Unit-IV

LASER PHYSICS

Introduction

The word LASER is an acronym for *"Light Amplification by Stimulated Emission of Radiation"*. It is a powerful monochromatic light source of collimated beam in which the light waves are highly coherent. The laser light has many superior features compared to conventional light source. Einstein introduced this concept in 1917. Dr. T.H. Maiman demonstrated the first laser namely the ruby laser in the year 1960.

Characteristics of LASER :

Laser differs from the ordinary light with respect to some properties. They are

- Monochromaticity
- Directionality
- Coherence
- Intensity

1. Monochromaticity :

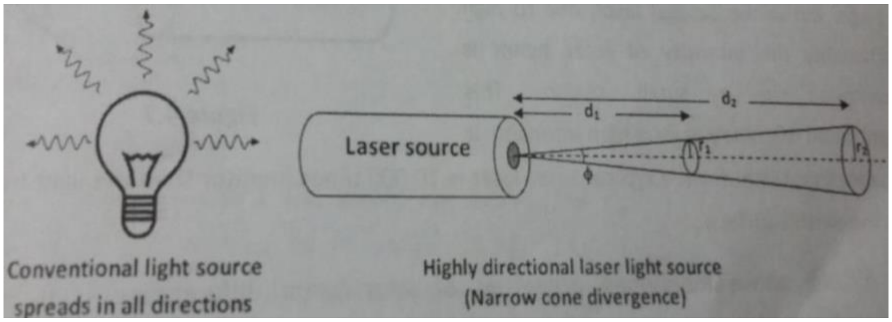
Laser beam is highly monochromatic. It emits single wavelength (one colour) because atoms or molecules are transition between two energy states. Hence it possesses good spectra since range of laser beam wavelength ($\Delta\lambda$) is very narrow. But ordinary light emits combination of wide range of wavelength (colors) because atoms or molecules are transition from several number of excited states to ground state, so it emits different energies, therefore it is polychromatic.

2. Directionality or Divergence :

The light ray coming ordinary light source travels in all directions, but laser light travels in single direction. For example, the light emitted from torch spreads 1km distance, But the laser light spreads a few centimeters distance even it travels longer distance. The ordinary source emits light in all directions and its angular spread is 1 metre/metre. But the laser is highly directional and non-divergent and its angular spread is 1mm/metre.

The angular spread (ϕ) or divergence is given by,

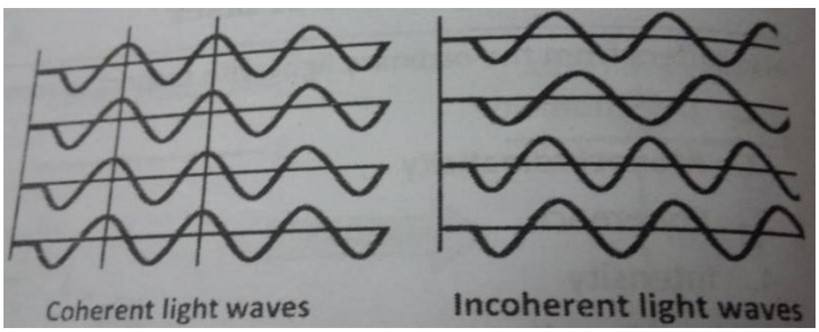
$$\Phi = \frac{r_2 - r_1}{D_2 - D_1} \quad degree$$



where D_1, D_2 are any two distances from the laser source emitted and r_1, r_2 are the radii of the beam spots at a distance D_1 and D_2, respectively.

3. Coherence

A predictable correlation of the amplitude and phase at any one point with other point is called coherence. The light from a source consists of wave pattern. These wave patterns when identical in phase and direction are called coherent. Laser has a high degree of coherence than the ordinary sources. The coherence of laser emission results in an extremely high power of 5×10^6 watt/m^2. A laser beam can be focused to a very small area of about 0.7 μm diameter.



4. Intensity

Laser light is highly intense than the ordinary light. This is because of coherence and directionality of laser. The ordinary light spreads in all directions, so the intensity reaching the target is very less. But in the case of laser, due to high directionality the intensity of laser beam is concentrated in a small region. This concentration of energy gives a high intensity. Since in Laser many number of photons are in phase with each other, the amplitude of the resulting wave becomes na and hence the intensity of laser is proportional to n^2a^2. It is estimated that light from a typical 1mW laser is 10,000 times brighter than the light from the sun at the earth's surface.

Ordinary light versus LASER :

Ordinary light	LASER
Ordinary light are Polychromatic since it consists of radiations of several wavelengths.	Laser light is monochromatic since it consists of only single wavelength.
Ordinary light is divergent because it spreads in all directions	Laser light is non-divergent because it travels in single direction
Intensity of ordinary light is lesser because concentration of photons is lesser	Intensity of Laser light is higher because concentration of photons is higher
Ordinary light is not Coherent	Laser light is highly Coherent
Due to less intensity brightness of ordinary light is low	Due to high intensity brightness of Laser light is high
Examples: Sunlight	Example: Laser light

Ground state and Excited states:

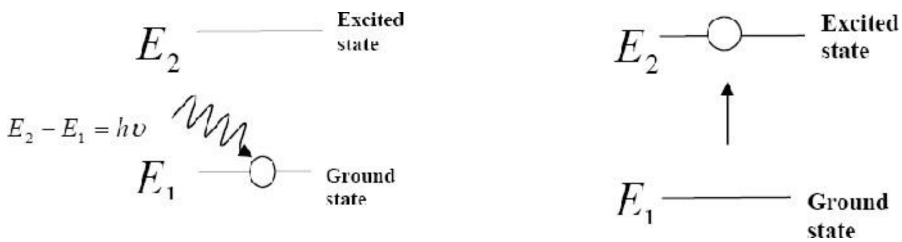
The lowest energy level for an individual atom occurs when its electrons are all in the nearest possible orbits to its nucleus ,this energy level is called the "**Ground state**".

When one or more of an atom's electrons have absorbed energy, they can move to outer orbits, and the atom is then referred to as being excited, and that energy level is called as **"Excited state."** Excited states are generally not stable; as electrons drop from higher-energy to lower-energy levels, they emit the extra energy as light.

Interaction of Radiation with matter

1. Induced Absorption or Stimulated Absorption :

An atom is in the ground state with energy E_1 absorbs a photon of energy $h\nu$ and goes to the excited state with energy E_2 as shown in Fig. This transition is known as stimulated absorption or induced absorption or simply absorption. Here the energy difference is given as $(E_2 - E_1) = h\nu$.



If there are many number of atoms in the ground state then each atom will absorb the energy from the incident photon and goes to the excited state then,

The rate of absorption (R_{12}) is proportional to,

$R_{12} \propto$ Energy density of incident radiation ($\rho\nu$)

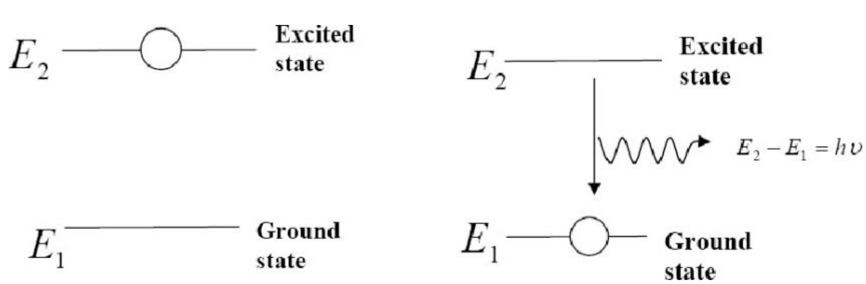
$\propto$ No. of atoms in the ground state (N_1)

$$\mathbf{R_{12} = B_{12}\ \rho\nu\ N_1}$$

Where, B_{12} is a constant which gives the probability of absorption transition per unit time.

2. Spontaneous emission

The natural tendency of an atom is to seek out the lowest energy configuration. The excited atoms do not stay in the excited state for longer time but tend to return to the lower state by giving up the excesses energy $h\nu$ as shown in fig. The atom in the excited state E_2 returns to the ground state E_1 by emitting a photon of energy $h\nu$ without any external energy. Such emission of radiation not initiated by any external influence is called spontaneous emission. This emission is uncontrollable.



The rate of spontaneous emission R21 (Sp) is proportional to number of atoms or molecules present in the excited state.

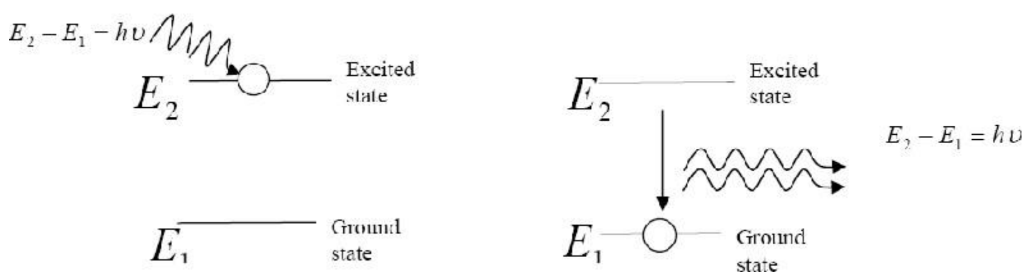
i.e $R_{21}\ (Sp) \propto N_2$

$$R_{21}\ (Sp) = A_{21} N_2$$

where A_{21} is a constant which gives the probability of spontaneous emission transitions per unit time.

3. Stimulated emission

The atom in the excited state E_2 as shown in fig. A photon of energy $h\nu$ can stimulate the atom to move to its ground state. During this process the atom emits an additional photon whose energy is also $h\nu$. As the emission is stimulated by external photon, this process is known as stimulated emission.



The rate of stimulated emission R21 (St) is proportional to,

$R_{21} \propto$ Energy density of incident radiation (ρ_ν)

$\propto$ No. of atoms in the excited state (N_2)

i.e $R_{21}\ (St) \propto \rho_\nu N_2$

$$R_{21}\ (St) = B_{21}\, \rho_\nu\, N_2$$

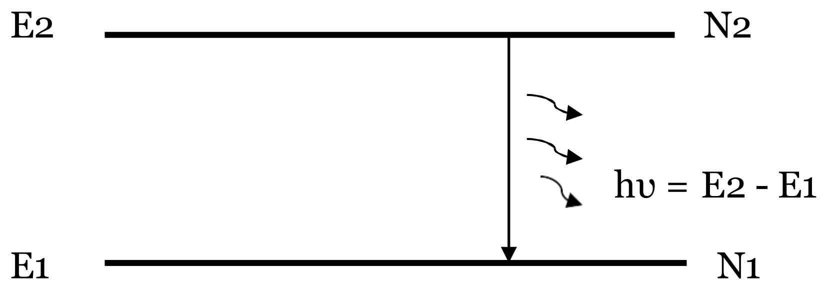
where B_{21} is a constant which gives the probability of stimulated emission transitions per unit time.

Einstein's A and B Coefficient:

(Relation between Einstein's coefficient and Energy density of radiation)

Einstein's theory of absorption and emission of light by an atom is based on Planck's theory of radiation.

Consider two energy levels E1 and E2 having number of atoms N1 and N2 respectively, as shown in figure.



According to Einstein's theory,

Rate of Stimulated absorption is, $R_{12} = B_{12} E_\nu N_1$

Rate of Spontaneous Emission is, $R_{21(Sp)} = A_{21} N_2$

Rate of Stimulated Emission is, $R_{21(St)} = B_{21} E_\nu N_2$

Where, A and B represents the Spontaneous and Stimulated process respectively. E_υ is the energy density of radiation.

At thermal equilibrium,

The rate of absorption = The rate of emission

$B_{12} E_\nu N_1 = A_{21} N_2 + B_{21} E_\nu N_2$ ----------------(1)

$E_\nu [B_{12} N_1 - B_{21} N_2] = A_{21} N_2$

$$E_\upsilon = \frac{A_{21} N_2}{[B_{12} N_1 - B_{21} N_2]}$$

$$E_\upsilon = \frac{A_{21}}{[B_{12}\frac{N_1}{N_2} - B_{21}]} \quad \text{------------- (2)}$$

Under thermal equilibrium, the population of energy levels obeys the Boltzmann's distribution law.

We know from Boltzmann distribution law,

$$N_1 = N_0\, e^{\frac{-E_1}{KT}}$$

$$N_2 = N_0\, e^{\frac{-E_2}{KT}}$$

Where, K is the Boltzmann constant,

T is the absolute temperature and

N_o is the number of atoms at absolute zero at equilibrium,

we can write the ratio of population as follows,

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

since $E_2 - E_1 = h\nu$, we have

$$\therefore \quad \frac{N_1}{N_2} = e^{\frac{h\upsilon}{KT}} \text{-----------------------------} (3)$$

Substitute eq(3) in eq(2), we get

$$E_\upsilon = \frac{A_{21}}{[B_{12} e^{\frac{hu}{KT}} - B_{21}]}$$

Divide both numerator and denominator by B_{12} , we get

$$E_\upsilon = \frac{\frac{A_{21}}{B_{12}}}{[e^{\frac{hu}{KT}} - \frac{B_{21}}{B_{12}}]} \quad ---------(4)$$

According to Maxwell-Boltzman statistics

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

Equation (4) becomes,

$$E_\upsilon = \frac{8\pi h \upsilon^3}{c^3\, [e^{\frac{hu}{KT}} - 1]}$$

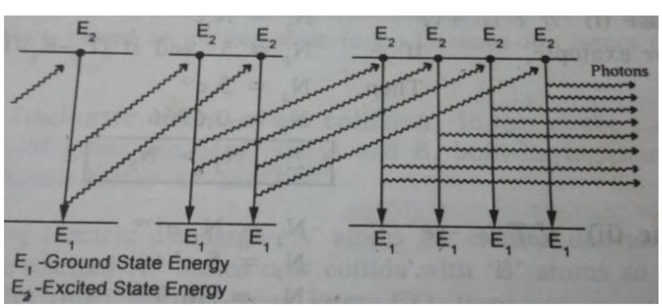
This is the relation between Einstein's coefficient and Energy density of radiations(E_υ).

Difference between Stimulated and Spontaneous Emission :

Sl.No	Stimulated Emission	Spontaneous Emission
1.	An atom in the excited state is induced to return to ground state, thereby resulting in two photons of same frequency and energy is called stimulated emission.	The atom in the excited state returns to ground state thereby emitting a photon, without any external inducement is called spontaneous emission.
2.	The emitted photons move in same direction and are highly directional.	The emitted photons move in all directions and are random.
3.	The radiation is high intense, monochromatic and coherent.	The radiationis less intense and is incoherent.
4.	The photons are in phase.	The photons are not in phase.
5.	The rate of transition is given by $R_{21}(St) = B_{21}\, \rho\nu\, N_2$	The rate of transition is given by $R_{21}(Sp) = A_{21}N_2$

Light amplification :

Let us consider many numbers of atoms in the excited state. We know the photons emitted during stimulated emission have same frequency, energy and are in phase as the incident photon. Thus results in 2 photons of similar properties. These two photons induce stimulated emission of 2 atoms in excited state thereby resulting in 4 photons. These 4 photons induce 4 more atoms and give rise to 8 photons etc., as shown in Fig.



Principle: Due to stimulated emission the photons multiply in each step giving rise to an intense beam of photons that are coherent and moving in the same direction. Hence the Light is Amplified by Stimulated Emission of Radiation, termed as LASER.

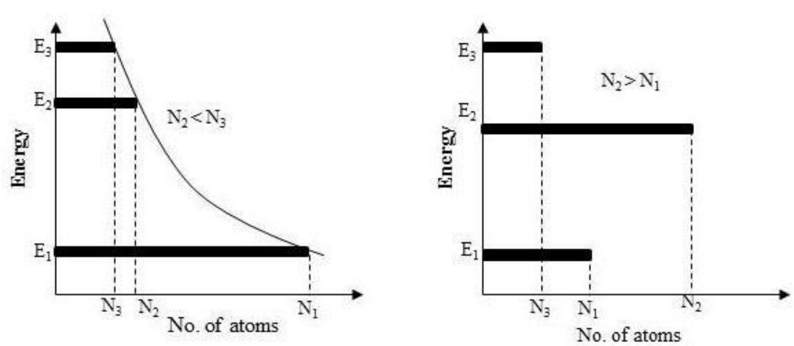
Population inversion:

When a system is in thermal equilibrium, the distribution of atoms in energy states at a given temperature follows the Boltzmann's law as

$$\frac{N_1}{N_2} = e^{\frac{h\upsilon}{KT}}$$

From the above equation, it is clear that the population is maximum in ground state as compared with excited state. i.e $N_1 > N_2$.

If the situation is reverse, i.e $N_2 > N_1$, there are more atoms in an excited state than the ground state as shown in fig(b), this condition is called **"Population inversion".**



When a suitable energy is supplied to the system, atoms get excited into E_3. After their lifetime 10^{-8} *seconds*, the atoms are transit to E_2. Due to more lifetime of an atom in state E_2(10^{-3} *secconds*), the atomsstay for longer time than compare with the state E_3. Due to the accumulation of atomsin E_2, the population inversion is established in between the E_2 and E_1 states.

Pumping methods :

The process of achieving population inversion is called pumping. Pumping can be classified into the following types based on the type of source of pumping.

1. **Optical pumping**: Here the atoms are excited with the help of photons emitted by an optical source. The atoms absorb energy from the photons and raises to excited state. Optical pumping is used in solid laser.
   Examples **:** Ruby Laser, Nd-YAG Laser

2. **Electrical pumping**: Electrical discharge pumping is used in gas lasers. Since gas lasers have very narrow absorption. The electrons are accelerated to very high velocities by strong electric field and they collide with gas atoms and these atoms are raised to excited state.
   Examples : Argon Laser, CO_2 Laser, He-Ne Laser

3. **Chemical pumping**: Due to some chemical reactions, the atoms may be raised to excited state. Examples : Dye Laser.

Metastable state :

It is an excited state of an atom with a longer life time than the other excited states. Atoms in the metastable state remain excited for a considerable time in the order of 10^{-6} to 10^{-3} seconds. Such relatively long-lived states are called as Metastable state. An atom can exist in a metastable energy level for a longer time before radiating than itcan in an ordinary energy level.

An atom can be excited to a higher level by supplying energy to it. Normally, excited atoms have short life times and release their energy in a matter of 10^{-8} seconds through spontaneous emission. It means atoms do not stay long to be stimulated. As a result, they undergo spontaneous emission and rapidly return to the ground level; thereby population inversion could not be established. In order to do so, the excited atoms are required to 'wait' at the upper energy level till a large number of atoms accumulate at that level, that is A Meta stable state.

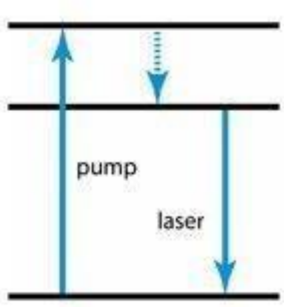
These levels lie in the forbidden gap of the host crystal. There could be no population inversion and hence no laser action, if metastable states don't exist.

Optical Pumping: Three- and Four-Level Systems

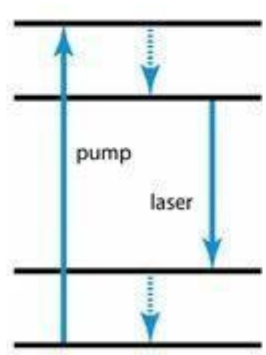
In a simple two-level system, it is not possible to obtain a population inversion with optical pumping because the system can absorb light (i.e., gain energy) only as long as population inversion, and thus light amplification, is not achieved. Essentially, the problem isstimulated emission caused by the pump light itself.

Inversion by optical pumping becomes possible when using a three-level system. Pump light with a shorter wavelength (higher photon energy) can transfer atoms from the ground state to the highest level. From there, spontaneous emission or a non-radiative process (e.g., involving phonons in a laser crystal) transfers atoms to an intermediate level, called the upper laser level. From that level down to the ground state, the laser transition with stimulated emission can occur. With sufficiently high pump intensity, population inversion for the laser transition can be reached as stimulated emission by the pump radiation is prevented by the transfer to the intermediate level.

Laser gain with a much lower excitation level is possible in a four-level system, such as Nd:YAG. Here, the lower level of the laser transition is somewhat above the ground state, anda rapid (most often non-radiative) transfer from there to the ground state keeps the population of the lower laser level very small. Therefore, a moderate population in the third level (the upper laser level), as achieved with a moderate pump intensity, is sufficient for laser amplification.



Three level



four level laser

Components of Lasers

Active Medium:

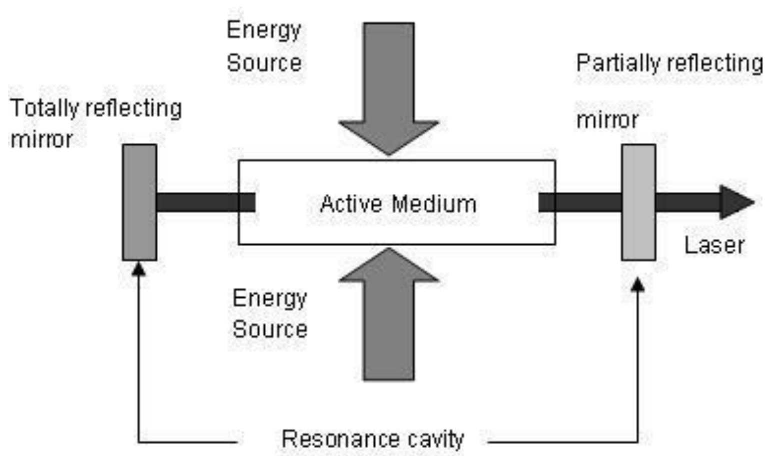
It is the material in which the laser action takes place. The active medium may be solid crystals such as liquid dyes, gases like CO_2 or Helium-Neon, or semiconductors such as GaAs. This medium decides the wavelength of laser radiation. Active mediums contain atoms which can produce more stimulated emission than spontaneous emission and cause amplification they are called “Active Centers”.

Pumping Energy Source (Excitation Mechanism):

Energy Source (Excitation mechanisms) pumps the active centers from ground state to excitedstate to achieve population inversion. The pumping by energy source can be optical, electricalor chemical depending on the active medium.

Resonance Cavity:

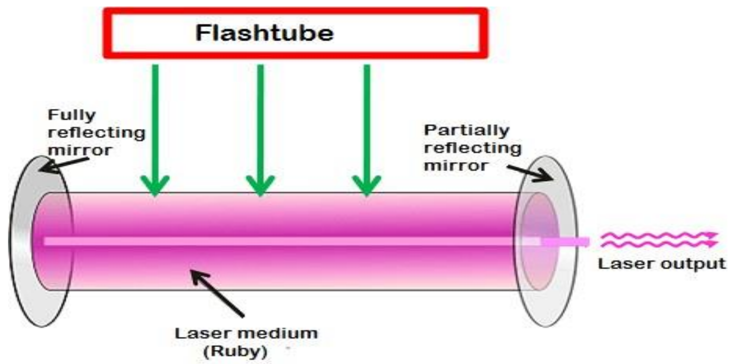
The optical resonator contains a pair of reflecting surfaces of which one is fully reflecting and the other partially reflecting. The active material is kept in between the two reflecting surfaces. Photons (light) emitted due to transitions between the energy states of the active material are bounced back and forth between the two reflecting surfaces, so the intensity of the light is increased. Finally the intense amplified beam called laser is coming out through the partial mirror as shown in the diagram.



Types of Lasers

1. Ruby Laser

The first working laser was built in 1960 by Maiman, using a ruby crytal and so called the Ruby laser. Ruby belongs to the family of gems consisting of Al_2O_3 with various types of impurities. For example, pink Ruby contains 0.05% Cr atoms. The schematic diagram of Ruby laser can be drawn as:



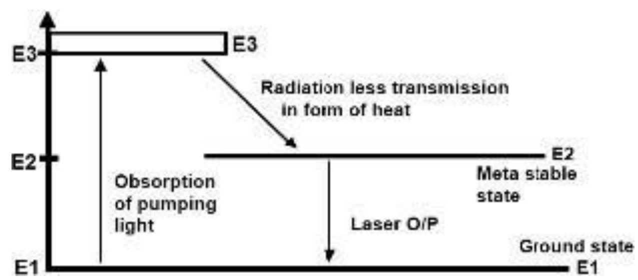
Construction of Ruby Laser

The ruby laser consists of a ruby rod. which is made of chromium doped ruby material. At the opposite ends of this rod there are two silver polished mirrors. Whose one is fully polished andother is partially polished. A spring is attached to the rod with fully polished end for adjustment of wave length of the laser light. Around the ruby rod a flash light is kept for the pump input. The whole assembly is kept in the glass tube. Around the neck of the glass tube the R.F source and switching control is designed in order to switch on and off the flash light for desired intervals.

Operation of Ruby Laser:

When we switch on the circuit the R.F operates. As a result, the flash of light is obtained aroundthe ruby rod this flash causes the electrons within ruby rod to move from lower energy band towards higher. This flash causes the electrons within ruby rod to move from lower energy band towards higher energy band. The population inversion take place at high energy band and electrons starts back to travel towards the lower energy band. During this movement the electron emits the laser light. This emitted light travels between the two mirrors where cross reflection takes place of this light. The stimulated laser light now escapes from partially polished mirror in shape of laser beam. The switching control of the R.F source is used to switch on and off the flash light so that excessive heat should not be generated due to very high frequency of the movement of the electron.

Energy Level Diagram for Ruby Laser



The above three level energy diagram show that in ruby lasers the absorption occurs, this makes raise the electrons from ground state E_1 to the band of level E_3 higher than E_1. At E_3 these excited levels are highly unstable and so the electrons decays rapidly to the level of E_2. This transition occurs with energy difference ($E_1 - E_2$) given up as heat (radiation less transmission). The level E_2 is very important for stimulated emission process and is known as Meta stable state. Electrons in this level have an average life time of about 5ms before they fall to ground state. After this the population inversion can be established between E_2 and E_1. The population inversion is obtained by opticalpumping of the ruby rod with a flash lamp. When the flash lamp intensity becomes large enough to create population inversion, then stimulated emission from the Meta stable level to the ground level occurs which result in the laser output.

Advantages of Ruby Lasers

- Beam diameter of the ruby laser is comparatively less than CO_2 gas lasers.
- Output power of Ruby laser is not as less as in He-Ne gas lasers.
- Since the ruby is in solid form therefore there is no chance of wasting material of

active medium.

- ❖ Construction and function of ruby laser is self-explanatory.

Disadvantages of Ruby Laser

- ❖ In ruby lasers no significant stimulated emission occurs, until at least half of the groundstate
- ❖ electrons have been excited to the Meta stable state.
- ❖ Efficiency of ruby laser is comparatively low.
- ❖ Optical cavity of ruby laser is short as compared to other lasers, which may beconsidered a disadvantage.

Applications of Ruby Laser

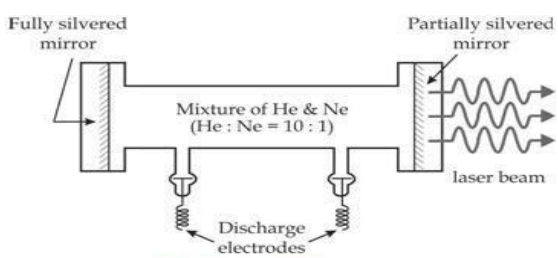
- ❖ Due to low output power they are class-I lasers and so may used as toys for children's.
- ❖ It can be used in schools, colleges, universities for science programs.
- ❖ It can be used as decoration piece & artistic display.

2. Helium -Neon (He-Ne) Laser

Construction:

Active medium:

It is a gas laser, which consists of a narrow quartz tube filled with a mixture of Helium and Neon gases in the ratio 10:1 respectively, at low pressure (~0.1 mm of Hg). Ne atoms act as active centers and responsible for the laser action, while He atoms are used to help in the excitation process. The length of the quartz tube is about 50 cm and the diameter is about 1 cm.



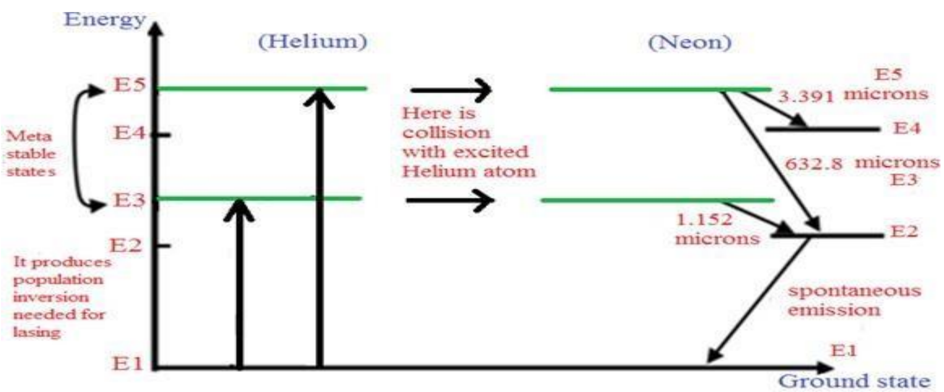
He-Ne LASER

Optical resonator:

To construct the optical resonator cavity, two parallel mirrors are placed at the ends of the quartz tube one of them is partly transparent while the other is fully reflecting. The spacing between the mirrors is adjusted such that it should be equal to the integral multiple of half- wavelengths of the laser light.

Pumping system:

The pumping is done through electrical discharge by using electrodes that are connected to a high frequency alternating current source.



The common helium-neon gas laser achieves a population inversion in a different way. A mixture of about 10 parts of Helium and 1 part of Neon at a low pressure is placed in a glass tube that has parallel mirrors, one of them partly transparent, at both ends. The spacing of the mirrors is equal to an integral number of half-wavelengths of the Laser light. An electric discharge is produced in the gas by means of electrodes outside the tube connected to a source of high-frequency alternating current, and collisions with electrons from the discharge excite He and Ne atoms to metastable states respectively above their ground states. Some of the excited He atoms transfer their energy to ground-state Ne atoms in collisions. The purpose of the He atoms is thus to help achieve a population inversionin the Ne atoms.

The laser transition in Ne is from the metastable state to an excited state with the emission of a 650nm of photon. Then another photon is spontaneously emitted in a transition to a lower metastable state; this transition yields only incoherent light.

Characteristics of He-Ne Laser

The He-Ne laser is a relatively low power device with an output in the visible red portion of the spectrum. The most common wavelength produced by He-Ne lasers is 632.8nm. Majority of He-Ne lasers generate less than 10m watt of power, but some can be obtained commercially with up to 50m watts of power. For He-Ne lasers the typical laser tube is from 10 to 100 cm in length and the life time of such a tube can be as high as 20,000 hours.

Applications of He-Ne Laser

The Helium-Neon gas laser is one of the most commonly used Laser today because of the following applications.

- Many schools / colleges / universities use this type of laser in their science programs and experiments.
- He-Ne lasers also used in super market checkout counters to read bar codes and QRcodes.
- The He-Ne lasers also used by newspapers for reproducing transmitted photographs.
- He-Ne lasers can be use as an alignment tool.
- It is also used in Guns for targeting.

Advantages of He-Ne Laser

- He-Ne laser has very good coherence property.
- He-Ne laser tube has very small length approximately from 10 to 100cm and best lifetime of 20.000 hours.
- Cost of He-Ne laser is less from most of other lasers.
- Construction of He-Ne laser is also not very complex.
- He-Ne laser provide inherent safety due to low power output.

Disadvantages of He-Ne Laser

- It is relatively low power device means its output power is low.
- He-Ne laser is low gain device.
- High voltage requirement can be considered its disadvantage.
- Escaping of gas from laser plasma tube is also its disadvantage.

Applications of Lasers

LASER Cutting

Laser is used as a tool to cut thin metal sheets by properly focusing the laser onto any particular area to be cut, for a longer time. Thus due to thermal effect the sheet is cut.

LASER Welding

In ordinary welding process the heat will be made to fall on the area to be welded, so that the material in that area will go to molten state. This on cooling will join the material. In this process the heat will spread all over the surroundings and will affect the other area of the material and hence the material gets damaged. This damage can be avoided by using laser welding. In laser welding the beam is focused onto the area to be welded and other areas remain unaffected. Without affecting the material the area to be welded alone melted and joined.

LASERS in Industry

Using high power lasers we can weld or melt any material. We can produce very small holes that cannot be done by mechanical drilling. Lasers can be used for cutting and for testing the quality of the materials. During laser welding and drilling there is no damage the structure of the materials. Lasers can be used for surface hardening techniques.

MEDICAL APPLICATIONS

Laser cosmetics surgery is used for removing tattoos, scars, stretch marks, sunspots, wrinkles and hairs.

1. Laser types used in dermatology:

   It include Ruby (694nm), pulsed diode arrays (810nm), Nd: YAG (1064nm) and Er : YAG (2940nm)
2. Laser eye surgery:

   Laser eye surgery is a medical procedure that uses a laser to reshape a surface of the eyes. This is done to correct short sightedness, long sightedness and astigmatism (uneven curvature of the eye surface).
3. Soft- Tissue surgery:
   a. In soft tissue laser surgery, a highly focused laser beam vapourises the soft tissue with the high water content.

b. Soft tissue laser surgery is used in a variety of applications which include general surgery, neuro surgery, ENT, dentistry and oral surgery.
c. Soft tissue laser surgery is also used in veterinary surgical fields.

4. Laser light therapy

   Laser light therapy involves exposure to laser light of specific variant. The light is administered for a prescribed amount of light. This is commonly used for skin diseases and disorders.

5. Laser is widely used for no-touch removal of tumors, especially of the brain and spinal cord
6. In dentistry, laser is used for tooth whitening and carries removal.

LASER SURGERY

A type of surgery that uses the cutting power of a laser beam to make bloodless cuts in tissue or remove a surface lens such as a skin tumor. There are a number of different types of lasers that differ in emitted light wavelengths and power ranges and in their ability to clot, cut or vapourise tissue. Among the commonly used lasers are pulsed dye laser, the YAG laser, the CO_2 laser and the argon laser.

Questions

1. Distinguish between Ordinary light and Laser light.
2. Distinguish between spontaneous and stimulated emission?
3. List out the characteristics of LASER.
4. What is meant by Spontaneous emission?
5. What is meant by stimulated emission?
6. What is meant by population inversion?
7. What is meant by pumping?
8. What are different methods of pumping?
9. What are the conditions required for laser action?
10. What are Einstein's coeffecients?
11. Define active medium.
12. What is meant by Optical resonator or Resonance cavity?
13. Explain construction and working of He-Ne Laser.
14. Explain construction and working of Ruby Laser.
15. Derive Einstein's relation for stimulated emission and hence explain the existence of stimulated emission.
16. Discuss the applications of laser in various fields.