LASER

Introduction:

Laser stands for 'Light Amplification by Stimulated Emission of Radiation'. It is a process by means of which we get a strong, intense, monochromatic, collimated, unidirectional and highly coherent beam of light.

Absorption and Emission of Radiation:

An atom has different discrete energy levels. It may undergo a transition between two energy states E_1 and E_2 if it emits or absorbs a photon of the appropriate energy given by the relation $E_1 - E_2 = \pm h\nu$, where the plus sign indicates absorption of quanta of energy and the minus sign that of emission. Consider an assembly of large number of free atoms some of which are in the ground state with energy E_1 and some in the excited state with energy state E_2. If photons of energy $h\nu = E_2 - E_1$ are incident on the sample, basically three transition process can take place: Absorption of radiation, spontaneous emission and stimulated emission of radiation.

Stimulated Absorption

If an atom is initially in a lower energy state E_1, it can rise to a higher energy state E_2 by absorbing a quantum of radiation (Photon). The frequency of corresponding photon is given by,

$$\nu = \frac{E_2 - E_1}{h}$$

This process is known as stimulated absorption or induced absorption.

The probable rate of occurrence of the absorption transition from state 1 to state 2 depends on the properties of states 1 and 2, and is proportional to the energy density $u(\nu)$ of the radiation of frequency ν. Thus,

$$P_{12} = B_{12}\, u(\nu)$$

Where B_{12} is proportionality constant and is known as Einstein's co-efficient of stimulated or induced absorption.

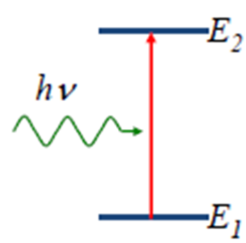

Fig. 1- Absorption

Spontaneous Emission:

Let us consider an atom initially in the higher (excited) energy state 2. Excited state with higher energy is inherently unstable (average life time 10^{-8} sec), hence atom in excited state does not stay for longer time and it jumps to the lower energy state 1emitting a photon of frequency v. This is spontaneous emission of radiation. If there is an assembly of atoms, the radiation emitted spontaneously by each atom has a random direction and a random phase and is therefore incoherent from one atom to another. The probability of spontaneous emission from energy state 2 to energy state 1 is determined only by the properties of states 2 and 1. This is denoted by,

$$\mathbf{A_{21}}$$

This is known as Einstein's co-efficient of spontaneous emission of radiation. In this case the probability of spontaneous emission is independent of energy density u(v).

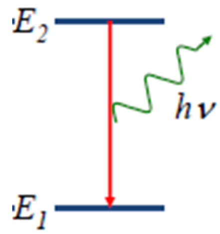

Fig. 2- Spontaneous Emission

Stimulated or Induced Emission:

According to Einstein, an atom in an excited energy state E_2 may, under the influence of the electromagnetic field of a photon of frequency v [$=\frac{E_2-E_1}{h}$] incident upon it, jump to a lower energy state E_1, emitting an additional photon of same frequency v. Hence two photons, one original and the other emitted, move together. This is stimulate (or Induced) emission of radiation.

The direction of propagation, phase, energy and state of polarization of the emitted photon is exactly same as that of the incident stimulated photon, so the result is an enhanced beam of coherent light. The probability of stimulated emission transition from energy state 2 to energy state 1 is proportional to the energy density u(v) of the stimulating radiation and is given by,

$$\mathbf{B_{21}\ u(}v\mathbf{)}$$

Where B_{21} is the Einstein's co-efficient of stimulated emission of radiation.

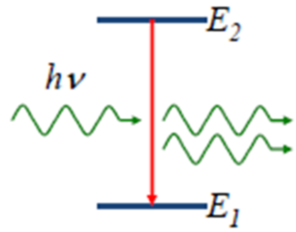

Fig. 3- Stimulated Emission

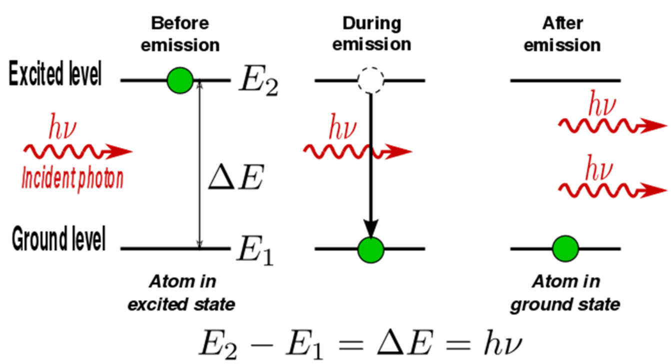

Fig. 4- Schematic diagram of stimulated emission

The total probability for an atom in state 2 to drop to the lower state 1 is therefore given by,

$$P_{21} = A_{21} + B_{21}\, u(\nu)$$

<u>Relation between different Einstein's Coefficients:</u>

Let us consider an assembly of atoms in thermal equilibrium at temperature T with radiation of frequency ν and energy density $u(\nu)$. Let N_1 and N_2 be the number of atoms in energy states E_1 and E_2 respectively at any instant. The number of atoms in state 1 that absorb a photon and rise to state 2 per unit time is,

$$\mathbf{N_1 P_{12} = N_1 B_{12}\, u(\nu)} \text{ .... (i)}$$

The number of atoms in state 2 that drop to state 1, either spontaneously or under stimulated emission, emitting a photon per unit time is,

$$\mathbf{N_2 P_{21} = N_2 [A_{21} + B_{21}\, u(\nu)]} \text{ .... (ii)}$$

For equilibrium, the absorption and emission must occur equally. Thus,

$$N_1 P_{12} = N_2 P_{21}$$
$$\text{or, } N_1 B_{12}\, u(\nu) = N_2 [\, A_{21} + B_{21}\, u(\nu)]$$

$$\text{or, } N_1 B_{12}\, u(\nu) - N_2 B_{21}\, u(\nu) = N_2 A_{21}$$

$$\text{or, } u(\nu) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

$$\text{or, } u(\nu) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right) - 1} \quad \text{………….. (iii)}$$

Einstein proved thermodynamically that the probability of stimulated absorption is equal to the probability of stimulated emission.

i.e. $B_{12} = B_{21}$

Then, we have, $$u(\nu) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\frac{N_1}{N_2} - 1} \quad \text{…………… (iv)}$$

The equilibrium distribution of atoms among different energy states is given by using Boltzmann's Distribution Law according to which,

$$\frac{N_2}{N_1} = \frac{e^{-\frac{E_2}{kT}}}{e^{-\frac{E_1}{kT}}}$$

$$\text{Or, } \frac{N_2}{N_1} = e^{-\frac{(E_2 - E_1)}{kT}}$$

$$\text{Or, } \frac{N_2}{N_1} = e^{-\frac{(h\nu)}{kT}}$$

Here, h is Planck's constant and $h\nu = (E_2 - E_1)$

Consequently, $$u(\nu) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{e^{\frac{h\nu}{kT}} - 1} \quad \text{……………. (v)}$$

This is the energy density of photon of frequency ν in equilibrium with atoms in energy states 1 and 2, at temperature T. Comparing it with the Planck's radiation formula (according to which the energy density of the black body radiation of frequency ν at temperature T is given as)

$$u(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{kT}} - 1} \quad \text{………… (vi)}$$

Comparing equation (v) and (vi) we get, $$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \text{………. (vii)}$$

This shows that the ratio of Einstein's co-efficient of spontaneous emission to the Einstein's co-efficient of stimulated absorption or emission (as $B_{12} = B_{21}$) of radiation is proportional to the cube of the frequency (ν^3). This means that the probability of spontaneous emission increases rapidly with the energy difference between two states.

Population Inversion:

Let us consider an optical medium and two energy states E_1 and E_2 . E_1 represents the lower state and E_2 represents the upper state. Let N_1 be the number of atoms in lower state and N_2 be the number of atoms in upper state. The ratio of the population densities at room temperature (17 ^{0}C) is,

$$\frac{N_2}{N_1} = 10^{-32}$$

In such situation absorption dominates and population difference ($N_1 - N_2$) is positive. If it were possible to achieve more atoms in upper state than in lower state then incoming signal stimulates the opposite transition; the applied signal then gains energy and we say that the signal is amplified. Thus we see that essential condition of amplification is to create negative population difference (i.e. $N_2 > N_1$).

If $N_2 < N_1$, stimulated absorption rate = N_1 Bu(ν)
and stimulated emission rate = N_2 Bu(ν)

Here u(ν) is the energy density of radiation and B is the Einstein co-efficient.

Stimulated emission rate will exceed stimulated absorption rate only of $N_2 > N_1$.

When $N_2 > N_1$, the situation is called population inversion.

Therefore, population inversion means a condition in the amplifying medium, in which the majority of the relevant entities are excited.

Again when $N_2 > N_1$, the state is non-equilibrium one.

From Boltzman distribution law,

$$\frac{N_2}{N_1} = e^{-\frac{(E_2 - E_1)}{kT}} \text{ .... (i)}$$

The inversion condition can be represented by equation (i) if T becomes negative.

The condition $N_2 > N_1$ is refer to as one of negative temperature.

Light beam will be amplified only if we generate a population inversion between the upper and lower levels by artificial means.

Population inversion cannot occur in a two level system. It can easily be achieved having 3 states of 3 levels system.

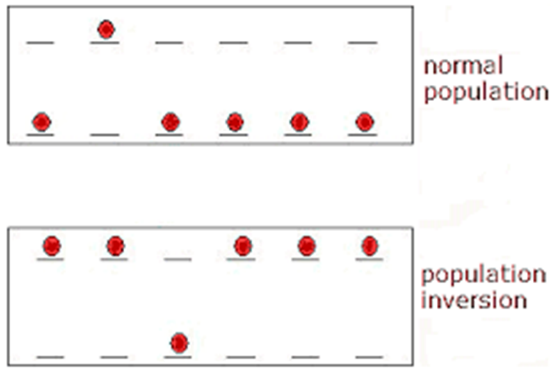

Fig. 5- Population inversion.

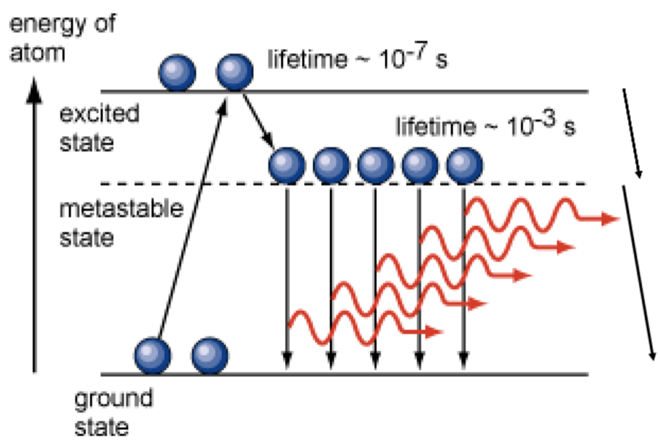

Fig. 6- The three steps mechanism in laser.

Difference between Spontaneous and Stimulated emissions:

<table>
<tr><th>Spontaneous emissions</th><th>Stimulated emissions</th></tr>
<tr><td>1. The transition of an electron from the excited state to the ground state happens as a result of the natural tendency of the electron without the action of any external agent. The radiation produced as a result of such transitions is called as spontaneous radiation.</td><td>1. Stimulated emission of radiation is the process whereby photons are used to generate other photons that have exact phase and wavelength as that of parent photon.</td></tr>
<tr><td>2. Spontaneous emission take place in any direction</td><td>2. Stimulated emission take place in a particular direction</td></tr>
<tr><td>3. This phenomenon is found in LEDs, Fluorescent tubes.</td><td>3. This is the key process of formation of laser beam.</td></tr>
<tr><td>4. There is no population inversion of electrons in spontaneous emissions.</td><td>4. Population inversion is achieved by various ‘pumping’ techniques to get amplification giving the LASER.</td></tr>
<tr><td>5. No external stimuli required.</td><td>5. Stimulated emission is caused by external stimuli.</td></tr>
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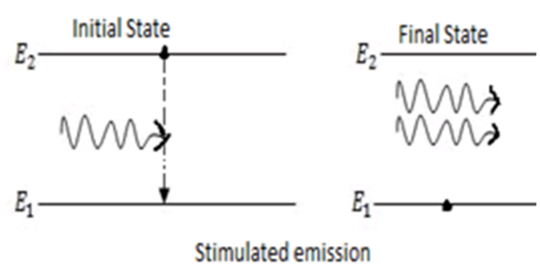
</td><td>
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Main components of LASER:

There are three basic components of a LASER:

(i) active medium, (ii) pumping system and (iii) optical resonator.

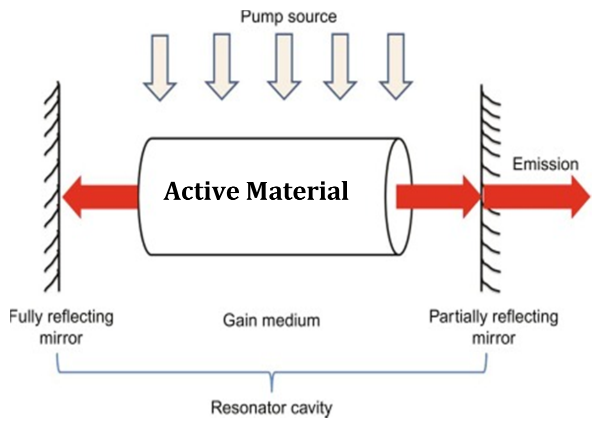


Fig.7- Main components of LASER

(i) Active medium:

The active medium in LASERS may be a solid, liquid, or gas. Different active media emit different energies or wavelengths of light. The basic requirement for the active medium of a LASER is that it should have suitable energy levels to achieve the condition of population inversion or it must have a metastable energy states to support stimulated emission. Those atoms of active medium, which are responsible for LASER action, are called active centers and rest of the medium is called as host.

(ii) Pumping System:

The pumping system consists of an external source that supplies energy to active medium and helps in obtaining the population inversion. The excitation of atoms may occur directly or through atom-atom collision. It can be optical, electrical or thermal in nature.

(iii) Optical Resonator:

It consists of a pair of parallel mirrors enclosing the active medium in between them. The reflectivity of one of the mirrors near to 100% and the other is partially transparent. It is basically a feedback device that reflects undesirable (off-axis) photons out of the system and directs the desirable (on-axis) photons back and forth through the active medium and in the process the number of photon is multiplied due to stimulated emission causing thereby amplification.

Working of Optical Resonator:

Atoms (active centers) of the lasing material normally reside in ground energy state. These atoms can be excited to a higher energy state by supplying external energy. The atoms are unstable at this state so they drop spontaneously to a metastable state in which they can stay longer in compare to the ordinary excited state and hence the population inversion can be achieved at this state. Some of the atoms can be de-excited spontaneously from the metastable state to their ground state emitting photons in random directions. Each spontaneous photon can stimulate other excited atoms to fall to their ground state by emitting a photon that travel in phase and in the same direction as the incident photon. If the direction of emitted photons is parallel to the optical axis, the emitted photons travel back and forth in the optical cavity through the lasing material between the totally reflecting mirror and the partially reflecting mirror. The light energy is amplified in this manner until sufficient energy is built up for a burst of laser light to be transmitted through the partially reflecting mirror.

Pumping:

The process of raising large number of atoms from lower energy to a higher energy level is called pumping. Population inversion is achieved through this process. It is essential requirement for producing a laser beam.

Methods of pumping action:

The methods commonly used for pumping action are:

1. Optical pumping (Excitation by Photons)

2. Electrical discharge method (Excitation by electrons)

3. Chemical Laser (Chemical Reaction)

4. Direct conversion (Directly converted electrical energy into radiation)

5. In elastic atom – atom collision (Between atoms)

1. Optical pumping: When the atoms are exposed to light radiations energy, atoms in the lower energy state absorb these radiations and they go to the excited state. This method is called Optical pumping. It is used in solid state lasers like ruby laser and Nd-YAG laser. In ruby laser, xenon flash lamp is used as pumping source.

2. Electrical discharge method (Excitation by electrons): In this method, the electrons are produced in an electrical discharge tube. These electrons are accelerated to high velocities by a strong electrical field. These accelerated electrons collide with the gas atoms. By the process, energy from the electrons is transferred to gas atoms. Some atoms gain energy and they go to the excited state. This results in population inversion. This method is called Electrical discharge method. It is represented by the equation $A + e^* = A^* + e$ Where A – gas atom in the ground state A^* = same gas atom in the excited state e^* = Electrons with higher Kinetic energy e – Same electron with lesser energy. This method of pumping is used in gas lasers like argon and CO_2 Laser.

3. Chemical Laser: The energy required to pump a laser comes from a chemical reaction in this process. Chemical lasers can achieve continuous wave output with power reaching to megawatt levels. They are used in industry for cutting and drilling, and in military as directed-energy weapons.

4. Direct Conversion: In this method, due to electrical energy applied in direct band gap semiconductor like Ga As, recombination of electrons and holes takes place. During the recombination process, the electrical energy is directly is converted into light energy.

5. In elastic atom – atom collision: In this method, a combination of two gases (Say A and B are 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 state A* (metastable state) due to collision with the electrons .

$$A + e^* = A^* + e$$

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

$$A^* + B = A + B^*$$

Ruby Laser:

A ruby laser is a solid-state laser that uses the synthetic ruby crystal as its laser medium. Ruby laser is the first successful laser developed by Maiman in 1960. Ruby laser is one of the few solid-state lasers that produce visible light. It emits deep pink light of wavelength 6943 Å.

Principal:

Let us consider three energy levels E_1, E_2 and E_3 which represents the energy of ground state, metastable state and pump state.

Let us assume that initially most of the electrons are in the lower energy state (E_1) and only a tiny number of electrons are in the excited states (E_2 and E_3)

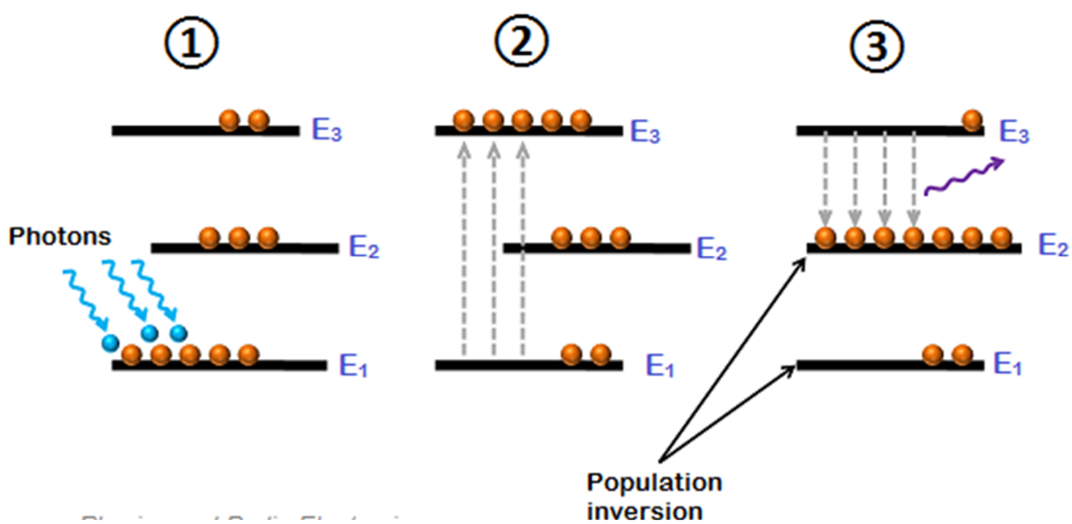


Fig. 8- Working Principle of laser.

When light energy is supplied to the laser medium (ruby), the electrons in the lower energy state or ground state (E_1) gains enough energy and jumps into the pump state (E_3).

The lifetime of pump state E_3 is very small (10^{-8} sec) so the electrons in the pump state do not stay for long period. After a short period, they fall into the metastable state E_2 by releasing radiation less energy. The lifetime of metastable state E_2 is 10^{-3} sec which is much greater than the lifetime of pump state E_3. Therefore, the electrons reach E_2 much faster than they leave E_2. This results in an increase in the number of electrons in the metastable state E2 and hence population inversion is achieved.

After some period, the electrons in the metastable state E_2 falls into the lower energy state E_1 by releasing energy in the form of photons. This is called spontaneous emission of radiation.

When the emitted photon interacts with the electron in the metastable state, it forcefully makes that electron fall into the ground state E_1. As a result, two photons are emitted. This is called stimulated emission of radiation.

When these emitted photons again interacted with the metastable state electrons, then 4 photons are produced. Because of this continuous interaction with the electrons, millions of photons are produced.

In an active medium (ruby), a process called spontaneous emission produces light. The light produced within the laser medium will bounce back and forth between the two mirrors. This stimulates other electrons to fall into the ground state by releasing light energy. This is called stimulated emission. Likewise, millions of electrons are stimulated to emit light. Thus, the light gain is achieved.

The amplified light escapes through the partially reflecting mirror to produce laser light.

Construction of ruby laser

A ruby laser consists of three important elements:
laser medium, the pumping source, and the optical resonator.

Laser medium or gain medium in ruby laser

Ruby laser consist of a synthetic ruby crystal, doped with chromium ions with concentration of about 0.05% by weight. Chromium ions act as active centers in ruby crystal, so it is the chromium ions that produce the laser .With this concentration of doping, there are about 1.6*1025 chromium ions per cubic meter .These ions have a set of three energy level suitable for the laser action. The ruby has good thermal properties. Ruby is a crystal of aluminum oxide (Al2O3) in which some of the aluminum ions (Al3+) are replaced by chromium ions (Cr3+). This is done by small amounts of chromium oxide (Cr2O3) doping in the melt of purified Al2O3.The ruby crystal is in the form of cylinder. Length of ruby crystal is usually 2 cm to 30 cm and diameter 0.5 cm to 2 cm.

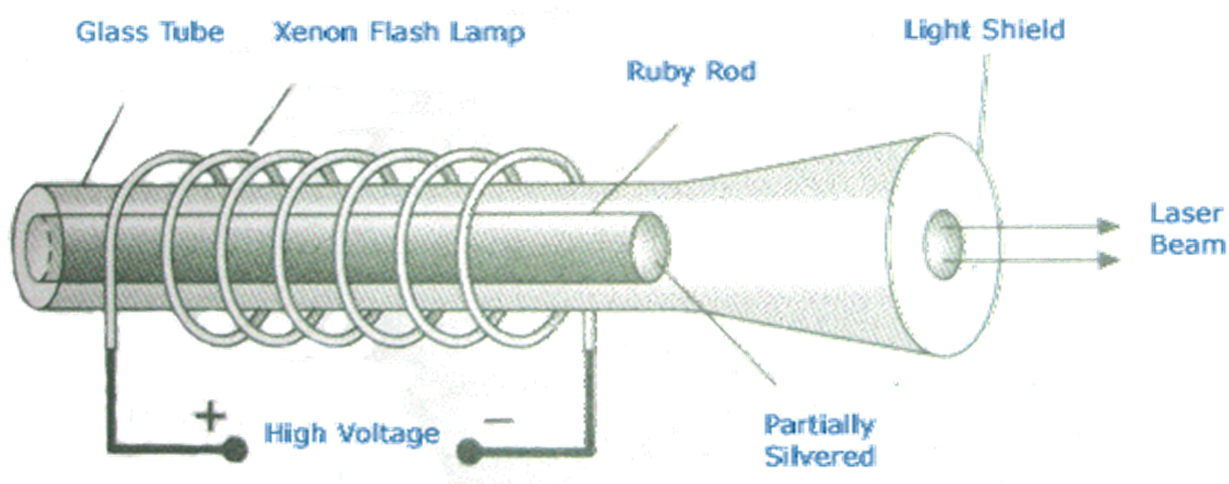


Fig.9- Construction of a Ruby Laser

Pump source or energy source in ruby laser

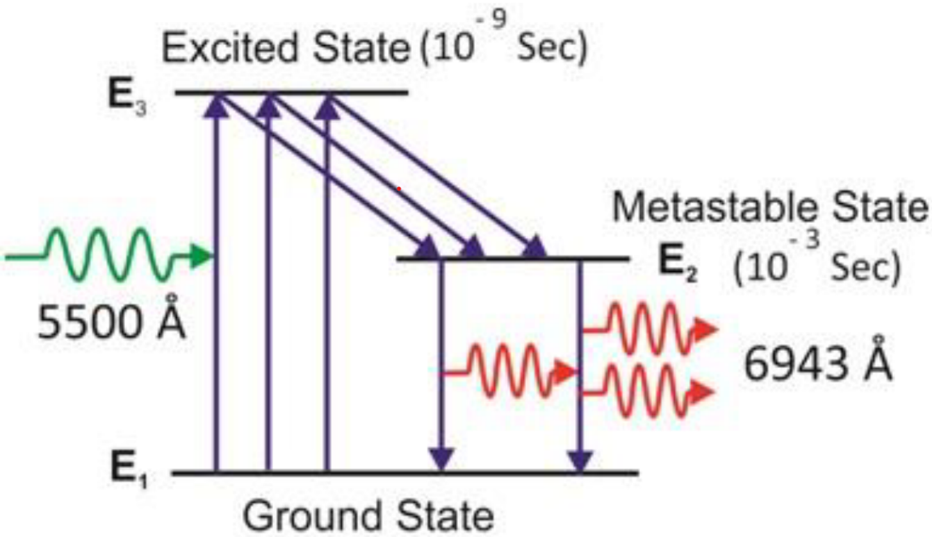
The pump source is the element of a ruby laser system that provides energy to the laser medium. In a ruby laser, population inversion is required to achieve laser emission. Population inversion is the process of achieving the greater population of higher energy state than the lower energy state. In order to achieve population inversion, we need to supply energy to the laser medium (ruby). In a ruby laser, we use a helical flash lamp filled with xenon is used as a pumping source. The ruby crystal is placed inside a xenon flash lamp. Thus, optical pumping is used to achieve population inversion. The flashtube supplies energy to the laser medium (ruby). When lower energy state electrons in the laser medium gain sufficient energy from the flashtube, they jump into the higher energy state or excited state.

Optical resonator

The ends of the cylindrical ruby rod are flat and parallel. The cylindrical ruby rod is placed between two mirrors. The optical coating is applied to both the mirrors. The process of depositing thin layers of metals on glass substrates to make mirror surfaces is called silvering. Each mirror is coated or silvered differently. At one end of the rod, the mirror is fully silvered whereas, at another end, the mirror is partially silvered. The fully silvered mirror will completely reflect the light whereas the partially silvered mirror will reflect most part of the light but allows a small portion of light through it to produce output laser light.

Working of Ruby Laser

Ruby is a three energy level laser system. After absorbing light photons of wavelength 5500Å from xenon flash lamp, some of the Cr^{+3} ions at ground energy level E_1 get excited to higher energy level E_3. At this energy level, they are unstable and by losing a part of their energy to the crystal lattice, they fall to the metastable energy level E_2, whose lifetime is much longer (approx. 10^{-3}sec). therefore, the number of Cr^{+3} ions goes on increasing in E_2 state while the number of these ions in the ground state E_2 goes on decreasing due to pumping by flash lamp and soon the population inversion is achieved between states E_2 and E_1.



Energy Level Diagram of Ruby LASER

Now some of the Cr^{+3} ions will decay spontaneously to the ground state E_1 by emitting photons of wavelength 6943Å. the photons those are moving parallel to the axis of the rod will reflect back and forth by the silvered ends of the rod and stimulate other excited Cr^{+3} ions to radiate another photon with same phase. Thus, due to successive reflections of these photons at the ends of the rod the number of photons multiplies. After a few microseconds a monochromatic, intense and collimated beam of pink light of wavelength of 6493Å emerges through partially silvered ends of the rod. The ruby laser is a pulsed laser that emits light in the form of very short pulses.