

UNIT-IV

LASER

Define Absorption of Radiation, Spontaneous Emission and Stimulated Emission :

Absorption of Radiation -

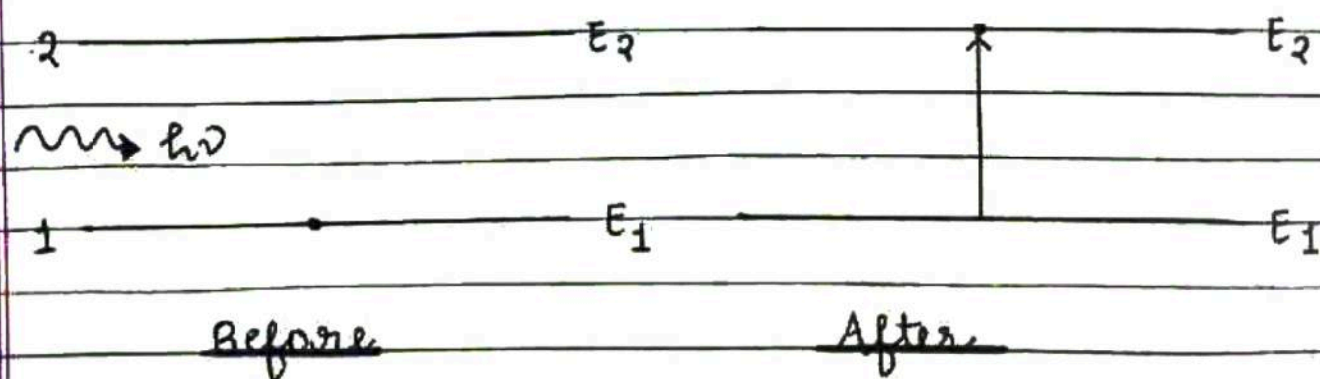
An atom, initially in a lower state 1, rises to a higher state 2 by absorbing a quantum of radiation (photon) of frequency ν , given by-

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

Or,

$$E_2 - E_1 = h\nu$$

$$; E_2 > E_1$$



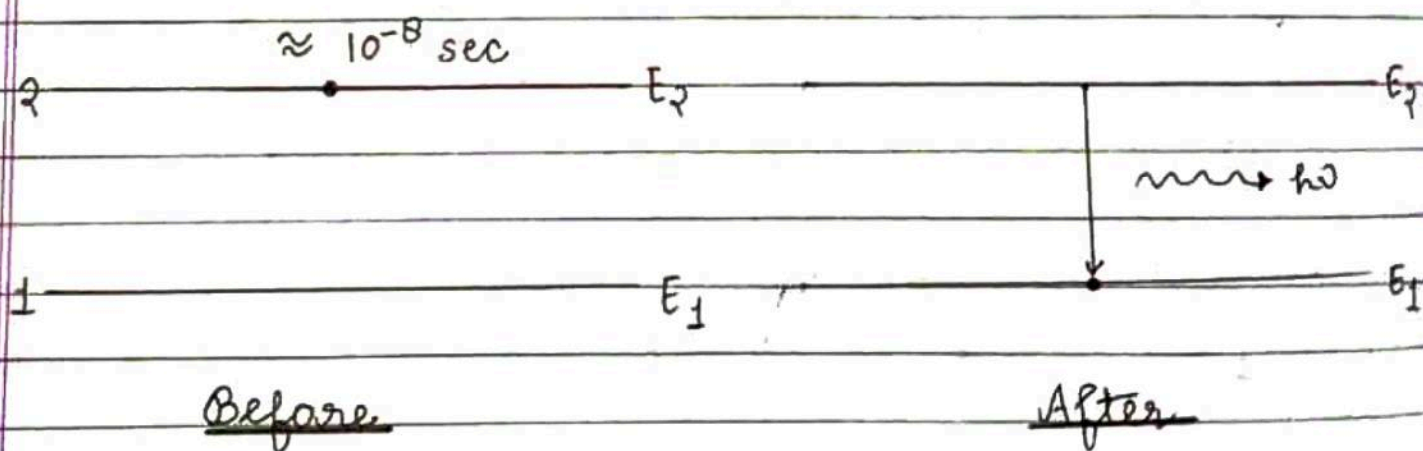
[Stimulated Absorption]

Where E_1 and E_2 are the energies of the atom

in the state 1 and 2 respectively. This is Stimulated (or induced) absorption of radiation, the absorbed photon being the stimulating photon.

• Spontaneous Emission of Radiation -

Consider an atom initially in the higher (excited) energy state 2, observations show that its lifetime in higher state is usually very small ($\approx 10^{-8}$ sec) and it, of its own accord, decays to the lower energy state 1, emitting a photon of frequency $\nu = (E_2 - E_1)/h$. This is Spontaneous emission of radiation. If there is an assembly of atoms, then the radiation emitted spontaneously by each atom has a random direction and a random phase, and is therefore incoherent from one atom to another.

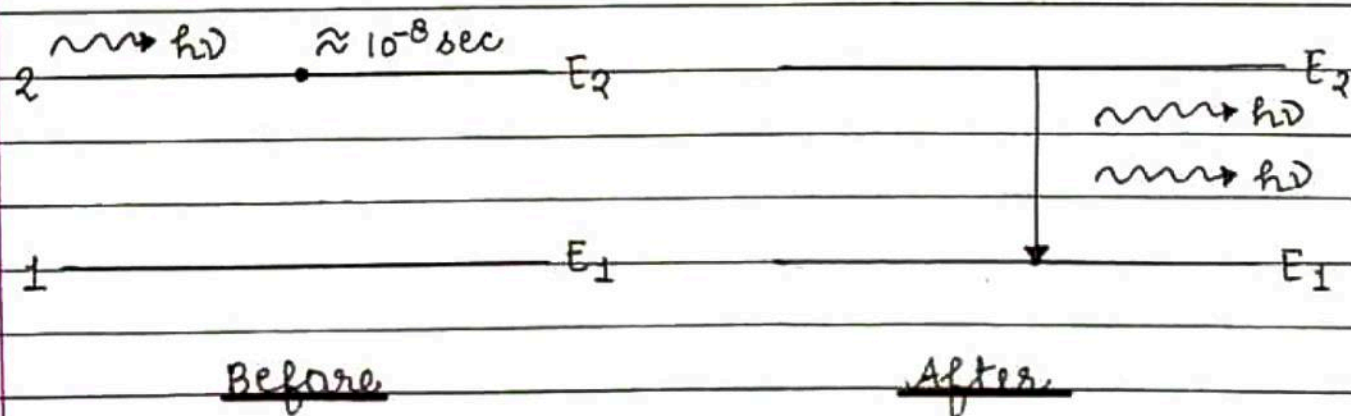


• Stimulated Emission of Radiation -

According to Einstein, an atom in an excited energy state, under the influence of the

electromagnetic field of a photon of frequency ' ν ' incident upon it, decays to a lower energy state, emitting an additional photon of same frequency ' ν '. Thus, two photons of same frequency, one incident and the other emitted, move on. This is stimulated (or induced) emission of radiation.

The direction of propagation, energy, phase and state of polarisation of emitted photon is exactly the same as that of the incident stimulating photon. In other words, the stimulated radiation is completely coherent with the stimulating radiation. As a result of this process, radiation passing through an assembly of atoms is amplified.



• Laser:

The word LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. It is a source which emits an intense, almost perfectly monochromatic,

directional & highly coherent beam of light.

The working of laser depends upon the phenomenon of stimulated emission.

- Maser:

• Einstein Coefficients :

Consider an assembly of atoms (sample of matter) which is in thermal equilibrium with radiation of frequency ' ν ', and spectral energy density $u(\nu)$ at temperature ' T '. Let N_1 and N_2 be the number of atoms per unit volume in energy states 1 and 2 with energies E_1 and E_2 respectively at any instant.

- An atom in the lower energy state E_1 can absorb radiation and get excited to the state E_2 . The probability rate of occurrence of the absorption transition $1 \rightarrow 2$ would be proportional to N_1 and also to $u(\nu)$. Thus the number of absorption transitions per unit time per unit volume can be written as-

$$P_{12} \propto N_1 u(\nu)$$

$$= B_{12} N_1 u(\nu)$$

The proportionality constant B_{12} is a characteristic of energy states 1 and 2, and is known as Einstein's B Coefficient of absorption of radiation.

- Now, consider the emission transitions at frequency ' ν ' (both spontaneous and stimulated emission) when an atom deexcites from energy state E_2 to E_1 .

- i). The probability rate of spontaneous emission $2 \rightarrow 1$ is determined only by the properties of the states 2 and 1, and is proportional to the number of atoms N_2 in the energy state 2. Thus, the number of spontaneous emission transitions per unit time per unit volume can be written as -

$$[P_{21}]_{\text{spontaneous}} \propto N_2$$

$$= \boxed{A_{21} N_2}$$

where; A_{21} is known as Einstein's A coefficient of spontaneous emission of radiation.

- ii). The probability rate of stimulated emission transition $2 \rightarrow 1$ is proportional to the energy density $u(\nu)$ of the stimulating radiation and the number of atoms N_2 in the energy state 2. Thus, the number of stimulated emission transitions per unit time per unit volume can be written as -

$$[P_{21}]_{\text{stimulate}} \propto N_2 u(\nu)$$

$$= \boxed{B_{21} N_2 u(\nu)}$$

where; B_{21} is known as Einstein's B coefficient of stimulated emission of radiation.

At thermal equilibrium, number of upward

transitions $1 \rightarrow 2$ should be equal to the number of downward transitions $2 \rightarrow 1$.

$$B_{12} N_1 u(\nu) = [A_{21} N_2]_{\text{spontaneous}} + [B_{21} N_2 u(\nu)]$$

Stimulated
-absorbed

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

$$= \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left[\frac{B_{12}}{B_{21}} \left(\frac{N_1}{N_2} \right) - 1 \right]} \quad \text{----- (i)}$$

The equilibrium distribution of atoms among different energy states at temperature 'T' is given by Boltzmann's law, according to which

$$\frac{N_1}{N_2} = \frac{e^{-E_1/KT}}{e^{-E_2/KT}} = e^{(E_2-E_1)/KT} \quad \left\{ \because \right. \quad \left. N_i = A e^{-E_i/KT} \right.$$

$$\frac{N_1}{N_2} = e^{h\nu/KT}$$

Therefore from eqs. (i), we have -

$$u(\nu) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left[e^{h\nu/KT} \frac{B_{12}}{B_{21}} - 1 \right]} \quad \text{----- (ii)}$$

This is a formula for the spectral energy density of radiation of frequency ν in thermal equilibrium with atoms in energy states 1 and 2, at temperature T.

Comparing it with Planck's radiation formula -

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

we get,

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

and

$$\frac{B_{12}}{B_{21}} = 1$$

Thus, the coefficient of stimulated absorption (B_{12}) is equal to the coefficient of stimulated emission (B_{21}). It means that in presence of electromagnetic radiation, the probabilities of stimulated absorption and stimulated emission in atom are equal.

- Necessary Condition for light Amplification

Population Inversion

Under ordinary condition of thermal equilibrium the number of atoms in higher energy state E_2 is considerably smaller than the number in the lower energy state E_1 ($N_1 > N_2$), so that there is very little stimulated emission compared with absorption.

If, however, by some means the number of atoms in the higher energy state be made sufficiently larger than the number in the lower energy state, then stimulated emission is promoted. The situation in which the number of atoms in the higher energy state exceeds that in the lower energy state ($N_2 > N_1$) is known as Population Inversion. In this situation, the assembly of atoms would lase.

Stimulated emissions are further encouraged by increasing the radiation density $u(\nu)$ of the stimulating radiation. This is achieved by enclosing the emitted radiation in a "cavity" between two parallel reflectors. The radiation repeatedly travels back and forth, and the photons passing through the atoms go on multiplying by repeated stimulated emission. Hence a strong coherent beam of light emerges from the system.

• Metastable State:

The normal life-time of an excited state is 10^{-8} sec, but for establishing population inversion, excited atoms should have lifetime higher than the normal state, to increase the population of excited state. Such excited states which have longer life time are known as metastable states.

Atoms in the metastable state remains excited for

a considerable time in the order of $(10^{-6} - 10^{-3}) \text{ sec}$. In absence of these states there will be no population inversion, no stimulated emission, thus no laser transition. Thus, presence of metastable state is the fundamental requirement of matter to act as active medium for laser transition.

• Pumping :

The process by which atoms are raised from a lower to a higher energy states is called pumping of atoms.

For any laser device to operate, the achievement of population inversion in the active medium is necessary. That is, a larger number of atoms of the medium should be excited to the higher energy states. Different methods of atomic excitation are adopted in different types of lasers. Some of the methods are :

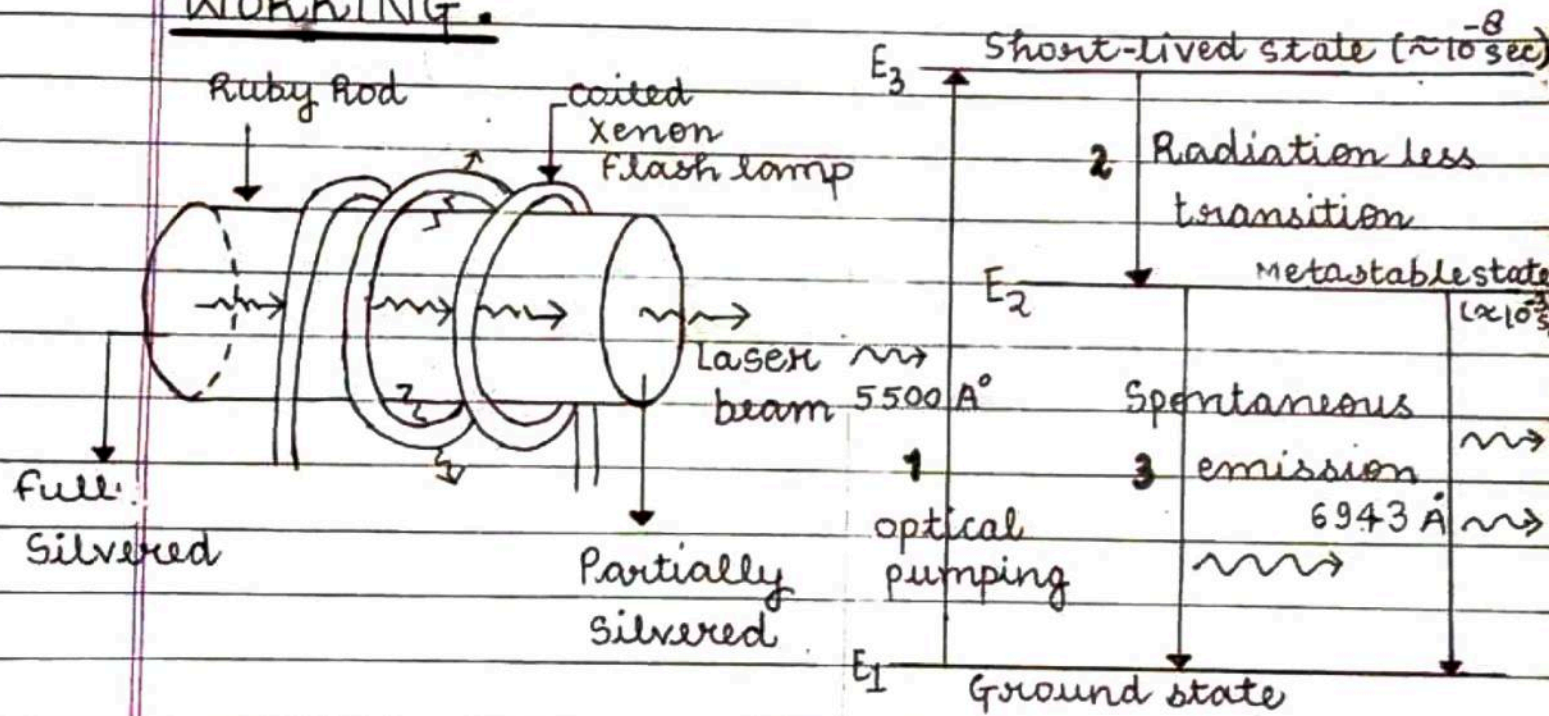
- (i). Excitation by a strong source of light, say flash lamp (Optical pumping).
- (ii). Excitation by electron impact (Electrical pumping).
- (iii). Excitation by chemical reaction (Chemical pumping).
- (iv). Excitation by supersonic gas expansion (gas dynamic pumping).

and so on.

• The Ruby Laser:

The Ruby Laser is a solid state laser. It consists of a pink ruby cylindrical rod whose ends are optically flat and parallel. One end is fully silvered and other is partially silvered. The two ends thus form a resonant cavity. The Ruby rod is placed inside a coiled xenon flash lamp.

WORKING:



The Ruby rod is a crystal of Aluminium oxide (Al_2O_3) doped with 0.05% chromium oxide (Cr_2O_3), so that some of the Al^{+3} ions are replaced by Cr^{+3} ions. These impurity chromium ions give pink colour to the Ruby and give rise to the laser action. The energy-level diagram of chromium ion is shown in figure

It consists of an upper short-lived energy-level E_3 above its ground state energy-level E_1 , the energy difference $E_3 - E_1$ corresponding to a wavelength of about $5500 \text{ \AA}$. There is an intermediate excited-state level E_2 which is metastable having a lifetime of 3×10^{-3} second (about 10^5 times greater than the lifetime of E_3 which is approximately 10^{-8} sec).

Normally, most of the chromium ions are in the ground state E_1 . When a flash of light falls upon the ruby rod, the $5500 \text{ \AA}$ radiation photons are absorbed by the chromium ions which are pumped (raised) to the excited state E_3 . The transition 1 is the optical pumping transition.

The excited ions rapidly give up, by collision, part of their energy to the crystal and decay to the metastable state E_2 . The corresponding transition 2 is thus a radiationless transition. Since the state E_2 has much longer lifetime, the number of ions in this state goes on increasing while, due to pumping, the number in the ground state E_1 goes on decreasing. Thus, population Inversion is established between the metastable state E_2 and the ground state E_1 .

When an excited ion passes spontaneously from the metastable state to the ground state (transition 3) it emits a photon of wavelength $6943 \text{ \AA}$. This

photon travels through the ruby rod and is reflected back and forth by the silvered ends until it stimulates an excited ion and causes the ion to emit a fresh photon in phase with the stimulating photon. This stimulated transition is the laser transition.

The process is repeated again and again because the photons repeatedly move along the crystal. The photons thus multiply. When the photon beam becomes sufficiently intense, part of it emerges through the partially silvered end of the crystal.

Drawback:

There is a drawback in the three-level laser such as; Ruby. The laser requires very high pumping power because the laser transition terminates at the ground state, and more than one half of the ground state atoms must be pumped up to the higher state to achieve population Inversion. Moreover, ions which happen to be in their ground state absorb the $6943 \text{ \AA}^{\circ}$ photons from the beam as it builds up.

The Ruby laser is a Pulsed laser, i.e., it emits laser light in pulses. The duration of an individual pulse is of the order of $0.1 - 1 \mu\text{s}$; the time interval between two successive pulses is about $1 - 10 \mu\text{s}$; the power of each pulse is as

high as $10^4 - 10^5$ Watt. The phenomenon is known as Spiking in ruby laser.

• The He-Ne Laser: [A Four-level laser]

The He-Ne laser is a four-level gas laser in which population inversion is achieved by electric discharge.

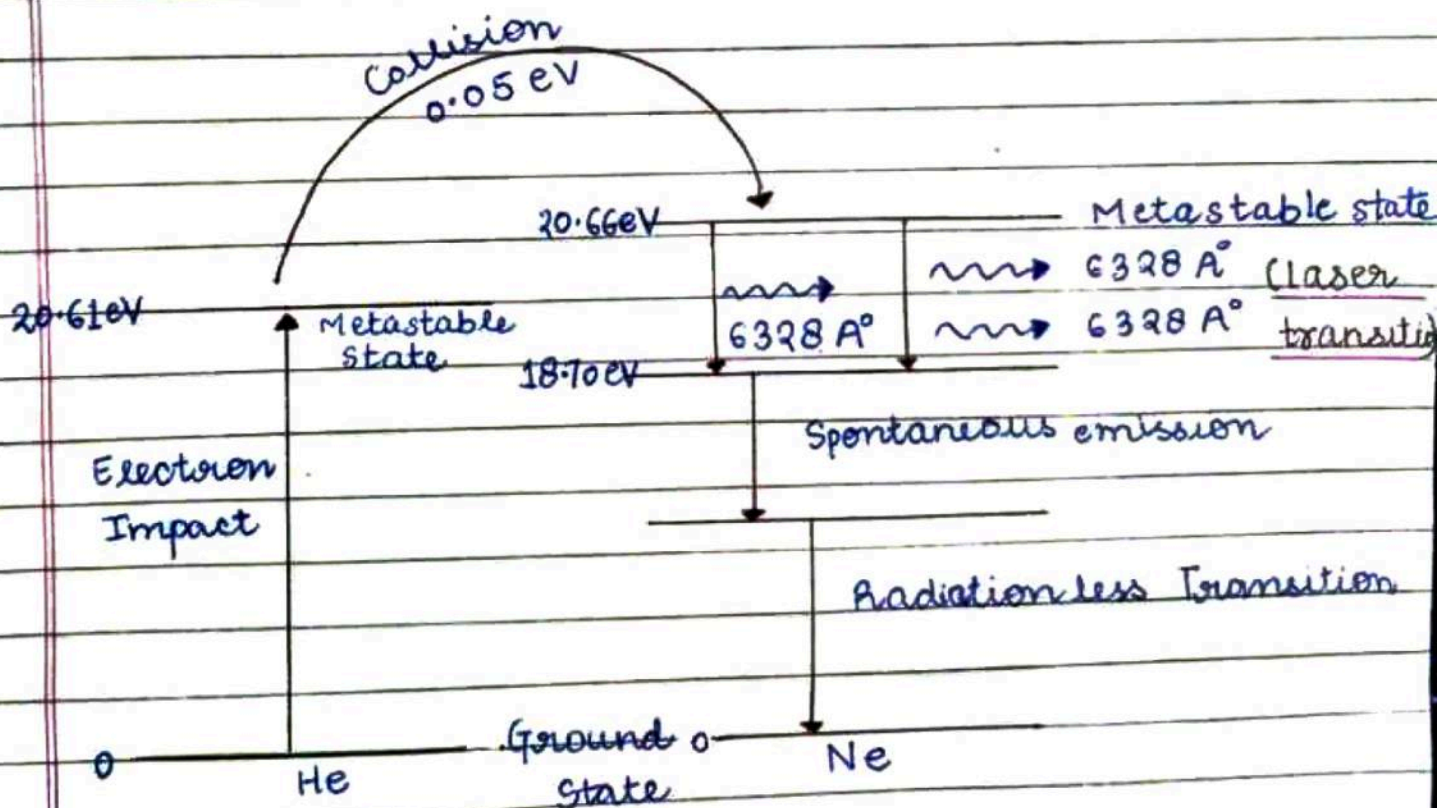
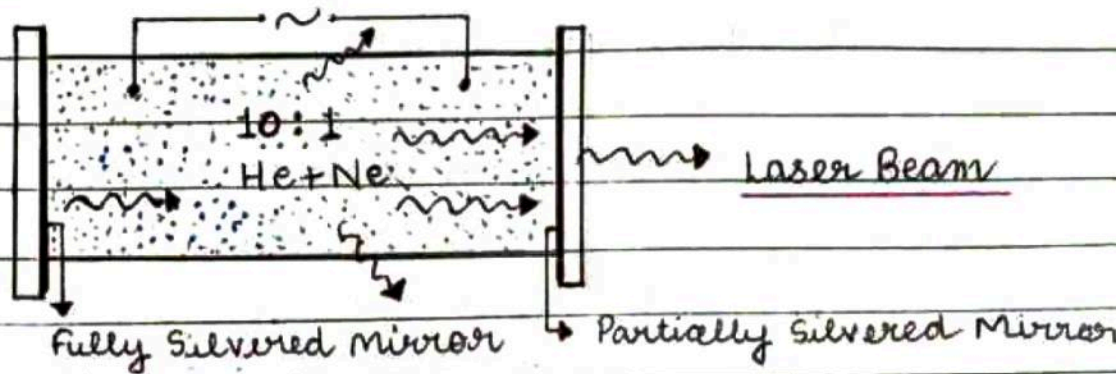
The He-Ne laser consist of a long and narrow discharge tube filled with a mixture Helium and Neon in a ratio of 10:1 at a pressure of about 1mm of Hg. The gas mixture (He + Ne) forms the lasing medium. It is placed between a pair of optically plane and parallel mirrors which form a resonant cavity. One of the mirror is fully silvered and the other is partially silvered.

An electric discharge may be produced in the gas mixture by electrodes connected to a high frequency electric source.

• Working:

When a discharge is passed through the gas mixture, electrons are accelerated down the tube. These accelerated electrons collide with, and pump (excite) the helium and neon atom to metastable states 20.61 eV and 20.66 eV respectively above their ground states. Some of the excited Helium atoms

transfer their energy to ground state Neon atoms by collision (which is $\approx 0.05 \text{ eV}$). Thus helium atoms help in achieving a population inversion in the Neon atoms.



A Four-level Laser

When an excited Neon atom passes spontaneously from the metastable state at 20.66 eV to the state at 18.70 eV , it emits a 6328 Å° photon. This photon travels through the gas mixture and

is reflected back and forth by the mirror-ends until it stimulates an excited Neon atom and causes it to emit a fresh $6328\text{\AA}$ photon in phase with the stimulating photon. This stimulated transition from 20.66 eV level to 18.70 eV level is the laser transition.

This process is continued and a beam of coherent radiation builds up in the tube. When this red-light beam becomes sufficiently intense, a portion of it escapes through the partially silvered ends as a laser beam. He-Ne gas laser is a 'tunable laser'. The He-Ne laser can be tuned (adjusted) to give radiation in any desired wavelength range. This can be done by choosing end mirrors having high reflectivity over only the required wave-length range.

- Advantages of Gas lasers over Solid state Lasers: [Advantages of Four-level Laser over Three-level Laser]

- (i) The gas lasers, in general, emit light which is more directional and more monochromatic as compared to that from solid state lasers. This is due to the absence of certain effects like Crystalline imperfection, thermal distortion and Scattering which appear in solid state lasers.
- (ii) Gas lasers can be operated continuously because

electron impacts that excites the Helium and neon atom occur all the time, unlike the pulsed (laser) excitation from the Xenon flash lamp in the Ruby laser. Hence gas lasers are capable of supplying a continuous laser beam without any cooling arrangement.

- (iii). Since the laser transition does not terminate at the ground state, the power needed for excitation is less than that in a three-level ruby laser (solid state laser).

• Characteristics of Laser Beam:

The most striking characteristic features of a laser beam are:

- (i). High coherence.
- (ii). Monochromaticity.
- (iii). High directionality.
- (iv). High Intensity.

- Laser beam is highly coherent, temporally as well as spatially. The coherence time and coherence length for a laser beam are much larger than those for an ordinary light source. The coherence time for a laser beam is about 2ms, giving a coherence length of 600km; against the coherence time of 10^{-9} sec and coherence length 30 cm for red cadmium light.

- laser beam is almost perfectly monochromatic