LASERS

Introduction

⊕ LASER stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation i.e. light gets amplified several times by the process called *Stimulated Emission*.

⊕ The laser light is treated as radiation of light having photons of energy $h\nu$, where ν is the frequency of the incident radiation.

⊕ Laser is a device that produces light (electromagnetic radiation) which is highly intense, highly coherent, highly directional and powerful.

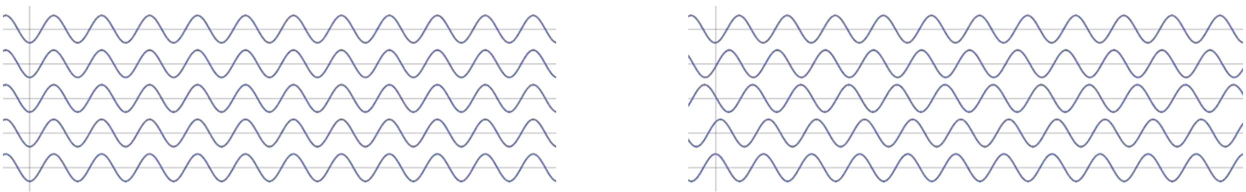
⊕ The first working laser was invented by T. Maimann in 1960.

⊕ The prominent applications of lasers are in optical storage device, barcode scanners, fiber optic communications, industries, military and printers etc.

Characteristics of Laser Light

1. Coherence

Coherence is one of the unique properties of laser beam. Different parts of laser beam are related to one another by phase. These phase relationship is maintained over long enough time. Due to this property we can form holograms with lasers.



Phase relationship between any two light beams

2. Monochromaticity

A laser beam is more or less in single wave length.*Mono*- means single and C*hrome* means color i.e. single wavelength. So, laser radiation is said to be highly monochromatic. The spectrum of the laser beam is pure i.e. the spectral width of laser is very very small order ($\Delta\lambda = 10^{-6}$ Å).

3. Directionality

Laser beam is highly directional because laser emits light only in one direction. It can travel very long distances without divergence and less loss of energy. The directionality of a laser beam has been expressed in terms of ***divergenc***e. Suppose if r_1 and r_2 are the radii of laser beam at distances D_1 and D_2 from a laser, and then we have,

Then the divergence, $\Delta\theta = (r_1 - r_2)/ D_2 - D_1$

The divergence for a laser beam is 0.01 milli-radian where as incase of search light it is 0.5 radian.

4. High intensity

In a laser beam lot of energy is concentrated in a small region. This concentration of energy exists both spatially and spectrally, hence there is enormous intensity for laser beam. This is because of highly coherent and low divergence value.

<u>Interaction of radiation with matter</u>

In lasers, the interaction between matter and light radiation is of three different types.

- ⊕ Stimulated Absorption
- ⊕ Spontaneous Emission
- ⊕ Stimulates Emission

(a) Stimulated Absorption: Let us consider two energy states E_1 and E_2 such that $E_1 < E_2$. Assume N_1 and N_2 are the number of atoms in lower energy level E_1 and higher energy level E_2 respectively such that $N_1 > N_2$. If a photon of energy $h\nu = (E_2 - E_1)$ is incident on atoms present in lower energy E_1 then the atoms completely absorbs the incident photon and makes transition to higher energy state E_2. This process is called stimulated absorption.

The rate of transition of atoms from lower energy level to higher energy level depends on properties of energy states E_1 and E_2 and energy of incident photon.

The rate of transition is given by $\mathbf{(P_{12})_{ab} = A_{12}\, u(\nu)}$

Where A_{12} is the Einstein coefficient of stimulated absorption and $u(\nu)$ energy density.

(b) Spontaneous emission: Let us consider two energy states E_1 and E_2 such that $E_1 < E_2$. Assume N_1 and N_2 are the number of atoms in lower energy level E_1 and higher energy level E_2 respectively such that $N_1 > N_2$. An atom initially present in the higher energy state remains only for 10^{-8} seconds (life time) and makes transition voluntarily on its own to the ground state and emits a photon of energy $h\nu$ ($=E_2 - E_1$). This is called spontaneous emission. These emitted photons are incoherent. (Photons travels in different direction)

The spontaneous emission depends on properties of energy states E_1 and E_2 only.

The rate of transition is given by $\mathbf{(P_{21})_{sp} = A_{21}}$

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

(c) Stimulated emission: Let us consider two energy states E_1 and E_2 such that $E_1 < E_2$. Assume N_1 and N_2 are the number of atoms in lower energy level E_1 and higher energy level E_2 respectively such that $N_1 > N_2$. An atom in higher energy state under the influence of other external incoming photon is forced to make a transition to lower energy level without completing life time, then such process is called stimulated emission. Here the emitted photon is in phase with the incident photon (Cohrent Photons).In this process all the emitted photons travel in same direction.

The stimulated emission depends on properties of energy states E_1 and E_2 and energy of incident photon $u(\nu)$.

The rate of transition is given by $(P_{21})_{st} = B_{21}\, u(\nu)$

Where B_{21} is the Einstein coefficient of stimulated emission and u(ν) energy density.

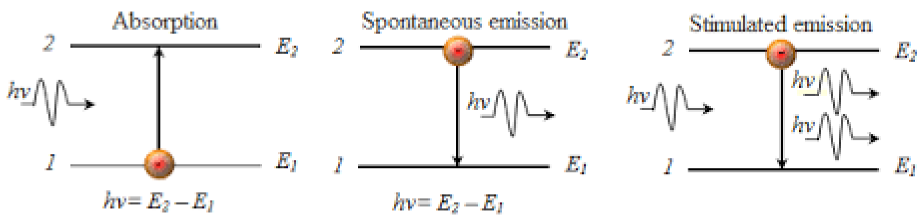


Fig. (a) Absorption ;(b) Spontaneous emission;(c) Stimulated emission

Differences between Spontaneous emission and stimulated emission of radiation

Spontaneous emission	Stimulated emission
1. Polychromatic radiation	**1.** Monochromatic radiation
2. Less intensity	**2.** High intensity
3. Only one photon emits in this process.	**3.** Two photons are emitted in this process.
4. Photons are not in phase and travel in all directions.	**4.** Photons are in phase and travels in only one direction.
5. Incoherent and low intensity	**5.** Coherent and highly intense
6. Spontaneous emission takes place when excited atoms make a transition to lower energy level voluntarily without any external stimulation.	**6.** Stimulated emission takes place when a photon of energy equal to $h\nu_{12}$ (=E_2-E_1) stimulates an excited atom to make transition to lower energy level.

<u>Einstein's Coefficients of LASERS and relation between them</u>

Let N_1 be the number of atoms per unit volume with energy E_1 and N_2 the number of atoms per unit volume with energy E_2. Let 'n' be the number of photons per unit volume at frequency ν such that $h\nu = E_2 - E_1$. Then the energy density of interacting photons u(v) is given by

$$u(\nu) = n\, h\, \nu \qquad \rightarrow (1)$$

When these photons interact with atoms, both upward (absorption) and downward (emission) transitions occur.

<u>Upward Transition</u>

Stimulated absorption rate depends on the number of atoms available in the lower energy state for absorption of photons as well as the energy density of interacting radiation.

i.e. stimulated absorption rate of transition α N_1

α u(ν)

therefore rate of transition = $A_{12}N_1$ u(ν) → (2)

Where the constant of proportionality A_{12} is the Einstein coefficient of stimulated absorption

Downward transition

This spontaneous emission rate depends on the number of atoms in the excited energy state.

i.e., spontaneous emission rate α N_2

Rate of transition is =N_2 A_{21} → (3)

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

Stimulated emission

The stimulated emission rate depends on the number of atoms available in the excited state as well as energy density of interacting photons

I.e. stimulated emission rate α N_2

α u(ν)

rate of transition = N_2u(ν) B_{21} → (4)

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

For a system in equilibrium, the upward and down word transition rates must be equal and hence we have

$$N_1 u(\nu) A_{12} = N_2 u(\nu) B_{21} + N_2 A_{21} \quad \rightarrow (5)$$

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

$$u(\nu) = \frac{A_{21}/B_{21}}{(A_{12}/B_{21})(N_1/N_2) - 1} \rightarrow (6)$$

The population of various energy levels in thermal equilibrium is given by Boltzmann distribution law.

$$N_i = g_i N_o \exp(-E_i / KT)$$

Where N_i is the population density of the energy level E_i, N_0 is the population density of the ground state at temperature T, g_i is the degeneracy of the i^{th} level and k is the Boltzmann constant (k =1.38x10^{-23}joule/k).

Hence population density for lower energy state $E_1$is $N_1 = g_1 N_o \exp(-E_1/kT)$

population density for higher energy state $E_2$is $N_2 = g_2 N_o \exp(-E_2/kT)$

Now, $$\frac{N_1}{N_2} = \frac{g_1}{g_2} \exp\left[\frac{(E_2 - E_1)}{kT}\right]$$

$$\frac{N_1}{N_2} = \frac{g_1}{g_2} \exp\left[\frac{h\nu}{kT}\right] \rightarrow (7)$$

Substituting eq (7) in eq (6) $u(\nu) = \frac{[A_{21}/B_{21}]}{[\frac{A_{12}g_1}{B_{21}g_2}\exp[\frac{h\nu}{kT}]-1]}$ → (8)

From Planck's law of blackbody radiation, the radiation density is given by

$$u(\nu) = \frac{8\pi h\nu^3}{C^3}\frac{1}{\exp[\frac{h\nu}{kT}]-1} \rightarrow (9)$$

Comparing equations (8) and (9), we get

$$\frac{A_{12}\, g_1}{B_{21}\, g_2} = 1$$

If $g_1 = g_2$ then,

$$A_{12} = B_{21} \rightarrow (10)$$

i.e. the Einstein's coefficient of stimulated absorption is equal to coefficient of stimulated emission.

And $$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{C^3} \rightarrow (11)$$

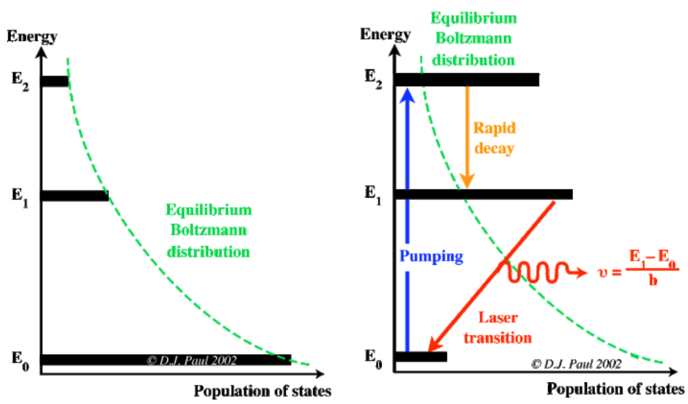
i.e. the ratio of coefficient of spontaneous emission to stimulated emission is proportional to the cube of frequency of the incident radiation.

Equation's (10) and (11) are referred to as the Einstein coefficients relation.

Population inversion

Usually in a system the number of atoms (N_1) present in the ground state (E_1) is larger than the number of atoms (N_2) present in the higher energy state. If the number of atoms is more in higher energy level than the number of atoms of lower energy level ($N_2>N_1$) is called population inversion. Conditions for population inversion are:

a) There should be a continuous supply of energy to the system such that the atoms must be raised continuously to the excited state.



Pumping

Population inversion can be achieved by a number of ways. The process of supplying suitable energy to the medium to achieve population inversion is called *pumping*. Some of the pumping methods are

(i) optical pumping

(ii) electrical discharge

(iii) chemical reaction

(iv) direct conversion

Metastable state

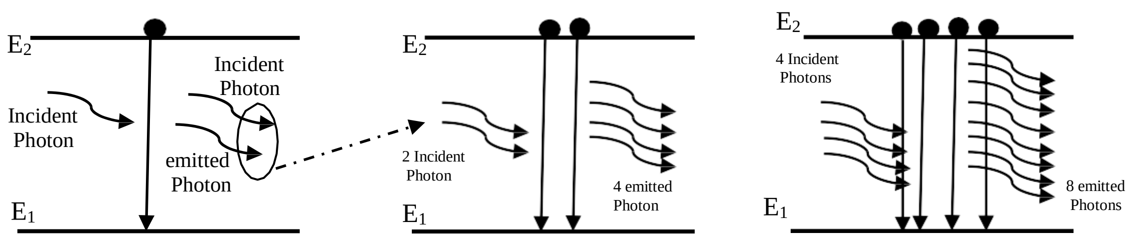
Meta-stable state is a particular excites state of an atom having longer life time than any other normal excited state but lesser than ground state. A meta-stable state can be considered as a energy trap or stable intermediate state. The existence of meta-stable state is necessary for lasers to occur lasing action. The atoms stay longer time in this state and provide necessary mechanism to achieve population inversion.

Life time

The amount of time in which the atoms stays in an excited state is called life time. The life time of an atom in excited state is 10^{-8} seconds and life time of atom in metastable state is 10^{-3} seconds.

Lasing action

The principle of lasing action is based on stimulated emission. We know that in stimulated emission, the emitted photon travels in the direction of incident photon. When these two photons incident on other two atoms in higher energy level (E_2) two stimulated emission occur, so that 4 photons are emitted as shown in figure. Again these four photons causes four stimulated emissions and 8 photons are emitted. In this way a chain reaction takes place and avalanche of photons are emitted. This is called lasing action.

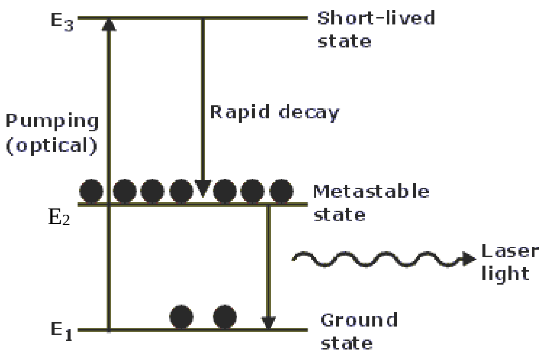


Pumping Schemes

There are two types of pumping schemes

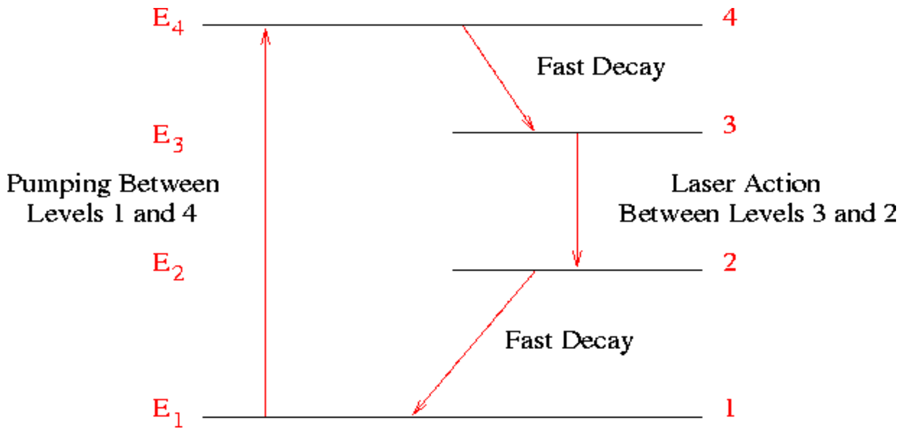
1) Three level pumping scheme 2) Four level pumping scheme

Three level pumping scheme: In this there are three energy levels E_1, E_2 and E_3 where E_1 is the ground state and other two levels E_2 and E_3 are excited states. Initially most of the atoms are in E_1 state but when the pumping is initiated, the atoms raises to E_3 state known as pump band. The excited atoms form E_3transfers to E_2 state by non-radiative transitions. The state E_2 is called metastable state and population inversion exists between E_2 and E_1. The atoms in E_2 state now return to E_1 by emitting photons. This is known as LASER transition.



A three level pumping scheme

Four level pumping scheme: In this there are four energy levels E_1, E_2, E_3 and E_3 where E_1 is the ground state and other three levels E_2,$E_3$and $E_4$are excited states. Initially most of the atoms are in E_1 state but when the pumping is initiated, the atoms raises to E_4 state known as pump band. The excited atoms form E_4 transfers to E_3 state by non-radiative quick transitions. The state E_3 is called meta-stable state and population inversion exists between E_3 and E_2. Atoms in E_2 decay to rapidly to ground state E_1 by non-radiative quick transitions.



A Four level pumping scheme

Components of LASER

Any type of Laser device consists of three parts. They are

1. **Active medium**: It consists of collection of atoms, molecules or ions which is capable of producing stimulated emissions. The active medium may be a solid, a liquid or a gas depending on type of laser.
2. **Pumping source**: The pumping source supplies the required energy to pump the atoms from lower energy level to higher energy level. This pumping provides favorable conditions for population inversion.
3. **Optical feedback**: The general function of laser depends on is based on optical feedback. The photons emitted from the active medium are reflected back and forth by the mirrors. In this

way the optical feedback is maintained and controls the process of stimulated emission. This is also called resonating cavity.

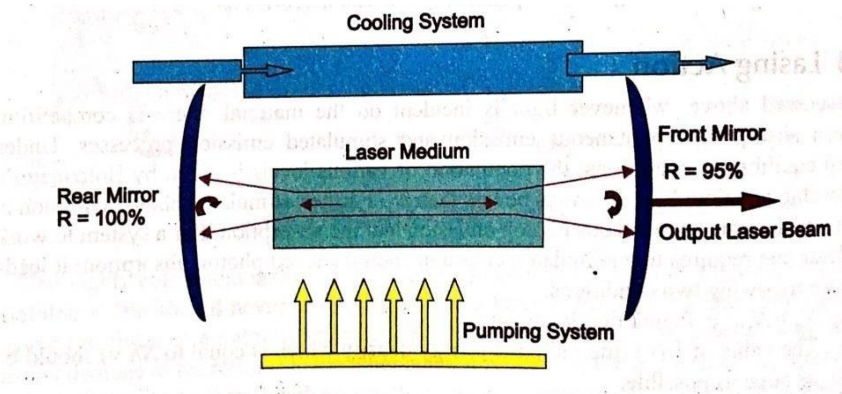


Fig. 15.4: Basic laser system

Types of LASERS

LASERS are classified into five categories depending on type active medium. They are (i) Solid state Lasers (ii) Gas Lasers (iii) Liquid Lasers (Dye Laser)(iv) Diode Lasers.

Most of the LASERS emit light in visible region and some emit light in infrared region. Lasers can be operated in continuous wave mode or pulsed wave mode.

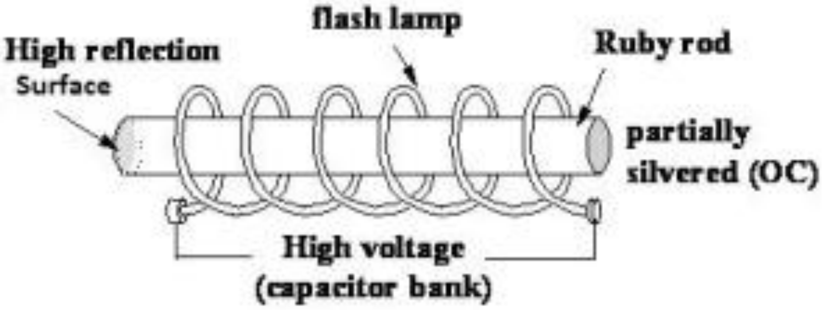
Ruby Laser

Ruby Laser is a solid state laser which is a pulsed wave mode and three level laser. Basically, ruby crystal is aluminum oxide [Al_2O_3] doped with 0.05 to 0.5% of chromium ions. These Cr^{+3}ions acts as active centers in Ruby laser which absorbs blue and green light. Due to presence of chromium, the ruby crystal appears in pink color.

Construction:

Ruby (Al_2O_3+Cr_2O_3) is a crystal of Aluminum oxide in which some of Al^{+3} ions are replaced by Cr^{+3} ions. When the doping concentration of Cr^{+3} is about 0.5%, the color of the rod becomes pink. The active medium in ruby rod is Cr^{+3}ions. In ruby laser a rod of 4cm long and 5mm diameter is used and the ends of the rod are highly polished. Both the ends of rod are coated with silver in such a way that one end is fully reflecting (Reflectance = 100%) and the other end is partially reflecting (Reflectance ≅ 95%).

The ruby rod is surrounded by helical xenon flash lamp tube which provides the optical pumping to raise the Chromium ions to upper energy level. The xenon flash lamp tube which emits intense pulses which lasts only few milliseconds and the tube consume several thousands of joules of energy.

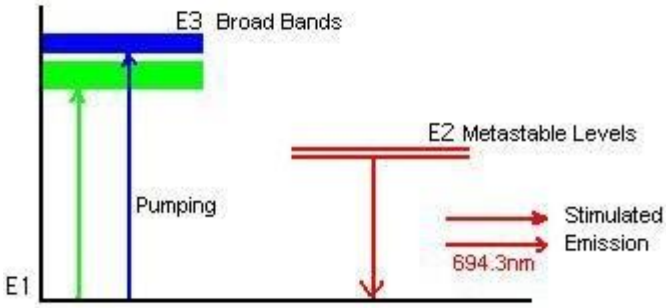


Ruby laser construction

Working:

1. Pumping Mechanism
   a. When the xenon flash lamp is switched ON, an intense flash of white light excites (which lasts for milliseconds) the Cr^{+3} ions to energy band E_3 (Pumping band) by absorbing light.
   b. The Cr^{+3}ions make a quick non-radiative transition to E_2 energy state.
   c. The energy state E_2 is a meta-stable state which has life time of 10^{-3} seconds. Therefore more number of Cr^{+3}ions accumulates at E_2 level.
2. Population Inversion
   a. As more number of Cr^{+3} ions accumulates in energy level E_2, population inversion is established between energy states E_2 and E_1.
3. Lasing action
   a. Photons are emitted spontaneously by few atoms in energy state E_2.
   b. These photons initiate stimulated emission by de-exciting the Cr^{+3}ion to lower energy state E_1 forcibly and emits photons.
   c. All photons travel along the axis of the ruby rod by reflecting back and forth between the two ends of mirror and triggers more stimulated emissions.
   d. Once all the photons attain sufficient energy, the laser beam emerges out through partially reflecting mirror. The laser emission occurs in visible region at wavelength of 6943 Å.

Once the stimulated transition starts, the metastable state E_2 depopulates very quickly and lasing action stops.The laser becomes active once again when the population inversion is established by pumping (flashing of Xenon lamp). Therefore the laser output is not continuous wave but occurs in form of pulses of duration in milli-seconds. So Ruby laser is a pulse wave laser.



Drawbacks of ruby laser:

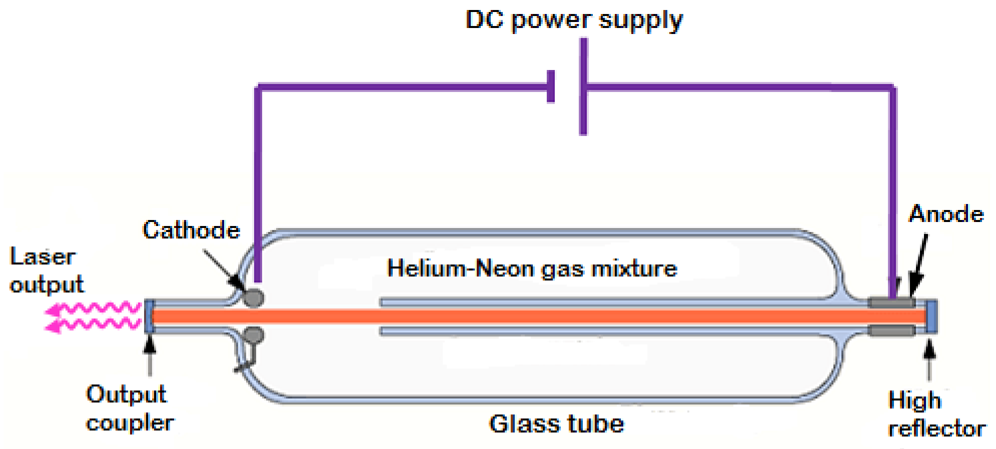
1. The laser requires high pumping power to achieve population inversion.
2. It is a pulsed laser.

Helium-Neon LASER

Helium-Neon gas laser is a continuous wave four level laser. It consists of a long, narrow cylindrical tube made up of quartz. The diameter of the tube will vary from 2 to 8 mm and length will vary from 10 to 100 cm. The tube is filled with helium and neon gases in the ratio of 10:1. The pressure of gas mixture is nearly 1 mm of Hg.

Construction

Laser action is due to the neon atoms. Helium is used for selective pumping of neon atoms to upper energy levels. Two electrodes are fixed near the ends of the tube to pass electric discharge through the gas. Two optically plane mirrors are fixed at the two ends of the tube at Brewster angle normal to its axis. One of the mirrors is fully silvered so that nearly 100% reflection takes place and the other is partially silvered so that 3% of the light incident on it will be transmitted.



Working

Pumping Mechanism:

1. When the power is switched ON, a high voltage of about 10kV is applied across the glass tube where the gas mixture inside the tube ionizes.
2. The electrons and ions produced in this process collide with helium atoms on the way since there are more number of helium atoms than neon atoms.
3. After collision the helium atom excites to higher energy state F_2 (energy= 20.61 eV) which is a meta-stable state.
4. The excited helium atoms return to ground level by transferring the energy to neon atoms through collisions. Such an energy transfer is called as resonating energy transfer.

5. The neon energy level is E_6 (energy= 20.66 eV) which is close to helium atom energy level F_2 (energy= 20.61 eV). Therefore energy transfer takes between these energy levels (F_2 and E_6).

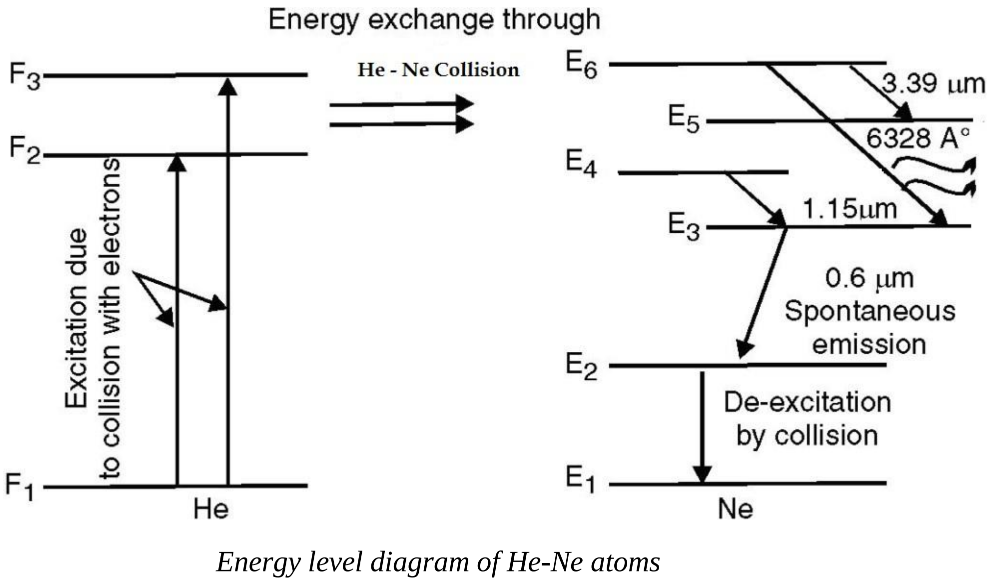
Population Inversion:

1. The upper energy state of neon atoms E_6 is a meta-stable state. Therefore accumulation of neon atoms is more in this energy level.
2. The energy state $E_3$is less populated at ordinary temperatures, so there exists a population inversion between E_6 and E_3 energy states.

Lasing action:

1. Photons are emitted spontaneously by few atoms in energy state E_6.
2. These spontaneous photons travel through gas mixture and initiate stimulated emissions of Photons of wavelength 6328Å (red color).
3. The photons reflect back and forth between the polished mirrors, triggers number of stimulated emissions at each stage.
4. When the stimulated photons gain sufficient energy, they come out from the partially reflecting mirror.
5. Thus the transition between $E_6 \rightarrow E_3$ is a laser beam of wavelength 6328Å (red color).
6. The neon atoms come to ground state E_1 by colliding with the walls of glass tube.

Here the neon atoms are excited to higher energy state continuously through collision with helium atoms, so the population inversion in maintained all the time. Hence the laser operates in continuous wave mode.



Energy level diagram of He-Ne atoms

Applications of Lasers

Lasers find applications in various fields. They are described below.

a) In Communications :

Lasers are used in optical fiber communications. In optical fiber communications, lasers are used as light source to transmit audio, video signals and data to long distances without attention and distortion.

b) The narrow angular spread of laser beam can be used for communication between earth and moon or to satellites.

c) As laser radiation is not absorbed by water, so laser beam can be used in under water (inside sea) communication networks.

2. Industrial Applications

a) Lasers are used in metal cutting, welding, surface treatment and hole drilling. Using lasers cutting can be obtained to any desired shape and the curved surface is very smooth.

b) Welding has been carried by using laser beam.

c) Dissimilar metals can be welded and micro welding is done with great case.

d) Lasers beam is used in selective heat treatment for tempering the desired parts in automobile industry

e) Lasers are widely used in electronic industry in trimming the components of ICs

3. Medical Applications

1. Lasers are used in medicine to improve precision work like surgery. Brain surgery is an example of precision surgery Birthmarks, warts and discoloring of the skin can easily be removed with an unfocussed laser. The operations are quick and heal quickly and, best of all, they are less painful than ordinary surgery performed with a scalpel.

2. Cosmetic surgery (removing tattoos, scars, stretch marks, sun spots, wrinkles, birthmarks and hairs).

3.Laser types used in dermatology include ruby(694nm),alexandrite(755nm),pulsed diode array(810nm), Nd:YAG(1064nm), HO:YAG(2090nm), and Er:YAG(2940nm)

4. Eye surgery and refracting surgery.

5. Soft tissue surgery: Co_2Er :YAG laser.

6. Laser scalpel (general surgery, gynecological, urology, laparoscopic).

7. Dental procedures.

8. Photo bio modulation (i.e. laser therapy)

9. “No-touch” removal of tumors, especially of the brain and spinal cord.

10. In dentistry for caries removal, endodontic/periodontic, procedures, tooth whitening, and oral surgery.

4. Military Applications

The various military applications are:

a) **Death rays**: By focusing high energetic laser beam for few seconds to aircraft, missile, etc can be destroyed. So, these rays are called death rays or war weapons.

b) **Laser gun:** The vital part of energy body can be evaporated at short range by focusing highly convergent beam from a laser gun.

c) **LIDAR (Light detecting and ranging)**: In place of RADAR, we can use LIDAR to estimate the size and shape of distant objects or war weapons. The differences between RADAR and LIDAR are that, in case of RADAR, Radio waves are used where as incase of LIDAR light is used.

5. In Computers: By using lasers a large amount of information or data can be stored in CD-ROM or their storage capacity can be increased. Lasers are also used in computer printers.

6. In Thermonuclear fusion: Toinitiate nuclear fusion reaction, very high temperature and pressure is required. This can be created by concentrating large amount of laser energy in a small volume. In the fusion of deuterium and tritium, irradiation with a high energy laser beam pulse of 1 nano second duration develops a temperature of 10^{17} ^{0}C, this temperature is sufficient to initiate nuclear fusion reaction.

5. In Scientific Research: In scientific, lasers are used in many ways including

a) A wide variety of interferometrie techniques.

b) Raman spectroscopy.

c) Laser induced breakdown spectroscopy.

d) Atmospheric remote sensing.

e) Investigating non linear optics phenomena

f) Holographic techniques employing lasers also contribute to a number of measurement techniques.

g) Laser (LADAR) technology has application in geology, seismology, remote sensing and atmospheric physics.

h) Lasers have been used abroad spacecraft such as in the cassini-huygens mission.

i) In astronomy lasers have been used to create artificial laser guide stars, used as reference objects for adaptive optics telescope.