

LASER

[Light Amplification by Stimulated Emission of Radiation]

→ Laser, a device that stimulates atoms or molecules to emit light at particular wavelengths & amplifies that light, typically producing a very narrow beam of radiation.

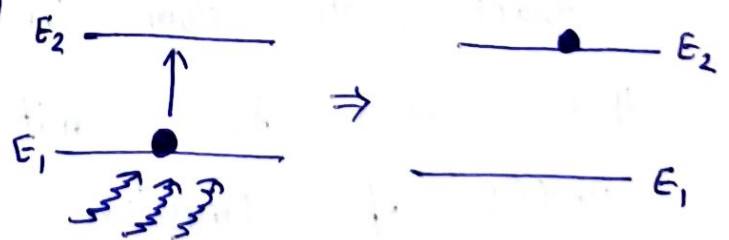
→ The theoretical basis for the development of laser was provided by Albert Einstein in 1917.

Definitions: — Production of LASER is a particular consequence of interaction of radiation with matter.

1. Stimulated absorption (Absorption) ⇒

Let us consider 3 energy levels in an atom. The lower energy level is E_1 & higher energy level is E_2 . As the atom or particle initially in E_1 & can be raised to E_2 by absorbing some energy incident on it in form of light.

The probability of this transition depends on the two energy levels under consideration. It also depends on no. of photons incident on system.



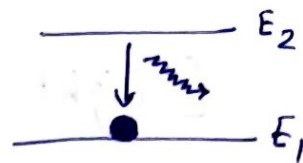
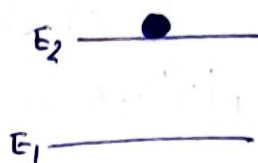
$$P_{12} \propto \rho(\nu), \quad P_{12} = B_{12} \rho(\nu)$$

So the rate of absorption will be

$$R_{12} = N_1 B_{12} \rho(\nu) \quad \text{--- (1)}$$

2. Spontaneous Emission

~~2.~~ When atom is excited to higher energy level, has small life time (10^{-8} sec).



So it can jump from higher energy level to its ground state by emitting a photon of frequency. This is called as spontaneous emission.

$$P_{21} = A_{21}$$

$$R_{21} = N_2 A_{21} \quad \text{--- (2)}$$

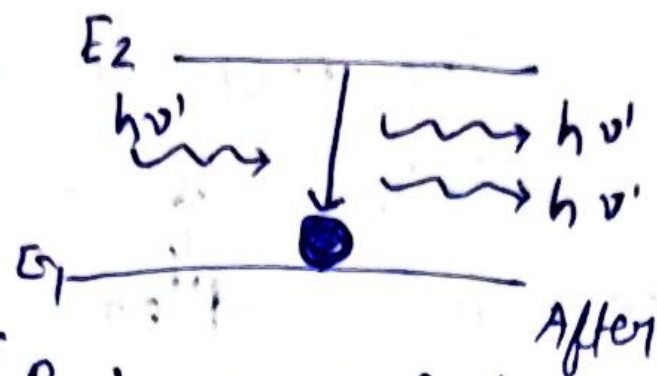
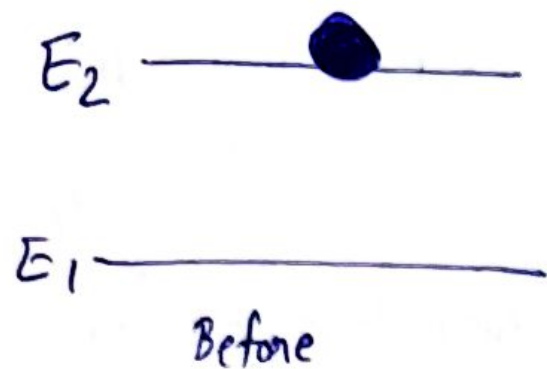
where N_2 = No. of atoms in E_2

R_{21} = Rate of no. of atom going from 2nd energy to 1st energy level

A_{21} = Einstein's co-efficient of spontaneous emission.

~~3.~~ Stimulated Emission:-

As per Einstein when energy incident on system it is not essential that it may always be absorbed by ground state atom. It can also interact with atom in excited state & induce that atom to emit a new photon. This process of emission is known as induced or stimulated emission.



$$(P_{21})_i \propto u(\nu)$$

$$(P_{21})_i = B_{21} u(\nu)$$

$$(R_{21})_i = N_2 B_{21} u(\nu) \quad \text{--- (3)}$$

Where $N_2 =$ No. of atoms in E_2

$(R_{21})_i =$ Rate of no. of atom going from 2nd energy to 1st energy level

$B_{21} =$ Einstein co-efficient of spontaneous emission.

Relation B/w Einstein's Coefficient

$$(R_{12})_{\text{ABS}} = N_1 B_{12} u(\nu) \quad \text{--- ①} \quad \checkmark$$

$$(R_{21})_{\text{SPE}} = N_2 A_{21} \quad \text{--- ②} \quad \checkmark$$

$$(R_{21})_{\text{STE}} = N_2 B_{21} u(\nu) \quad \text{--- ③} \quad \checkmark$$

And in thermal equilibrium

Rate of absorption = rate of emissions

$$\text{Rate of absorption} = (R_{21})_{\text{SPE}} + (R_{21})_{\text{STE}}$$

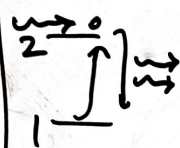
$$(R_{12})_{\text{ABS}} = (R_{21})_{\text{SPE}} + (R_{21})_{\text{STE}}$$

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

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

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

Dividing numerator & denominator by $N_2 B_{21}$



$$u(\nu) =$$

$$\frac{\frac{N_2 A_{21}}{N_2 B_{21}}}{\frac{N_1 B_{12}}{N_2 B_{21}} - \frac{N_2 B_{21}}{N_2 B_{21}}}$$

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

$$u(\nu) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left[\frac{N_1}{N_2} - 1\right]} \quad \text{--- ④}$$

Relation B/w Einstein's Coefficient

According to Boltzmann's
Distribution Law

$$N_1 = N_0 \cdot e^{-E_1/k_B T} ; N_2 = N_0 \cdot e^{-E_2/k_B T}$$

$$\frac{N_2}{N_1} = \frac{N_0 e^{-E_2/k_B T}}{N_0 e^{-E_1/k_B T}}$$

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

$$\therefore E_2 - E_1 = h\nu$$

$$\Rightarrow \mu(\nu) = \left(\frac{A_{21}}{B_{21}} \right) \frac{1}{\left(\frac{B_{12}}{B_{21}} \cdot e^{h\nu/k_B T} - 1 \right)} \quad \text{--- (5) } \left[\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3} \right] \Rightarrow \frac{A_{21}}{B_{21}} \propto \nu^3 \quad \text{--- (1)}$$

→ According to Planck's radiation Law $\frac{B_{12}}{B_{21}} = 1$

$$\mu(\nu) = \frac{8\pi h \nu^3}{c^3} \cdot \frac{1}{\left(e^{h\nu/k_B T} - 1 \right)} \quad \text{--- (6)}$$

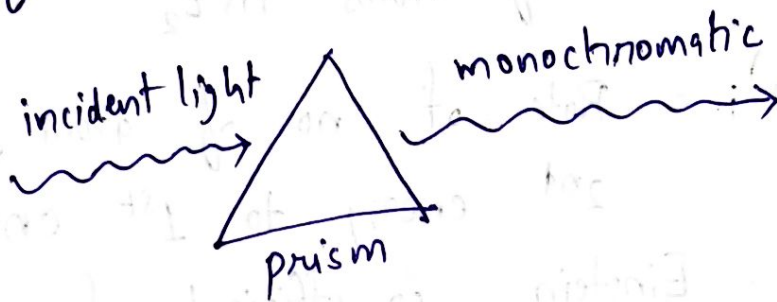
$$B_{12} = B_{21} \quad \text{--- (2)}$$

Basic Properties of a Laser :-

Laser light source when compared with any conventional light source, it shows some extraordinary characteristics given as follows:

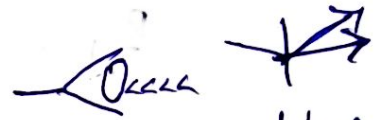
1. Monochromaticity ✓
2. High Intensity ✓
3. High Directionality ✓
4. Coherence ✓

1. Monochromaticity:- The property of exhibiting the emission of a single wavelength by a light source is called monochromaticity.
When laser is passed through a prism then a single line will be appeared in the optical spectrum, but not in case of ordinary light.



2. Directionality:-

During the propagation of laser its angular spreading is very small & possessed very less where it is incident.



3. Intensity:- Due to its lower spreading property many beams of light incident in a small area, hence intensity of laser light is very sharp. Due to this property it is used for the laser welding.

4. Coherence :- In case of conventional light, the property of coherence exists between a source & its virtual source where as in case of laser the property of coherence exists b/w any two or more light wave of same type.

★ Basic Principle of Laser :-

As we know Maxwell-Boltzmann law, the ratio of

$$\frac{\text{Rate of Emission}}{\text{Rate of Absorption}} = \frac{R_{21}}{R_{12}} = \frac{N_2(A_{21} + B_{21}u(\nu))}{N_1 B_{12} u(\nu)}$$

Since $B_{12} = B_{21}$ ✓

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



So we can say for LASER Action

$$\frac{A_{21}}{B_{12} u(\nu)} + 1 = 1 \Rightarrow \frac{A_{21}}{B_{12} u(\nu)} = 0 \Rightarrow A_{21} \ll B_{12} u(\nu)$$

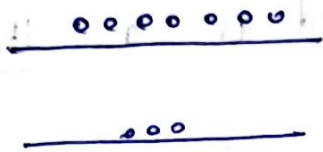
(a) It means Probability of spontaneous emission should be very less than probability of stimulated ~~emission~~ absorption.

$$\frac{R_{21}}{R_{12}} = \frac{N_2}{N_1} \Rightarrow R_{21} = \frac{N_2}{N_1} R_{12}$$

(b) The emission rate should be large than absorption rate

These conditions can be achieved by using following steps :-

1.



no. of atoms
in higher
level

no. of atoms
in lower
level

This condition is known as population inversion. Due to population inversion stimulated emission can be achieved (1st condition of LASER Action.)

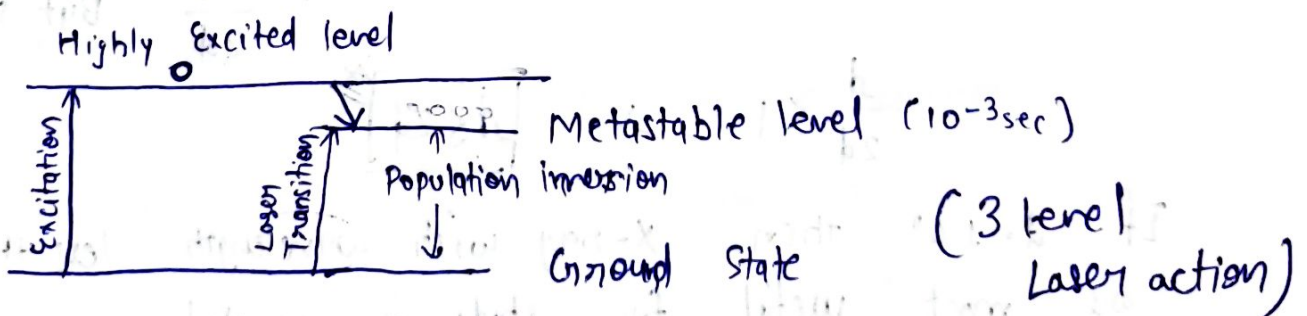
2.

The system of method by which we can achieve to population inversion is known as PUMPING METHOD.

There are several methods of pumping such as

- (a) Optical Pumping [Ruby laser]
- (b) Electrical Discharge [He-Ne laser]
- (c) Flash discharge [Ruby laser]
- (d) Chemical pumping
- (e) Gas dynamic pumping
- (f) Atom-atom collision

3.

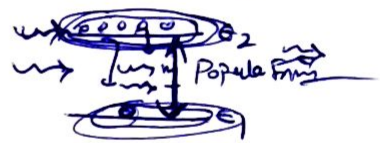


If the pumping method is intense enough we can obtain a population inversion; more atoms in metastable than ground state.

MAIN Component of LASER

1. Active Medium:- It consists of collection of atoms, molecules or ions which is capable of amplifying light waves or medium in which light gets amplified is called Active Medium. A small fraction of active medium is responsible for amplification. These are called Active Centers & remaining part of this medium supports active centers.

2. Population Inversion:- Emission of high intensity of radiation by stimulated emission in laser requires a large amount of excited atoms in upper levels.



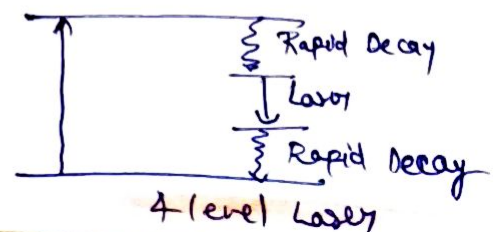
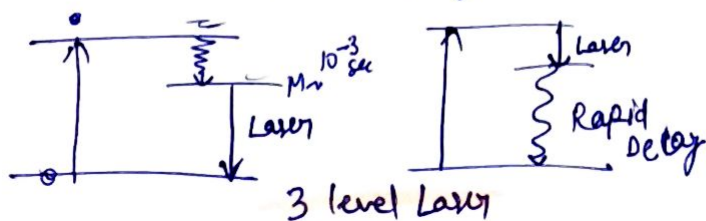
from Boltzmann's statistics

$$N_1 \propto e^{-E_1/kT}, \quad N_2 \propto e^{-E_2/kT}$$
$$\frac{N_1}{N_2} = e^{(E_2-E_1)/kT} \Rightarrow \frac{N_2}{N_1} = e^{-(E_2-E_1)/kT}$$

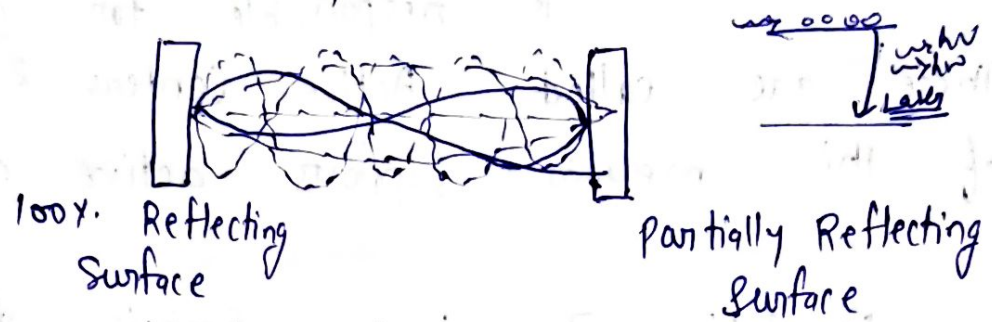
The negative sign implies that $N_2 \ll N_1$ at equilibrium.

● Pumping :- The process of achieving population inversion is known as pumping.

→ Optical pumping, Electrical Pumping, Direct pumping, Chemical Pumping.



3. Optical Resonator:- In a LASER, the active medium is enclosed in an optical cavity that is made up of two parallel surfaces, one of which is perfectly reflecting & the other surface is partially reflecting. In this resonant cavity, the intensity of photons is raised through stimulated emission process.



He-Ne Laser

He-Ne laser is a gaseous laser system & is used to produce a continuous laser beam. This laser source gives highly directional, monochromatic, coherent & stable light.

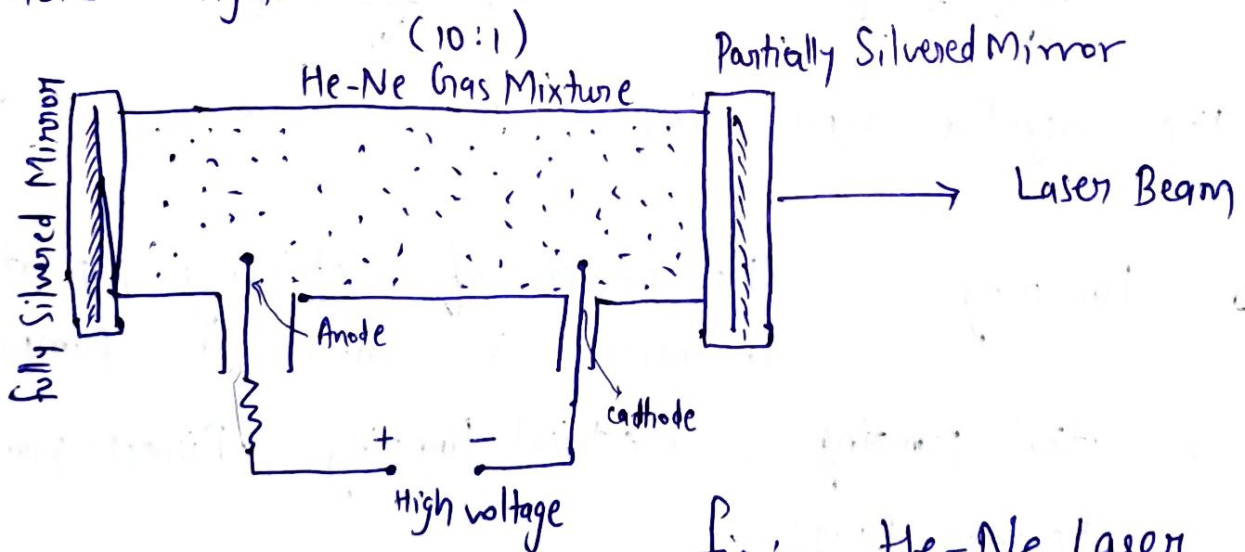


fig:- He-Ne Laser

- He-Ne Laser is 4-level laser
- It employs electrical Pumping

Construction :- $\rightarrow$ He-Ne Laser consists of long & narrow quartz tube of 80-100 cm & diameter of 1 cm.

$\rightarrow$ Quartz tube is filled with a mixture of helium & neon gases in ratio 10:1 respectively at pressure of about 0.1 mm of mercury. This mixture of gases acts as active medium.

$\rightarrow$ This system is enclosed between a pair of plan mirrors so that optical resonator is formed.

$\rightarrow$ One of these mirrors is highly reflective & another one is partially reflective. The spacing b/w the two mirrors is equal to an integral multiple of half wavelengths of Laser Light.

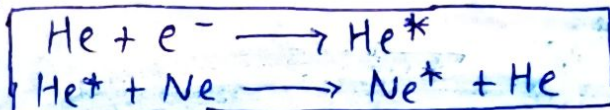
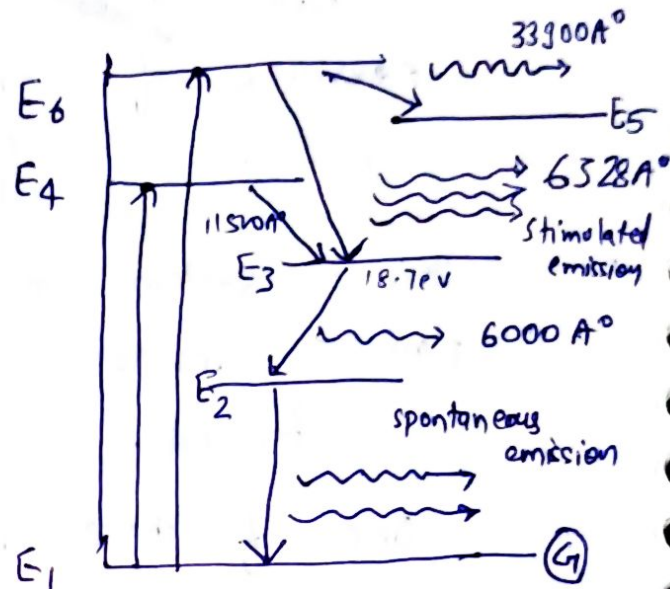
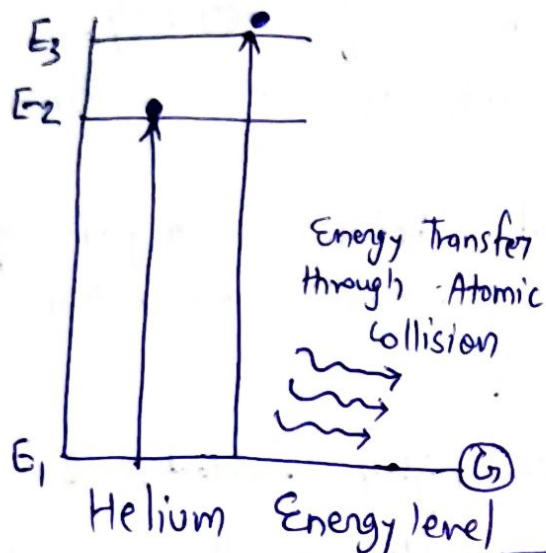
$\rightarrow$ An electrical discharge is used as pumping source.

Working :- $\rightarrow$ When an electric discharge take place through the gas mixture, charges of this discharge collide with the atoms in ground state & excites them to higher energy levels of He.

$\rightarrow$ E_2 & E_3 of He atom are metastable states & due to long time before getting excited the no. of excited state atoms of He increases.

$\rightarrow$ Now these excited electrons of He collides with electron in ground state of Ne.

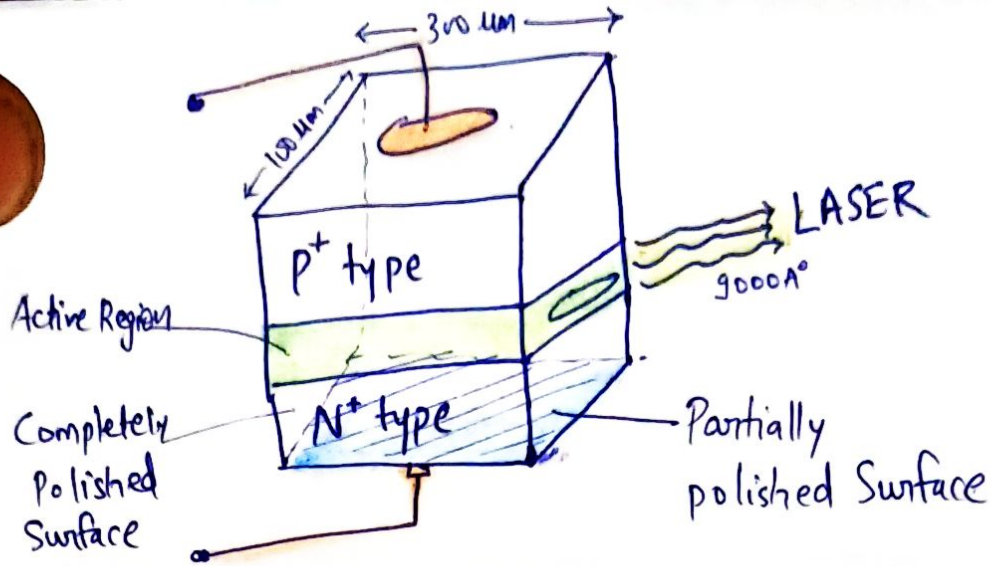
This results the excitation of Ne atoms to the level E_4 & E_6 . This process is highly probable due to longer life time of E_2 & E_3 of He atom.



This results population increase in E_4 & E_6 of Neon. Thus the purpose of He atoms is the help to achieve a condition of population inversion in the Ne - atom.

$E_6 \rightarrow E_5 \Rightarrow 33900 \text{ Å}$ Not in visible regions
 ~~$E_4 \rightarrow E_3 \Rightarrow 6328 \text{ Å}$~~ gives red light of He-Ne Laser
 $E_4 \rightarrow E_3 \Rightarrow 11500 \text{ Å}$ Not in visible regions.

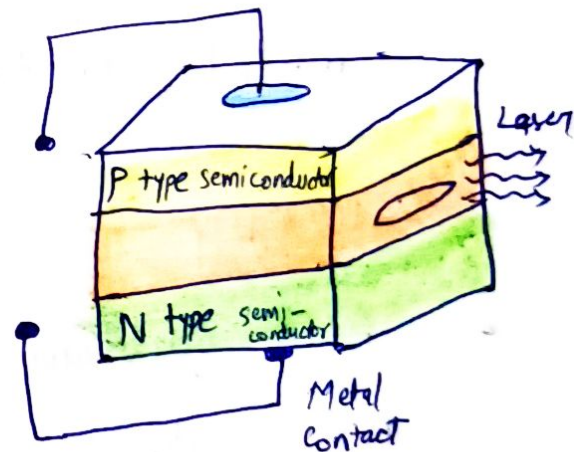
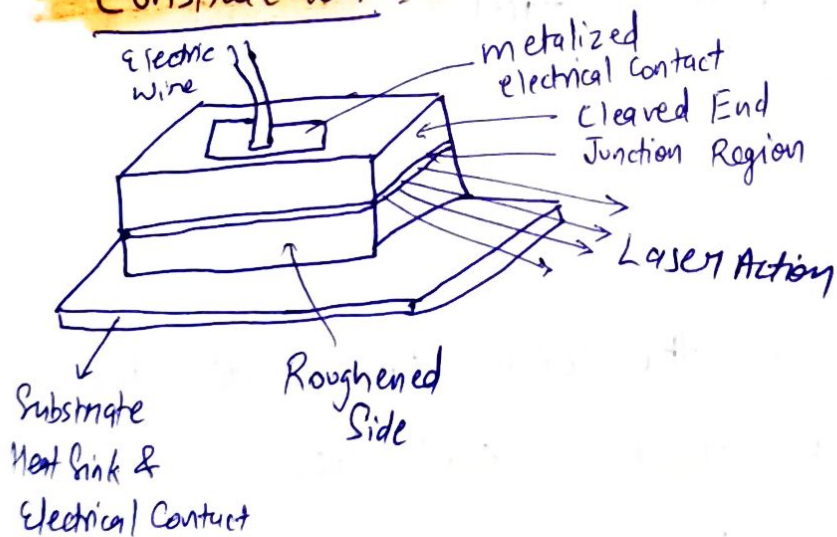
These photons of wavelength 6328 Å travelling parallel to axis bounces back & forth b/w mirrors & will stimulate another excited neon atom to emit another photon of same frequency & phase & the radiation gets amplified & an emerge a red laser.



Semiconductor LASER:-

Semiconductor laser is conventional laser. Laser action results through transitions associated with the properties of energy bands of the materials.

Construction:-



1. Excitation of electrons on pumping from valence band to conduction band.
2. Large concentration of electrons in conduction band & large concentration of holes in valence band so that inverted charge carriers give sufficient stimulated emission to overcome the losses.

3. A resonant cavity to provide positive amplification.

→ Both P & N sides of junction are heavily doped so that the fermi levels are within the conduction & valence band edges respectively.

→ A pair of parallel planes perpendicular to the plane of the junction are cleaved to prepare Resonator.

→ The two remaining sides are roughened to eliminate lasing in directions.

The structure is called Fabry-Perot cavity.

→ The top & bottom faces are made a metal contact.

Working:-

- At equilibrium in the zero-bias state, due to high doping the fermi level lies in the valence band on P-side & in the conduction band on N-side.
- The state filled with electrons are shown by shaded regions.
- When a small forward bias is applied electrons start following from conduction band on

~~Java~~ Construction

N-side to the vacant sides on P-side & holes start following to N-side.

- Thus, charge carriers are pumped by the dc voltage source into junction region & a small forward current is produced. At this stage electron hole recombination causes spontaneous emission of photons & the device acts as a LED.
- As the applied voltage is increased the forward current through the junction increases.
- When this voltage is high enough the current reaches a threshold value & population is inverted on junction active region. This narrow zone is called inverse region.
- At threshold Laser action begins. the dependence of radiation output increase of current. The coherent radiation gets amplified in the cavity. and is finally emitted from optical plane reflecting ends.

Q - Switching :- As we know laser is an oscillator, its resonator-cavity is characterized by quality factor Q .

→ Quality factor is defined as the ratio of the energy W stored in the system to energy losses ΔW per cycle.

$$Q = 2\pi \times \frac{\text{Energy stored in resonator}}{\text{Energy lost in a cycle}}$$

$$Q = 2\pi \times \frac{W}{\Delta W}$$

In case of Laser,
 Q is very high &
is the order of 10^8

- Q -factor is a measure of mirror losses in laser.
- The power of laser can be increase by increasing no. of atoms in active medium participating in stimulated emission.

→ In a laser without Q -switch, the atoms are excited to the lasing level at certain rate. Lasing starts as soon as 'population inversion' is created.

→ In a laser with Q -switch, the feedback which helps in establishing the population inversion is blocked, thus as long as switch is 'on' there is no lasing.

Mode Locking:- Mode locking is another technique for producing high power, short duration pulses. Single mode operation can be achieved by forcing random modes to oscillate in phase so that it produces pulse of short duration & higher gain.

This phenomenon is called Mode Locking.

→ There are several ways a laser can be mode locked.

1. Active Mode Locking:- A physical device is placed in the cavity, which modulates the frequencies of cavity modes. It depends on an external source to incite oscillation in the resonant cavity, creating modulated light.

2. Passive Mode Locking:- An intensity dependent loss mechanism placed in cavity causes less intense radiation to be damped out, leaving only a single, intense pulse oscillating back & forth in the cavity.

3. Self Mode Locking:- The lasing mechanism itself has an intensity dependent index of refraction.