Unit II
Chapter 1

LASERS

Introduction

- Laser is one of the outstanding inventions of the 20th century.
- A laser is a ***photonic device*** that emits light (electromagnetic radiation) through a process o optical amplification based on the ***Stimulated Emission of Radiation.***
- The term "laser" originated as an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- In 1960 An American Scientist T.H .Maiman was first invented solid state laser (Ruby LASER) .
- In 1961 ,A.Javan and associates developed the first gas laser (He-Ne gas LASER).Further many lasers was invented based on their applications.
- In now a days, laser is a important tool in a wide variety of fields such as optical communication systems, metal working, entertaintment, surgery and weapon guidance in wars.

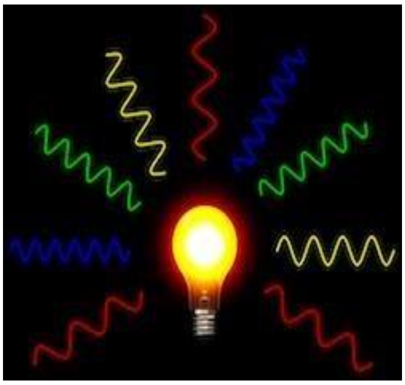
Characteristics of Lasers

Laser has certain unique properties when compared to ordinary sources of light. They are

1. Monochromaticity
2. Directionality
3. Intensity
4. Coherence

Monochromaticity

- Monochromatic light means a light containing a single color or wavelength. The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors. Hence, ordinary light sources emit polychromatic light.
- On the other hand, the photons emitted from laser light sources have same energies, frequencies, wavelengths, or colors. Hence, laser emits a single wavelength or color light.



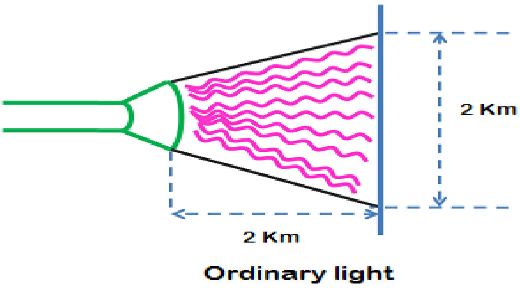
a) Ordinary light

b) Laser Light

Fig.2.1

Directionality

- Directional means that the beam is well collimated (very parallel) and travels over long distances with very little spread.
- In conventional light sources (lamp, sodium lamp and torchlight), photons will travel in random direction. Therefore, these light sources emit light in all directions and is highly divergent.
- On the other hand, in laser, all photons will travel in same direction. Therefore, laser emits light only in one direction. This is called directionality of laser light.
- The width of a laser beam is extremely narrow. Hence, a laser beam can travel to long distances without spreading.
- Therefore, the divergence or angular spread of a laser is very small and high directional.



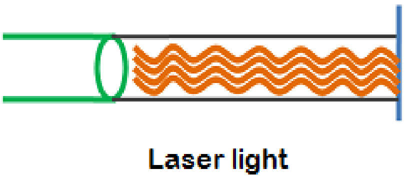


Fig.2.2.

Intensity

- The intensity of a light is defined as the energy or light per unit time flowing through a unit normal area.
- In an ordinary light spreads in all directions; the intensity reaching the target is very less. But in the case of laser, due to high directionality many beams of light incident in small area, therefore the intensity of light high.

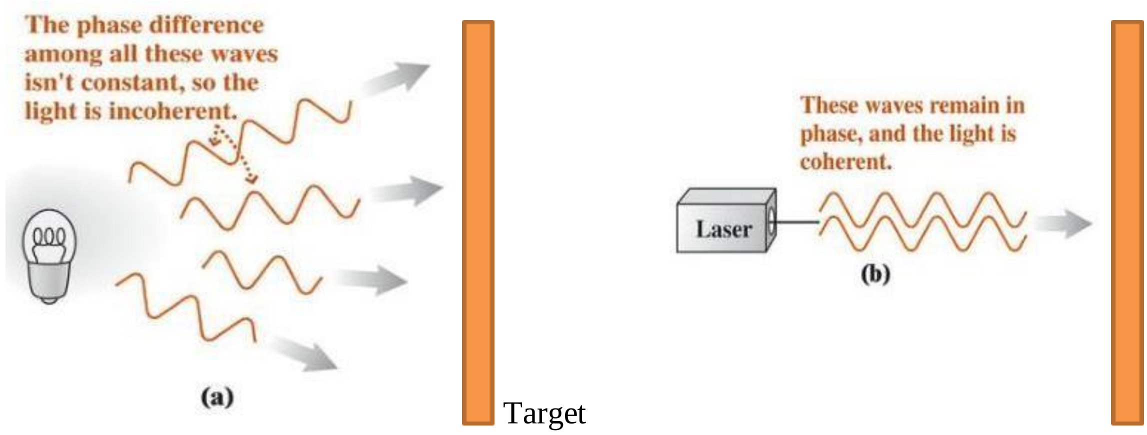


Fig.2.3

Coherence:

- The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors and are out of phase. Therefore, ordinary light sources produce incoherent light.
- The photons emitted from laser light sources have same energies, frequencies, wavelengths, or colors and are in phase. Therefore, a laser light source produces coherent light. To produce coherent light in a laser, a new technique used called stimulated emission of radiation.

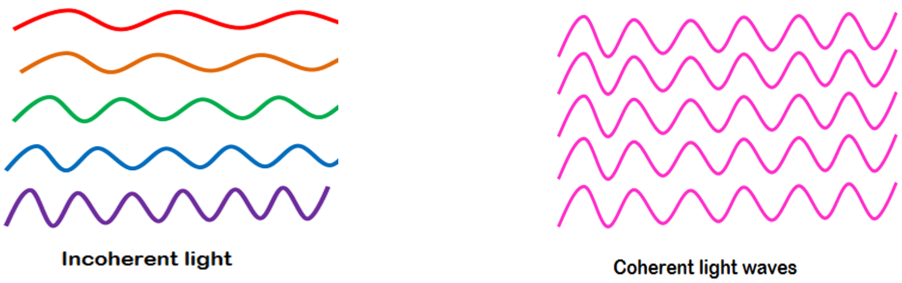


Fig.2.4.

Interaction of radiation with matter

When the incident radiation (Photon) interacts with atoms in the energy levels then three three distinct processes can takes place.

- Absorption of radiation
- Spontaneous emission of radiation
- Stimulated emission of radiation

Absorption of radiation

Suppose if an atom in the lower energy level (or) ground state energy level E_1 and absorbs the incident photon radiation of energy then it goes to the higher energy level (or) excited state E_2 as shown in Fig 2.5. This process is called absorption of radiation.

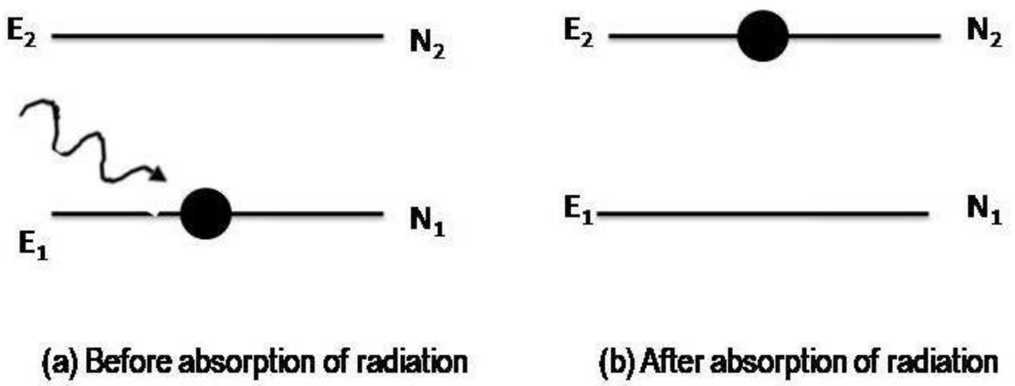


Fig.2.5. Absorption of radiation

- The number of absorptions depend upon the number of atoms per unit volume (N_1) in lower energy level (E_1) and the number of photons per unit volume of radiation i.e. incident radiation density ρ_υ.
- The rate of absorption (R_{12}) is proportional to the following factors

i.e., $R_{12} \propto$ incident radiation density (ρ_υ)

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

$$\therefore \boxed{R_{12} = B_{12}\,\rho_\upsilon\, N_1} \quad \longrightarrow \quad (2.1)$$

Where B_{12} is a constant and is known as Einstein's coefficient of absorption of radiation.

Spontaneous emission of radiation

Normally the atom in the excited state will not stay there, for a long time i.e., it can stay up to 10^{-9} second. This called life time of atom. After the life time of the excited atom it returns to the ground state by emitting photon energy $E = E_2 - E_1 = h\nu$, spontaneously without any external energy as shown in Fig 2.6.

This process is known as Spontaneous emission of radiation.

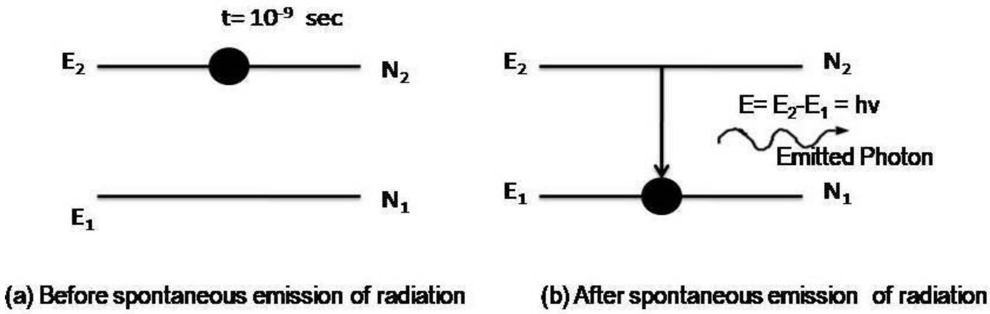


Fig.2.6. Spontaneous emission of radiation

- The number of spontaneous emission of radiation depends on the number of atoms per unit volume in higher energy level E_2 i.e. N_2
- ∴The rate of spontaneous emission is $R_{21(SP)}$ a N_2

$$\therefore \quad \boxed{R_{21(SP)} = A_{21} N_2} \qquad \longrightarrow (2.2)$$

Where A_{21} is a constant called Einstein's coefficient of spontaneous emission of radiation.

Stimulated emission of radiation

Suppose if we incident some suitable form of energy on the atom in the excited state, then it can also return to the ground by emitting a photon, known as stimulated emission. In this process two photons are released. They have same frequency, wavelength and in phase difference and of same directionality as shown in Fig.2.7.

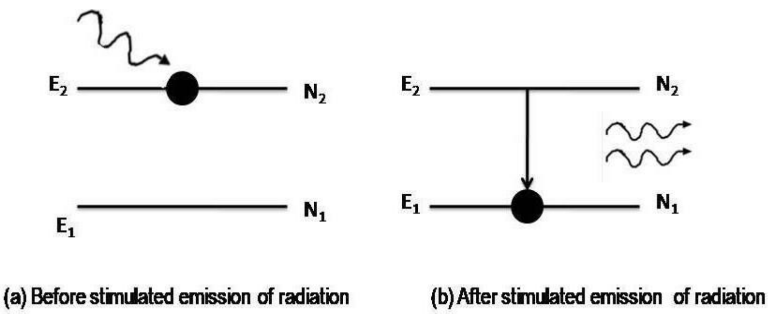


Fig.2.7.Stimulated emission of radiation

The number of stimulated emission depends on the number of atoms in the E_2 energy level N_2 and the incident radiation density ρ_υ.

∴ The rate of stimulated emission R_{21} is given by

$$R_{21(St)} \propto N_2$$

$$\propto \rho_\upsilon$$

$$R_{21(St)} \propto N_2 \rho_\upsilon$$

$$\therefore \boxed{R_{21(St)} = B_{21} \rho_\upsilon N_2} \longrightarrow (2.3)$$

Where B_{21} is a constant called Einstein coefficient of stimulated emission of radiation

Difference between spontaneous and stimulated emission of radiation

Spontaneous Emission of radiation	**Stimulated Emission of radiation**
1. This emission is postulated by Bhor	1. This emission is postulated by Einstein.
2. Emission of radiation takes place without any external energy.	2. Emission of radiation takes place with help of inducement or stimulus energy.
3. The emitted photons move in all directions and are random.	3. The emitted photons move in same direction and is highly direction
4.Incoherent radiation	4.Coherent radiation
5. Low intense and less directional	5. High intense and more directional
6.Polychromatic radiation	6.Monochromatic radiation
7.It is an uncontrollable process	7.It is controllable process
8.The rate of spontaneous emission is $R_{12(SP)} = A_{21}N_2$	8. The rate of stimulated emission is $R_{21(St)} = B_{21} \rho_\upsilon N_2$
9. Example: Light from sodium vapor lamp and mercury vapor lamp	9. Example: Light from Ruby laser, He-Ne laser and GaAs laser etc.

Important Factors affecting interaction of radiation with matter

The absorption of radiation and emission of radiation manly depends on the two factors

1. Population(N)
2. Incident Radiation density (ρ_υ)

Population

The number of atoms per unit volume in an energy level is known as population of that energy level. According to Boltzmann`s distribution law; if N is the number of atoms per unit volume in an energy state E, at temperature T , then the population of that energy level E is given by

$$N=N_O \exp^{\frac{-E}{K_B T}} \qquad \longrightarrow (2.4)$$

Where, N_0 is the population of lower energy level and K_B is Boltzmann`s constant ($1.3807 \times 10{-}23$ J K^{-1})

Incident Radiation density (ρ_υ)

The number of photon incident present per unit volume is known as incident Radiation density. According to Planck's quantum theory of radiation, the incident radiation density is given by,

$$\rho_\upsilon = \frac{8\pi h\nu^3}{C^3} \left[\frac{1}{\exp^{\frac{h\nu}{k_B T}} - 1}\right] \qquad \rightarrow (2.5)$$

Einstein's coefficients and their relations

In 1917 Einstein proposed a mathematical relation between absorption and emission of radiation based on Boltzmann's distribution law and Planck's theory of radiation.

We know that when the incident radiation (photon) interacts with atoms in the energy levels then three distinct processes takes place.

1) **Absorption :-**

   The rate of absorption is given by R_{12} (ab) $=B_{12}\ \rho_\upsilon\ N_1$

2) **Spontaneous emission :-**

   The rate of spontaneous emission is given by $R_{21\,(SP)} = A_{21}N_2$

3) **Stimulated Emission:-**

   The rate of stimulate emission is given by $R_{21(St)} = B_{21}\ \rho_\upsilon\ N_2$

Under thermal equilibrium,

The rate of absorption = The rate of emission

i.e., $R_{12}(ab) = R_{21\,(SP} + R_{21(St)}$

$$B_{12}\ \rho_\upsilon\ N_1 = A_{21}N_2 + B_{21}\ \rho_\upsilon\ N_2$$

$$B_{12}\ \rho_\upsilon N_1 - B_{21}\ \rho_\upsilon N_2 = A_{21}N_2$$

$$\rho_\upsilon(B_{12} N_1 - B_{21} N_2) = A_{21}N_2$$

$$\rho_\upsilon = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}\ N_2} = \frac{A_{21}N_2}{N_2(B_{12}\frac{N_1}{N_2} - B_{21})}$$

$$\rho_\upsilon = \frac{A_{21}}{B_{12}\ (\frac{N_1}{N_2}) - B_{21}} \rightarrow (2.6)$$

$$= \frac{A_{21}}{B_{12}\ [\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}}]} \rightarrow (2.7)$$

We know that; Boltzmann distribution law

$$N_1 = N_0 \exp\frac{-E_1}{K_BT} \rightarrow (2.8)$$

Similarly $N_2 = N_0 \exp\frac{-E_2}{K_BT}$ $\rightarrow (2.9)$

And $\frac{N_1}{N_2} = \exp\frac{-E_1}{K_BT} \cdot \exp\frac{E_2}{K_BT}$

i.e., $\frac{N_1}{N_2} = \exp\frac{(E_2 - E_1)}{K_BT}$

Since $E_2 - E_1 = hu$, we have

$$\frac{N_1}{N_2} = \exp\frac{h\upsilon}{K_BT} \rightarrow (2.10)$$

Substituting Eq (2.10) in Eq (2.7) we have

$$\rho_\upsilon = \frac{A_{21}}{B_{21}[\ \exp\frac{h\upsilon}{K_BT} - \frac{B_{21}}{B_{12}}]} \rightarrow (2.11)$$

According to Planck's quantum theory of radiation, the incident radiation density is given by,

$$\rho_\upsilon = \frac{8\pi h v^3}{C^3}\ [\frac{1}{\exp^{\frac{h\upsilon}{k_BT}} - 1}] \rightarrow (2.12)$$

Therefore comparing equations (2.11) and (2.12), we can write

$$\boxed{\frac{B_{21}}{B_{12}} = 1 \text{ or } B_{21} = B_{12} = 1 \text{ and}} \rightarrow (2.13)$$

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h v^3}{C^3}} \rightarrow (2.14)$$

From eq. (2.12), we conclude that the coefficient of absorption B_{12} is equal to the coefficient of stimulated emission B_{21}.

From eq. (2.13), we conclude that the coefficient of spontaneous versus stimulated emission is proportional to the third power of frequency of the radiation.

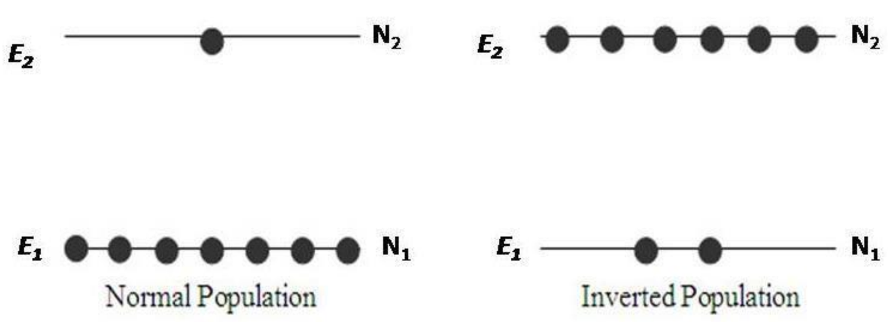
$$\text{i.e.,} \quad \frac{A_{21}}{B_{21}} \alpha\, \nu^3$$

Thus, the spontaneous emission of radiation dominates the stimulated emission of radiation at normal conditions. This is why it is difficult to achieve laser action. The spontaneous emission produces incoherent light, while stimulated emission produces coherent light. In an ordinary conventional light source, the spontaneous emission is dominated. For, laser action stimulated emission should be predominant over spontaneous emission and absorption. To achieve this, an artificial condition is required, known as population inversion.

Population Inversion

In general, the population of lower energy level will be greater than that of the higher energy level. To get stimulated emission of radiation, the population of higher energy level (E_2) should be greater than the population of the lower energy level (E_1).i.e., $N_2>N_1$.

The process of making a state in which the population of higher energy level (E_2) is greater than the population of the lower energy level (E_1) is known as population inversion.



$N_1>N_2$ **$N_2>N_1$**

Fig.2.8.

Explanation

- In general, a two energy level diagram is suitable for spontaneous emission of radiation the life time of higher energy level is in the order of 10^{-9}sec. But, to attain population inversion the life time of higher energy level must be longer. Hence population inversion cannot be attained in a two energy level diagram.
- To explain Population Inversion, let us consider a there energy level system in which three energy levels E_1, E_2 and E_3 are present and populations in those energy levels are N_1, N_2 and N_3 respectively as shown in Fig.2.9.
- In normal conditions $E_1 < E_2 < E_3$ and $N_1 > N_2 > N_3$ obeying Boltzmann's distribution law.
- E_1 is the lower energy state with more time of an atom, E_3 is the higher energy state with less lifetime of an atom (10^{-9}sec) and E_2 is the intermediate energy state with more life time of an atom (10^{-3}sec) compare to that of E_3.
- This intermediate energy state with more life time of atoms is known as meta-stable state.
- This state provides necessary population inversion for the laser action.
- When suitable form of energy is supplied to the system, then the atoms excite from ground state E_1 to higher energy state E_3 and E_2.
- Graphically this has been as shown in Fig.2.10.

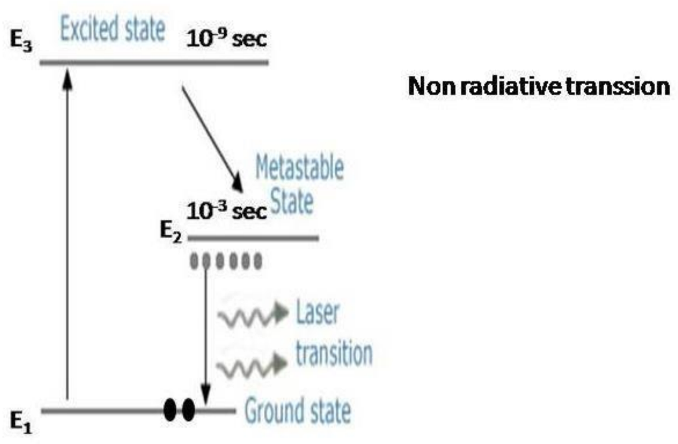
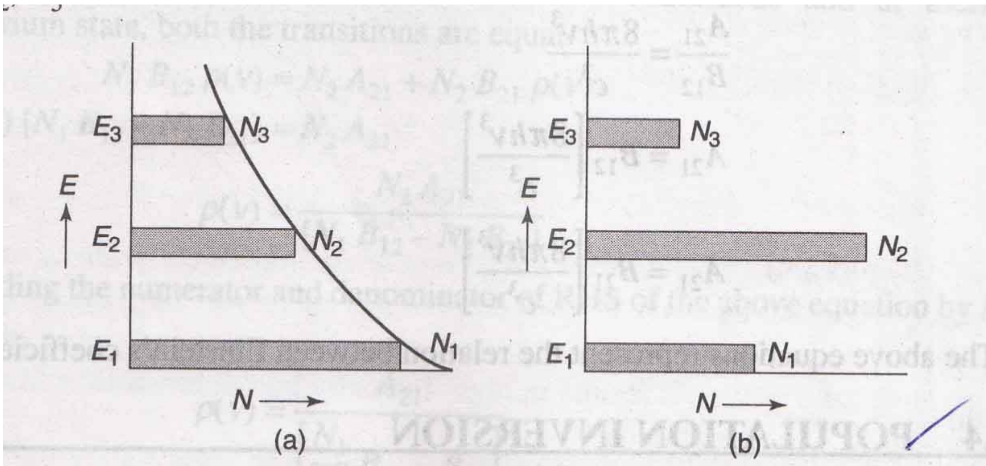


Fig.2.9.Three energy levels diagram



(a) Boltzmann's distribution (b) Population inversion between E_1 and E_2

Fig.2.10.

- Let the atoms in the system be excited from E_1 state to E_3 state by supplying energy equal to E_3-E_1= $h\upsilon$ from an external source.
- The atoms in E_3 state are unstable; they can stay up to 10^{-9} s. This called life time of atoms. After the life time of the excited atoms, they can returns to the meta stable state E_2 without emission of any radiation .This process is called *non-radiative transition.*
- In E_2 state, the atoms can stay for a very long time (10^{-3}s).
- As atoms in E_1 state are continuously exciting to E_3 , so the population in E_1 energy state goes decreasing.
- A state will reach at which the population in E_2 State is greater than E_1 state (i.e.N_2>N_1). This situation is known as population inversion.

Excitation mechanisms-Pumping

The population inversion cannot be achieved thermally. To achieve population inversion suitable form of energy must be supplied. *The process of supplying suitable form of energy to a system to achieve population inversion is called pumping.* There're several methods for achieving the condition of population inversion and necessary for laser action. Some of the most commonly used pumping methods are,

(i) Optical pumping method

(ii) Electrical discharge(Direct electron excitation) pumping method

(iii)Inelastic atom-atom collision pumping method

(iv) Direct conversion pumping method

(v) Chemical reactions pumping method.

Optical pumping method

- The process of supplying suitable form of optical energy to a system to achieve population inversion is called optical pumping.
- In this method, light source is used to supply suitable form of optical energy to excite the atoms to higher energy level to achieve population inversion.
- This type of pumping is used in solid state lasers (Ex: Ruby laser and Nd-YAG Laser).

Electrical discharge (Direct electron excitation) pumping method

- In this method, a high voltage or electric field is applying to electrodes at both sides of the discharge tube containing the gas causes Electrons are ejected from the cathode, accelerated toward the anode, and collide with the gas molecules along the way. During the collision, the mechanical kinetic energy of the electrons is transferred to the gas molecules, and excites them.
- This type of pumping is used in gaseous ion lasers (Ex: He-Ne laser and co_2 Laser).

Inelastic atom-atom collision pumping method

- In this method a combination of two types of gases are used say A and B, both having same or nearly coinciding excited states A* and B* .
- In the first step ,during electric discharge , A gets excited to A* (meta stable state) due to collision with electrons .The excited atom now collide with the B atoms so that B goes to excited state B*

$$e^- + A \longrightarrow A^*$$

$$A^* + B \longrightarrow B^* + A$$

- For example, in the helium-neon laser the electrons from the discharge collide with the helium atoms, exciting them. The excited helium atoms then collide with neon atoms, transferring energy so that Ne atoms go the excited state.

Direct conversion pumping method

- In this method, when a p-n junction diode is forward biased and then the recombination of electrons and holes across the junction emits the radiation

$$\boxed{\text{Electron} + \text{hole} \longrightarrow \text{photon}}$$

- This method is used in semiconductor lasers.

Chemical reactions pumping method

- In this method, due to some chemical reactions, the atoms may be raised to excited state.
- For example, hydrogen fluoride chemical laser, in which hydrogen can react with fluorine to produce hydrogen fluoride liberating heat energy. This heat energy will try to excite the atoms to higher energy level.

$$H_2 + F_2 \longrightarrow 2HF + \text{Heat energy}$$

Block diagram of a laser system

The block diagram of laser system contains three parts, they are

(i) Source of energy

(ii) Active medium and

(iii) Optical resonator.

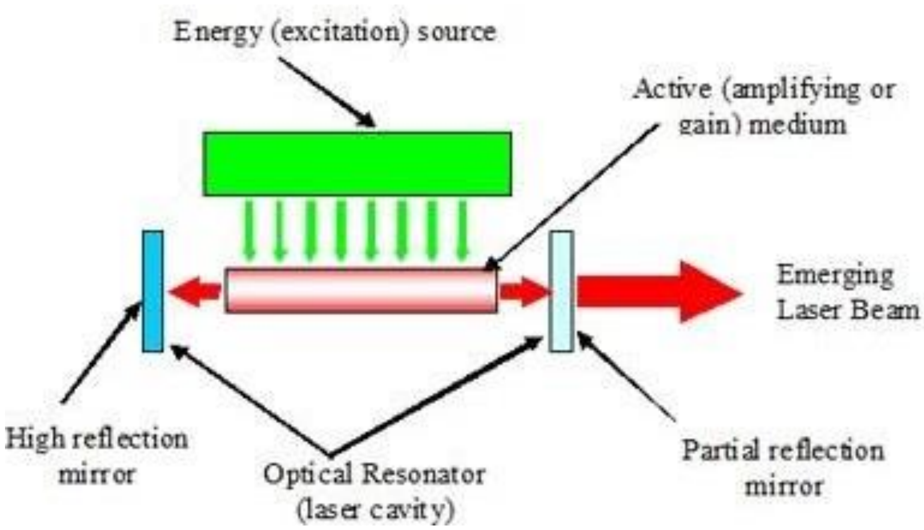


Fig.2.11. Components of LASER system

(i) Source of energy

- To achieve population inversion suitable form of energy must be supplied. It supplies suitable form of energy by using any one of the pumping methods.
- For example in ruby laser, helical xenon flash tube used as pumping source.
- In helium-neon laser, electrical discharge tube used as pumping source.

(ii) Active medium

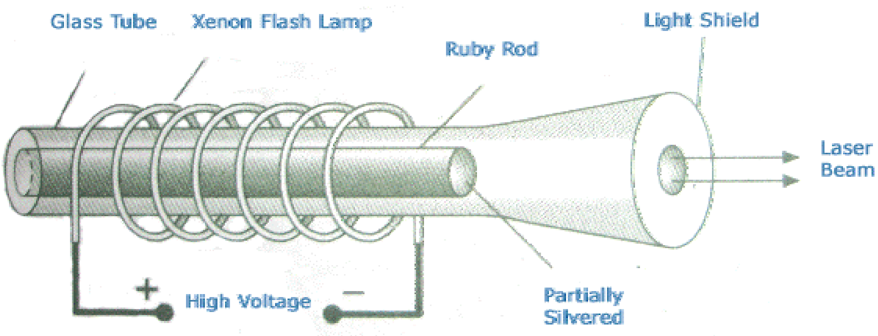
- To achieve population inversion medium is necessary**.**
- The material medium in which population inversion takes place is called as active medium. In which meta-stable state is present.
- In meta-stable state only the population inversion takes place. It can be a solid, liquid, gas or semiconductor diode junction.
- The material medium in which the atoms are raised to exited state to achieve population inversion is called as active centers.
- For example in ruby laser, the active medium is aluminum oxide (Al_2O_3) doped with chromium oxide (Cr_2O_3). In which chromium ions (Cr^{3+}) act as active centers.
- In helium -neon laser it is the combination of helium and neon in the ratio of 10:1 in which Ne atoms act as active centers.

(iii) Optical resonator

- An optical resonator which consists of two mirrors. One mirror is fully reflective and other is partially reflective.
- An active medium is kept between in them. The light emitted due to the stimulated emission of radiation bounces back and forth between the two mirrors and hence the intensity of the light is increased enormously.
- Finally the intense, amplified beam called laser is allowed to come out through the partial mirror as shown in Fig. 2.11.

Types of lasers

<u>RUBY LASER: [Solid Laser]</u>



Ruby laser is a solid laser developed by Maiman in 1960. It is a pulsated laser used for several industrial purposes.

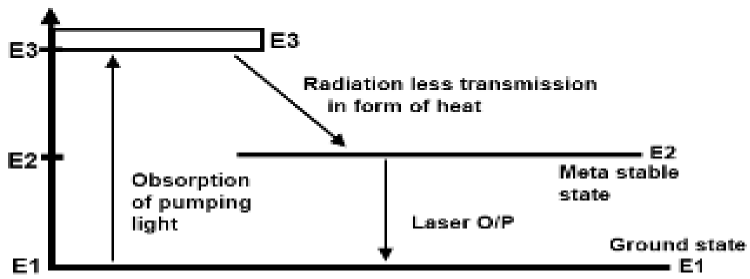
<u>Apparatus</u>: Source of energy: - Xe flash bulb

Active medium : - Ruby rod

<u>Construction</u>: The experimental apparatus consists of a ruby road (Al_2O_3 + Cr_2 O_3) whose length is about 5 to 15 cm and diameter is 0.5cm. The rod is fully coated with silver on one side and partially coated on the other side. A xenon flash bulb is arranged around the rod from which green colour xenon light is emitted.A cooling arrangement is provided to keep the experimental setup at normal temperature.

<u>Working:</u> The chromium atoms in ruby rod for three energy levels E_1, E_2 and E_3, when the xenon flash bulb is switched on the light from the bulb are incident on the chromium atom present in the ground state. The chromium atoms get excited from E_1 to E_2 and E_3. The atoms present in the energy level E_3 come down to E_2 after 10^{-8}s.This transition is radiation less. Hence this radiation will make the population of E_2 more than the population of E_1. The atoms spent more time in E_2 hence E_2 is metastable state. At this position when a light photon from the xenon flash bulb is incident on the atoms present in E_2 stimulated emission takes place and a laser beam of wave length 6943A^0 is emitted.

A part of laser beam comes out through ruby rod and another part is again incident to the atoms present at E_2. In this way a pulsated laser beam is produced for every 10 nano second



Applications of Ruby Laser

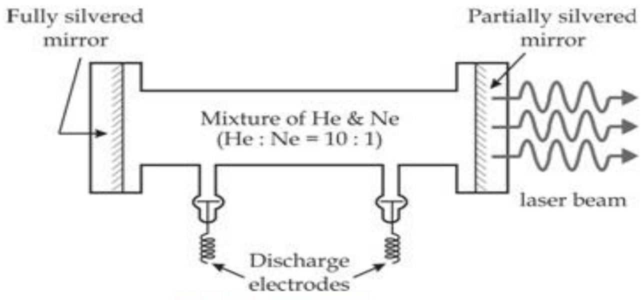
- These lasers are widely used for cutting, drilling, welding in the industrial products.
- It is used in long haul communication systems.
- It is also used in the endoscopic applications.

<u>He – Ne Laser</u>:

Gas laser was invented in 1961 by William Bennet. It is four level laser system, it is useful in making holograms etc.

Source of energy	:	RF oscillator
Active medium	:	He + Ne gas mixture
Cavity	:	Quartz discharge tube with reflectors

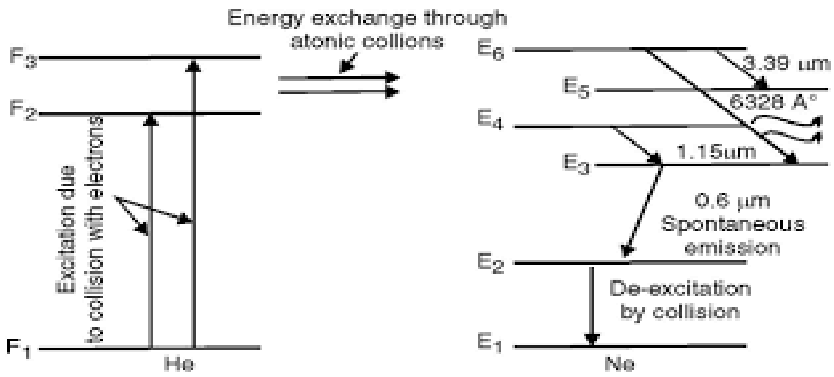
Construction



He-Ne LASER

The apparatus consists of a quartz discharge tube which is 80cm long and 1.5cm in diameter. He and Ne gas mixture is taken in the ratio of 10:1 in which He is maintained under a pressure of 1mm of Hg and Ne under a pressure of 0.1mm of Hg. The ends of discharge tube are arranged with reflector window on one side and partial reflector window at the other side. The gas mixture is excited by applying voltage to the electrodes through a radio frequency oscillator.

. **Working**: When a voltage in applied to the electrodes Helium atoms first gets excited because they are maintained at high pressure. Helium has three energy levels [F_1, F_2, F_3] in which F_2 and F_3 are meta stable state. Ne has 6 energy levels E_1, E_2, E_3, E_4, E_5 and E_6. Here the energy of E_6 is equal to energy of F_3 and energy of E_4 is equal to energy to $F_{2,}$ the excited He atoms spent a long time in F_2 and F_3 meta stable states and while returning down they excited Ne atoms to higher energy levels. In Ne E_6 and E_4 are meta stable states hence population inversion is achieved in E_4 and $E_{6.}$ Stimulated emission takes place at E_6 to E_5 , E_6 to E_3 and E_4 to $E_{3.}$ A laser beam of wavelength 6328A^0 is produced when the atoms come from E_6 to $E_{3.}$ E_4 to $E_3$and E_6 to E_5 transactions gives infrared light of wave lengths 11500A^0, 33900A^0 and finally de-excited from E_2 to E_1 by the colleens of walls it is radiation less



Merits

It is contineous laser

It is monochromatic and polarized laser

They are small and compact.

They have longer life, usually 50,000 hours or more.

They generate relatively little heat. They have relatively low acquisition and operating cost. Construction of He-Ne laser is very simple.

Demerits of He-Ne Laser:

➨Its output power is lower.

➨It is a low gain device.

➨In order to have operation at single wavelength, the other two wavelengths are required to be suppressed. This requires use of special techniques and extraordinary skills. This increases cost of the device.

➨It requires high voltage for its operation.

➨Escaping of gas from laser plasma is considered to its drawback.

Applications of He-Ne Laser

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

- He-Ne lasers are produced in large quantities from many years.
- 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 QR codes.
- 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 can produce three wavelengths that are 1.152µm, 3.391 µm and 632.8nm, in which the 632.8nm is most common because it is visible usually in red color.
- Cost of He-Ne laser is less from most of other lasers.
- Construction of He-Ne laser is also not very complex.

Disadvantages of He-Ne Laser

The weak points of He-Ne laser are

- It is relatively low power device means its output power is low.
- He-Ne laser is low gain system/ device.
- To obtain single wavelength laser light, the other two wavelengths of laser need

suppression, which is done by many techniques and devices. So it requires extra technical skill and increases the cast also.

- High voltage requirement can be considered its disadvantage.
- Escaping of gas from laser plasma tube is also its disadvantage.

Applications of lasers

Lasers find applications in various fields of science technology. They are described below.

Medical applications

- Lasers are used in eye surgery.
- Lasers are used for treatments such as plastic surgery, skin injuries and to remove moles and tumors developed in skin tissue.
- Lasers are used in cancer diagnosis and therapy.

Scientific field

- Lasers are used in counting of isotopes separation and to separate isotopes of uranium.
- Lasers are used to estimate size and shape of biological cells such as erythrocytes.
- Lasers are used to produce chemical reaction
- Lasers are used in recording and reconstruction of a hologram.

Industry applications

- Lasers are used to cut glass and quartz.
- Lasers are used to drill holes in ceramics.
- Lasers are used to drill aerosol nozzles.