UNIT-II
LASERS

Characteristics of Lasers, Spontaneous and Stimulated Emission of Radiation, Meta-stable State, Population Inversion, Lasing Action, Einstein's Coefficients and Relation between them and significance, Ruby Laser, Helium-Neon Laser, Semiconductor Diode Laser, Applications of Lasers.

LASER – Light Amplification by Stimulated Emission of Radiation

Characteristics of LASER:

LASER when compared with any conventional light (Sun light or tube light etc.) Laser possesses few outstanding characteristics. They are

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

1). Monochromaticity:

The light emitted from a laser is more **monochromatic.**

Due to Stimulated emission, the light emitted by a laser is more monochromatic than that of any conventional monochromatic source(Ex: Sodium lamp).

2). Directionality:

- Lasers emit light that is highly directional, i.e., laser light is emitted as a relatively narrow beam in a specific direction.
- The directionality of a laser beam has been expressed in terms of divergence.
- To obtain high directionality there should be low divergence.
- For a Laser, the beam spread is less than **0.01mm** for **every 1 meter** but for ordinary light is **0.5m** for **every 1 meter**.

3). Intensity:

The laser light is more **intense** than conventional light.

The number of photons coming out from a laser per second per unit area is given by

$$n = \frac{P}{h\upsilon\pi r^2}$$

4). Coherence:

Laser radiation has high degree of coherence.

Coherence is expressed in terms of ordering of light field i.e., amplitude and phase.

Coherence is of two types

Temporal Coherence and Spatial Coherence:

Temporal Coherence:

The amplitude and phase at a point on a wave with respect to another point on the same wave is said to be the temporal coherence(time related).

Spatial Coherence:

The amplitude and phase at on a wave with respect to another point on a second wave then the waves are said to be spatially coherence.

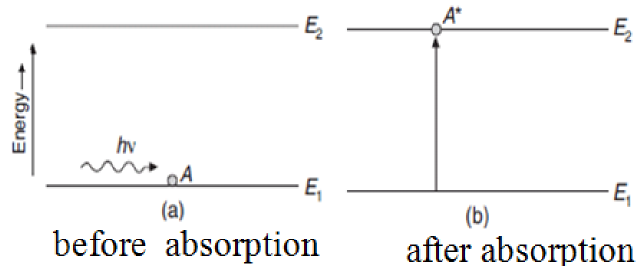
ATOMIC EXCITATION AND ENERGY STATES:

When light interacts with matter three types of atomic mechanisms takes place in a material

i) Stimulated Absorption ii) Spontaneous Emission and iii) Stimulated Emission

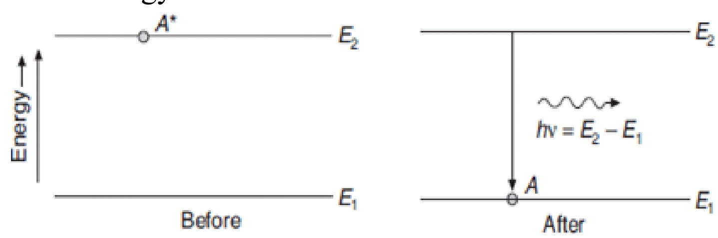
<u>Stimulated Absorption:</u>

In absorption, suitable amount of energy is absorbed by the atoms of the ground state and get excited to the higher energy states.



<u>Spontaneous emission:</u>

In spontaneous emission, the excited atom comes back by itself to the lower energy state. In the process a photon of energy $h\upsilon$ is emitted.



<u>Important features of spontaneous emission:</u>

(i) It is very difficult to control this process from outside.

(ii) It is essentially probabilistic in nature.

(iii) The emitted photons moves at random and will not follow any phase relations.

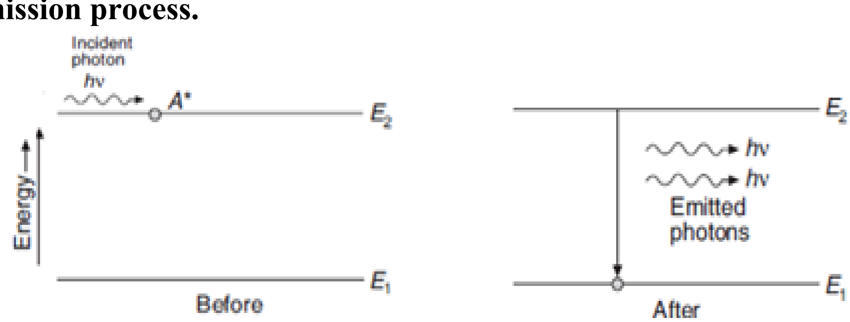
(iv) The light emitted in this process is incoherent and non-monochromatic.

(v) The intensity of light decreases rapidly with distance from the source.

(vi)This process proposed by Neil's Bohr.

<u>Stimulated emission:</u>

In stimulated emission, with the influence of suitable energy impetus, excited atom is triggered to the lower energy state, with the release of same energy of incident photon energy **Stimulated emission process.**



<u>Important features of stimulated emission:</u>

(i) The process of stimulated emission can be controlled from outside.

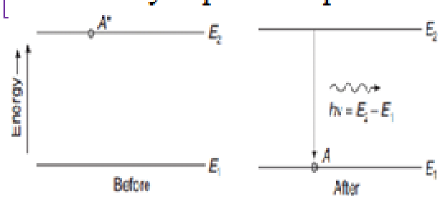
(ii) The emitted photon and incident photon have same direction, phase, frequency and plane of polarization.

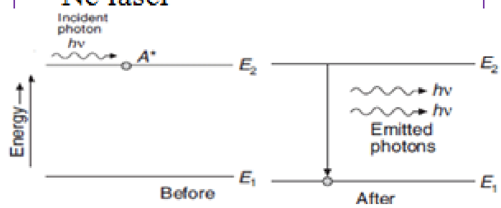
(iii) The light produced during stimulated emission is perfectly coherent and monochromatic.

(iv) Proposed by Einstein's.

Distinction between spontaneous and stimulated emission:

Spontaneous Emission	Stimulated emission
• Emission takes place without any stimulus energy.	• Emission takes place with the help of stimulus energy.
• Single photon is emitted.	• Two photons are emitted.
• Incoherent radiation.	• Coherent radiation.
• Low intense and less directional.	• High intense and more directional.
• Poly chromatic radiation.	• Monochromatic radiation.
• More angular spread.	• Less angular spread.
• Postulated by Bohr.	• Postulated by Einstein.
• Ex: Light from Sodium or mercury vapour lamp	• Ex: Light from Ruby or He-Ne laser



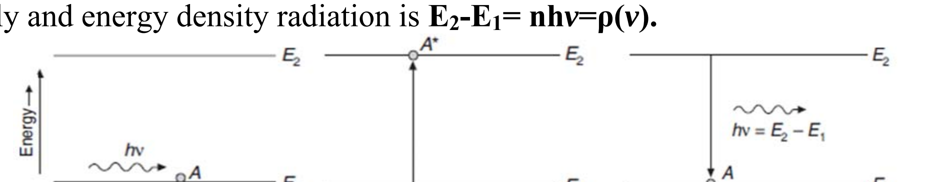


Einstein's Coefficients and Relation Between them:

Einstein's coefficients are mathematical quantities which are a measure of the probability of absorption or emission of light by an atom or molecules.

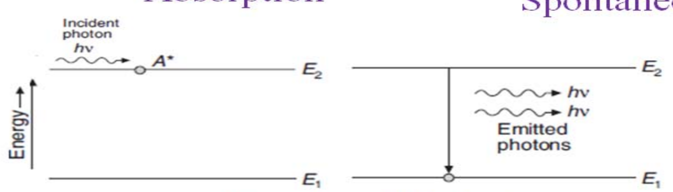
Consider two energy levels of an atomic system $\mathbf{E_1}$ and $\mathbf{E_2}$ respectively such that $\mathbf{E_2 > E_1}$.

Let $\mathbf{N_1}$ and $\mathbf{N_2}$ be the number of atoms per unit volume present at the levels $\mathbf{E_1}$ and $\mathbf{E_2}$ respectively and energy density radiation is $\mathbf{E_2 - E_1 = nh\nu = \rho(\nu)}$.



Absorption

Spontaneous Emission



Stimulated Emission

Stimulated Absorption:

Stimulated Absorption rate is proportional to incident energy density $\boldsymbol{\rho(\nu)}$ of the radiation and the number of atoms $\mathbf{N_1}$ present in the atomic system.

Therefore, $\quad \mathbf{P_{12} \,\alpha\, \rho(\nu) N_1}$

$$\mathbf{P_{12} = B_{12}\rho(\nu) N_1} \text{ ---------(1)}$$

Where $\mathbf{B_{12}}$ is Einstein's Coefficient of Absorption., and its represent the property of energy states.

Spontaneous Emission:

Spontaneous Emission rate is proportional to the number of atoms $\mathbf{N_2}$ present in excited state.

Therefore, $\quad \mathbf{(P_{21})_{Spont} \,\alpha\, N_2}$

$$\mathbf{(P_{21})_{Spont} = A_{21}N_2} \text{ --------(2)}$$

Where A_{21} is Einstein's Coefficient of Spontaneous Emission and its represent the property of energy states.

Stimulated Emission:

Stimulated Emission rate is proportional to Stimulated energy density $\rho(v)$ of the radiation and the number of atoms N_2 present in the excited state.

Therefore, $(P_{21})_{Stimu} \propto \rho(v) N_2$

$$(P_{21})_{Stimu} = B_{21}\rho(v) N_2 \quad ------(3)$$

Where B_{21} is Einstein's Coefficient of Stimulated Emission and it's represent the property of energy states and is known as.

The total transition probability of atoms from state2 to state1 can be written as

$$P_{21} = (P_{21})_{Spont} + (P_{21})_{Stimu}$$

$$P_{21} = A_{21}N_2 + B_{21}\rho(v) N_2 \quad ------(4)$$

At equilibrium temperature, the number of transitions from state**1** to state**2** (Upward transition) will be equal to the number of transitions from state**2** to state**1** (Downward transition).

Therefore, $P_{12} = P_{21}$, From **eqns. (1) & (4)**

$$B_{12}\rho(v) N_1 = A_{21}N_2 + B_{21}\rho(v) N_2$$

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

$$\rho(v) = \frac{N_2 A_{21}}{B_{12}N_1 - B_{21}N_2}$$

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

$$\rho(v) = \frac{A_{21}/B_{21}}{\left[\frac{B_{12}N_1}{B_{21}N_2} - 1\right]} ----(5)$$

According to Boltzmann's distribution law, the distribution of atoms among the energy levels E_1 and E_2 at thermal equilibrium temperature T is given by

$$N_1 = N_0 \exp(-E_1/KT) \ \& \ N_2 = N_0 \exp(-E_2/KT)$$

where N_0 is population in the ground state and

K is Boltzmann's constant.

Therefore, $N1/N2 = \exp(E_2 - E_1)/KT = \exp(hv/KT)$ **----(6)**

Substituting eqn. **(6)** in eqn. **(5)** we get

$$\rho(v) = \frac{A_{21}/B_{21}}{\left[\left(\frac{B_{12}}{B_{21}}\right)\exp(hv/KT) - 1\right]} ----(7)$$

According to Planck's law, the energy density of radiation is given by

$$\rho(v) = \frac{8\pi h v^3}{c^3}\frac{1}{\exp(hv/KT) - 1} ----(8)$$

Comparing equations (7) & (8) we get

$$\boxed{\frac{B_{12}}{B_{21}} = 1 \quad ----- (9)}$$

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\upsilon^3}{c^3} \quad ----- (10)}$$

The above equations are the relation between Einstein's coefficients.

Conclusions:

1). From equation (**10**), **(A_{21}/B_{21})**αv^3 i.e., the ratio of Einstein's Coefficients of Spontaneous emission to stimulated emission is directly proportional to cube of the frequency of incident photon.

2) The rate of spontaneous emission increases rapidly with the energy difference between two states.

3). From equation (**9**), **$B_{12}=B_{21}$,** i.e., thermodynamically, it was proved by Einstein's that the probability of stimulated emission and absorption are equal.

Note: The equation shows ratio of spontaneous Emission Rate to stimulated emission rate.

$$R = \frac{N_2 A_{21}}{N_2 \rho(v) B_{21}}$$

$$R = \frac{A_{21}}{\rho(v) B_{21}}$$

$$R = \frac{(\frac{8\pi h \upsilon^3}{c^3})}{\rho(v)} \rightarrow \frac{(\frac{8\pi h \upsilon^3}{c^3})}{\frac{8\pi h \upsilon^3}{c^3}\{\frac{1}{\exp(\frac{h\upsilon}{kT})-1}\}}$$

$$R = \exp(\frac{h\upsilon}{kT}) - 1$$

- When **hv>>kT**, the spontaneous emission rate predominates stimulated emission.
- When **hv<<kT**, the stimulated emission rate predominates spontaneous emission.

Life time:

The duration of time spent by an atom in the excited state is known as life time of that energy state.

For example, the life time for hydrogen atom is **10^{-8}** sec.

Population:

The number of atoms per unit volume in an energy level is known as population of that energy level. According to Boltzmann relation we have

N= No Exp{-E/kT}

E_2>E_1 and **N_1>N_2**, i.e., the population of lower energy level is more.

Population Inversion:

The stage of making the population of the higher energy level to be greater than the population of the lower energy level is known as population Inversion. i.e., **E_2>E_1** and **N_1<N_2**.

Meta-stable state:

The excited state of an atom or other system with a longer life time than the other excited states is known as Meta stable state.

Pumping:

"The process of sending the atoms from lower energy state to higher energy state by supplying the suitable energy is called pumping".

In several ways pumping can be done. Most commonly used pumping methods are

1). Optical Pumping,

2). Direct Electron Excitation or Electric Discharge,

3). In-elastic atom-atom Collision and

4). Chemical Reaction.

(1) Optical Pumping:

In optical pumping, a light source (suitable photons) is used to supply luminous energy. Most often this energy is given in the form of short flashes of light.

Ex: Xenon flash lamp in Ruby Laser.

(2)Electric Discharge:

In this method of pumping direct electron excitation occurs through an electric discharge.

This method is preferred in gaseous ion lasers. An electric current flowing through the gas excites the atoms to the excited levels from where they are dropped to the metastable upper laser level leading to population inversion.

Ex: He-Ne Laser.

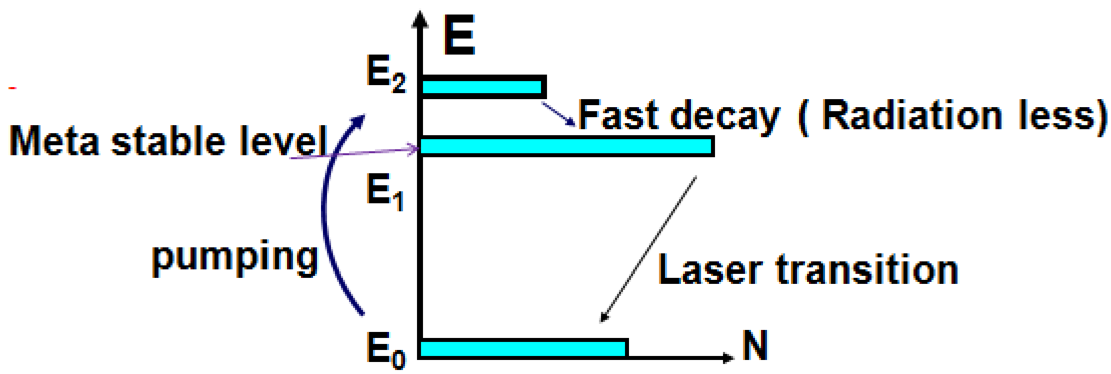
(3) Inelastic Collisions between Atoms:

- In an important class of lasers, pumping by electrical discharge provides the initial excitation which raises one type of atoms to their excited states.
- These atoms collide in-elastically with other atoms and provide them enough energy to excite them to the higher energy level and thus help in population inversion. This type of pumping occurs in CO_2 laser.

(4) Chemical Reaction:

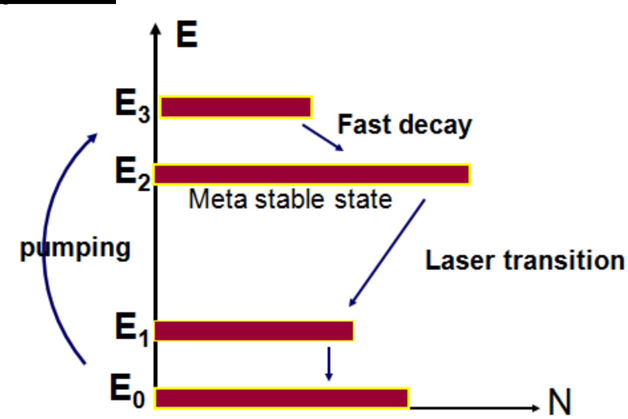
In chemical lasers, radiations come out of a chemical reaction, without any need of other energy source.

Three level Laser system:



If the collection of atoms is intensely pumped (a large number of atoms are excited) through stimulated absorption to the highest energy level E_2. With intense pumping from E_0 to E_2, because of rapid decay to E_1 (meta-stable state where has longer life time), it is possible to bring non-equilibrium distribution of atoms where E_1 more populated than E_0 (N_1>N_2) and laser transition takes place between E_0 and E_1.

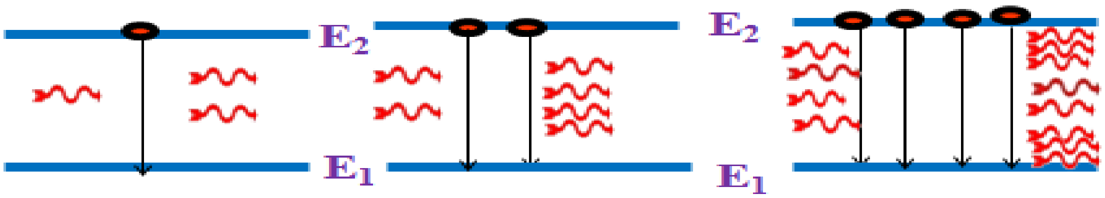
<u>Four level laser system</u>:



<u>Lasing Action:</u>

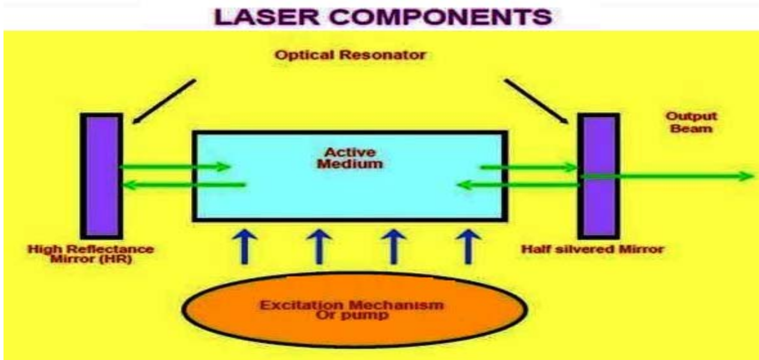
In stimulated emission, the emitted photon travels in the same direction as that of incident photon(as shown in fig.). These two photons again stimulate two more photons. As a result four photons are released. In a similar way a chain reaction or avalanche effect is produced. This phenomenon is known as Lasing Action.

So, a monochromatic, intense and coherent beam having the same frequency as that of incident beam is obtained. This is called Laser beam. This is the principle of working of a Laser.



Block Diagram of a Laser System:

The Block diagram of Laser System contains three components.



Source of Energy (Pump):

It is an external source which supplies energy to obtain population inversion. The pump can be optical, electrical or thermal. In Ruby Laser, we use optical pumping and in He -Ne Laser, we use electric discharge pumping.

Active Medium:

It is a 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.

Optical or Resonant Cavity:

It consists of a pair of plane or spherical mirrors having common principal axis. The **reflection coefficient** of one of the mirrors is **very near to 1** and that of the other is kept **less than 1**. The resonator is basically a feed-back device, which directs the photons back and forth through the laser medium.

VARIOUS TYPES OF LASERS ARE NOW IN OPERATION WHICH CAN BE BROADLY CLASSIFIED INTO:

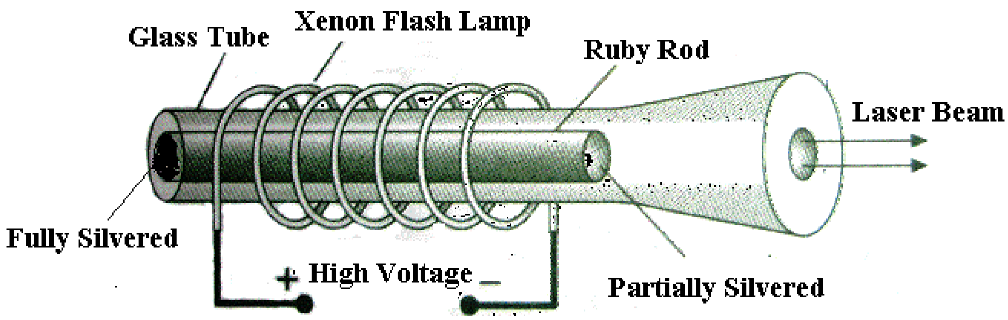
- **SOLID STATE LASERS**
  Ex: Ruby Laser & Nd:YAG
- **LIQUID AND DYE LASERS**
  Ex: Europium Chelate
- **GASEOUS LASERS**
  Ex: He-Ne, CO_2 lasers etc…
- **SEMICONDUCTOR LASERS**
  Ex: GaAs

RUBY LASER

- A ruby laser is a solid-state laser that uses a synthetic ruby crystal as its gain medium.
- It was the first type of laser invented, and was first operated by Theodore H. Maiman in 1960.

Construction:

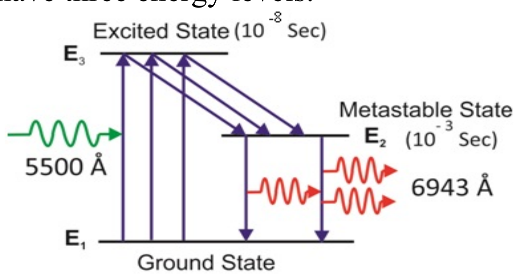
- The active laser medium (laser gain/amplification medium) is a synthetic cylindrical ruby rod.
- Ruby is made up of Al_2O_3 which is doped with 0.05% weight of Cr_2O_3 and whose length is few centimeters and diameter is 0.5cm.
- The end faces of the rod are silvered in such a way that one end face becomes fully reflecting while other end is partially reflecting, so that the two ends will act as optical cavity.



- A xenon lamp is rolled over ruby rod and is used for pumping ions to excited state.
- Chromium atoms absorb green and blue light and emit or reflect only red light.

<u>Working</u>

- An energy diagram illustrating the operation principle of a ruby laser as shown in figure.
- The chromium ions have three energy levels.



Energy Level Diagram of Ruby LASER

- The pumping light from the flash lamp is absorbed by Cr^{3+} ions, raising them from the ground state E_0 to the excited state E_2.
- The desired Population inversion is achieved in between E_0 and E_1.
- The photons are allowed to pass back and forth millions of times in the active medium with the help of mirrors at the ends.
- When the condition for laser action is satisfied, an intense pulse of light of the wavelength 694.3nm or 6943A^o.
- It is a Pulsed Laser.

Applications of Ruby Lasers

1. Distance measurement using ‘pulse echo’ technique.
2. Holography
3. Atmospheric ranging, scattering measurement.
4. Trimming resistors
5. Drilling high quality holes
6. Target designators and range finders in military applications etc.
7. Ruby lasers were used extensively in tattoo and hair removal

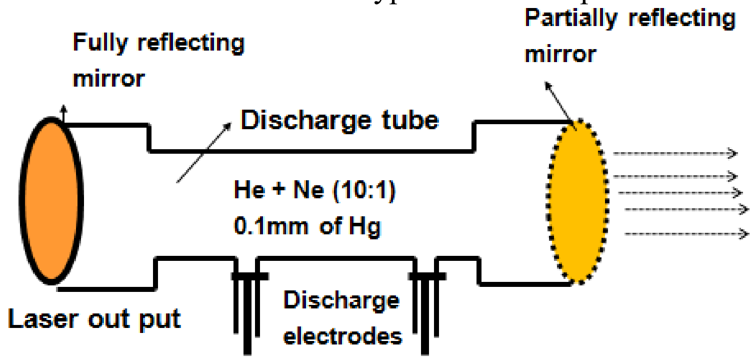
<u>He-Ne LASER</u> (Ali Javan in 1961)

- ➢ A helium-neon laser, usually called a He-Ne laser, is a type of small gas laser. He-Ne lasers have many industrial and scientific uses, and are often used in laboratory demonstrations of optics.
- ➢ He-Ne laser is a four-level laser.
- ➢ Its usual operation wavelength is 632.8 nm, in the red portion of the visible spectrum.
- ➢ It operates in Continuous Working (CW) mode.

<u>Construction</u>

- The Helium-Neon laser system consists of a gas discharge tube of length 80cm and diameter of 1cm.
- The tube is made up of quartz and is filled with a mixture of Neon under a pressure of 0.1mm Hg and Helium under the pressure of 1mm of Hg.

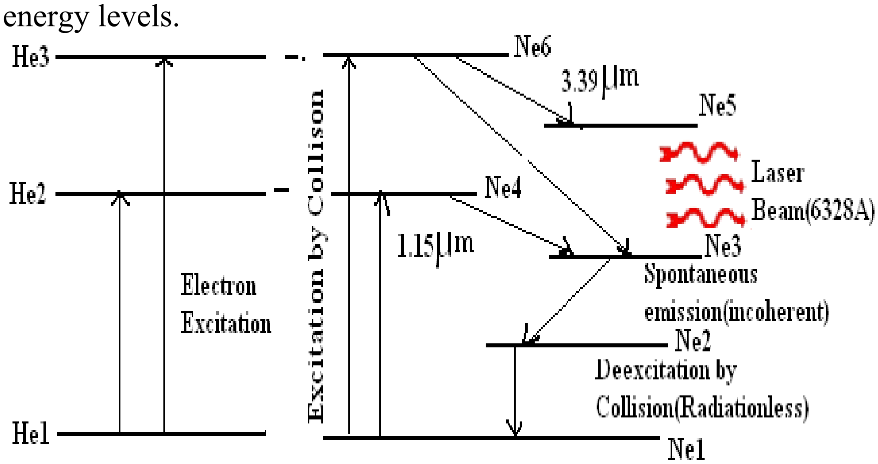
- The ratio of He-Ne mixture is about 10:1 ie., the number of Helium atoms are greater than Neon atoms.
- The output power from these lasers depends upon the length of the discharge tube and the pressure of gas mixture.
- The energy or pump source of the laser is provided by an electrical discharge of around 1000 volts. A current of 5 to 100 mA is typical for CW operation.



- The optical cavity of the laser typically consists of a plane, high-reflecting mirror at one end of the laser tube, and a concave output coupler mirror of approximately 1% transmission at the other end.

Working

- When a discharge is passed through the gaseous mixture electrons are accelerated down the tube these accelerated electrons collide with the helium atoms and excite them to higher energy levels.



This process is given by the reaction equation:

He* + Ne → He + Ne* + ΔE

Where (*) represents an excited state, and ΔE is the small energy difference between the Energy states of the two atoms, of the order of 0.05 eV.

- Since these levels are Meta stable energy levels helium atoms spend sufficiently long time.
- The metastable state of the helium atoms cannot return to ground state by spontaneous emission. However, they can return to ground state by transferring their energy to the lower energy state (**Ne1**) of the neon atoms.
- Then neon atoms are excited to the higher energy levels **Ne4** & **Ne6** and helium atoms are de excited to the ground state **Ne1**.
- Since **Ne6** & **Ne4** are Meta stable states, population inversion takes place at these levels.
- The stimulated emission takes place between **Ne6** to **Ne3** gives a laser light of wave length **6328**A^0.
- The stimulated emission between **Ne6** and **Ne5** gives a laser light wave length of **3.39**µm.
- Another stimulated emission between **Ne4** to **Ne3** gives a laser light wave length of **1.15**µm.
- The neon atoms undergo spontaneous emission from **Ne3** to **Ne2** and **Ne5** to **Ne2.**

- Finally the neon atoms are returned to the ground state **Ne1** from **Ne2** by non- radiative diffusion and collision process.
- After arriving the ground state, once again the neon atoms are raised to **Ne6** & **Ne4** by excited helium atoms thus we can get continuous output from He-Ne laser.
- But some optical elements placed insides the laser system is used to absorb the infrared laser wave lengths **3.39**µm and**1.15**µm.
- Hence the output of He-Ne laser contains only a single wave length of **6328**A^0 and the output power is about few milliwatts

Applications of He – Ne Lasers

1. All inter- ferometric experiments
2. Metrological applications
3. Bar code reading
4. Image processing
5. Holography

Semiconductor Laser:

A semiconductor diode laser is specially fabricated p-n junction device, which emits coherent light when it is forward biased. R.N Hall and his coworkers made the first semiconductor laser in 1962.

It is made from Gallium arsenide (GaAs) direct band gap semiconductor, which operated at low temperatures and emitted light in the near IR region.

Now, p-n junction lasers are made to emit light almost anywhere in the spectrum from UV to IR. Diode lasers are remarkably small in size(0.1mm long) and they have high efficiency of the order of 40%.

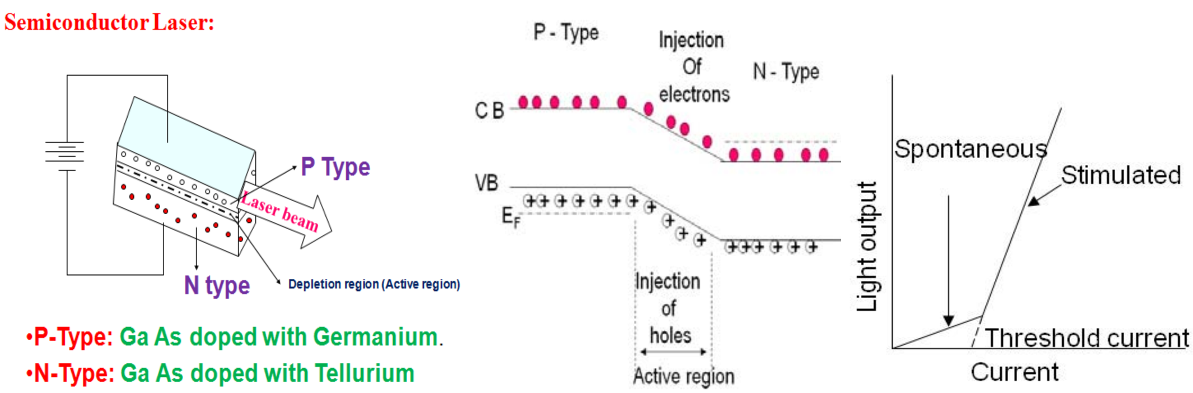


Fig. P–N Junction under forward biased resulting injection and recombination Of charge carriers

Output Wave length: GaAlAs:750-900nm,.GaAsP:1100-1600nm..

<u>Principle:</u>

- The energy band structure of a semiconductor consists of a valence band and a conduction band separated by an energy gap, E_g
- The conduction band contains electrons and the valence band contains holes and electrons.
- When an electron from the conduction band jumps into a hole in the valence band, the excess energy E_g is given output in the form of photon.
- Thus, the electron – hole recombination is the basic mechanism responsible for emission of light.
- The wavelength of emitted light depends upon the energy band gap of the material.

$$\mathbf{E_g = h\nu = hc/\lambda}$$

$$\mathbf{\lambda = hc/E_g}$$

- Semiconductors having a suitable value of E_g emit light in the optical region.

<u>Note:</u>

The chief advantage of a diode laser is that that it is portable. Because of the rapid advances in semiconductor technology, diode lasers are mass produced for use in optical fiber communications, in CD players, CD-ROM drivers, optical reading, and high speed laser printing etc wide variety of applications.

Types of semiconductor diode lasers:

- **Homo-junction** means that a p – n junction is formed by a single crystalline material such that the basic material has been the same on both sides of the junction.
  Ex: GaAs
- **Hetero-junction** means that the material on one side of the junction differs from that on the other side of the junction.

Ex:- Hetero junction having GaAs on one side and GaAlAs on the other side.

Draw backs of homo – junction lasers:

- Threshold current density is very large
- Only pulsed mode output is obtained.
- Laser output has large beam divergence.
- Poor coherence and poor stability.
- Electromagnetic field confinement is poor

Advantages of Hetero-junction laser:

- Low threshold current density.
- Output is continuous
- High output power.
- Narrow beam, high coherence, high monochromaticity
- Long life time of the device.
- Highly stable.

Applications of LASERS:

1. **Communication**
2. **Computers**
3. **Industry**
4. **Scientific Research**
5. **Military operation**
6. **Medicine**

Lasers in communication and Atmospheric science:

1. More amount data can be sent because of large band width.
2. More channels
3. Signals cannot be trapped
4. Highly directional, hence greater potential use in space crafts and submarines.
5. Lidars (Light detection and ranging) to study about atmospheric features, i.e. to measure atmospheric pollutants, Ozone concentration, water vapor concentration.

Lasers in computers:

1. In LAN, data transfer from one computer to other for short time.
2. During reading and recording the data on CD's

Lasers in Industry:

1. Blast holes in hard materials like diamond, hard stell etc.
2. Source as intense heat
3. To measure distance to making maps by surveyors
4. To cut teeth saws, drill in surgical needle, guide bulldozers
5. In welding: Purity of the material is not altered.

Lasers in Scientific Research:

1. To separate isotopes of uranium.
2. To create plasma, this may help the scientists to control nuclear fusion reaction.

3. To create 3D-photography called holography.
4. Recording and reconstruction of hologram to data storage.
5. Holography in optical signal processing.
6. To produce some chemical reactions
7. To produce monomers to polymers
8. Internal structure of the microorganisms and cells are studied accurately.

Lasers in Military applications:

1. To target enemy air plane or ship, to determine its distance.
2. To destroy enemy aircraft and missile.
3. As war weapon.
4. To find the velocity of moving object.
5. Target is judged from the strength and spectral distribution of bounced signal.

Lasers in Medicine:

1. To remove diseased body tissues.
2. Retinal detachment by eye specialist.
3. To instantly weld injured muscles, ligaments without use of the heat.
4. Argon and CO_2 lasers are used in liver and lungs treatment.
5. To elimination of moles and tumors on skin tissues.
6. In the treatment of Glaucoma.
7. Argon lasers in – Neuro surgery, Ophthalmology, general surgery, dermatology, gynecology.
8. He-Ne Lasers- Diagnostic applications.
9. Ruby lasers – Ophthalmology, dermatology.

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