis of the molecule departing or approaching fixed carbon atom.

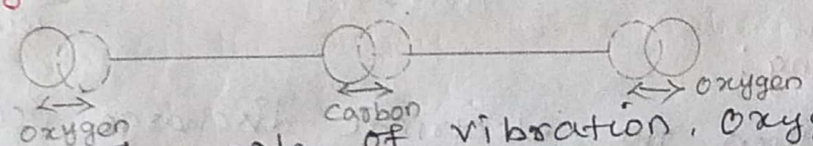


(b) Bending mode :



In this mode of vibration, oxygen atoms and carbon atom vibrate perpendicular to molecular axis.

(c) Asymmetric Stretching mode :



In this mode of vibration, oxygen atoms vibrate asymmetrically. oxygen and carbon atoms vibrate in one direction while carbon atoms move in one direction while carbon atom moves in the opposite direction.

Principle:

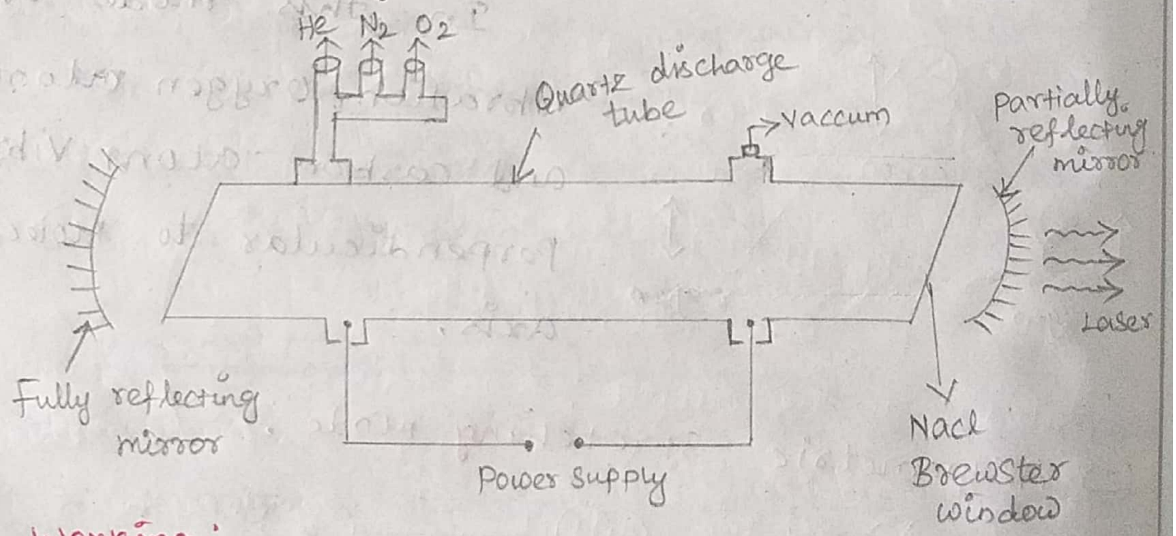
The active medium is a gas mixture of CO_2, N_2 and He. The laser transition takes place between the vibrational states of CO_2 molecules.

Construction:

It consist of a quartz discharge tube 5m long and 2.5 cm in diameter. This discharge tube is filled with the gaseous mixture of CO_2, helium and nitrogen with suitable partial pressures.

The terminals of the discharge tube are connected to a D.C power supply. The ends of this tube are fitted with Nacl Brewster windows so that the laser light generated will be polarized.

The optical resonator is formed with two concave mirrors one fully reflecting and other partially reflecting.



Working:

When the electrical discharge occurs in the gas, the electrons collide with nitrogen molecules and they are raised to excited states. This process is represented by the equation

$$N_2 + e^* \rightarrow N_2^* + e$$

N_2 → Nitrogen molecule in ground state

e^* → Electron with kinetic energy.

N_2^* → Nitrogen molecule in excited state.

e → Same electron with lesser energy.

Now, N_2 molecules in excited state collide with CO_2 atoms in ground state and excite them to higher electronic, vibrational and rotational levels.

This process is represented by the equation

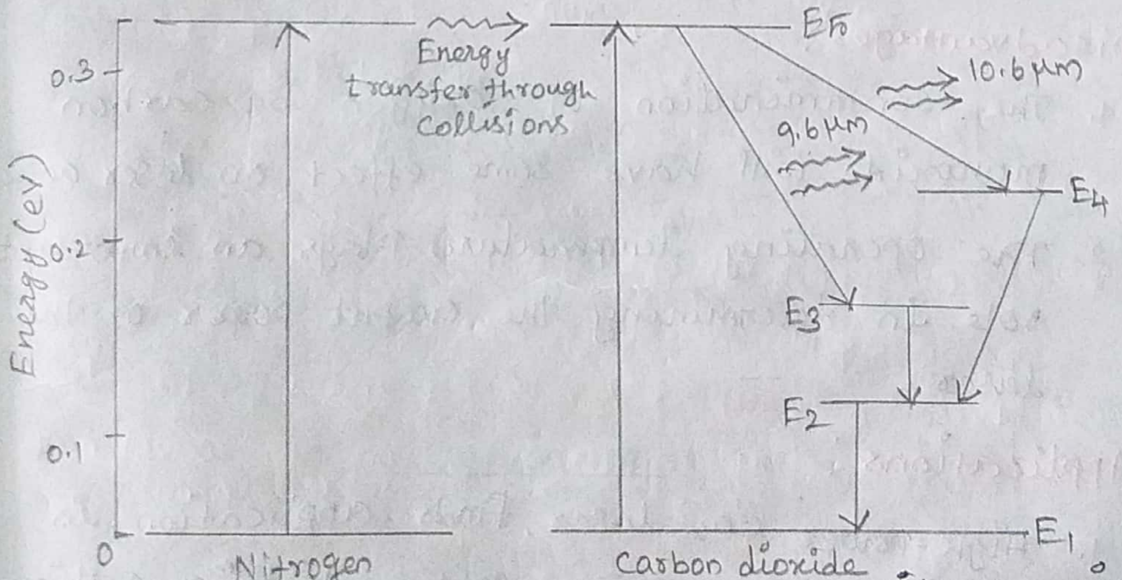
$$N_2^* + CO_2 \rightarrow CO_2^* + N_2$$

N_2^* → Nitrogen molecule in excited state

CO_2 → Carbon dioxide atoms in ground state

CO_2^* → Carbon dioxide atoms in excited state

N_2 → Nitrogen molecule in ground state.



Since the excited level of nitrogen is very close to E5 of CO_2 atom, population in E5 level increases. As soon as population is reached, any of the spontaneously emitted photon will trigger laser action in the tube.

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There are two possible types of laser transition.

(i) Transition $E_5 - E_4$

This transition will produce a laser beam of wavelength 10.6 μm.

(ii) Transition $E_5 - E_3$

This transition will produce a laser beam of wavelength 9.6 μm.

Normally 10.6 μm transition is more intense than 9.6 μm transition. The power output from this laser is 10 kW.

Advantages:

1. The construction of CO_2 laser is simple.
2. The output from this laser is continuous.
3. It has very high output power.
4. The output power can be increased by extending the length of gas tube.

Disadvantages:

1. The contamination of oxygen by carbon monoxide will have some effect on laser action.
2. The operating temperature plays an important role in determining the output power of the laser.

Applications:

1. High-power CO_2 laser finds application in materials processing, welding, drilling, cutting, soldering etc.
2. It is used in the treatment of liver and lungs diseases.

3. It is mostly used in neurosurgery and general surgery.

4. It is used to perform microsurgery and bloodless operations.

Nd-YAG LASER

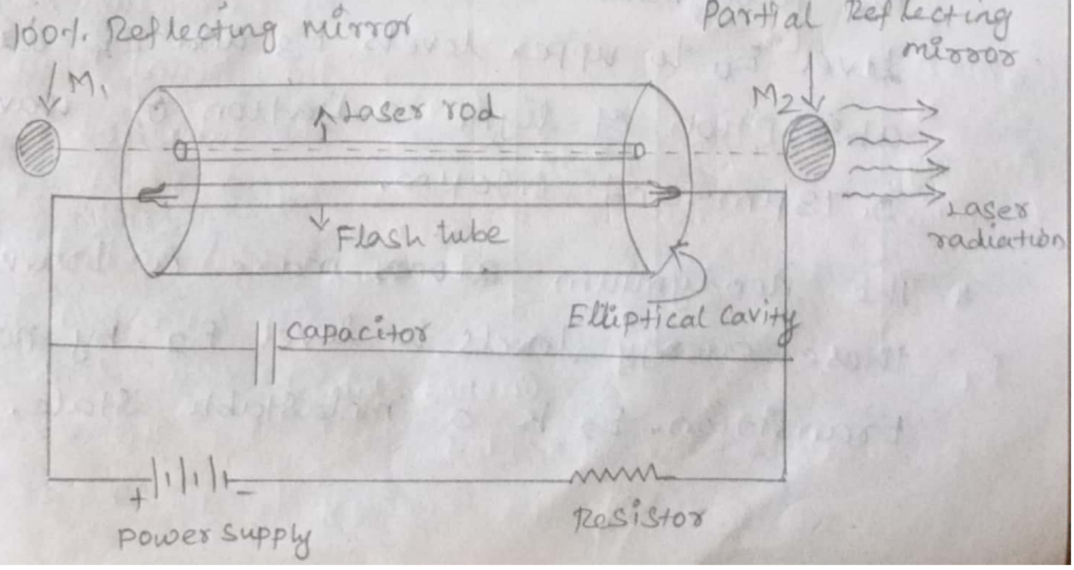
Nd-YAG laser is a Neodymium based laser. Nd stands for Neodymium (rare earth element) and YAG stands for Yttrium Aluminium Garnet ($Y_3Al_5O_{12}$). It is a four level solid state laser.

Principle:

The active medium Nd-YAG rod is optically pumped by krypton flash tubes. The neodymium ions (Nd^{3+}) are raised to excited levels. During the transition from metastable state to ground state, a laser beam of wavelength $1.064\,\mu m$ is emitted.

Construction:

The construction of Nd-YAG laser is a small amount of yttrium ions (Y^{3+}) is replaced by Neodymium ions (Nd^{3+}) in the active element of Nd-YAG crystal.

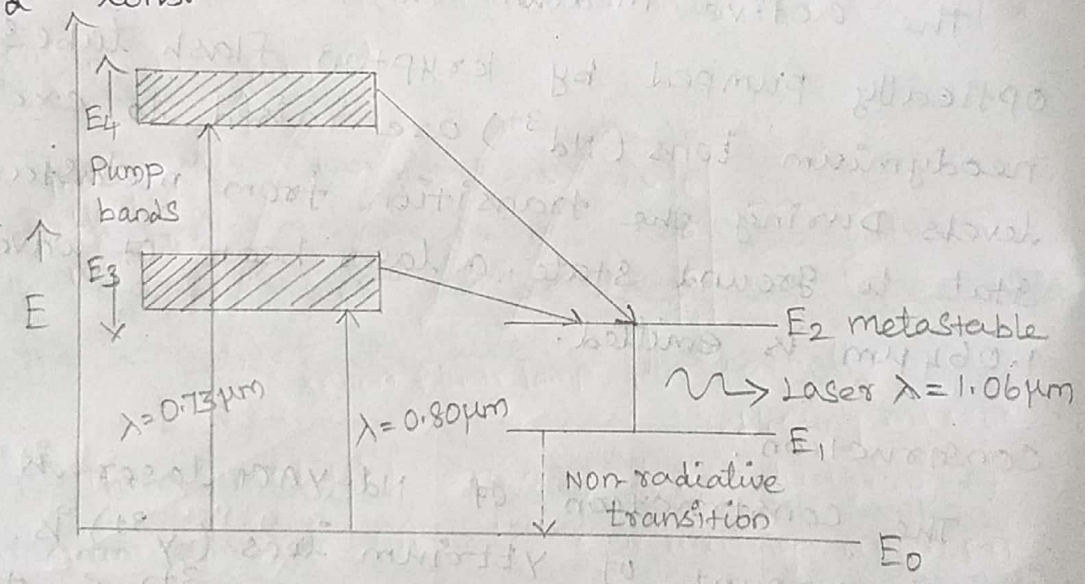


This active element is cut into a cylindrical rod. The ends of the rod are highly Polished and they are optically flat and Parallel. This cylindrical rod and a pumping source are placed inside an elliptical reflector cavity.

The optical resonator is formed by using two external reflecting mirrors. one mirror (M_1) is 100% reflecting while the other mirror (M_2) is partially reflecting.

Working :

These energy levels are those of neodymium Nd^{3+} ions.



* When the krypton flash lamp is switched on, the neodymium atoms are raised from ground level E_0 to upper levels E_3 and E_4 due to absorption of light radiation of wavelength $0.73\mu m$ and $0.80\mu m$.

* The neodymium atoms make a transition from these energy levels to level E_2 by non-radiative transition. E_2 is a metastable state.

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* The neodymium ions are collected in the level E_2 and the population inversion is achieved between E_2 and E_1.
* An ion makes a spontaneous transition from E_2 to E_1, emitting a photon of energy $h\nu$. This emitted photon will trigger a chain in stimulated photons between E_2 and E_1
* Two photons thus generated travel back and forth between two mirrors and grow in strength. After some time, the photon number multiplies more rapidly.
* After enough strength is attained an Intense laser light of wavelength $1.06 \mu m$ is emitted through the partial reflector. This corresponds to transition from E_2 to E_1.

Advantages:

1. It has high energy output.
2. It has very high repetition rate operation.
3. It is much easy to achieve population Inversion in this laser.

Disadvantages:

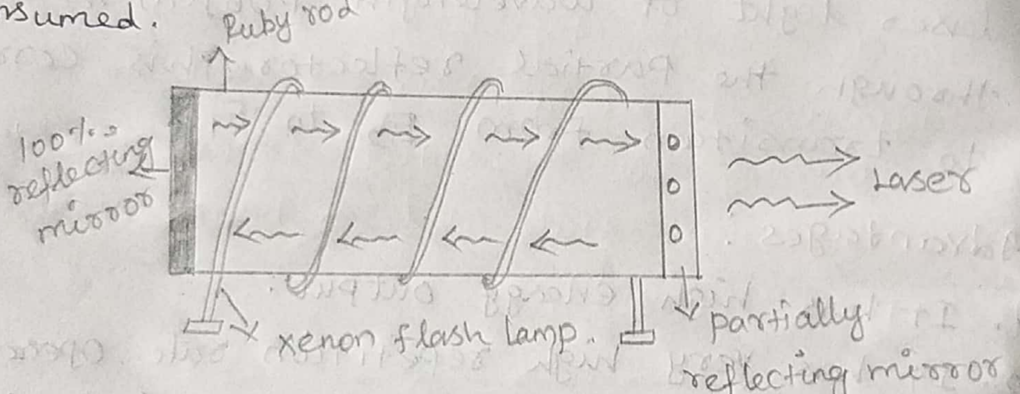
The electron energy level structure of Nd^{3+} in YAG is complicated.

Applications:

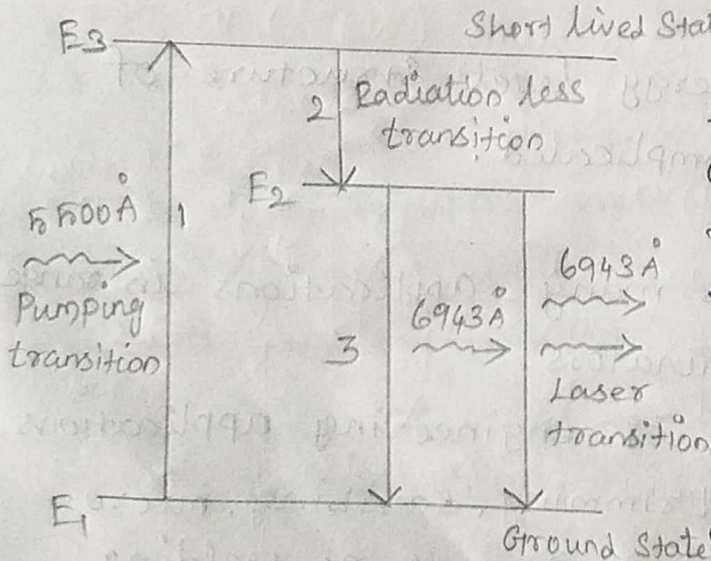
1. Nd-YAG laser has many applications in range finders and illuminators.
2. It is widely used in engineering applications such as resistor trimming, scribing, micro-machining operations as well as welding, drilling etc.

RUBY LASER

The Ruby laser was first developed by T. Mainman in 1960. It consist of a single crystal of ruby rod of length 10cm and 0.8cm in diameter. A ruby is a crystal of aluminium oxide Al_2O_3. in which some of aluminium ions (Al^{3+}) are replaced by Chromium ions (Cr^{3+}). The opposite ends of ruby rod are flat and parallel. One end is fully silvered and the other is partially silvered. The ruby rod is surrounded by a helicon xenon flash tube which provides the pumping light to rise the chromium ions to upper level. In the xenon flash tube, each flash lasts several milliseconds and each flash a few thousand Joules of energy is consumed.



The simplified energy level diagram of chromium ions in ruby laser, indicating appropriate excitation and decay.



In normal state, most of chromium ions are in the ground state E_1. When the ruby rod is irradiated by a flash of light, the 5500Å radiation photons are absorbed by the Chromium ions which are pumped to the excited state E_3. The excited state gives up part of it's energy to the crystal lattice and decay without giving any radiation to the meta Stable State E_2. Since the State E_2 has a much longer lifetime (10^{-3}s). The number of ions in this State goes on Increasing. Thus population inversion is achieved between the States E_2 and E_1. When the excited ion from the metaStable State E_2 drops down Spontaneously to the ground State E_1, it emits a Photon of wavelength 6943 Å. This Photon travels through the ruby rod and is reflected back and forth by the Silvered ends until it Stimulates other excited ion and causes it to emit a fresh Photon in Phase with Stimulating photon. Thus the reflections will amount to the additional Stimulated emission. It is Called amplification by Stimulated emission. The Stimulated emission is the laser transition. Finally, a Pulse of red light of wavelength 6943 Å emerges through the partially Silvered end of the crystal.