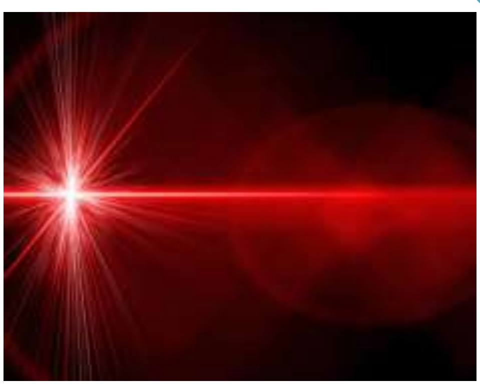
T.Y.B.Sc. SEM – VI

Subject: Physics

Paper- 603

Unit -5

LASER



- Introduction
- Characteristics of Laser
- Spontaneous emission
- Stimulated emission
- Types of Laser
- He-Ne laser
- Ruby laser
- Application

Syllabus:-

Characteristics of laser – spontaneous and stimulated emission of radiation – Einstein's coefficients - population inversion – excitation mechanism and optical resonator – Nd:YAG laser –He-Ne laser – semiconductor diode laser – applications of lasers.

1. A short sketch of laser history

1917: Einstein – stimulated absorption and emission of light

1954: Charles Townes and Schawlow – maser, prediction of the optical laser - Nobel Prize (1964)

1960: Maimann – first demonstration of a laser: Ruby laser

Rapid progress in the 1960s:

1961: first gas laser, first Nd laser

1962: first semiconductor laser

1963: CO_2 laser (IR)

2. Introduction

- A laser is a device that generates light by a process called **STIMULATED EMISSION**.
- The acronym LASER stands for Light Amplification by Stimulated Emission of Radiation

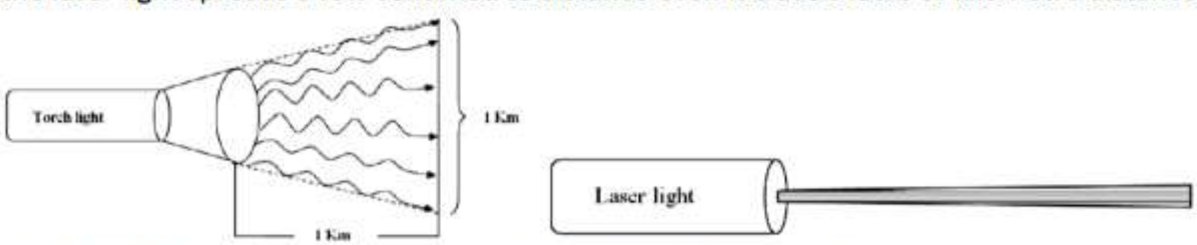
3. Characteristic of laser

Th The laser light exhibits some peculiar properties than compare with the convectional light. Those are

- Highly directionality
- Highly monochromatic
- Highly intense
- Highly coherence

Highly directionality

- 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 light travels 1km distance it spreads around 1 km wide.
- But the laser light spreads a few centimetres distance even it travels lacks of kilometre distance.



- The directionality of laser beam is expressed in terms of divergence Ø

$$\phi = \frac{arc}{radius} = \frac{d_2 - d_1}{s_2 - s_1}$$

- Where d_2 and d_1 are the diameters of laser spots at distances of s_2 and s_1 respectively from laser source.
- For laser light divergence $\phi = 10^{-3} radians.$
- Since the divergence of light is very low, so we say that the laser light having highly directional.

Highly monochromatic

- In laser radiation, all the photons emitted between discrete energy levels will have same wavelength.
- As a result the radiation is monochromatic in nature.
- Due to the stimulated characteristic of laser light, the laser light is more monochromatic than that of a convectional light.
- laser radiation -the wavelength spread = 0.001 nm
- So it is clear that the laser radiation is highly monochromatic

Highly intense

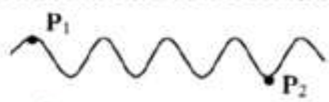
- Laser light is highly intense than the convectional light.
- one mill watt He-Ne laser is highly intense than the sun intensity
- when two photons each of amplitude are in phase with other; the resultant amplitude of two photons is **2a** and the intensity is $4a^2$
- in laser much number of photons 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
- So 1mW He-Ne laser is highly intense than the sun

Highly coherence

- Coherence is the property of the wave being in phase with itself and also with another wave over a period of time, and space or distance. There are two types of coherence
- Temporal coherence
- Spatial coherence.
- For laser radiation all the emitted photons are in phase, the resultant radiation obeys spatial and temporal coherence.

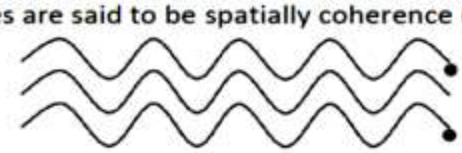
Temporal coherence (or longitudinal coherence):-

The predictable correlation of amplitude and phase at one point on the wave train w .r. t another point on the same wave train, then the wave is said to be temporal coherence.



spatially coherence (or transverse coherence).

The predictable correlation of amplitude and phase at one point on the wave train w. r .t another point on a second wave, then the waves are said to be spatially coherence (or transverse coherence).

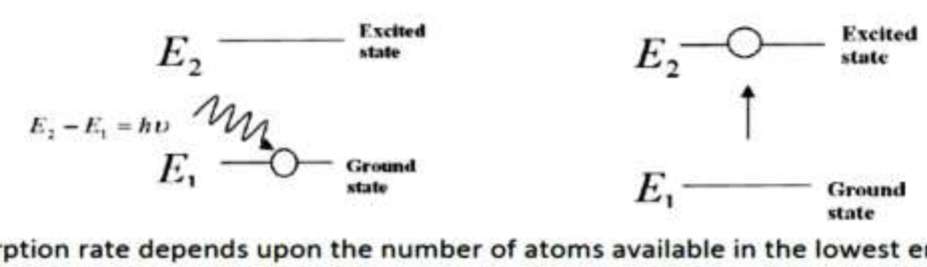


4. Stimulated absorption

Let $\mathbf{E_1}$ and $\mathbf{E_2}$ **are** the energies and N_1 and N_2 are the number of atoms per unit volume of ground and excited states and ρ (υ) be the density of photon density.

Suppose, if a photon of energy $E_2 - E_1 = h\upsilon$ interacts with an atom present in the ground state, the atom gets excitation form ground state to excited state by absorbing the photon energy.

It is the *process of excitation of atom into excited state from ground state by absorbing the incident photon.*



Stimulated absorption rate depends upon the number of atoms available in the lowest energy state as well as the energy density photons.

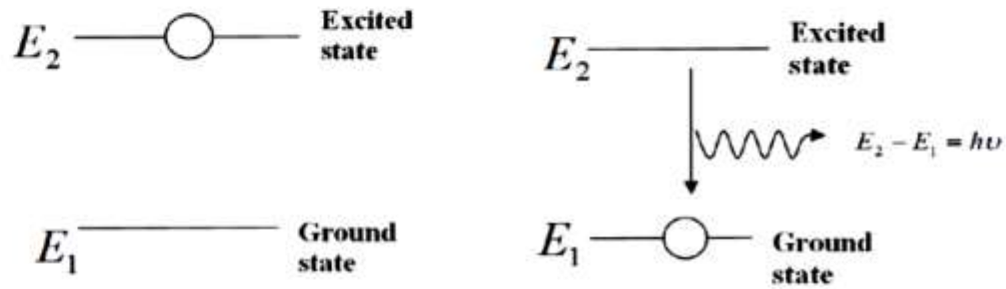
Stimulated absorption rate $\propto N_1$

$$\propto \rho(\upsilon)$$
$$\propto \rho(\upsilon)\, N_1$$
$$= B_{12}\, \rho(\upsilon)\, N_1$$

Where B_{12} is known as Einstein coefficient of stimulated absorption

5. *Spontaneous emission*

- Spontaneous emission was postulated by Bohr.
- The excited atom does not stay in a long time in the excited state.
- The lifetime of excited atom in higher state E_2 is up to 10^{-8} seconds.
- After the life time of the excited atom, gets de-excited into ground by emitting a photon of energy $E_2 - E_1 = h\upsilon$.



It is the process of de-excitation of atom itself into ground state after its life time from excited state by emitting a photon

Spontaneous emission rate $\propto N_2$

$= A_{21} N_2$

Where A_{21} is known as Einstein coefficient of spontaneous emission

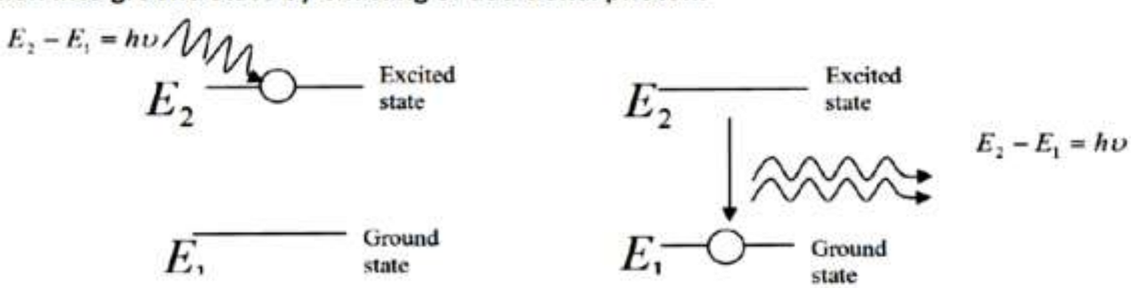
Characteristics of spontaneous emitted radiation

- The emitted radiation is poly-monochromatic
- The emitted radiation is Incoherent
- The emitted radiation is less intense
- The emitted radiation has less directionality
- Example: light from sodium or mercury lamp

6. *Stimulated emission*

Stimulated emission was postulated by Einstein.

Let, a photon of energy $E_2 - E_1 = h\upsilon$ interacts with the excited atom with in their life time; the atom gets de-excitation into ground state by emitting of additional photon.



It is the *process of de-excitation of atom into ground state from excited state by interacting with an additional photon within its life time by emitting of an additional photon.*

Stimulated emission rate depends upon the number of atoms available in the excited state as well as the energy density of photons.

Stimulated emission rate $\propto N_2$

$\propto \rho$

$\propto N_2 \rho$

$= B_{21} N_2 \rho$

Where B_{21} is known as Einstein coefficient of stimulated emission

Characteristics of stimulated emitted radiation

- The emitted radiation is monochromatic
- The emitted radiation is Coherent
- The emitted radiation is high intense
- The emitted radiation has high directionality
- Example: light from laser source

7. Spontaneous and Stimulated emission

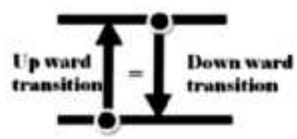
Spontaneous emission	Stimulated emission
1. The spontaneous emission was postulated by Bohr	1. The stimulated emission was postulated by Einstein
2. Additional photons are not required in spontaneous emission	2. Additional photons are required in stimulated emission
3. One photon is emitted in spontaneous emission	3. Two photons are emitted in stimulated emission
4. The emitted radiation is poly-monochromatic	4. The emitted radiation is monochromatic
5. The emitted radiation is Incoherent	5. The emitted radiation is Coherent
6. The emitted radiation is less intense	6. The emitted radiation is high intense
7. The emitted radiation have less directionality	7. The emitted radiation have high directionality
8. Example: : light from sodium or mercury lamp	8. Example: light from laser source

8. Einstein coefficients

It establishes the relation between the three coefficients i.e. stimulated absorption, spontaneous emission, and stimulated emission coefficients

Let N_1 be the number of atoms per unit volume with energy E_1 and N_2 be the number of atoms per unit volume with energy E_2 and $\rho(\upsilon)$ be the the density of photons. When the photons interact with ground level atoms, both upward (absorption) and downward (emission) transition occurs.

At the equilibrium the upward transitions must be equal downward transitions.



Upward transition

Stimulated absorption rate depends upon the number of atoms available in the lowest energy state as well as the energy density photons.

Stimulated absorption rate $\propto N_1$

$$\propto \rho(\upsilon)$$

$$= B_{12} N_1 \rho(\upsilon)$$

Where B_{12} is the Einstein coefficient of stimulated absorption.

Downward transition

The spontaneous emission rate depends up on the number of atoms present in the excited state.

Spontaneous emission rate $\propto N_2$

$$= A_{21} N_2$$

Where A_{21} is the Einstein coefficient of spontaneous emission.

Stimulated emission rate depends upon the number of atoms available in the excited state as well as the energy density of photons.

Stimulated emission rate $\propto N_2$

$$\propto \rho(\upsilon)$$

$$= B_{21}N_2\,\rho(\upsilon)$$

Where B_{21} is the Einstein coefficient of stimulated emission.

If the system is in equilibrium the upward transitions must be equal downward transitions.

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

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

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

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

Divide with $B_{21}N_2$ in numerator and denominator in right side of the above equation

$$\rho(\upsilon) = \frac{A_{21}N_2/B_{21}N_2}{(B_{12}N_1 - B_{21}N_2)/B_{21}N_2} = \frac{A_{21}/B_{21}}{\frac{B_{12}N_1}{B_{21}N_2} - 1} \qquad (1)$$

$$\rho(\upsilon) = \frac{A_{21}N_2/B_{21}N_2}{(B_{12}N_1 - B_{21}N_2)/B_{21}N_2} = \frac{A_{21}/B_{21}}{\frac{B_{12}}{B_{21}}e^{(E_2-E_1)/KT} - 1} \qquad (2)$$

From Maxwell Boltzmann distribution law

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

From Planck's law, the radiation density

$$\rho(\upsilon) = \frac{8\pi h\upsilon^3/C^3}{e^{(E_2-E_1)/kT} - 1} \qquad (3)$$

Comparing the two equations (2) and (3)

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

The above relations referred to as Einstein coefficients relations.

From the above equation for non degenerate energy levels the stimulated emission rate is equal to the stimulated absorption rate at the equilibrium condition.

$$B_{21} = B_{12}$$

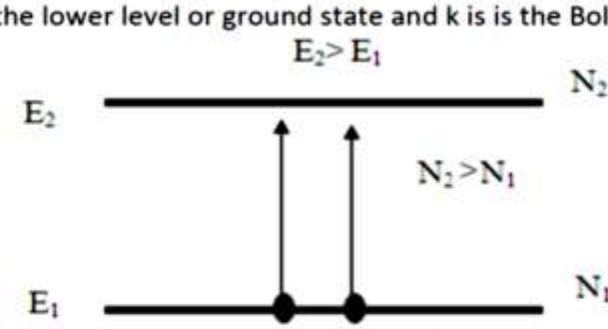
9. Population inversion

Let us consider two level energy system of energies $\mathbf{E_1}$ and $\mathbf{E_2}$ as shown in figure. Let $\mathbf{N_1}$ and $\mathbf{N_2}$ be the populations of energy levels $\mathbf{E_1}$ and $\mathbf{E_2}$. The number of atoms present in an energy level is known as population of that energy level. At ordinary conditions, i.e., the population in the ground or lower state is always greater than the population in the excited or higher states. The stage of making, population of higher energy level is greater than the population of lower energy level is called population inversion.

According to Boltzmann's distribution the population of an energy level E_i at temperature T is given by

$$N_i = N_0 e^{\left(\frac{-E_i}{KT}\right)}$$

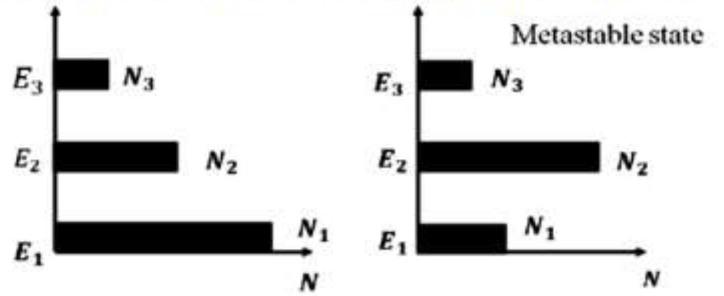
Where N_0 *is* the population of the lower level or ground state and k is is the Boltzmann's constant.



The number of atoms present in the excited state (N₂) is greater than the number of atoms present in the ground state (N₁) is called population inversion.

The process of raising the particles from ground state to excited state to achieve population inversion is called pumping. (Or the process of achieving of population inversion is called pumping)

To understand the concept of laser emission (stimulated emission) let us consider a three energy level system with energies E_1, E_2 and E_3 of populations, N_1, N_2 and N_3.At normal conditions, $E_1 < E_2 < E_3$ and $N_1 < N_2 < N_3$. In the ground state the life time of atom is more and the life time of atom in the excited state is 10^{-8}sec. But in the intermediate state the atom has more life time. So it is called metastable state.



At normal conditions $N_1 > N_2 > N_2$ After population inversion is achieved $N_2 > N_1$

When a suitable energy is supplied to the system, atoms get excited into E_3. After their lifetime the atoms are transit into E_2. Due to more lifetime of an atom in state E_2, the atoms stay for longer time than compare with the state E_3. Due to the accumulation of atoms instate E_2, the population inversion is established in between the E_1 and E_2 states.

10. Types of lasers

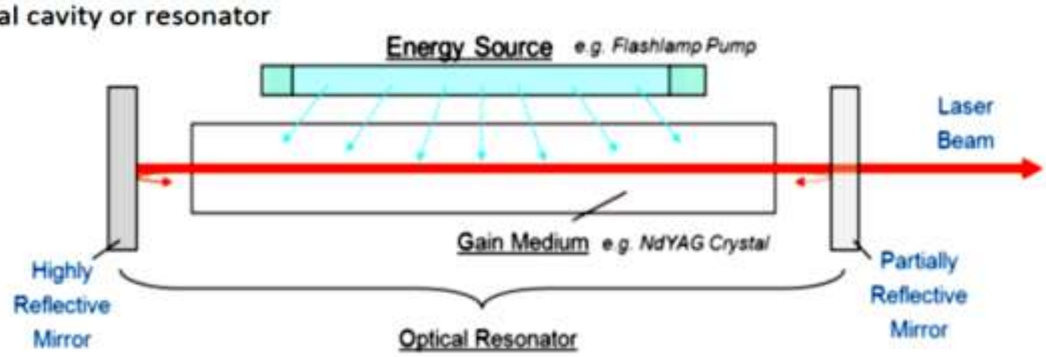
On the basis of active medium used in the laser systems, lasers are classified into several types

I. Solid lasers : Ruby laser, Nd;YAG laser, Nd;Glass
II. Liquid lasers : Europium Chelate laser, $SeOCl_2$
III. Gas lasers : CO_2, He-Ne, Argon-Ion Laser
IV. Dye lasers : Rhodamine 6G
V. Semiconductor lasers : InP, GaAs.
VI. Chemical lasers : HF, DF.

11. Construction and components of laser

Generally, every laser system consists of three components. They are

a. Energy source
b. Active medium
c. Optical cavity or resonator



Energy source

- To get laser emission, first we must have population inversion in the active medium.
- The energy source supplies the energy to the active medium.
- By absorbing that energy, the atoms or molecules or ions can be excited into higher levels.
- As a result we get population inversion in the active medium.

Active medium

Definition: - *In which medium we are creating population inversion to get stimulated emission of radiation is called active medium.*

- After receiving the energy from the source, the atoms or molecules or ions get excites into higher energy levels.
- While de-excitation to lower energy level, the emitted photons starts stimulated emission which results laser emission.
- Depending upon the active medium the lasers or classified as solid state, liquid state, gaseous state and semiconductor lasers.

Optical cavity or resonator

- ***The active medium is enclosed between a fully reflective mirror and partially reflective mirror. These mirrors constitute the optical cavity or resonator.***
- The reflectors enhance the stimulated emission process by reflecting the photons into the active medium.
- As a result we get high-intensity monochromatic and coherent laser light through the partially reflecting portion of the mirror.

12. Excitation mechanisms

Excitation of atom can be done by number of ways. The most commonly used excitation methods are

- Optical pumping
- Electrical discharge pumping
- Chemical pumping
- Injection current pumping

Optical pumping

- Optical pumping is a process in which light is used to raise the atoms from a lower energy level to higher level to create population inversion.
- Optical pumping is used in solid laser.
- The solid materials have very broad absorption band, so sufficient amount of energy is absorbed from the emission band of flash lamp to create population inversion.
- Xenon flash tubes are used for optical pumping.
- Examples: - Ruby laser, Nd:YAG Laser (Neodymium: Yttrium Aluminum Garnet), Nd: Glass Laser

Electrical discharge pumping

- In electric discharge pumping, atoms are excited into excited sate by collisions with fast moving electrons in electric discharge tube.
- Electrical discharge pumping is used in gas lasers.
- Since gas lasers have very narrow absorption band, so optical pumping is not suitable for gas lasers.
- Examples:- He-Ne laser, CO_2 laser, argon-ion laser, etc

Chemical pumping

- In this method the chemical energy released during the chemical process, that energy will excite the atoms to higher level and create population inversion.
- Whenever hydrogen reacts with fluorine, it liberates lot of heat energy. By utilizing this heat energy the atoms excites into higher states and create population inversion.
- Examples:-HF and DF lasers.

Injection current pumping

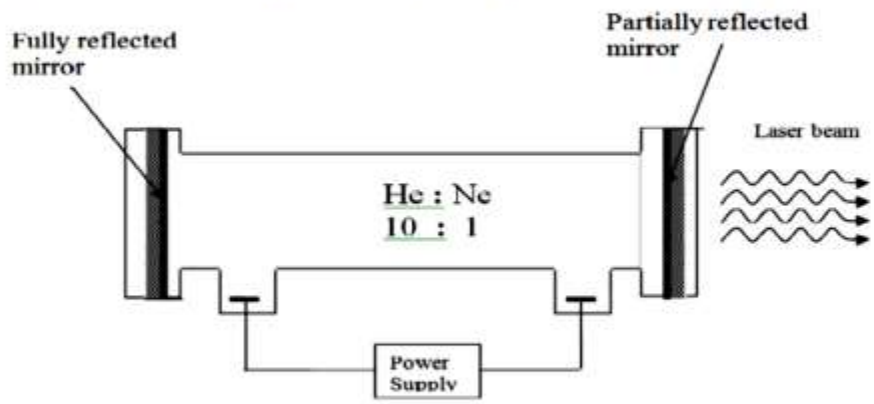
- This pumping mechanism is used in semiconductor lasers.
- In semiconductor lasers, by passing high currents across the junction, the population inversion will create.
- In semiconductors lasers the population inversion always creates among majority and minority charge carriers.
- Examples:- InP and GaAs lasers

13. He-Ne laser

- In 1960, the first laser device was developed by T.H. Mainmann.
- Ruby laser is a pulse laser, even it have high intense output.
- For continuous laser beam gas lasers are used.
- The output power of the gas laser is generally in few milli watts.
- The first He-Ne gas laser was fabricated by Ali Javan and others.

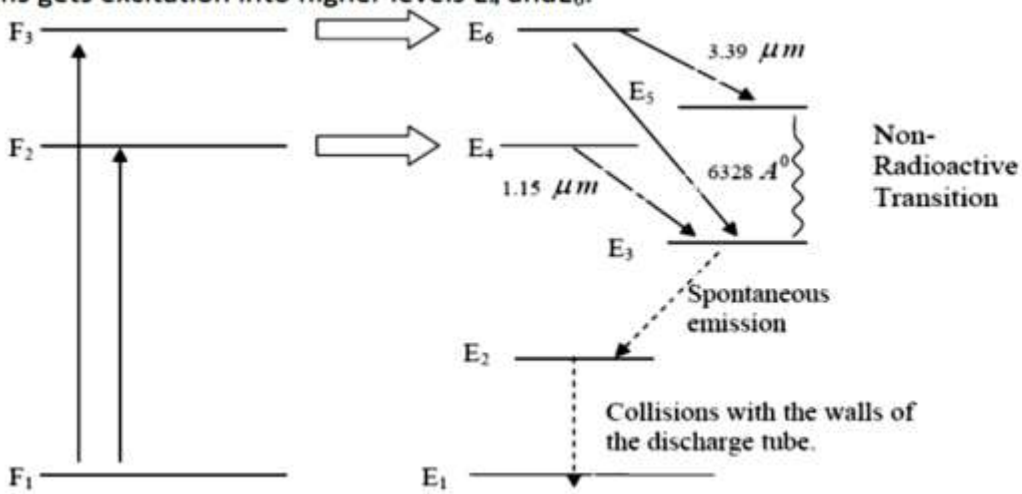
Construction

- In He-Ne gas laser, the He and Ne gases are taken in the ratio 10:1 in the discharge tube.
- Two reflecting mirrors are fixed on either ends of the discharge tube, in that, one is partially reflectin and the other is fully reflecting which serve as optical cavity or resonator.
- In He-Ne laser 80 cm length and 1 cm diameter discharge tube is generally used.
- The out power of these lasers depends on the length of the discharge tube and pressure of the gas mixture.
- When the two windows are set at Brewster's angle, the output laser is linearly polarized.



Working

- When the electric discharge (fast moving electrons) is passing through the gas mixture, the electrons collide with the He gas atoms excites into higher levels F_2 and F_3 form F_1 by absorbing the electrons energy.
- In He atoms higher levels F_2 and F_3, the life time of He atoms is more.
- Since F_2 and F_3 states are acting as metastable states, so the He atom cannot return to ground groun level through spontaneous emission.
- So there is a maximum possibility of energy transfer between He and Ne atoms through atomic collisions.
- When He atoms present in the levels F_2 and F_3 collide with Ne atoms present ground state E_1, the Ne atoms gets excitation into higher levels E_4 and E_6.



- Due to the continuous excitation of Ne atoms, we can achieve the population inversion between the higher levels E_4 (E_6) and lower levels E_3 (E_5).
- The various transitions $E_6 \to E_5$, $E_4 \to E_3$ and $E_6 \to E_3$ leads to the emission of wavelengths $3.39\mu m$, $1.15\mu m$ and $6328A^0$.
- The first two corresponding to the infrared region while the last wavelength is corresponding to the visible region.
- The Ne atoms present in the E_3 level are de-excited into E_2 level, by spontaneously emitting a photon of around wavelength $6000A^0$.
- When a narrow discharge tube is used, the Ne atoms present in the level E_2 collide with the walls of the tube and get de-excited to ground level E_1.
- The excitation and de-excitation of He and Ne atoms is a continuous process and thus it gives continuous laser radiations.

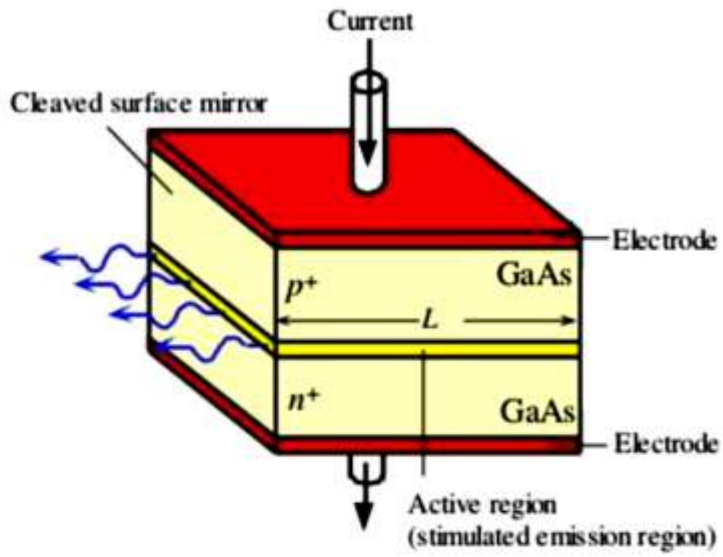
Advantages:

- He-Ne laser emits continuous laser radiation.
- Due to the setting of end windows at Brewster's angle, the output laser is linearly polarized.
- Gas lasers are more monochromatic and directional when compared with the solid state laser.

14. Semiconductor diode laser

- Laser diode is a specially fabricated *p-n* junction device that emits coherent radiation.
- It is operated at forward biased condition.
- Direct band gap semiconductors are preferred in the fabrication of semiconductor laser diodes because they emit energy in terms of light when an electron and hole recombination takes place.
- Compound semi-conductors like GaAs and InP are examples for direct band gap semiconductors

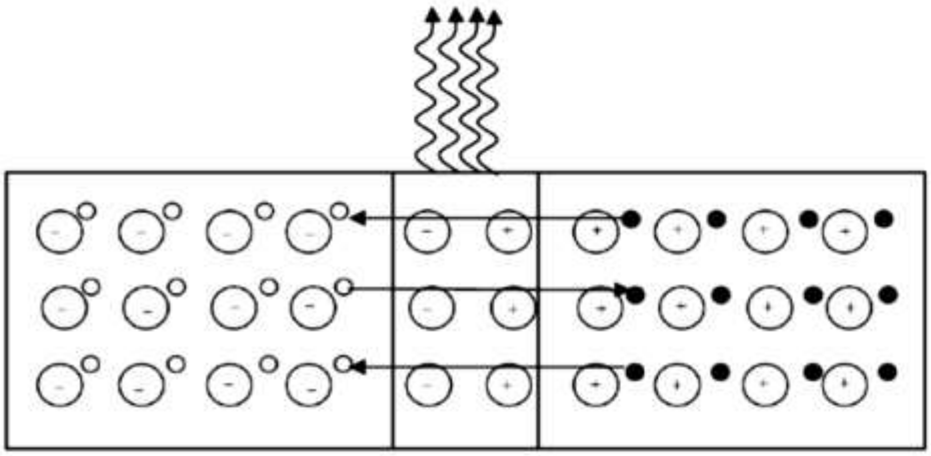
Construction



- In this laser system, the active medium is a p-n junction diode made from crystalline gallium arsenide.
- The p-region and n-region in the diode are obtained by heavily doping with germanium and tellurium respectively in GaAs.
- The thickness of the p-n junction is very narrow so that the emitted radiation has large divergence and poor coherence.
- At the junction two sides are roughed to avoid laser emission and the remaining two faces one is partially polished and the other is fully polished.
- The laser emission takes place from the partially polished face.
- To provide bias two metal contacts are provided in the top and bottom of the diode as shown in figure.

Working

- The semiconductor laser device is always operated in forward bias condition.
- Electrons and the holes are the minority charge carriers in n-region and p-region semiconductors.
- When a huge current (10^4 Amp/mm^2) is passing through the p-n junction, p-region is positively biased, holes are injected into n-region from p-region and n-region is negatively biased electrons are injected into p-region from n-region as shown in figure.



- The continuous injection of charge carriers creates the population inversion of minority carriers in n and p sides' respectively.
- The electrons and holes recombine and release of light energy takes place in or near the junction as shown in figure.
- The emitted photons increase the rate of recombination of injected electrons from the n-region and holes in p-region by inducing more recombinations.

  From Planck's law $E_g = h\upsilon = h\frac{c}{\lambda}$

  $$\lambda = \frac{hC}{E_g} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{1.4 \times 1.6 \times 10^{-19}} = 8874A^0$$

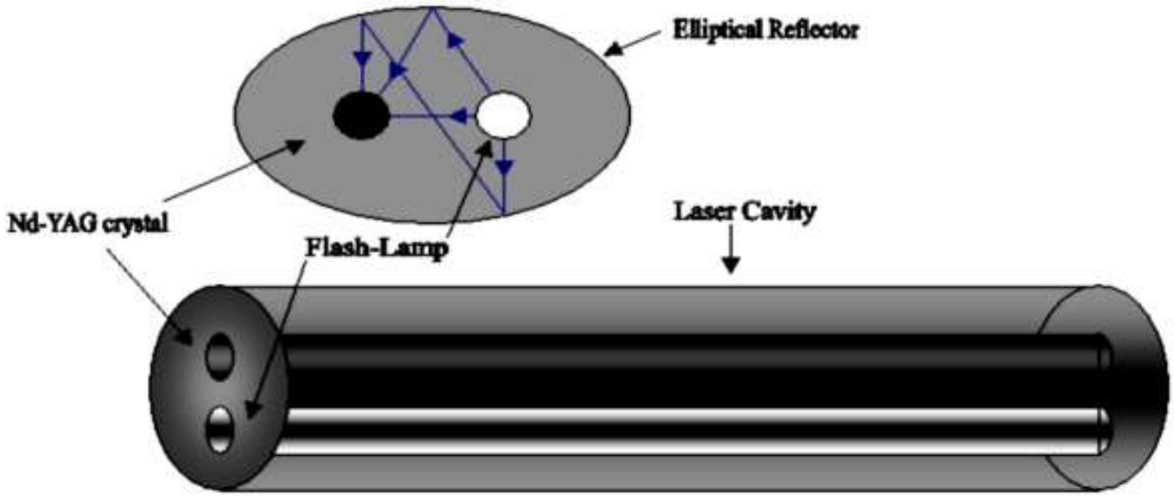
- In case of GaAs homo-junction which has an energy gap of 1.44eV gives a laser beam of wave length around $8874A^0$.
- The wave length of emitted radiation depends up on the concentration of donor and acceptor atoms in GaAs.
- The efficiency of the laser emission is increases when we cool the GaAs diode.

15. Nd:YAG [Neodymium-Yttrium Aluminium Garnet] laser

- Nd: YAG laser is a solid state four level laser.
- Nd stands for Neodymium and YAG for Yttrium Aluminium Garnet ($Y_3Al_5O_{12}$).
- Nd-YAG rod, Nd^{3+} ions are act as active medium.
- It is developed by H.M Marcos and L.G Van Vitert in 1964.

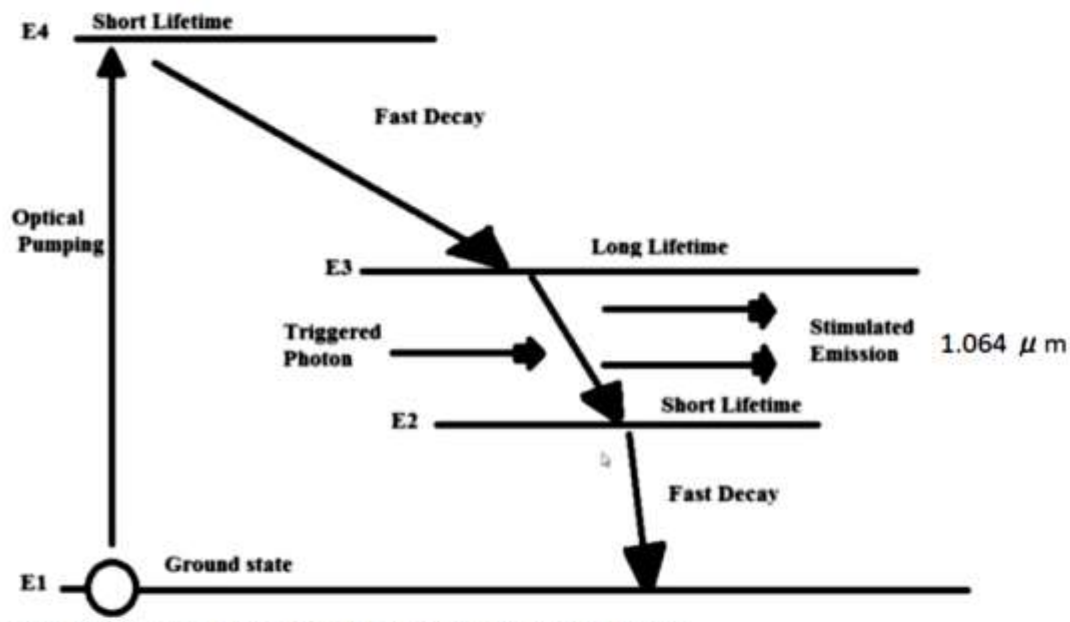
Construction

- An Nd-YAG laser consists of a crystalline cylindrical Nd-YAG rod [$Y_3Al_5O_{12}$].
- Nd: YAG crystalline material is formed by 1% Y^{3+} replaced by the triply ionised neodymium (Nd^{3+})
- The dimensions of the Nd: YAG rod is 10 cm length and 6-9 cm diameter.
- One end of the Nd-YAG rod is fully silvered and the other end is partially silvered which serve as optical cavity or resonator.
- The Nd-YAG rod surrounded by elliptical glass cavity which in turn is enclosed by xenon flash lamp filled with xenon gas s shown in fig1.



Working

- When xenon flash lamp is switched on, it emits thousand joules of light energy is discharged in a few milliseconds. A part of this light energy will be flashes on the Nd-YAG rod.
- Then the Nd^{3+} are excited to higher energy states E_4 from ground state E_1 by absorbing the light 7200 A^0 to 8000 A^0 wavelength.



- The excited Nd^{3+} ions then make a transition from these energy levels.
- In the excited state E_4 the life time of Nd^{3+} ions are very small so it de-excites into E_3 state through non-radioactive transition.
- In E_3 state the life time of Nd^{3+} ions is large, so it will act as Meta stable state.
- In Meta stable state, the Nd^{3+} ions remain for longer duration of the order 10^{-3} second, so population inversion takes place between Meta stable E_3 and E_2 state.
- The Nd^{3+} Ions are de-excited into ground E_1 state through fast decay.
- Hence, pulsed form of laser beam of wavelength 1.064 μm is emitted during transition from $E_2$to E_1.

Applications of Nd-YAG 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

16. Applications of lasers

Due to high intensity, high monocromacity and high directionality of lasers, they are widely used in various fields.

1. communication
2. computers
3. chemistry
4. photography
5. industry
6. medicine
7. military
8. scientific research

1. communication

In case of optical communication semiconductors laser diodes are used as optical sources and its b width is (10^{14}Hz) is very high compared to the radio and microwave communications.

- More channels can be sent simultaneously
- Signal cannot be tapped
- As the band width is large, more data can be sent.
- A laser is highly directional and less divergence, hence it has greater potential use in space crafts submarines.

2. Computers

- In LAN (local area network), data can be transferred from memory storage of one computer to o computer using laser for short time.
- Lasers are used in CD-ROMS during recording and reading the data.

3. Chemistry

- Lasers are used in molecular structure identification
- Lasers are also used to accelerate some chemical reactions.
- Using lasers, new chemical compounds can be created by breaking bonds between atoms are molecule

4. Photography

- Lasers are also used in the construction of holograms.
- Lasers can be used to get 3-D lens less photography.

5. Industry

- Lasers can be used to blast holes in diamonds and hard steel
- Lasers are also used as a source of intense heat
- Lasers are used to drill holes in ceramics.
- Lasers are used to cut glass and quartz.
- Lasers are used for heat treatment in the tooling and automotive industry.
- Lasers are used in electronic industry in trimming the components of ICS.
- High power lasers are used to weld or melt any material.
- Lasers are also used to cut teeth in saws and test the quality of fabric.

6. Medicine

- Lasers are used for cataract removal.
- Lasers are used for eye lens curvature corrections.
- Lasers are used in bloodless surgery.
- Lasers are used in cancer diagnosis and therapy.
- Lasers are used in destroying kidney stones and gallstones.
- Argon and carbon dioxide lasers are used in the treat men of liver and lungs.
- Lasers used in endoscopy to scan the inner parts of the stomach.
- Lasers used in the elimination of moles and tumours which are developing in the skin tissue.
- Lasers are used in plastic surgery.
- Lasers are used in the treatment of mouth diseases.

7. Military

- Lasers can be used as a war weapon.
- High energy lasers are used to destroy the enemy air-crofts and missiles.
- Lasers can be used in the detection and ranging likes RADAR.

8. **Scientific field**

- Lasers are used for isotope preparation.
- Lasers are employed to create plasma.
- Lasers are used in air pollution, to estimate the size of the dust particles.
- Lasers are used in the field of 3D-photography
- Lasers used in Recording and reconstruction of hologram.
- Lasers used to produce certain chemical reactions.
- Lasers are used in Raman spectroscopy to identify the structure of the molecule.
- Lasers are used in the Michelson- Morley experiment.