Engineering Physics: PHY110

LASER AND APPLICATIONS: UNIT-2

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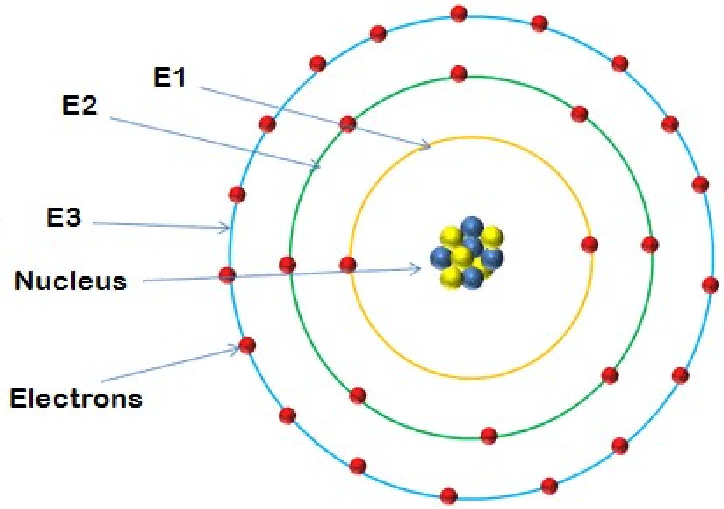
What is Light?

- Light is a kind of energy released by an atom. Light is made up of very small particles called photons having energy hv.

- Einstein believed that light is a particle or photon and the flow of photons is a wave. Light is obtained from various sources like candles, lamps and sun-rays.

- Candles and lamps are called as the man made light sources and sun-rays is called natural light source.

- The first reliable artificial light source (incandescent light bulb) was invented in 1879 by Thomas Edison.



What is LASER ?

- LASER stands for Light Amplification by Stimulated Emission of Radiation. Laser is a device that amplifies or increases the intensity of light and produces highly directional light.

- Laser light is different from the conventional light. Laser light has extra-ordinary properties which are not present in the ordinary light sources like sun and incandescent lamp.

- In 1917, Einstein gave the theoretical basis for the development of laser, when he predicted the possibility of stimulated emission.

- In 1954, using Einstein's idea, C.H. Townes and his co-workers invented a device called MASER (Microwave Amplification by Stimulated Emission of Radiation).

- In 1960, Theodore Harold Maiman built the first laser device.

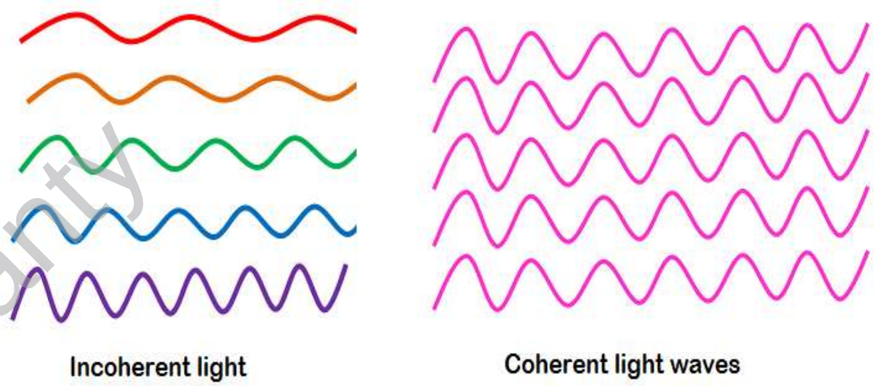
Characteristics of Laser:

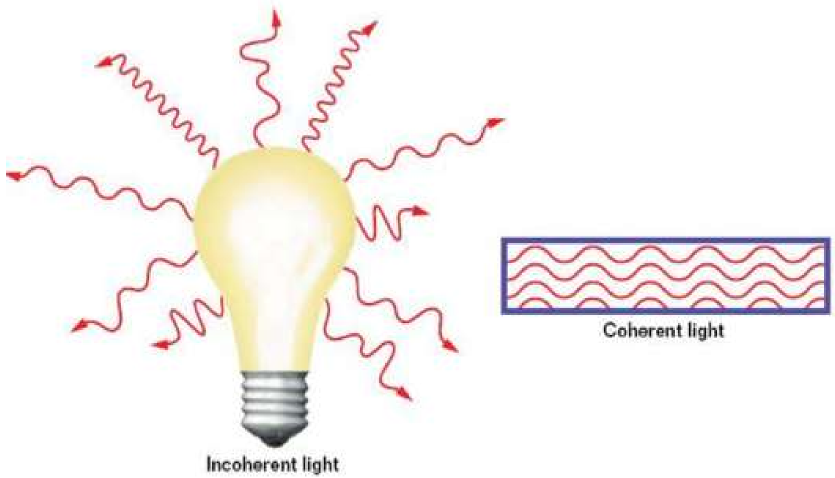
Laser light has four unique characteristics that differentiate it from ordinary light: These are

- Coherence
- Directionality
- Monochromatic
- High intensity

Coherence:

- In Laser, the wavelengths of the laser light are in phase in space & time.
- Light generated by laser is highly coherent.
- Because of this coherence, a large amount of power can be concentrated in a narrow space.
- TWO types:
  - ✓Spatial/ Transverse Coherence
  - ✓Temporal/ Longitudinal Coherence

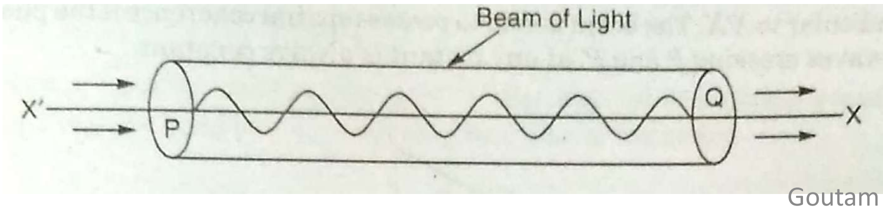




Types of Coherence:

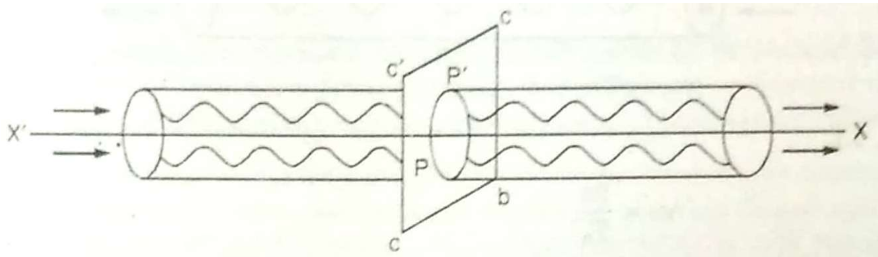
Temporal or Time coherence:

- If the phase difference of waves crossing the two points lying along the direction of propagation of the beam is time dependent, then a beam of light is said to possess temporal or time coherence.
- This coherence is also known as longitudinal coherence.
- Average Length of wave trains is called Coherent Length (L_c). i.e. $\boxed{L_c = c.T_0}$
- Natural line width, $\boxed{\Delta\lambda = \lambda^2/ L_c}$



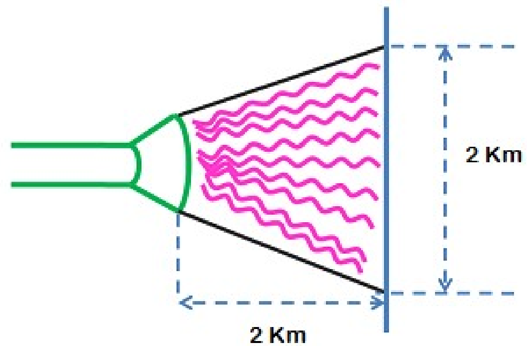
Spatial Coherence:

- A laser beam is said to possess spatial coherence, if the phase difference of the waves crossing the two points lying on a plane perpendicular to the direction of propagation of the beam is time-independent.
- This coherence is also termed as transverse or lateral coherence.

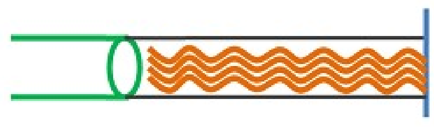


Directionality

- In conventional light sources (lamp, sodium lamp and torchlight), photons will travel in random direction. Therefore, these light sources emit light in all directions.
- 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.
- If an ordinary light travels a distance of 2 km, it spreads to about 2 km in diameter. On the other hand, if a laser light travels a distance of 2 km, it spreads to a diameter less than 2 cm.



Ordinary light



Laser light

Monochromatic

- Monochromatic light means a light containing a single colour or wavelength.

- In laser, all the emitted photons have the same energy, frequency, or wavelength. Hence, the light waves of laser have single wavelength or colour.

- Therefore, laser light covers a very narrow range of frequencies or wavelengths.

High Intensity

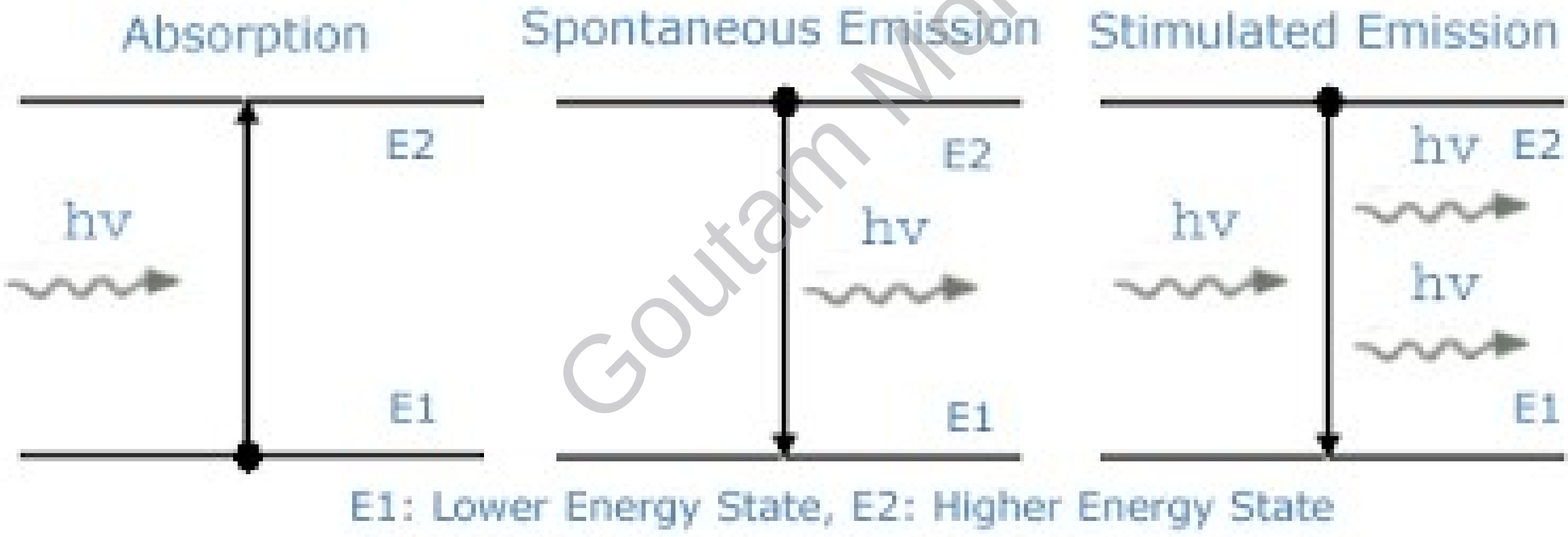
- The intensity of light is the energy per unit time flowing through a unit normal area.

- In laser, the light spreads in small region of space and in a small wavelength range. Hence, laser light has greater intensity when compared to the ordinary light.

- Example, If you look at a 100 Watt lamp filament from a distance of 30 cm, the power entering your eye is less than 1/1000 of a watt. However, in Laser, a 1 Watt laser would appear many thousand times more intense than 100 Watt ordinary lamp.

Interaction of external energy with atomic energy states:

- Different types of radiations:



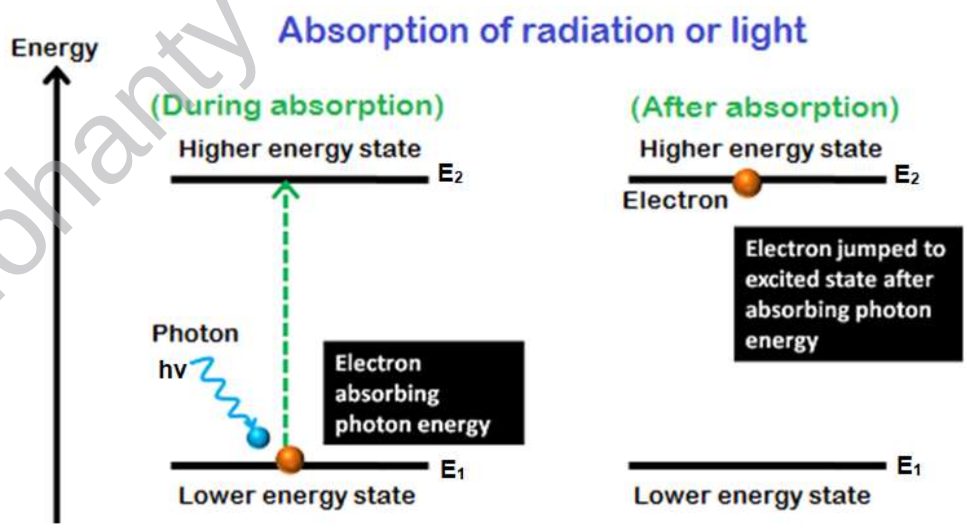
Absorption:

- The process of absorbing energy from photons is called absorption of radiation.
- If an atom is initially in a lower state 1, it can rise to a higher state 2 by absorbing a quantum of radiation (Photon) of frequency ν given by

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

Where E1 and E2 are the energies Of the atom in the states 1 and 2 respectively.

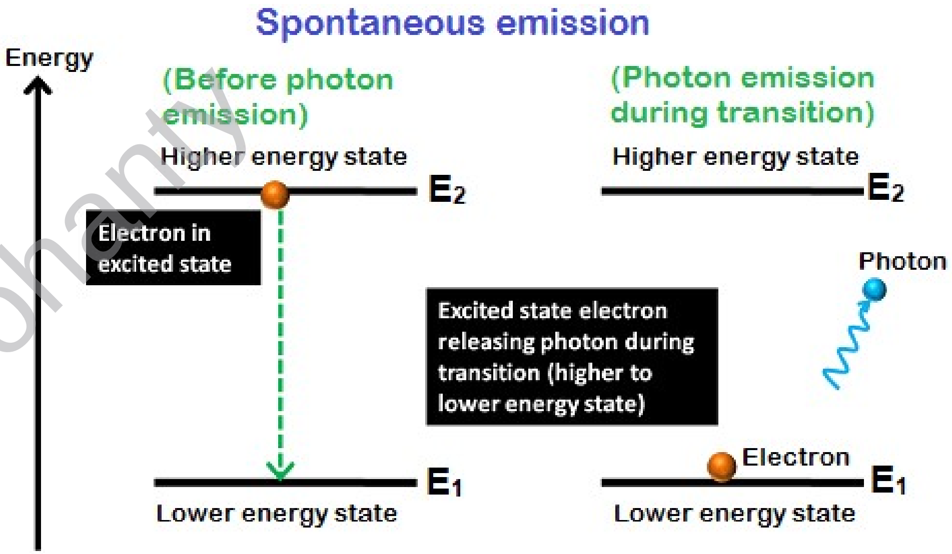
- This process is known as absorption of radiation.



- The probable rate of occurrence of the absorption transition 1→2 depends on the properties of states 1 and 2 and is proportional to the energy density u(ν) of the radiation of frequency ν incident on the atom.
- Thus, $\boxed{P_{12}=B_{12}u(\nu)}$ where B_{12} is proportionality constant and is known as Einstein's coefficient of radiation.

Spontaneous Emission:

- The process by which excited electrons emit photons while falling to the ground level or lower energy level is called spontaneous emission.
- Consider an atom initially in the higher (excited) state 2. Excited state with higher energy is inherently unstable, hence atom in excited state does not stay for longer time and it jumps to the lower energy state 1 emitting a photon of frequency v. This is spontaneous emission of radiation.
- If there is an assembly of atoms, the radiation emitted spontaneously by each atom has a random direction and a random phase and is therefore incoherent from one atom to another.



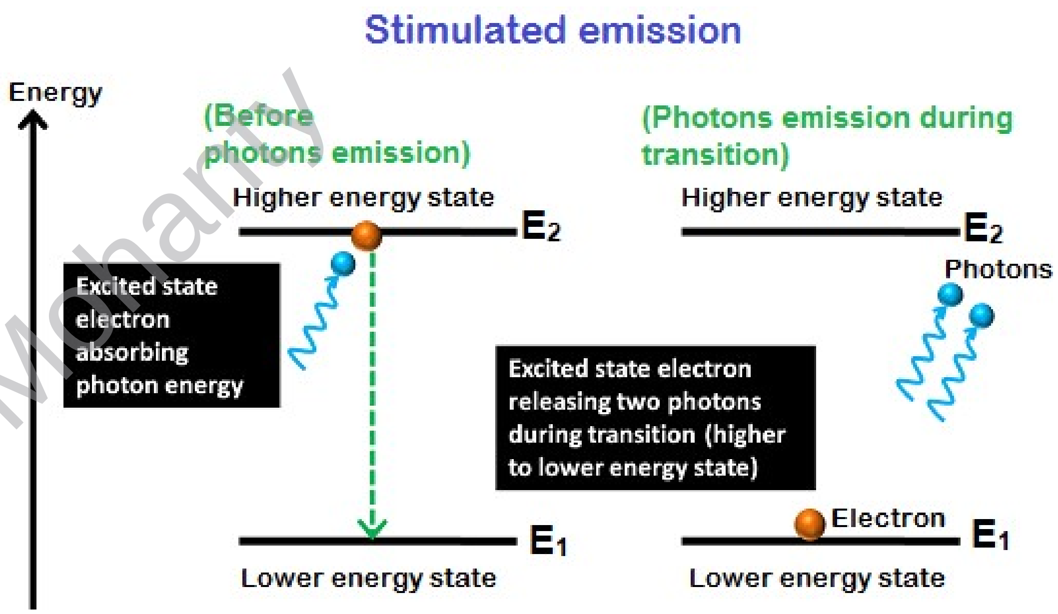
- The probability of spontaneous emission 2→ 1 is determined only by the properties of states 2 and 1. This is denoted by

$$\boxed{P_{21}=A_{21}}$$

Where A_{21} is known as 'Einstein's coefficient of spontaneous emission of radiation'. In this case the probability of spontaneous emissions is independent of it.

Stimulated (Induced)emission:

- The process by which electrons in the excited state are stimulated to emit photons while falling to the ground state or lower energy state is called stimulated emission.
- According to Einstein, an atom in an excited energy state may, under the influence of the electromagnetic field of a photon of frequency v incident upon it, jumps to a lower energy state, emitting an additional photon of same frequency (v). Hence two photons, one original and the other emitted, move together. This is stimulated (or induced) emission of radiation.
- The direction of propagation, phase, energy and state of polarisation of the emitted photon is exactly same as that of the incident stimulating photon, so the result is an enhanced beam of coherent light.



- The probability of stimulated emission transition 2→1 is proportional to the energy density u(v) of the stimulating radiation and is given by

$\boxed{P_{21}=B_{21}\, u(v)}$, Where B_{21} is the 'Einstein's coefficient of stimulated emission of radiation'

- The total probability for an atom in state 2 to drop to the lower state 1 is therefore

$\boxed{P_{21}=A_{21}+B_{21}\, u(v)}$

Relation bet^n Einstein's co-efficient:

- Let us consider an assembly of atoms in thermal equilibrium at temperature T with radiation of frequency v and energy density u(v). Let N_1 and N_2 be the number of atoms in states 1 and 2 respectively at any instant. The number of atoms in state 1 that absorb a photon and rise to state 2 per unit time is

$$N_1 P_{12} = N_1 B_{12}\, u(v)$$

- The number of atoms in state 2 that drop to state 1, either spontaneously or under stimulation, emitting a photon per unit time is

$$N_2 P_{21} = N_2 [A_{21} + B_{21}\, u(v)]$$

- For equilibrium, the absorption and emission must occur equally.

$$\text{i.e. } N_1 P_{12} = N_2 P_{21}$$

- Relation bet. Einstein's co-efficient

$$N_1 B_{12}\, u(v) = N_2 [A_{21} + B_{21}\, u(v)] \Rightarrow\Rightarrow$$

$$u(\nu) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

$$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right) - 1}$$

- Einstein proved thermodynamically that the probability of (stimulated) absorption is equal to the probability of stimulated emission i.e.

B12 = B21

- Then, we have

$$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\left(\frac{N_1}{N_2} - 1\right)}$$

- The equilibrium distribution of atoms among different energy states is given by using Boltzmann's Distribution Law according to which

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

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

- Consequently, $$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{e^{\frac{h\nu}{KT}} - 1}$$

- This is the energy density of photon of frequency v in equilibrium with atoms in energy states 1 and 2, at temperature T. Comparing it with the Planck's radiation formula (according to which the energy density of the black body radiation of frequency v at temperature T is given as:

$$u(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{KT}} - 1}$$

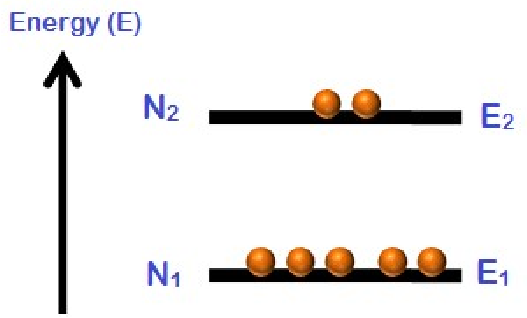
- We get $$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}}$$

- This shows that the ratio of Einstein's coefficient of spontaneous emission to the Einstein's coefficient of absorption of radiation is proportional to cube of the frequency (v3). This means that the probability of spontaneous emission increases rapidly with the energy difference between two states.

Population Inversion

- Population inversion is the process of achieving greater population of higher energy state as compared to the lower energy state. Population inversion technique is mainly used for light amplification. The population inversion is required for laser operation.
- Consider a group of electrons with two energy levels E_1 and E_2.
- The number of electrons per unit volume in an energy state is the population of that energy state.
- Population inversion cannot be achieved in a two energy level system. Under normal conditions, the number of electrons (N_1) in the lower energy state (E_1) is always greater as compared to the number of electrons (N_2) in the higher energy state (E_2).

  i.e. $N_1 > N_2$
- When temperature increases, the population of higher energy state (N_2) also increases. However, the population of higher energy state (N_2) will never exceeds the population of lower energy state (N_1).
- At best an equal population of the two states can be achieved which results in no optical gain. i.e. $N_1 = N_2$



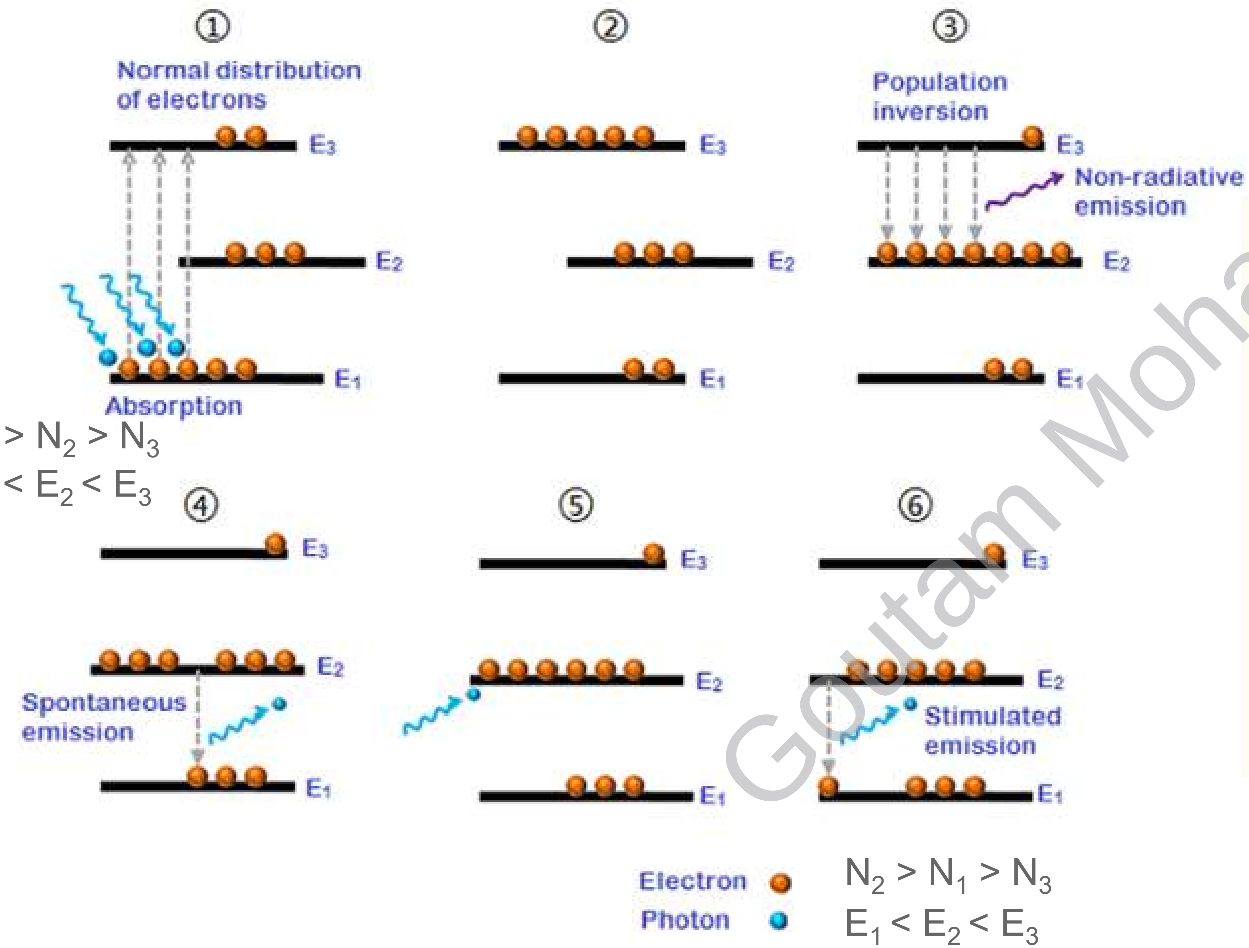
- Therefore, we need 3 or more energy states to achieve population inversion. The greater is the number of energy states the greater is the optical gain.
- There are certain substances in which the electrons once excited; they remain in the higher energy level or excited state for longer period. Such systems are called active systems or active media which are generally mixture of different elements.
- When such mixtures are formed, their electronic energy levels are modified and some of them acquire special properties. Such types of materials are used to form 3-level laser or 4-level laser.

3-level laser:

- Consider a system consisting of three energy levels E_1, E_2, E_3 with N number of electrons. Let N_1 be the number of electrons in the energy state E_1, N_2 be the number of electrons in the energy state E_2 and N_3 be the number of electrons in the energy state E_3.
- We assume that $E_1 < E_2 < E_3$.
- The energy level E_1 is known as the ground state or lower energy state and the energy levels E_2 and E_3 are known as excited states. The energy level E_2 is sometimes referred to as Meta stable state. The energy level E_3 is sometimes referred to as pump state or pump level.
- Under normal conditions, $N_1 > N_2 > N_3$. But to get laser emission or population inversion, N_2 should be greater than N_1.
- Under certain conditions, $N_2 > N_1$ is achieved. Such an arrangement is called population inversion.
- Let us assume that initially the majority of electrons will be in the lower energy state or ground state (E_1) and only a small number of electrons will be in excited states (E_2 and E_3).
- When we supply light energy which is equal to the energy difference of E_3 and E_1, the electrons in the lower energy state (E_1) gains sufficient energy and jumps into the higher energy state (E_3). This process of supplying energy is called pumping.

- The lifetime of electrons in the energy state E_3 is very small as compared to the lifetime of electrons in the energy state E_2. Therefore, electrons in the energy level E_3 does not stay for long period. After a short period, they quickly fall to the Meta stable state or energy state E_2 and releases radiation less energy instead of photons. Because of the shorter lifetime(10^{-8} sec), only a small number of electrons accumulate in the energy state E_3.
- The electrons in the Meta stable state E_2 will remain there for longer period because of its longer lifetime(10^{-3} sec). As result, a large number of electrons accumulate in Meta stable state. Thus, we can get $N_2 > N_1 > N_3$. So we can achieve population inversion between energy levels E_1 and E_2.
- After completion of lifetime of electrons in the Meta stable state, they fall back to the lower energy state or ground state E_1 by releasing energy in the form of photons. This process of emission of photons is called spontaneous emission.
- When this emitted photon interacts with the electron in the Meta stable state E_2, it forces that electron to fall back to the ground state. As a result, two photons are emitted. This process of emission of photons is called stimulated emission.
- When these photons again interacted with the electrons in the Meta stable state, they forces two Meta stable state electrons to fall back to the ground state. As a result, four photons are emitted. Likewise, a large number of photons are emitted.
- As a result, millions of photons are emitted by using small number of photons. Thus, light amplification is achieved by using population inversion method. The system which uses three energy levels is known as 3-level laser.
- Drawbacks: In a 3-level laser, at least half the population of electrons must be excited to the higher energy state to achieve population inversion. Therefore, the laser medium must be very strongly pumped. This makes 3-level lasers inefficient to produce photons or light.

Population inversion in 3-level laser

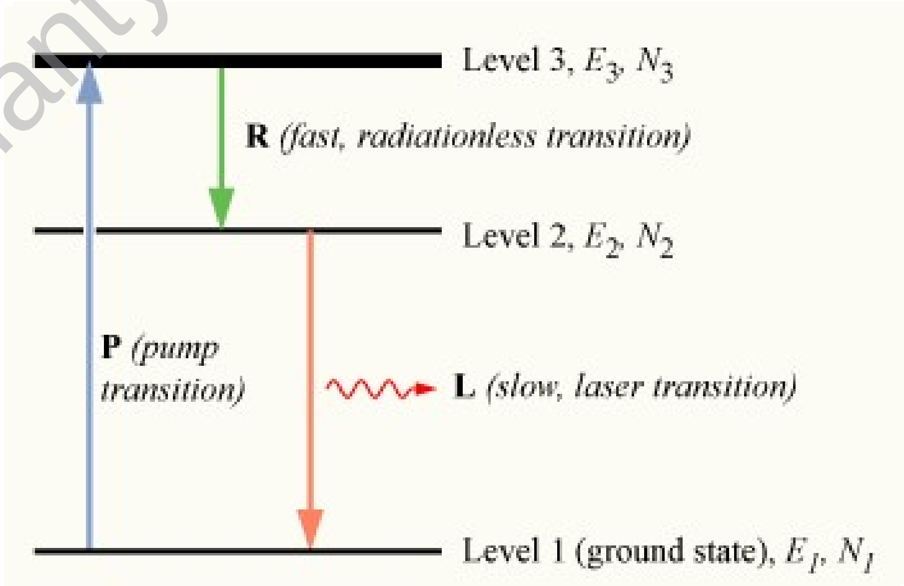


$N_1 > N_2 > N_3$

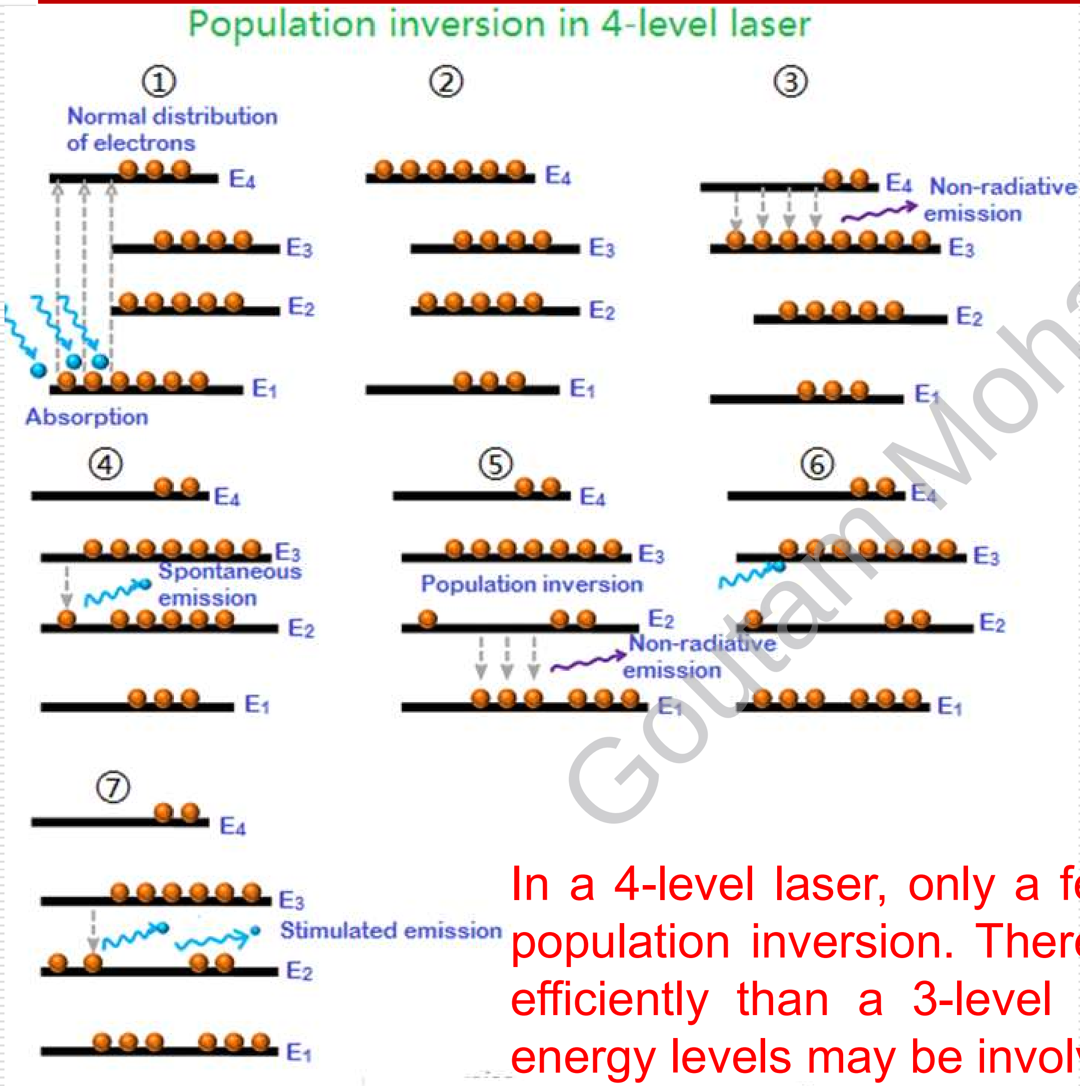
$E_1 < E_2 < E_3$

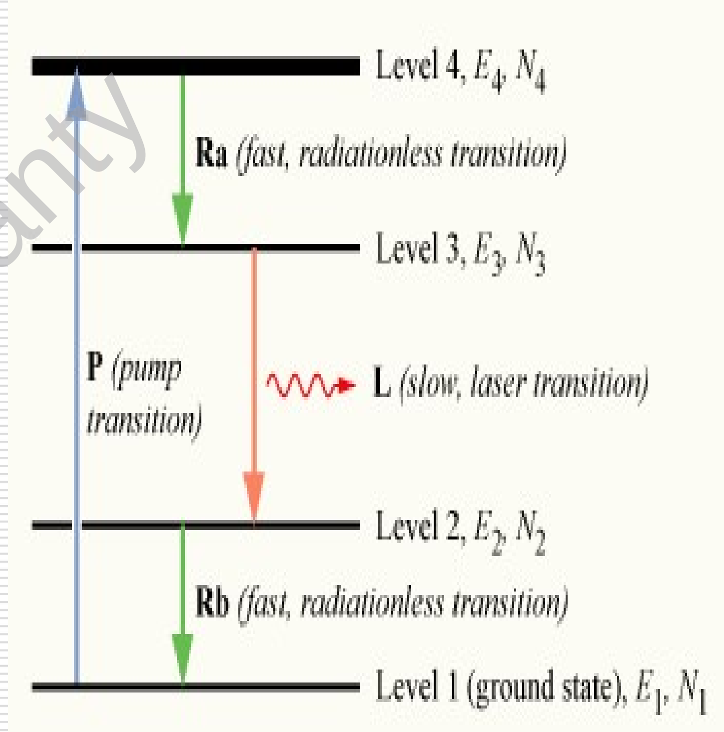
$N_2 > N_1 > N_3$

$E_1 < E_2 < E_3$



4-level laser





In a 4-level laser, only a few electrons are excited to achieve population inversion. Therefore, a 4-level laser produces light efficiently than a 3-level laser. In practical, more than four energy levels may be involved in the laser process.

Components of Laser

A laser or laser system consists of three important components:

- Pump source,
- Active medium
- Optical Resonator

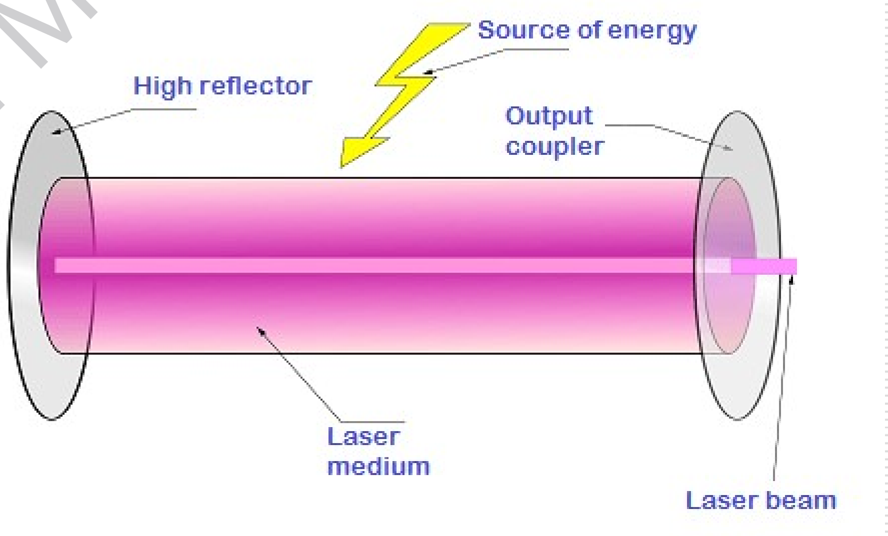
Components of Laser

Pump source:

- The pump source or energy source is the part of a laser system that provides energy to the laser medium. To get laser emission, first we need to produce population inversion.

Examples of energy source:

- ✓ electric discharges,
- ✓ light from another laser,
- ✓ chemical reactions,
- ✓ flash lamps.



Components of Laser

Active medium:

- The active medium is a medium in which laser action is made to take place. The laser medium will determine the characteristics of the laser light emitted.
- The laser medium can be solid, liquid, or gaseous where atoms/ions are lying in excited state to facilitate stimulated emission. It should capable of population inversion
- This is also called gain medium or laser medium

Example:

- ✓ Ruby laser is an example for solid-state laser. In this, a ruby crystal is used as an active medium. In this laser, xenon discharge tube which provides a flash light acts as pump source.
- ✓ Helium – Neon laser is an example for gaseous laser. In this, neon is used as an active medium. In this laser, radio frequency (RF) generator acts as pump source.

Components of Laser

Optical Resonator:

- The laser medium is surrounded by two parallel mirrors which provides feedback of the light. One mirror is fully reflective (100 % reflective) whereas another one is partially reflective (<100 % reflective). These two mirrors as a whole is called optical resonator. Optical resonator is also known as optical cavity or resonating cavity.
- The completely reflective mirror is called high reflector whereas the partially reflective mirror is called output coupler. The output coupler will allows amplified light to leave the optical cavity to produce the laser's output beam.
- This condition is must:

$$l = \frac{n\lambda}{2}$$

Where,
l = length of cavity,
λ = wavelength of laser
n= 1,2,3..

Methods of Achieving Population Inversion

- In order to achieve population inversion, we need to supply energy to the laser medium. The process of supplying energy to the laser medium is called pumping. The source that supplies energy to the laser medium is called pump source. The type of pump source used is depends on the laser medium.

- Optical pumping:
- Electric discharge or excitation by electrons
- Inelastic atom-atom collisions
- Direct conversion
- Chemical reactions

Methods of Achieving Population Inversion

- **Optical pumping**:
  - ✓ In this method, light is used to supply energy to the laser medium. For example xenon flash lamp
  - ✓ This method of pumping is used in solid state lasers such as ruby laser.

- **Electric discharge or excitation by electrons**:
  - ✓ In this method of pumping, electric discharge acts as the pump source or energy source.
  - ✓ A high voltage electric discharge (flow of electrons, electric charge, or electric current) is passed through the laser medium or gas.
  - ✓ The intense electric field accelerates the electrons to high speeds and they collide with neutral atoms in the gas. As a result, the electrons in the lower energy state gains sufficient energy from external electrons and jumps into the higher energy state.
  - ✓ This method of pumping is used in gas lasers such as argon lasers.

Methods of Achieving Population Inversion

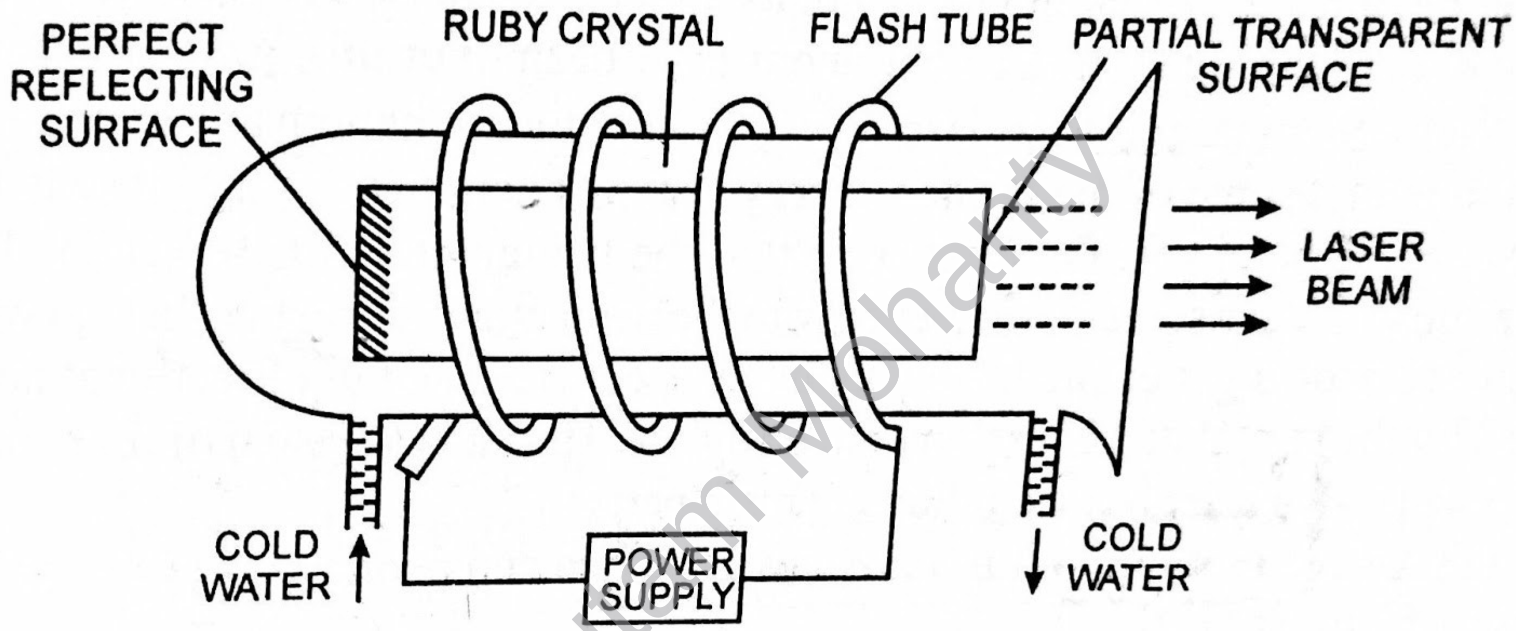
- **Inelastic atom-atom collisions**
  - In this method, pumping by electrical discharge provides the initial excitation which raises ONE type of atoms to their excited states. These atoms collide inelastically with another type of atoms and provide them sufficient energy to excite them to higher state and thus population inversion achieved
  - This method of pumping is used in gas lasers such as He-Ne laser.
- **Direct Conversion:**
  - In this method, the electrons combine with holes producing laser light. This it is direct conversion of electrical to light.
  - This method of pumping is used in gas lasers such as Semiconductor lasers.
- **Chemical Reaction:**
  - In this method, Radiation come out of a chemical reaction, without any need of other energy source. For example when hydrogen combine with fluorine, heat energy is produced
  - This method of pumping is used in gas lasers such as CO_2 lasers.

Ruby Laser

- In 1960, T. H. Maiman developed 1st Ruby Laser
- It is a 3-level solid state laser in which population inversion is achieved with the help of Xenon flash tube.
- It emits deep red light of wavelength 694.3 nm.

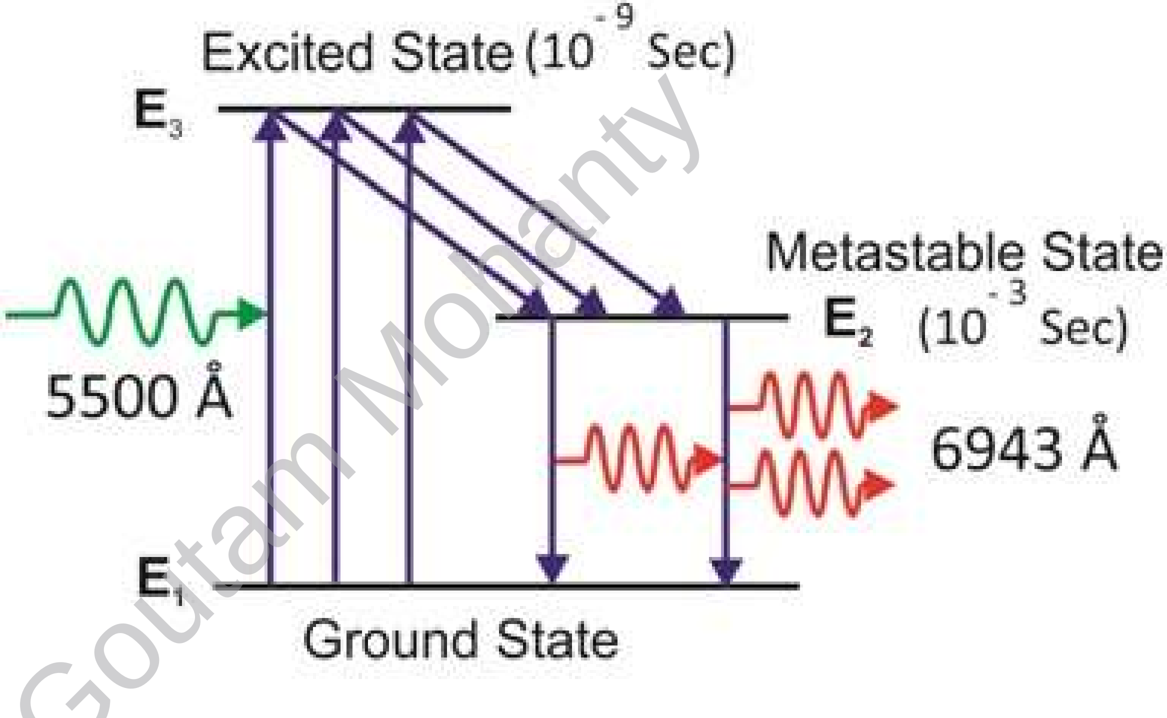
Construction:

- A ruby laser consists of three important elements: laser medium, the pump source, and the optical resonator.
- Laser medium: In a ruby laser, a single crystal of ruby ($Al_2O_3 : Cr^{3+}$) in the form of cylinder acts as a laser medium or active medium. The laser medium (ruby) in the ruby laser is made of the host of sapphire (Al_2O_3) which is doped with small amounts of chromium ions (Cr^{3+}). The length of the rod is about 2-30cm and diameter is 0.5-2cm.
- Energy Source: The Xenon flashtube is used as the energy source or pump source. The flashtube supplies energy to the laser medium (ruby). When lower energy state electrons in the laser medium gain sufficient energy from the flashtube, they jump into the higher energy state or excited state.



Optical Resonator: The ends of the cylindrical ruby rod are flat and parallel. The cylindrical ruby rod is placed between two mirrors. The optical coating is applied to both the mirrors. At one end of the rod, the mirror is fully silvered whereas, at another end, the mirror is partially silvered. The fully silvered mirror will completely reflect the light whereas the partially silvered mirror will reflect most part of the light but allows a small portion of light through it to produce output laser light.

❖ video



Energy Level Diagram of Ruby LASER

Drawback:

- ✓ It produces pulsed beam
- ✓ Efficiency is very low
- ✓ It requires high pumping power

He-Ne Laser

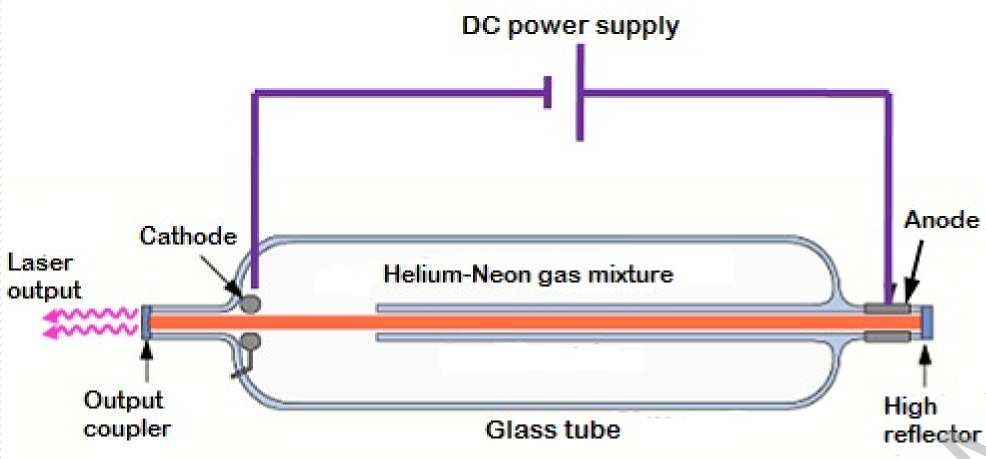
- In 1961, Ali Javan *et al*. developed He-Ne laser at Bell Telephone Laboratories, US.
- This laser is a 4-level as laser which produces continuous wave(CW).

Construction:

The helium-neon laser consists of three essential components

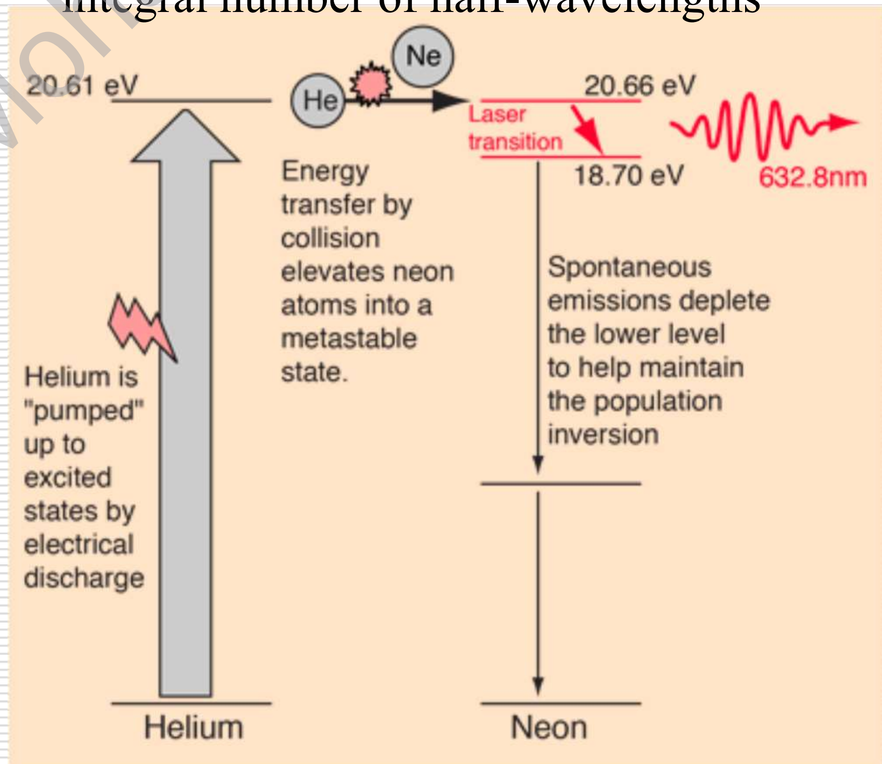
- ✓ Pump source (high voltage power supply)
- ✓ Gain medium (laser glass tube or discharge glass tube)
- ✓ Resonating cavity

He-Ne Laser



Construction:

- Mixture of gas He-Ne is 10:1
- Discharge tube 50cm length, 1 cm diameter
- Inside pressure is low at 1torr
- spacing of the mirrors is equal to an integral number of half-wavelengths



Working Principle:

- When the power is switched on
- He-atoms excited to 20.61eV
- He-atom give energy (0.05eV) to unexcited Ne-atom
- Ne-atom transit to 20.66eV
- Population inversion achieved
- Ne-atom transit from 20.66eV to 18.70eV
- Stimulation process occurs
- Laser having 632.8nm emits

He-Ne Laser

Advantages:

- Helium-neon laser emits laser light in the visible portion of the spectrum.
- High stability
- Low cost
- Operates without damage at higher temperatures

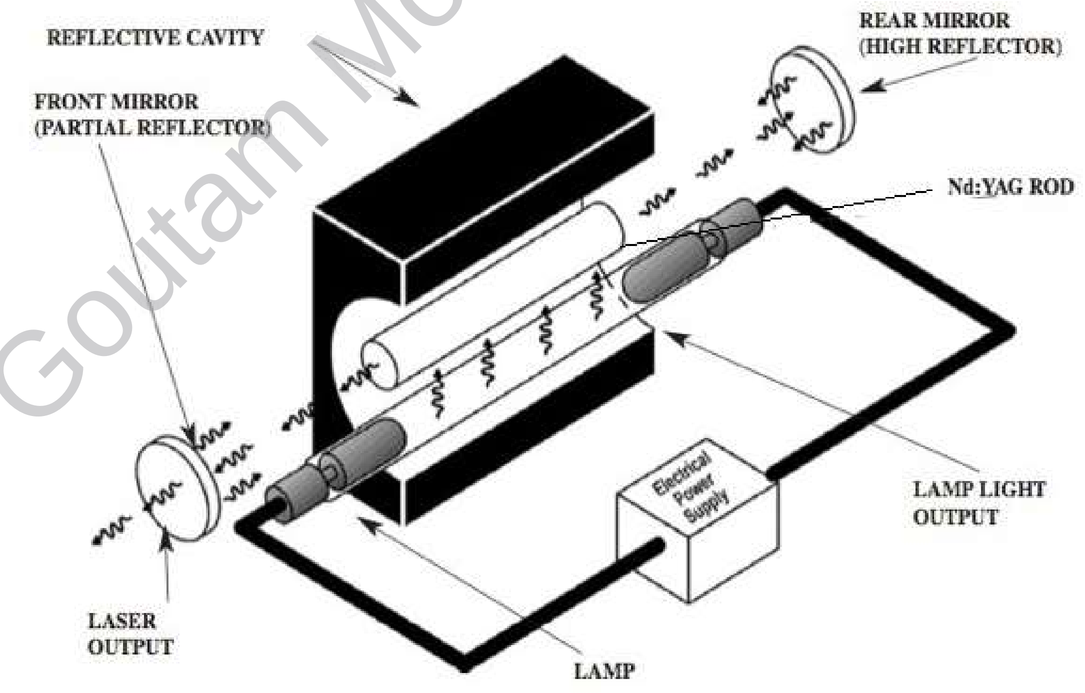
Applications:

- Helium-neon lasers are used in industries.
- Helium-neon lasers are used in scientific instruments.
- Helium-neon lasers are used in the college laboratories.

ND:YAG Laser

Introduction:

- It was developed by J.E.Geusic, H.M. Marcos and L.G. Van Vitert in 1964
- Nd stands for neodymium and YAG for Yttrium Aluminium Garnet ($Y_3Al_5O_{12}$).
- Nd: YAG is a solid state laser.
- It is 4-level laser.



ND:YAG Laser

Construction:

- The rod $Y_3Al_5O_{12}$ is doped with 1% neodymium ions and Y^{3+} ions replaced by Nd^{3+} ions.

- The maximum length of the rod is 10 cm and diameter is 6-9 cm.

- Active medium: Nd^{3+} ions acts as an active medium or active centers. YAG is just host.

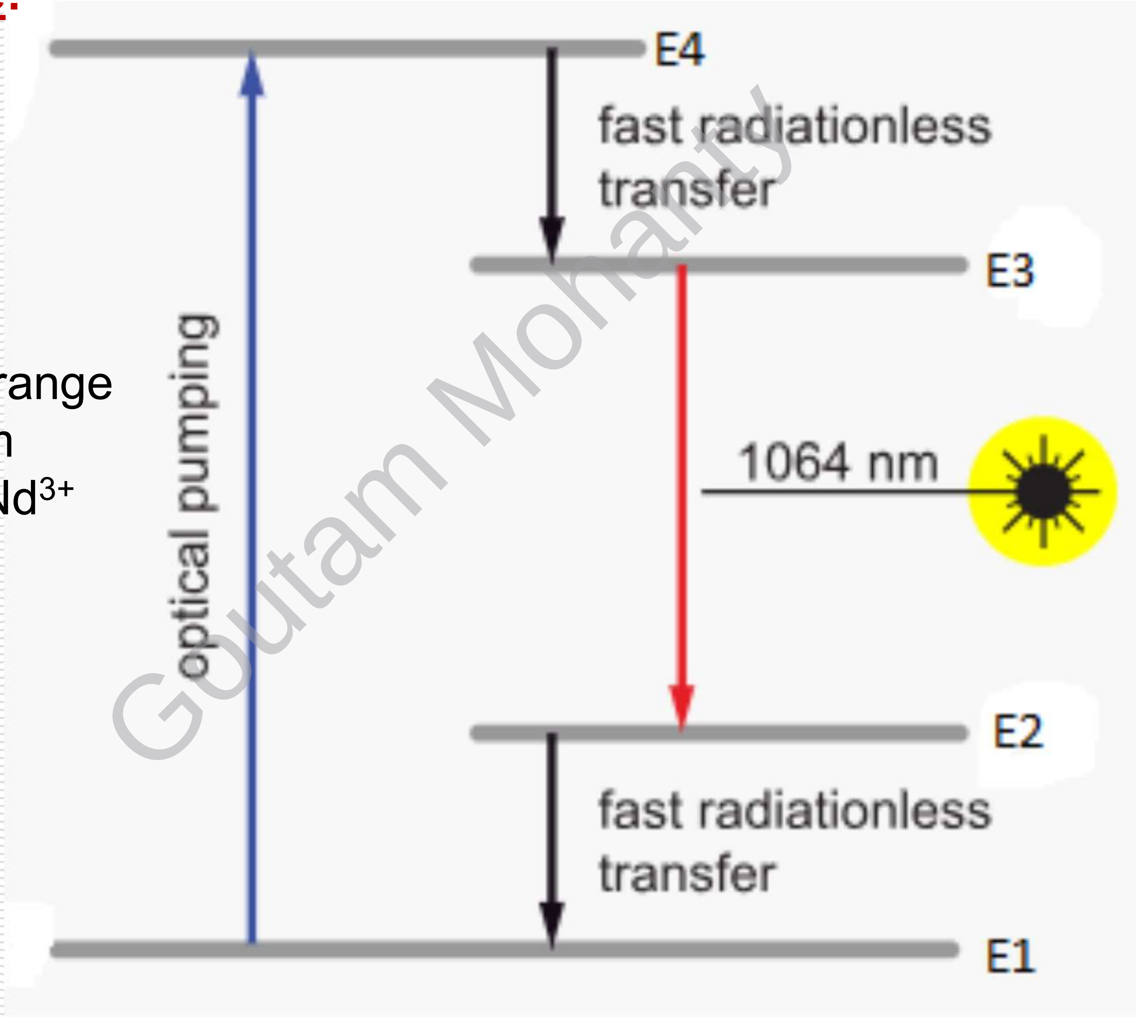
- Pumping source is xenon flash lamp or krypton flash lamp which excites Nd^{3+} ions to upper level

- Optical Resonator: The ends of the YAG rod are polished and silvered so as act as optical resonator.

ND:YAG Laser

Working Principle:

wavelength range 500 – 800nm excites the Nd^{3+} ions



ND:YAG Laser

Advantages

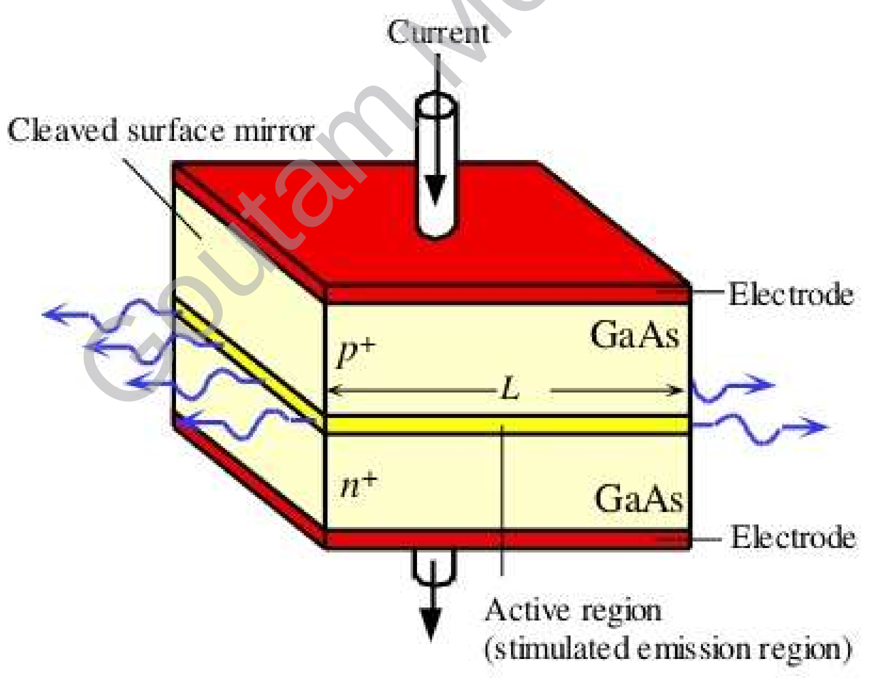
- CW is emitted
- Low power consumption
- Nd:YAG laser offers high gain.
- Nd:YAG laser has good thermal properties.
- Nd:YAG laser has good mechanical properties.
- The efficiency of Nd:YAG laser is very high(2%) as compared to the ruby laser(0.1%).

Applications

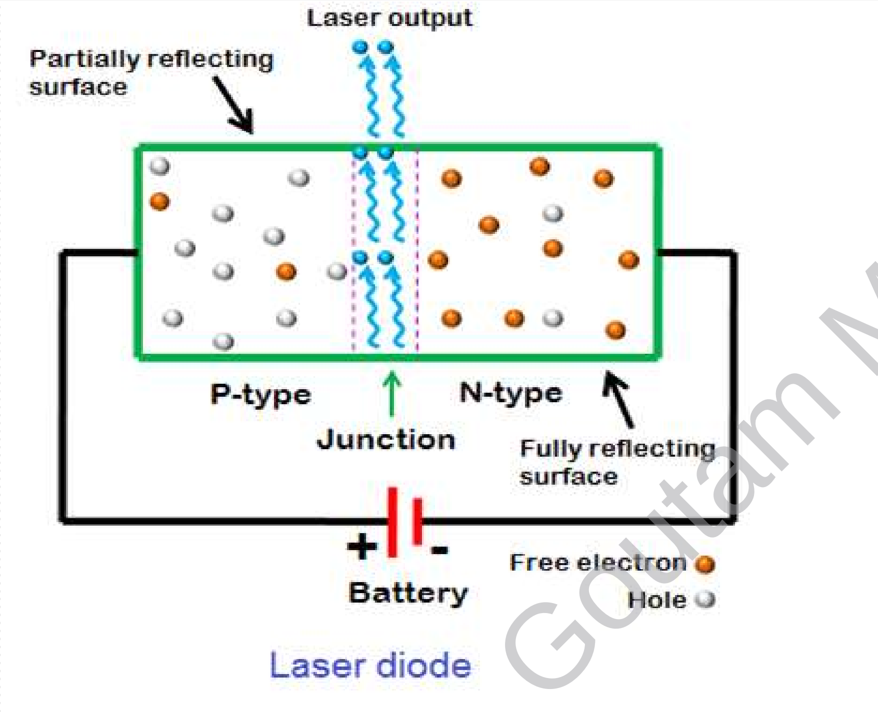
- Medical: remove skin cancers, to correct posterior capsular opacification (a condition that may occur after a cataract surgery).
- Nd:YAG lasers are used to remove skin cancers.
- Manufacturing: cutting and welding
- Nd:YAG lasers are used for etching or marking a variety of plastics and metals.
- Military

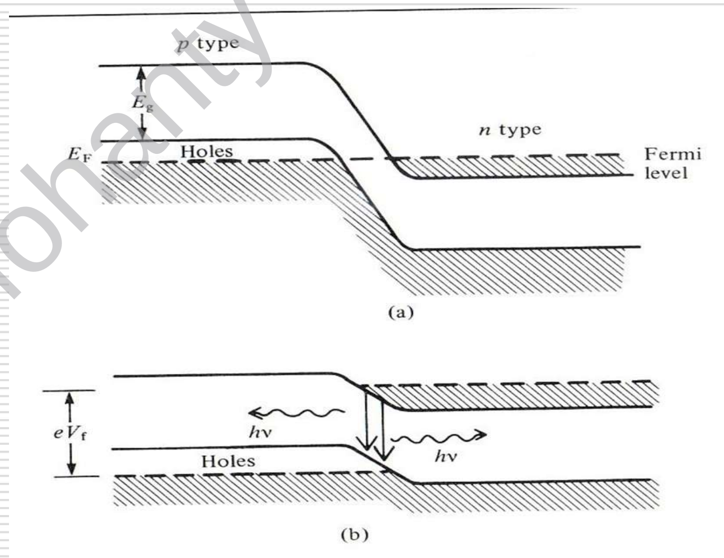
Semiconductor Laser

- In 1962, the 1st semiconductor laser at low temperature was developed by R.N. Hall and coworkers in USA.
- GaAs is used to make semiconductor laser.
- This laser is produces light in the infrared region(IR).
- Later semiconductor laser was developed in the visible region at room temperature.



Semiconductor Laser





Semiconductor Laser

Advantages:

- Simple construction
- Lightweight and portable
- Low cost
- Small size (0.1mm long)
- Highly reliable compared to other types of lasers.
- Longer operating life
- High efficiency (40%)
- Mirrors are not required in the semiconductor lasers.
- Low power consumption

Disadvantages:

- Not suitable for the applications where high powers are required.
- Semiconductor lasers are highly dependent on temperature

Applications:

- Laser diodes are used in laser pointers.
- Laser diodes are used in fiber optic communications.
- Laser diodes are used in barcode readers.
- Laser diodes are used in laser printing.
- Laser diodes are used in laser scanning.
- Laser diodes are used in range finders.
- Laser diodes are used in laser absorption spectrometry.

Applications of Laser

The most significant applications of lasers include:

- Lasers in medicine: destroy kidney stones, fiber-optic endoscope to detect ulcers in the intestines, eye lens curvature corrections, remove tumors successfully.

- Lasers in communications: optical fiber communications to send information over large distances with low loss, underwater communication networks, space communication, radars and satellites.

- Lasers in industries: cut glass and quartz, trimming the components of Integrated Circuits (ICs), photolithography.

- Lasers in science and technology: retrieve stored information from a CD, computer printers, detecting earthquakes and underwater nuclear blasts

- Lasers in military: determine the distance to an object, LiDAR's to accurately measure the distance to an object.