Unit-2

LASER

Syllabus:

Properties of lasers, types of lasers, derivation of Einstein A & B Coefficients, Working He-Ne and Ruby lasers.

LASER:

The word LASER is acronym for light amplification by stimulated emission of radiation. Laser source produces coherent, monochromatic, least divergent, unidirectional and high intense beam. Einstein gave the theoretical description of stimulated emission in 1917. In 1954 G.H. Towne developed microwave amplifier MASER using Einstein's theory and put forward to light and first Laser was developed.

Characteristics of Laser beam:

i) Coherent: The Laser light is coherent. A Laser emits the light waves of same wavelength and in same phase.

ii) Monochromatic: If the light coming from a source has only one frequency or single wavelength is called monochromatic source and the light is called monochromatic light. In case of Laser beam it has the wavelength confirmed to very narrow range of a few angstroms.

iii) Divergence: Divergence is the measure of its spread with distance. The angular spread in ordinary light is very high because of its propagation in the form of a spherical wave front. The divergence in the Laser beam is negligible. A very small divergence is due to the diffraction of Laser light when it emerges out from the partially silvered mirror.

iv) Directionality: An ordinary source of light emits light in all directions. In case of Laser the photons of a particular direction are only allowed to escape. Thus the Laser beam is highly directional.

v) Intensity: The intensity of ordinary light decreases as it travels in the space. This is because of its spreading. The Laser does not spread with distance. It propagates in the space in the form of narrow beam and its intensity remains almost constant over long distance.

Three Quantum Process:

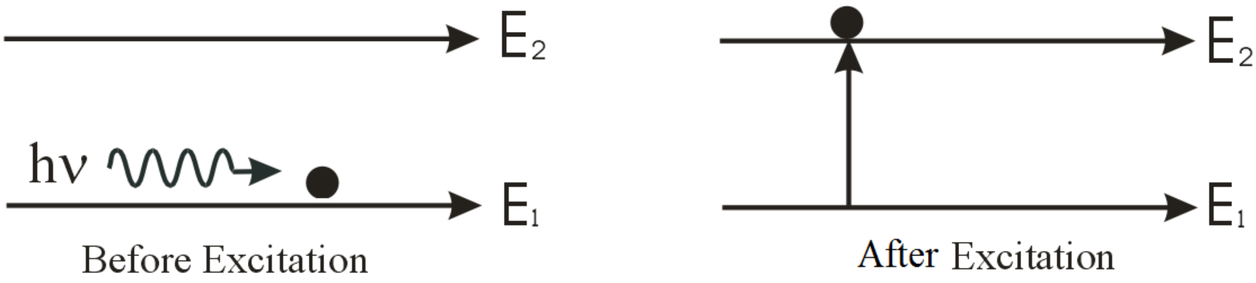
1. Induced absorption: When an atom gains some energy by any mean in the ground state, the electrons of the atoms absorbs some energy and are excited to high energy level.

Let us consider two energy levels E_1 and E_2 of an atom. Suppose this atom is expose to light radiation it can excite the atom from ground state E_1 to the high energy state E_2 by absorbing a photon of frequency ϑ. The frequency ϑ is given as

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

This process is called the induced absorption.

Pictorially it is represented as in figure(1)



Figure(1):Induced absorption

This may also be shown by the equation

$$A + h\vartheta \longrightarrow A^*$$

[* represents the exited state]

The probability of absorption transition is given by

$$p_{12} \propto p(\vartheta)$$
$$p_{12} = B_{12}\, p(\vartheta)$$

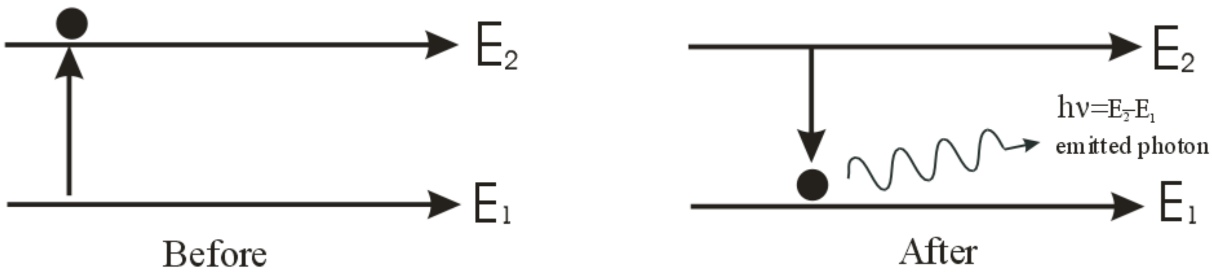
Where $p(\vartheta)$ is the energy state density

And the number of absorption transition in material is equal to the product of number of atoms at E_1 and absoption transition is given as

$$N_{ab} = N_2\, p_{12}$$
$$N_{ab} = B_{12} N_1\, p(\vartheta)$$

Where N_1 is the number of atoms in ground state E_1

2. Spontaneous Emission: When an atom at lower energy level is exited to the high energy level, it cannot stay in the exited state for relatively longer time. In a time of about $10^{-8}\ sec$, the atom reverts to the lower energy state by releasing a photon of energy $h\vartheta = E_2 - E_1$. This emission of photon by an atom without any external input is called spontaneous emission.



Figure(2): Spontaneous emission

We may write the transition as

$$A^* \longrightarrow A + h\vartheta$$

Probability of spontaneous emission depends only on the properties of energy states and is depends on the photon density. It is equal to the life time of E_2

$$(p_{21})_{sponteneous} = A_{21}$$

A_{21} is Einstein's coefficient for spontenious emission.

Number of spontaneous transition depends only on number of atoms N_2 in the excited state E_2. Thus

$$N_{sponteneous} = A_{12} N_2$$

Process of spontaneous emission cannot be controlled from outside and photon are emitted in random order so light is non-directional, non-monochromatic, incoherent and no amplification of light takes place.

3. Stimulated Emission: In 1916 Einstein predicted the existence of stimulated emission. A photon of appropriate energy when incidents to an atom which is in the exited state, then it may causes the de-excitation by the emission of an additional photon of same frequency as that of incident one, now the two photons of same frequency moves together. This process is called the stimulated or induced emission. The emitted photon have same direction, phase, energy and state of polarization as that of incident photon we can rewrite the transition as

$$A^* + h\vartheta \longrightarrow A + 2h\vartheta$$

The probability of stimulated emission is given by

$$(p_{21})_{stimulated} \propto p(\vartheta)$$

$$(p_{21})_{stimulated} = B_{21}\, p(\vartheta)$$

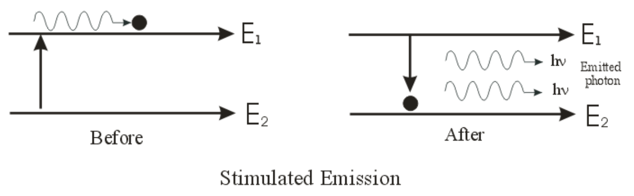
B_{21} is Einstein's coefficient of stimulated emission.

The number of stimulated transition in a material is given by

$$N_{stimulated} = B_{21} N_2\, p(\vartheta)$$

Where N_2 is the number of atoms in excited state E_2

The light produced by this process is essentially directional, monochromatic, and coherent, the outstanding feature of this process is the multiplication of photons i.e. if there are N exited atoms, $2N$ photons will be produced.



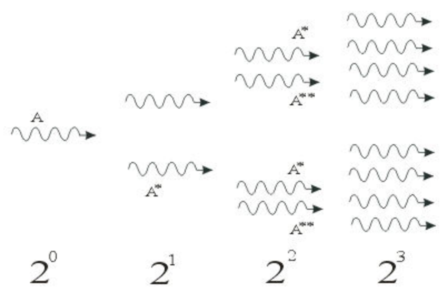


Figure (3): Multiplication of stimulated photons into an avalanche

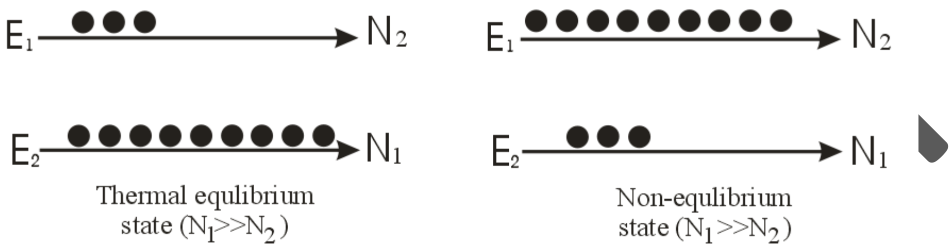
Population Inversion:

In the thermal equilibrium number of atoms in higher energy levels N_2 is less than population of lower energy level N_1. Then if E_1 and E_2 are two energy levels with population N_1 and N_2 then by Boltzmann relatin.

$$\frac{N_1}{N_2} = \exp\left(\frac{E_2 - E_1}{kT}\right)$$

Since $E_2 > E_1 \Longrightarrow N_2 < N_1$ In this situation the system absorbes electromagnetic radiation incident on it for laser action to take place, the higher energy level should be more populated as compared to the lower energy state i.e. $N_2 > N_1$

Thus the process by which the population of a particular high energy state is made more than that of a specified lower energy state is called population inversion.



Figure(4): Population inversion

Meta stable States:

An atom in the exited state has very short life time which is of the order of $10^{-8}\,sec$. Therefore even if continuous energy is given to the atoms in ground state to transfer them to exited state they immediately comes back to the ground state. Thus population inversion cannot be achieved. To achieve population inversion, we

Figure(5):

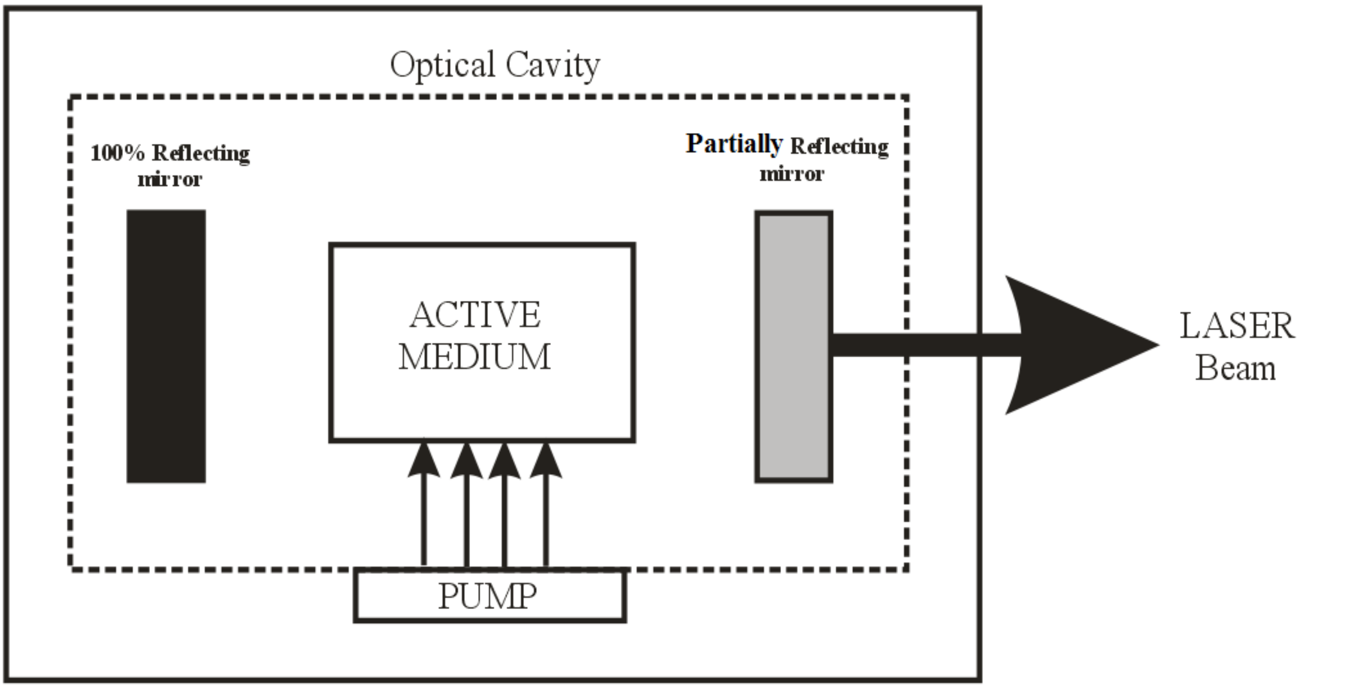
must have energy states which has a longer lifetime. The life time of meta stable state is 10^{-3} to $10^{-6}\,sec$ which is $10^3\ to\ 10^6$ time of exited states thus allows accumulation of large number of excited atoms and result in population inversion.

Components of Laser

the essential components of Laser are-

Active Medium:

The active medium is the material in which the laser action takes place. It may be solid, liquid, or gas. The medium determines the wavelength of the laser radiation. Atoms are characterized by the large number of the energy levels, but all types of atoms are not suitable for Laser operation. Even in a medium consisting of different species of atoms, only a fraction of atoms of particular type have energy level system suitable for achieving population inversion. Such atoms can produce more stimulated emission than spontaneous emission causes amplification of light. These atoms are called active center. The rest of the medium acts as the host medium and supports the active medium. Thus the active medium is the one which when excites,



Figure(6): Component of LASER

Optical Resonator:

It is specially designed cylindrical tube having two opposite optically plane mirrors with active medium filled between them, one mirror is fully silvered and other is partially silvered and are normal to the light intensity by multiple reflection. Science active medium is maintained in population inversion state photon produced through spontaneous emission produces the stimulated emission in every direction. The photons having parallel to the axis of the resonators are only augmented while other are reflected trough the walls of resonator. If these unidirectional photons reach fully reflecting mirror they reflects and while transverse through the medium they produce the stimulated emission in other atoms thus increased stimulated photons reaches partially silvered mirror. At this end some photons are transmitted and other are reflects back in the medium. This process repeats itself again and again.

Working of optical resonator:

a) Non-exited medium before pumping.
b) Optical pumping.

c) Spontaneous/stimulated emission.

d) Optical feedback.

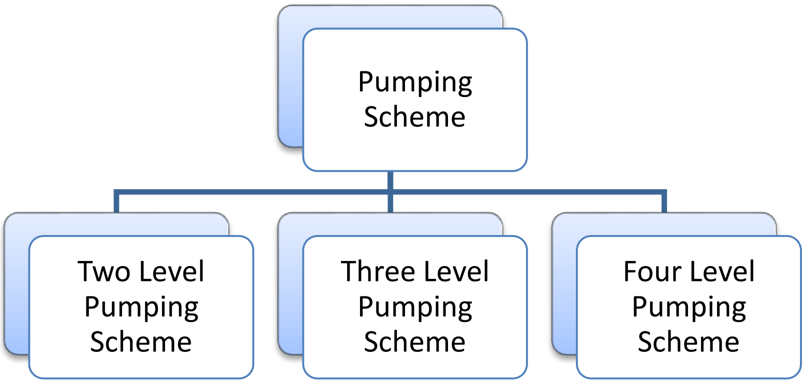
e) Light amplification.

f) Light oscillation and laser output.

Pumping:

The process by which we can achieve the population inversion is called the pumping.

Pumping Schemes:



Figure(7): Pumping scheme

Two level pumping scheme:

A two level pumping scheme is not suitable for obtaining population inversion. The time span Δt, for which atom has to stay at upper level E_2, must be longer for achieving population inversion condition.

As according to the Heisenberg's uncertainty principle

$$\Delta E. \quad \Delta t \frac{\hbar}{2} \geq$$

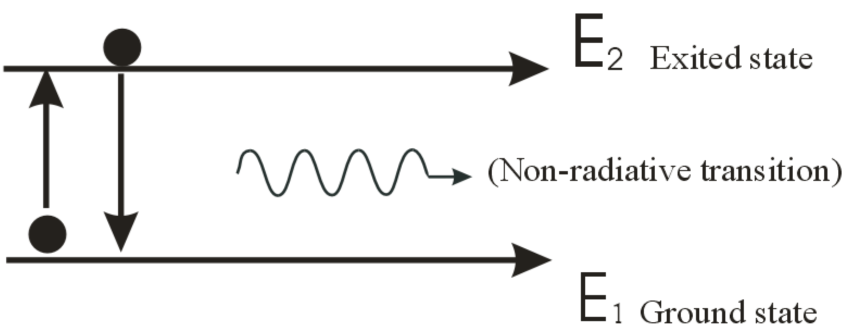


Figure (8): Two level pumping scheme.

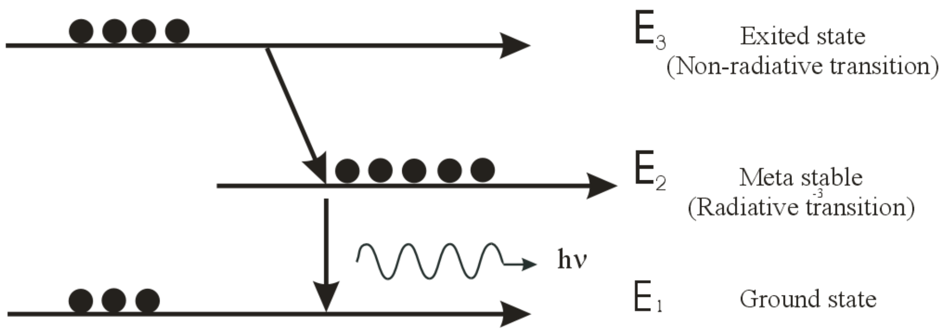
Δt will be longer if ΔE is smaller i.e. E_2 is narrow. If ΔE is smaller, the pumping efficiency is smaller as a consequence of which less number of atoms are exited and population inversion is not achieved.

Three level pumping:

Let an atomic system has three energy levels, the state E_1 is the ground state, E_2 is the metastable state and E_3 is the energy excited state. When light is incident, the atom are rapidly exited to upper most state E_3. They comes back in the lower energy level.

The atom does not stay at the E_3 level for long time. The probability of spontaneous transition $E_3 \longrightarrow E_1$ is comparable to $E_3 \longrightarrow E_2$, E_2 is the metastable state. Science probability of $E_2 \longrightarrow E_1$ transition is extremely small when the medium is expose to a large number of photons a large number of atoms will be exited to the higher energy level E_3. Some of these atoms make spontaneous transition to the E_2 state trough the radiative transition.

As the spontaneous transition from E_2 to E_1 occurs rarely. The atoms get trapped into the state E_2. This process continues when more than half of the ground state atoms accumulate at E_2, the population inversion is achieved between E_1 and E_2.



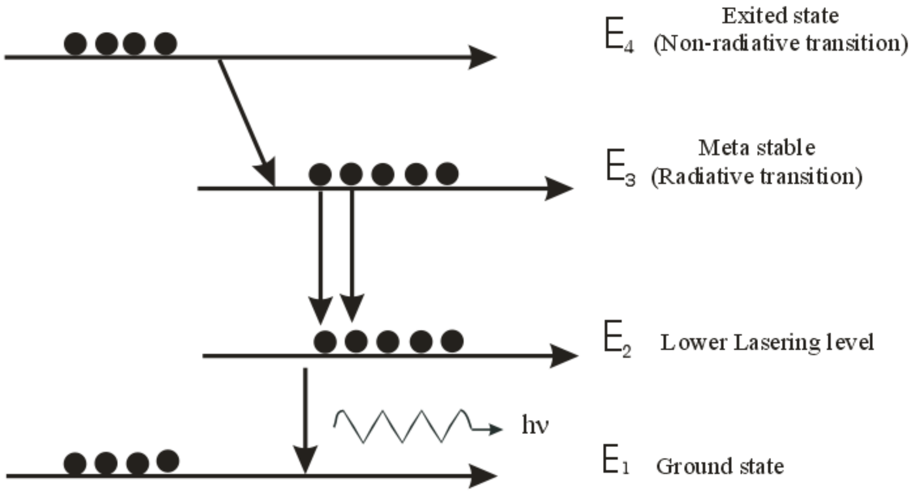
Figure(9): Three Level Pumping

In this scheme a very useful-pumping process is required because to achieve population inversion more than half of ground state atoms must be pumped to the upper state.

<u>Four Level Pumping:</u>

In four level pumping process the active medium are pumped from ground state E_1 to the uppermost level E_4 from where they rapidly fall to intermediate E_3 level i.e. meta stable state, leaving level E_2 empty. Now E_3 is populated inversely with respect to E_4.

If a triggering incident beam has frequency ϑ_{32} the transition $E_3 \longrightarrow E_2$ is the stimulated transition. It could be the atom from E_2 may go to E_1 sponteniously. This transition $E_2 \longrightarrow E_1$ is non radiative transition.



Figure(10): Four level pumping

Einstein's coefficient:

Let there is a lasering medium in which the number of atoms in the ground state are N_1 and number of atoms in the excited state are N_2 , $U(\vartheta)$ is the energy density of radiation for frequency ϑ.

The rate of self-emission

$$(r_a) \propto N_2$$

$$(r_a) = A_{12}N_2$$

And the rate of stimulated emission

$$(r_b) \propto N_2$$

And $$(r_a) \propto U(\vartheta)$$

$$\therefore \quad (r_b) \propto N_2 U(\vartheta)$$

$$(r_b) = B_{21} N_2 U(\vartheta)$$

The rate of absorption

$$(r_C) \propto N_1$$

And $$(r_C) \propto N_1 U(\vartheta)$$

$$(r_C) = B_{12}N_1 U(\vartheta)$$

Here, coefficient A_{21} and $B_{12}$and B_{21} are respectively called the Einstein's A and B coefficients. It is clear that the rate of stimulated emission and rate of absorption determined by the same coefficient B. This is why simulated emission is also called the inverse absorption.

Relation between Einstein's A and B coefficient:

Let there be an assembly of N_0 atoms in thermal equilibrium at temperature T with radiation frequency ϑ.

Since the rate of absoption of radiation i.e. transition from state $E_1 \longrightarrow E_2$ is proportional to the energy desity of radiation $U(\vartheta)$. The number of transition per unit time per unit volume from $E_1 \rightarrow E_2$ is given by

$$N_1 p_{12} = N_1 B_{12} U(\vartheta)$$

Where N_1 is the number of atoms in energy state E_1 and p_{12} is the probability of the transition from $E_1 \rightarrow E_2$

Similarly the number of transition per unit time per unit volume from state $E_2 \rightarrow E_1$ may be given as

$$N_2 p_{21} = N_2\{A_{21} + B_{21} U(\vartheta)\}$$

Where N_2 is the number of atpms in energy state E_2 and p_{21} is the probability of the transition from $E_2 \rightarrow E_1$

In equilibrium state

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

$$N_1 B_{12} U(\vartheta) = N_2\{A_{21} + B_{21} U(\vartheta)\}$$

$$N_1 B_{12} U(\vartheta) = N_2 A_{21} + N_2 B_{21} U(\vartheta)$$

$$N_1 B_{12} U(\vartheta) - N_2 B_{21} U(\vartheta) = N_2 A_{21}$$

$$[N_1 B_{12} - N_2 B_{21}] U(\vartheta) = N_2 A_{21}$$

$$U(\vartheta) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

$$U(\vartheta) = \frac{A_{21}}{B_{21}}\left[\frac{N_2}{N_1\left(\frac{B_{12}}{B_{21}}\right)-N_2}\right]$$

$$U(\vartheta) = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right)-\frac{N_2}{N_2}}\right]$$

$$U(\vartheta) = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right)-1}\right]$$

By Boltzmann distribution law

$$N_1 = N_0\, e^{-(E_1/kT)}$$

$$N_2 = N_0\, e^{-(E_2/\,kT)}$$

Where N_0 is the total number of atoms

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

Then

$$U(\vartheta) = \frac{A_{21}}{B_{21}}\left[\frac{1}{\left\{e^{\frac{E_2-E_1}{kT}}\right\}\left(\frac{B_{12}}{B_{21}}\right)-1}\right]$$

But $E_2 - E_1 = h\vartheta$

So

$$U(\vartheta) = \frac{A_{21}}{B_{21}}\left[\frac{1}{\left\{e^{\frac{h\vartheta}{kT}}\right\}\left(\frac{B_{12}}{B_{21}}\right)-1}\right]$$

But according to the Plank's the energy density of the radiation of frequency ϑ at temperature T is given by

$$U(\vartheta) = \frac{8\pi h\vartheta^3}{c^3}\cdot\left[\frac{1}{\left(e^{h\vartheta/kT}\right)-1}\right]$$

On comparing

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

Ruby Laser:

Solid state laser is the first laser operated successfully. It was fabricated by Mainman in 1960. Ruby is the lasing medium consist of the crystal of mixture Al_2O_3 and the Cr_2O_3. Here some aluminum atoms are replaced by the 0.05% cromiume atoms.

Construction:

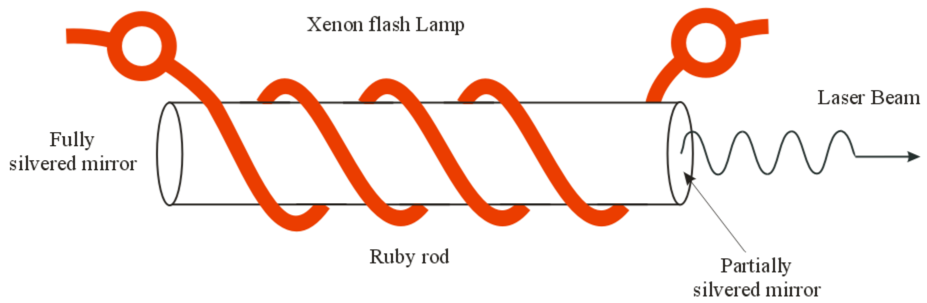
Chromium atoms doped into the aluminum atoms. The active medium in ruby with which main laser action takes place is Cr^{3+} ions.

Length of the cylindrical rod lies in between 2 to 20cm and the diameter of the rod is about 0.1 to 2cm. The end faces of the rod are polished flat and parallel. In this one face is partially silvered and other face is fully silvered.

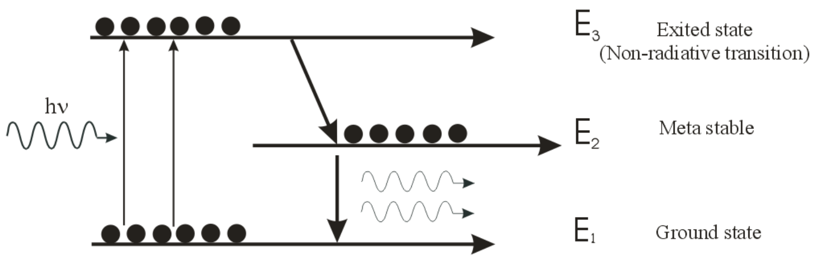
Ruby rod is surrounded by the helical Xenon photo flash lamp which provides the pump energy to rise the chromium atom to higher energy level. The parallel ends rod forms an optical cavity so that the photon traveling along the axis of the optical cavity gets reflects back and fro the end surfaces.

Working:

The energy level of Cr^{3+} ions on the crystal lattice. Consists of three level systems. Upper energy level is short lived state.



Figure(11):



Figure(12)

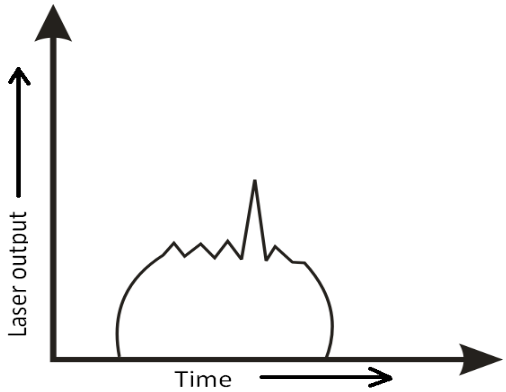
When a flash light falls upon the ruby rod, the 5500 Å radiation photon are absorbed by Cr^{3+} ions which are pumped to the exited state E_3. The transition from E_1 to E_3 is the optical pumping transition.

Now the Cr^{3+} ions in the exited state give a part of their energy to the crystal lattice and decay to the meta stable state E_2. Hence the transition from E_3 to E_2 is radiation less transition. Metastable state E_2 is long lived state; hence the number of Cr^{3+} ions goes on increasing, while due to pumping the number in the ground state E_1 goes on decreasing.

Population inversion is established between the E_2 and E_1. The spontaneous photon emitted by Cr^{3+} ion at E_2 level is of the wave length of about 6943 Å.

Drawbacks :

1) Efficiency of ruby Laser is very low.
2) The Laser Output is not continuous occurs in the form of pulse of microseconds duration.
3) The Laser requires the high pumping power.
4) The defects due to crystalline impurities are also presents in the laser.



Figure(13): Ruby Laser output

Gas Laser:

Gas Lasers are most widely used Lasers. The ranges from low power Lasers like Helium-Neon Laser to high power Laser like CO_2 laser. These lasers operate with rarified gases as the active medium and are excited by and electrical discharge.

In gases the energy levels of the atoms involves the lasing process are narrow and as such require sources with sharp wavelength to excite atoms. Most common method to excite gas molecules is by passing an electric discharge through the gas electrons present in the discharge through the gas electrons presents in the discharge transfer energy to atoms of laser gas by collision.

He-Ne Laser:

Helium-Neon Laser was first gas Laser to be invented by Ali-Jawan in 1961. The pumping method employed in He-Ne Laser is electrical pumping method and is based on four level pumping scheme. Since He-Ne laser is a gas laser so He-Ne laser have sharp energy levels.

Construction:

It consists of a long discharge tube made up of fused quartz which is $10 - 100\ cm$ the length and $2\ to\ 8\ mm$ in the diameter. The tube is filled with He and Ne gases under the pressure of $1\ mm$ Hg and $0.1\ mm$ of Hg respectively. And are filled in the ratio ranging from $10:\ 1\ to\ 20:1$. Neon is the active center and have energy levels suitable for laser transition. While He atoms help in exiting Neon atom. The electrodes are provided in the discharge tube to provided discharge in the gas which are connected to a high power supply. The optical cavity of laser consists plane and highly reflecting mirror at one end of the laser tube and a Plano-concave output mirror of an approximately 1% transmission at the other end.

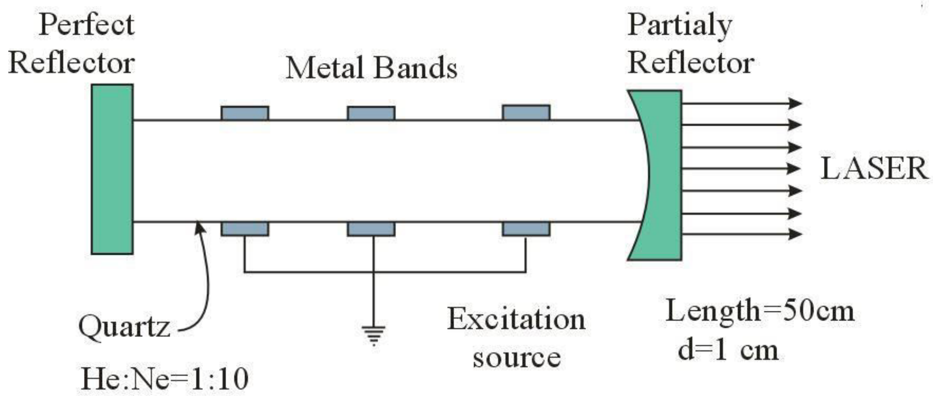
To minimize reflection Laser the discharge tube edges are cut at the angle. This arrangement causes the laser output to be linearly polarized.

Working:

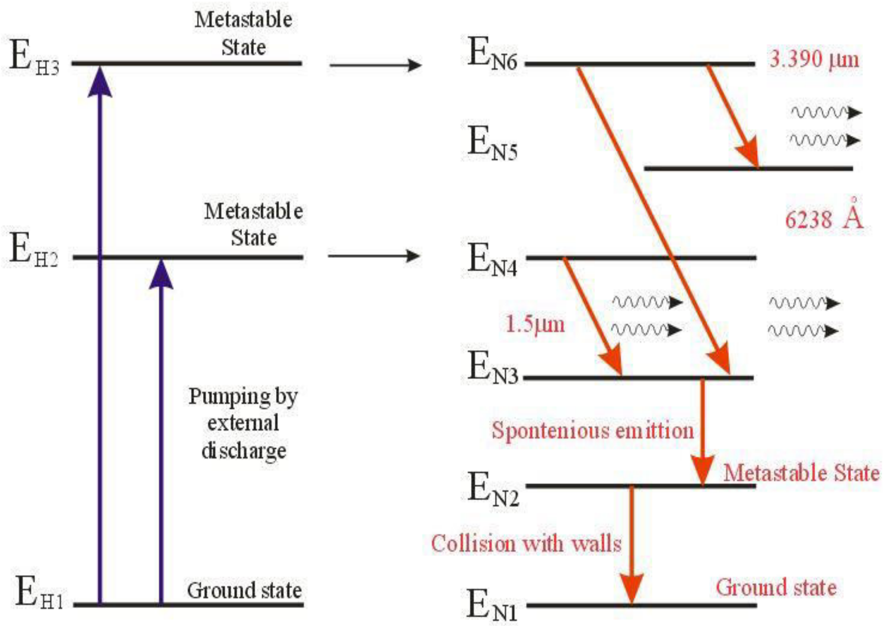
A high voltage is applied across the gas mixture produces electrical breakdown of the gas into ions and electrons. Fast moving electrons are collide with Helium and Neon atoms and exit them to high energy level. He atom are more easily excitable than Ne atoms as they are lighter.

The life time of the energy levels E_2 and E_3 of He is more therefore these levels of He becomes densely populated. As the Ne energy levels E_3 and E_6 are close to the exited levels E_2 and E_3 of He. The probability of the atoms transferring their energy to Ne atom by inelastic collision is greater than the probability of coming ground state E_1 by spontaneous emission. Since the pressure of the He is 10 times greater than the pressure of Neon, the levels E_6 and E_4 of Neon are densely populated than any other energy levels.

Photons with the energy $h\vartheta$ stimulate the transition from E_6 to E_5, E_6 to E_3 and E_4 to E_3. During these transition radiation are emitted with the wavelength of 3.39 μm, 6328 Å and 1.15 μm respectivly.



Figure(16): He-Ne Laser



Figure(17): Energy level diagram of He-Ne Laser

From the energy levels E_3 spontaneous emission occurs in the energy level E_2. Since the energy level E_2 is the lower Metastable state then the possibility of atom in the level E_2 getting de-exited to the level E_3 may occur, if it happened then number of atoms in ground state will go on diminishing and the laser ceases to function. This can be protected by reducing the diameter of the tube so that atoms in E_2 follows direct transition to the level E_1 through collision with the walls of tube.

The He-Ne Laser operate in continuous wave mode.

Application of Laser:

1) The laser beam is used to vaporize unwanted materials during the manufacturing of electronic circuits on semiconductors chips.
2) Laser is used to detect and destroy the enemy missiles during war.
3) Metallic rod can be melted and joined by means of laser beam.

4) Low price semiconductor lasers are used in CD players, laser printers.
5) High power lasers are used to leasing thermo nuclear reactions which would become the ultimate exhaust little power source for human civilization.
6) Laser is also being employed for separating the various isotopes of an element.
7) Laser beam are also been used to the internal confinement of plasma.