LASERS & HOLOGRAPHY

CHAPTER - 7

LASER → Light Amplification by stimulated Emission of Radiation

Laser is a device which produce highly intense, highly coherent parallel beam of monochromatic and coherent light.

" Laser are amazing devices which emits beam of light powerful enough to vaporize a bulldozer, yet are so precise that they can be used in optical surgery, provide more information (Dave Barry)

" What the laser does essentially is to gives us electronic type light. It is a marriage of optics & electronics"
(T. Towens, 1964 Nobel Prize)

Properties of the Laser light

1. Highly monochromatic
2. Highly directional
3. Extreme intense & Brightness
4. Highly coherent
5. Focusability.

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IMPORTANT TERMS

✓ Ground state :- All the atoms & molecules can exist only in certain energy states. The state of lowest energy is called ground state

✓ Excited states :- All other state having more energy than ground state are called excited states.

1. ⇒ ✓ Absorption :→ When an incoming photon excites the atomic sytem of lower energy state to a higher energy state is called absorption or sometimes called stimulated absorption

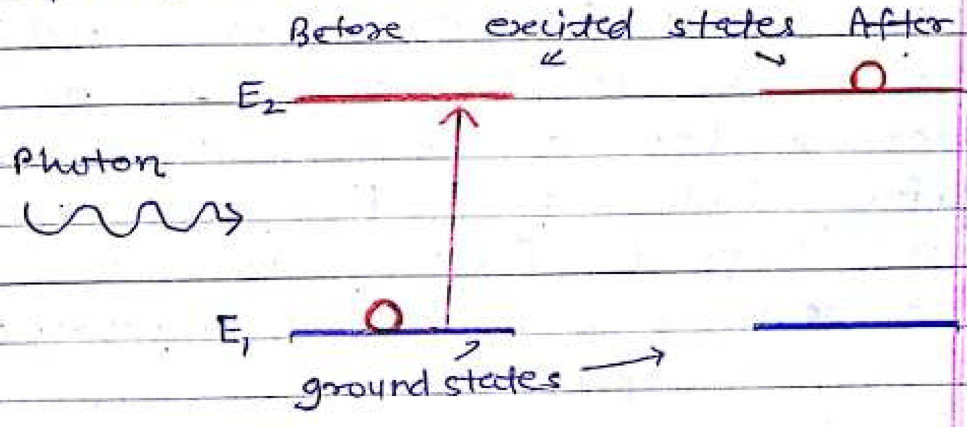

Fig. Stimulated absorption

When a photon of energy $h\nu$ strikes an atom of the laser medium in the state E_1 and disappeared, exciting atom to the higher states E_2 so

$$\boxed{E_2 - E_1 = h\nu} \quad \text{——— (1)}$$

h – plancks Constant
ν – frequency

The probability of absorption is depends on intensity of incident radiation (Photon) $u(\nu)$ and the population (Number of electrons) N_1 in ground state so

The rate of absorption

$$\boxed{R_{12} = B_{12} N_1 u(\nu)} \longrightarrow (2)$$

B_{12} is the einstein coefficient for stimulated absorption, N_1 is the number of atoms

2 ⇒ ✓ Spontaneous Emission :→ Each level has a specific life time of electrons remains in specific level are of 10 to 100 nano second (nsec) after that they will radiate energy (photon) and decay to lower energy state is called spontaneous emission or fluorescense.

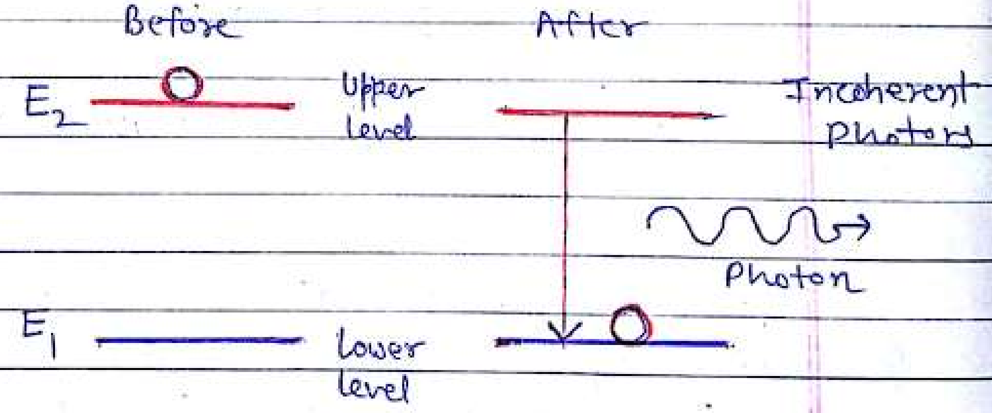

Fig. Spontaneous emission

The rate of emission R_{21} from level 2 to 1 is given as

$$\boxed{R_{21} = A_{21} N_2} \longrightarrow (3)$$

A_{21} is Einstein coefficient for spontaneous emission.

3⇒ ✓ Stimulated Emission (Induced emission) :→ It is also possible that the emission is stimulated by incoming photons, which is called stimulated emission. Both the photon incident and induced have the same phase, direction, spectral and polarization properties. so the output is coherent This is the main principle of laser (of light amplification)

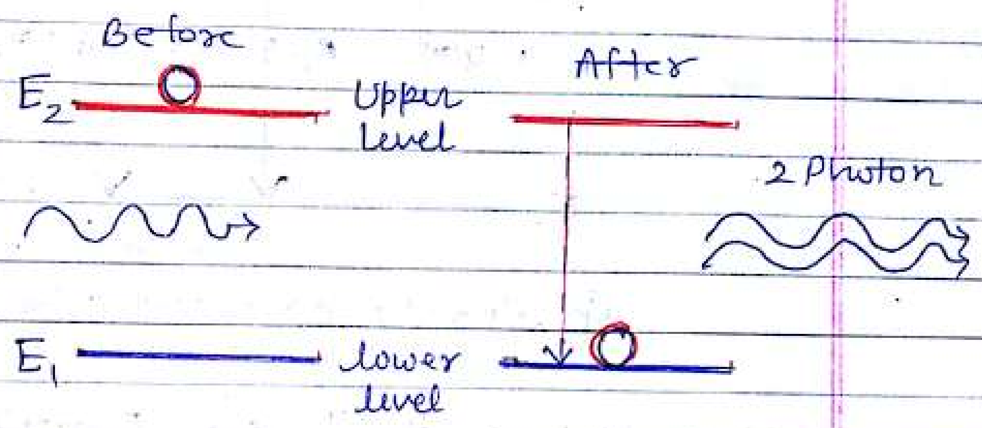

Fig. Stimulated Emission

The rate of stimulated emission R_{21} is given as

$$\boxed{R_{21} = B_{21} N_2 u(\nu)} \quad \text{—— (4)}$$

where B_{21} Einstein coefficient for stimulated emission, N_2 is the population in upper level $u(\nu)$ is the energy density of photons.

There is a definite phase relation between incident photons and emitted photons so amplification of light is observed.

V.Imp ✓ **Relation between Einstein's Coefficients**

Under the thermal equalibrium condition the rate of upward transition by absorption should be equal to rate of emission as shown in fig.

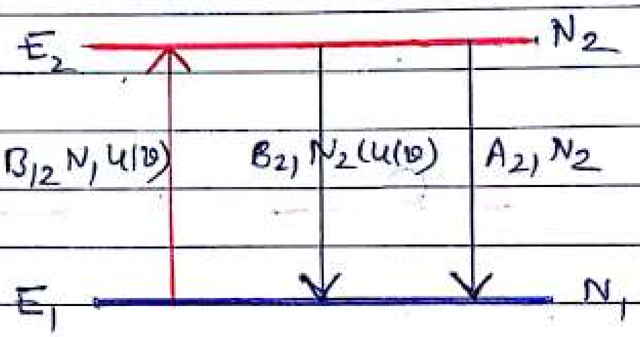

Fig. Spontaneous and stimulated Processes

Absorption = Spontaneous Emission + Stimulated em

$$B_{12} N_1 u(\nu) = A_{21} N_2 + B_{21} N_2 u(\nu) \quad \text{--- (1)}$$

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

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

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

Eienstein show that due to time reversal symmetry the transition probability for absorption is equal to the probability of stimulated emission $B_{12} = B_{21}$

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$$u(\nu) = \left(\frac{A_{21}}{B_{21}}\right) \frac{1}{\left(\frac{N_1}{N_2}\right) - 1} \quad \text{———} \quad (2)$$

The population density N in a given state depends on the energy E of the state and Temperature T given by Boltzmann's equation

$$N = N_0 \exp\left(-\frac{E}{kT}\right)$$

$$\text{So} \quad N_1 = N_0 \exp\left(-\frac{E_1}{kT}\right), \quad N_2 = N_0 \exp\left(-\frac{E_2}{kT}\right)$$

$$\frac{N_1}{N_2} = \frac{\cancel{N_0} \exp(-E_1/kT)}{\cancel{N_0} \exp(-E_2/kT)} = \exp(-E_1/kT) \exp^{-(-E_2/kT)}$$

$$\frac{N_1}{N_2} = \exp\left(\frac{E_2 - E_1}{kT}\right) = \exp\left(\frac{h\nu}{kT}\right) \quad \text{———} \quad (3)$$

By putting the value of eq (3) in eq (2)

$$u(\nu) = \left(\frac{A_{21}}{B_{21}}\right) \left(\frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}\right) \quad \text{———} \quad (4)$$

we know that Planck's Radiation formula is given as

$$u(\nu) = \left(\frac{8\pi h\nu^3}{c^3}\right) \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1} \quad \text{———} \quad (5)$$

Compare eq (4) & (5)

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \text{———} \quad (6)$$

This conclude that

(1) stimulated emission and absorption are competing processes ($B_{12} = B_{21}$)

(2) The rate of sponteneous emission is much larger than the induced emission.

Rate of spontaneous emission > Rate of stimulated emi.

(3) The ratio $\left(\frac{A_{21}}{B_{21}}\right)$ depends on the cube of the frequency or inversely proportional to the cube of wavelength.

probability $\frac{(P_{21})_{sp}}{(P_{21})_{in}} = \frac{A_{21}}{B_{21}u(\nu)} = (e^{h\nu/kT}-1)$

Now applying two conditions

(1) If $h\nu >> kT$, $(P_{21})_s >> (P_{21})_{in}$, then spontaneous emission much more probable than induced imission

(2) If $h\nu << kT$, $(P_{21})_s << (P_{21})_{in}$ the stimulated emission no more negligiable it dominent over stimulated emission.

Threshold Conditions for laser Action

The ratio of emission and absorption rate is given by

$$\frac{[A_{21} + B_{21}u(\nu)]}{[B_{12}u(\nu)]}\left(\frac{N_2}{N_1}\right) = \frac{\text{Emission rate}}{\text{Absorption rate}}$$

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

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

For laser action two condition must be satisfied.

(1) The total emission rate must be larger than absorption rate.

i.e $\left(1 + \frac{A_{21}}{B_{12}u(\nu)}\right)\left(\frac{N_2}{N_1}\right) > 1$

(ii) The probability for stimulated must be higher than the probability of spontaneous emission

i.e. $A_{21} << B_{21}u(\theta)$

$$\frac{A_{21}}{B_{21}} << u(\nu)$$

The higher probability for stimulated emission may be achieved by the following ways

(A) By increasing the intensity of incident radiation i.e. the energy density $u(\nu)$ shold be higher.
(B) Anothr method to increase the probability of stimulated emission is to decrease the ratio (A_{21}/B_{21}). This ratio can be minimize by using metastable states.
(C) The system must acheive population inversion i.e. $N_2 > N_1$

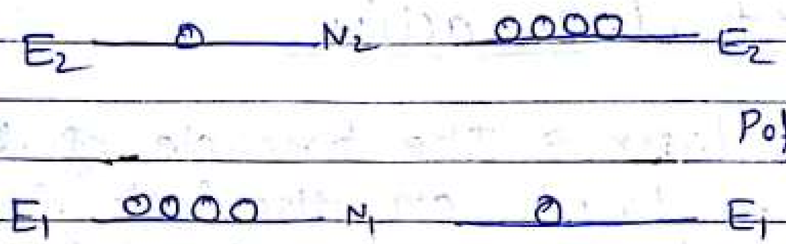
Metastable States

In certain material there are some energy levels which have the spontaneous life time of the order of 10^{-3} sec which is 10^{5} time more than the life time of other excited states. These states are known as Metastable states.

Population Inversion :-

It is a condition of matter in which more electron are in a high energy state than in a lower energy state

In thermal equalibrium the lower energy state is usually more populated than the higher energy state. If the ratio could be inverted such that $\frac{N_2}{N_1} > 1$, then the system is said to have population inversion



Population inversion by pumping

Pumping

The process two achieve population inversion is called pumping.

The laser active medium is pumped by an external energy source, by absorbing energy.

Pumping is performed by following forms:-

(I) Optical pumping :- It uses either continuous wave or pulsed light emitted by a powerful lamp. Exp - Ruby laser.

(II) Electrical pumping :→ It is achieved by means of an intense electric discharge in the gain medium. Ex - He-Ne laser.

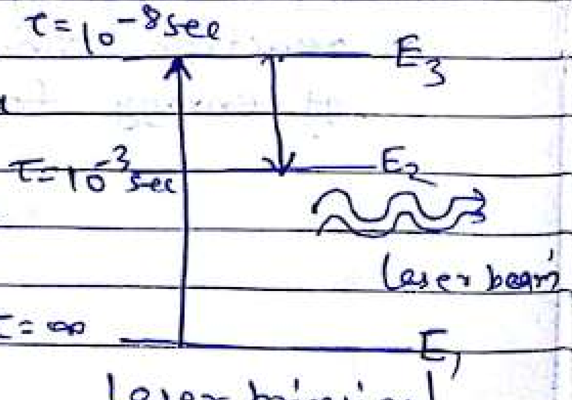
(III) Chemical pumping → It uses direct chemical reaction whithout any need of other sources of energy for excitation of atoms. CO_2 laser.

Theory of laser action

Principle of laser:→ The principle of laser production is based on the fact that atoms of a material have a number of energy levels in which at least one is metastable state

Consider a three level atomic system having energies E_1, E_2 and E_3 respectively. let the atoms are at ground state E_1. If the Photon interact with an atom in ground state, the atom absorb the photon and reach to excite state E_3. we know that the excited state is an unstable state, therefore electron must return back to ground state E_1 but such transition are not allowed and the electron first reach to state E_2. we know that life time of metastable state (E_2) is 10^{-3} sec which is 10^5 times higher than unstable state E_3. i.e the atom reach E_2 state faster and leave state E_2 very slower compared to ~~to~~ reach. This result in an increase in number of atoms in states E_2 and hence population inversion achived.

After achieving population inversion it is exposed to a beam of photons which cause induced emission of photon so a beam of laser will produce.



Laser principal

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Helium – Neon Laser

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The first gas laser was fabricated and was put into operation by Ali Javan, Bennett and Harriott in 1961. It is very useful device for lab demonstration and experiments

Construction :→

As shown in fig. The He-Ne laser uses a mixture of helium and Neon gas in the ratio of 10:1, kept in narrow pyrex glass tube with an internal diameter of 2mm and length of about 40 cm

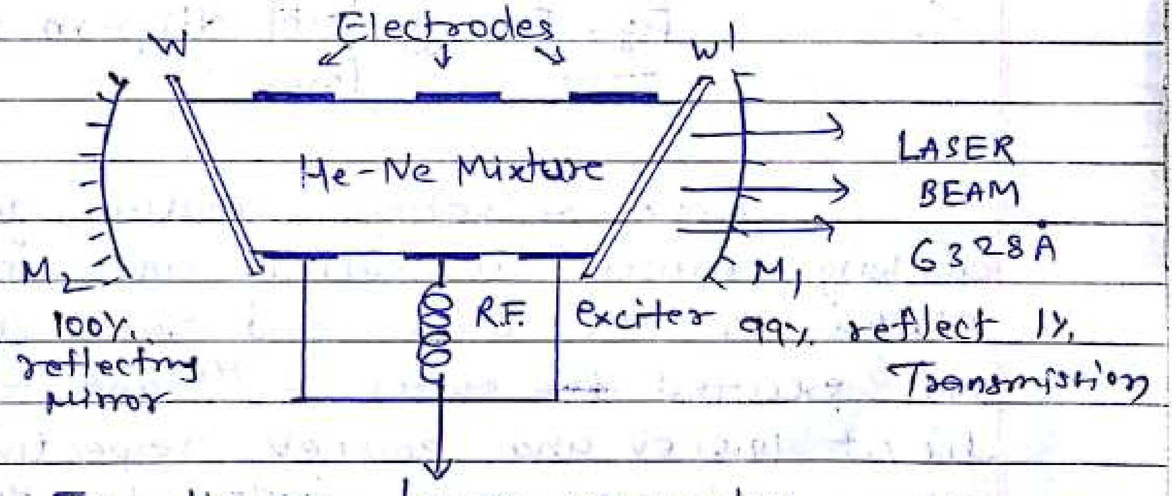


Fig. He-Ne Laser apparatus

The window WW' cemented at brewster angle at the end of discharge tube. The reflectors M_1, M_2 are two dielectric coated mirrors one act as partial reflector and other is fully reflected mirror. Thus a cavity resonator system is formed. Pumping is achived by electric discharge.

Working :→ The first few energy levels of He & Ne are shown in fig.

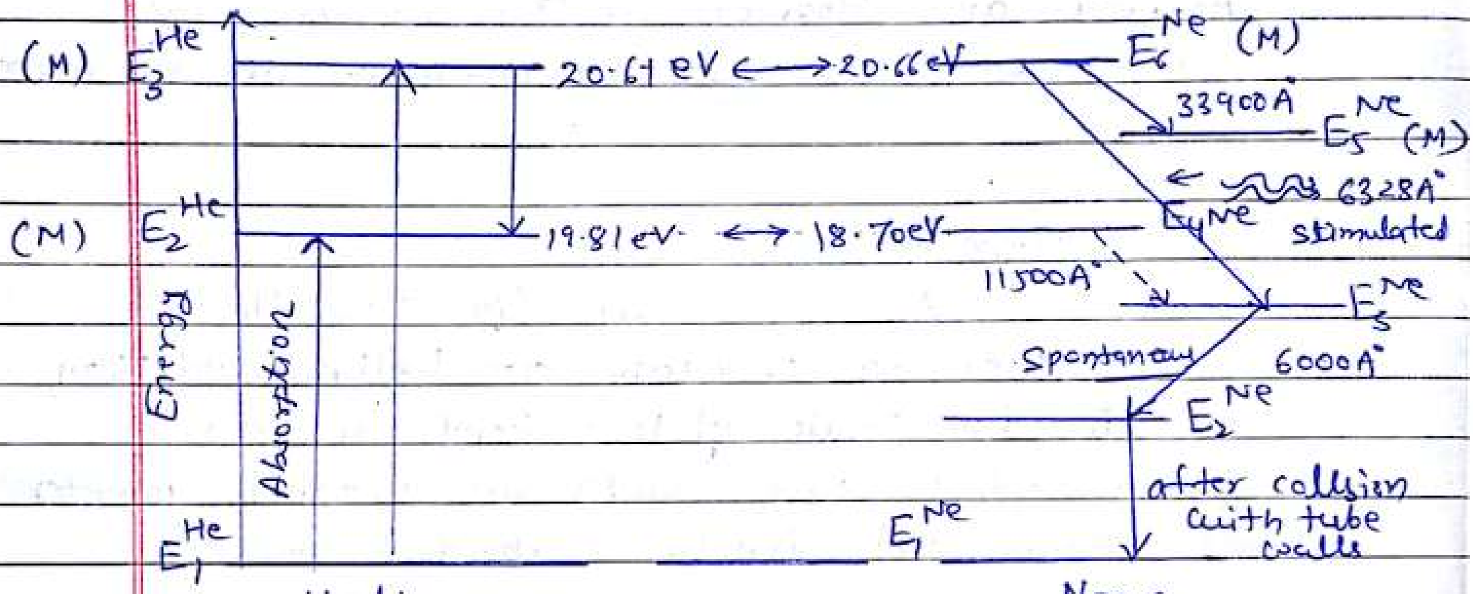


Fig. Energy level diagram of He-Ne laser.

When a voltage applied, an electric discharge causes ionisation and ionize atom strikes to He atoms and raise them to the excited ~~the~~ states E_2^{He} and E_3^{He} which lie at 19.81 eV and 20.61 eV respectively above the ground state. The E_1^{He} and E_2^{He} are long lived metastable states so transition from these states to ground states by spontaneous emission are forbidden (10^{-3} sec).

Once the helium atom excited, the neon atoms come into play. The energy need to excite helium to the E_2^{He} and E_3^{He} energy states is almost exactly same as the energy needs to excite the neon to its E_4^{Ne} and E_6^{Ne} energy states. Once the helium population is successfully inverted, excieted helium atom strikes neon atoms and transfer their energy to the neon. Since the energy levels E_4^{Ne}, & E_6^{Ne} of Ne atoms lies at 18.70 eV and 20.66 eV, which very close to E_2^{He} and E_3^{He} energy levels of He atoms. This process is given by this reaction

$$He^* + Ne \longrightarrow Ne^* + He + \Delta E$$

where * repersent excited state and is the small energy difference between the energy states of two atoms, of the order of 0.05 eV.

This additional kinetic energy of He atoms provides the Ne atom to E_6^{Ne} energy state i.e. He atom ~~at~~ act as pumping medium to neon atom. Since E_6^{Ne} & E_4^{Ne} excited states of neon atoms, in these states the atom goes to ~~metastable~~ other metastable states as shown in fig.

Now any spontaneous emitted photon trigger laser action in the transition $E_6^{Ne} - E_3^{Ne}$ (6328 Å) of wavelength red light in visible region. The transitions $E_6^{Ne} - E_5^{Ne}$, and $E_4^{Ne} - E_3^{Ne}$ 33900 Å & 11500 Å are having radiation in infered region. Another photon spontaneously emitted by $E_3^{Ne} - E_2^{Ne}$ state by emitting 6000 Å light. The Ne atom then drops down from E_2^{Ne} to ground state by collision with the walls of glass tube. By proper design of the resonator, laser action in neon atom is obtained by large number of transitions in the visiable region. The high directivity of a laser beam is achived by the parrallel mirror fixed at the end of the tube and the resonator cavity made by them.

Brewster window in a laser cavity : Brewster window are used to ensure that laser light after reflection from mirror emerge as linearly ~~po~~ polarised light.

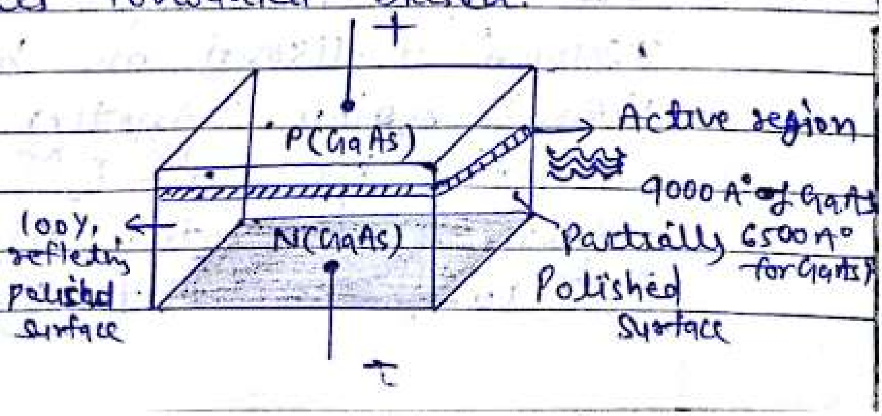
Advantage of He-Ne laser

(1) It is most common & inexpensive gas laser.
(2) The beam quatity usually excillent. It is used for alingment purpose.

SEMICONDUCTOR DIODE LASER (V.Imp)

A semiconductor diode laser is a specially fabricated pn-junction device that emits coherent light when it is forwarded biased.

Construction :→



The diode laser's are extremly small in size with sides of order of 1 mm. The Top and bottom faces are metalized and outer contact are provided to pass current through the diode it consists two semiconductor layer separated by a middle layer (active region) and generate laser radiation. It also consist optical amplifier and resonator.

Working :-

The energy band diagram of semiconductor and n-p-doped semiconductor shown in fig. 1 & 2 when a forward bias applied to the junction Electrons & Holes are injected into the depletion layer region. At a low forward current level the electron & holes recombination cause spontaneous emission of photon and the junction act as LED light source

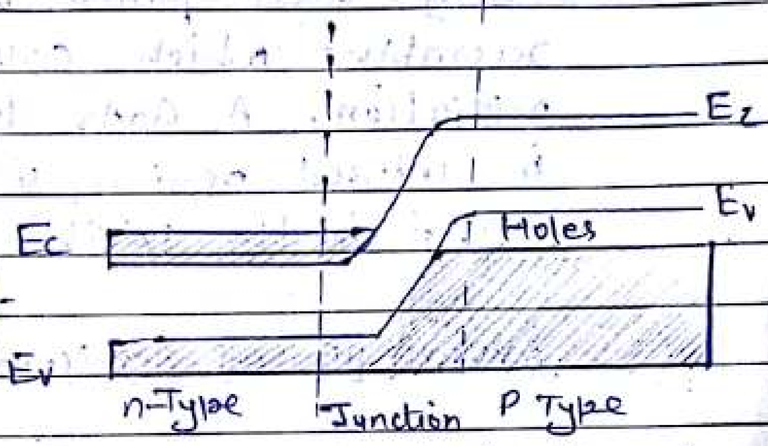


Fig. 1 Energy band structure of a semiconductor diode.

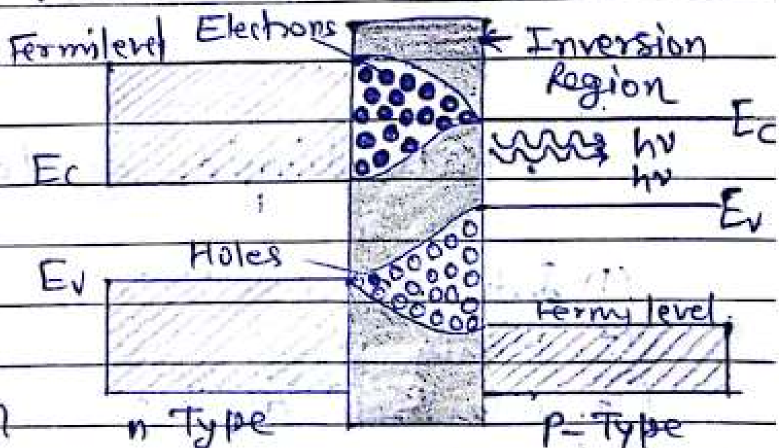


Fig. 2 n-p-doped semiconductor diode Band structure

As a current is increased, the

Intensity of light increase linearly. When the current reaches a threshold value The upper level in depletion laser are having high population density of electrons while the lower levels in the same region are vacant This is state of population inversion. The region is called active region. Thus the forward biasing will pump electrons and holes to recombine which cause emission of coherent radiation. A GaAs laser radiate 9000 Å radiation in infrared region while GaAsP laser radiate 6500 Å in the visible red region.

Advantage of semiconductor laser

(i) Small size 4 weight
(ii) Low current 4 power requirement
(iii) Low Intense
(iv) Wide Angle beam.

Application's of lasers (write in details)

(1) Industry
(2) Media
(3) Electrical devices
(4) Surgery
(5) Military
(6) Market
(7) Environmental study
(8) Nuclear fusion
(9) Recording Hologram
(10) Education 4 research