Naveen

LASER SYSTEM

BHM

Laser system :-

LASER :- " Light Amplification by Stimulated Emission of Radiation".

→ It is a source which emits an intense, almost perfectively monochromatic, directional, less divergence and highly coherent beam of light. (characterstics) 3

→ The working depends on the phenomenon of stimulated emission first proposed by Einstein in 1916. It is also quantum optics because it was explained by the how to intensity is increases interact with the matter the waves are different in different medium like solid, liquid and gases. (4)

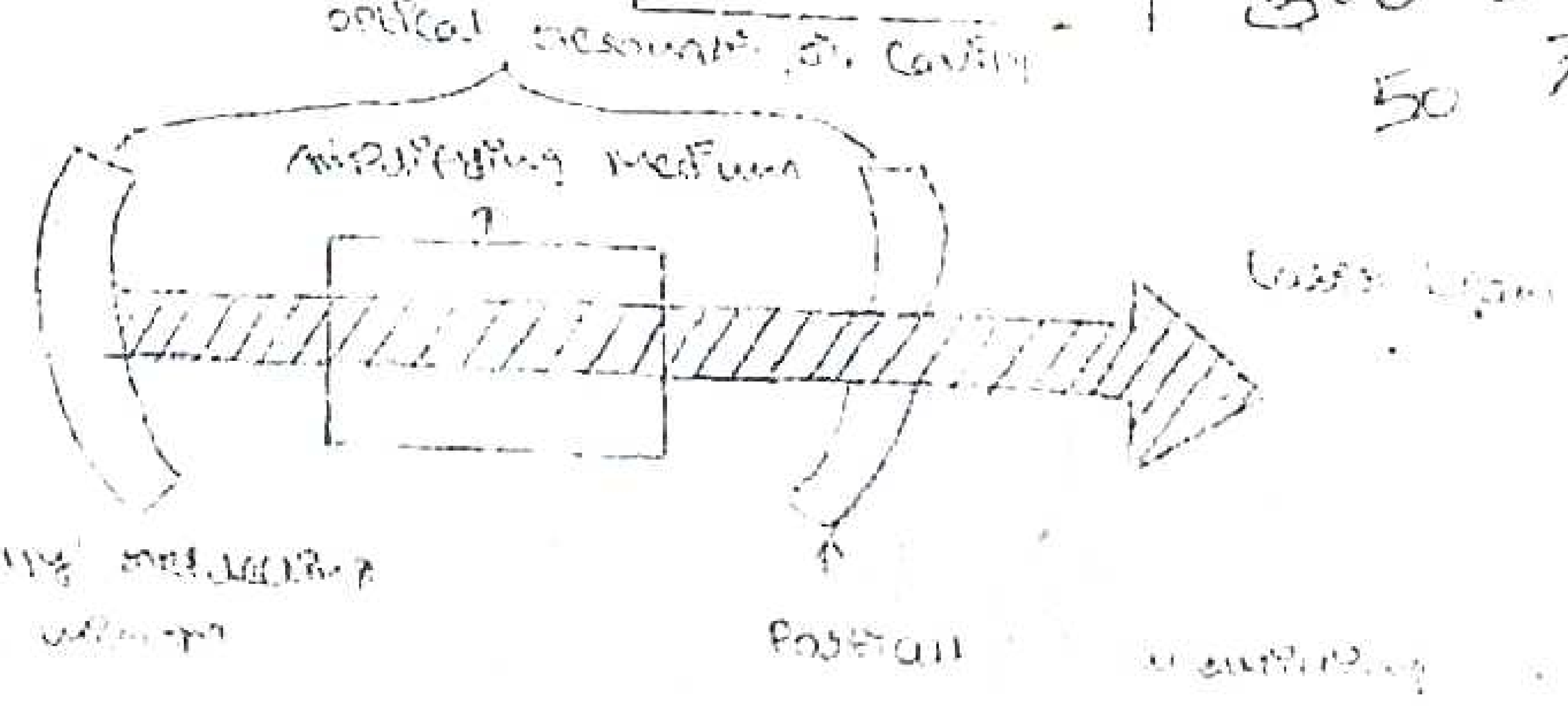
→ (5) The medium must be entered into the amplification medium (atoms, molecules, ions) then the intensity of the beam is increase. (5)

The light is interact with amplifying medium then the light is high intensity with coherent light i.e in phase.

Total intensity $\boxed{I_{total} = N^2 I}$

$\frac{206}{300}$ 1

50 70%



(1) F.R. : ... ...

Interaction of radiation with matter :-

An atom is in a lower energy state may be excited to a higher energy state through a nt ~~(no) of~~ process ~~(are given)~~ They are

1. stimulated absorption of radiation
2. spontaneous emission of radiation.
3. stimulated emission of radiation.

1. stimulated absorption of radiation :-

An atom (or), molecule (or), ions initially in lower state E_1 rises to a higher state E_2 by absorb-ing a quantum ~~(of)~~ radiation of frequency (ν)

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

Where E_1 & E_2 are the energies of the atom in the state E_1 and state E_2 respectively and N_1 & N_2 are the population of the state 1 & state 2. i.e as shown in figure.

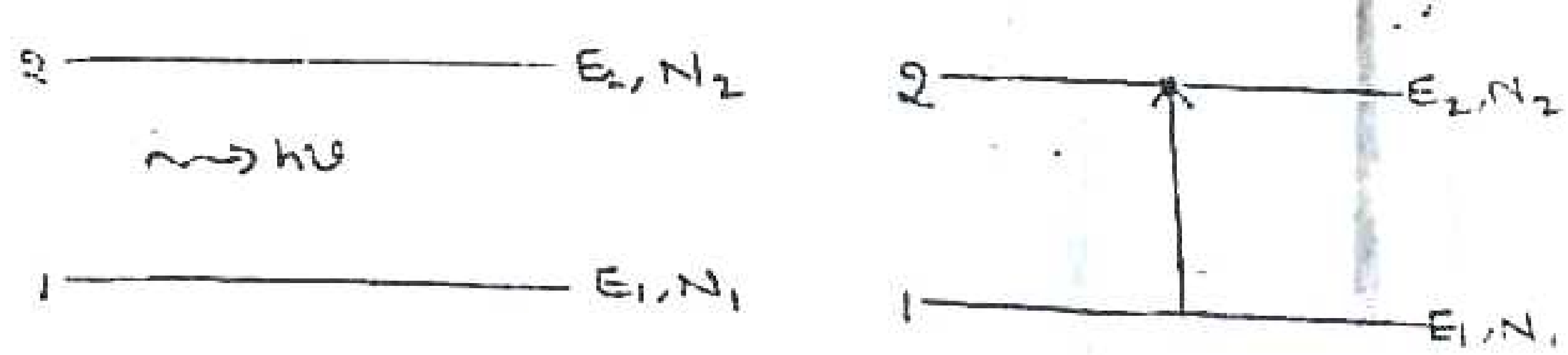


Fig : stimulated absorption.

This is stimulated (or), induced absorption of radiation. The absorbed photon is being the stimulated photon.

2. Spontaneous Emission of radiation :-

When an atom in the excited state emits radiation without any external ~~agency~~ energy i.e after the life time 10^{-8} sec in excited state is completed than this type of emission is called spontaneous emission of radiation.

→ It was proposed by "Niels Bohr"

→ The net emission depends on the no. of atoms in the excited state and on the decay constant.

→ This is characterist of transition by the spontane emission the emitted light is coherence i.e random phase distribution and the emitted waves will be in different directions

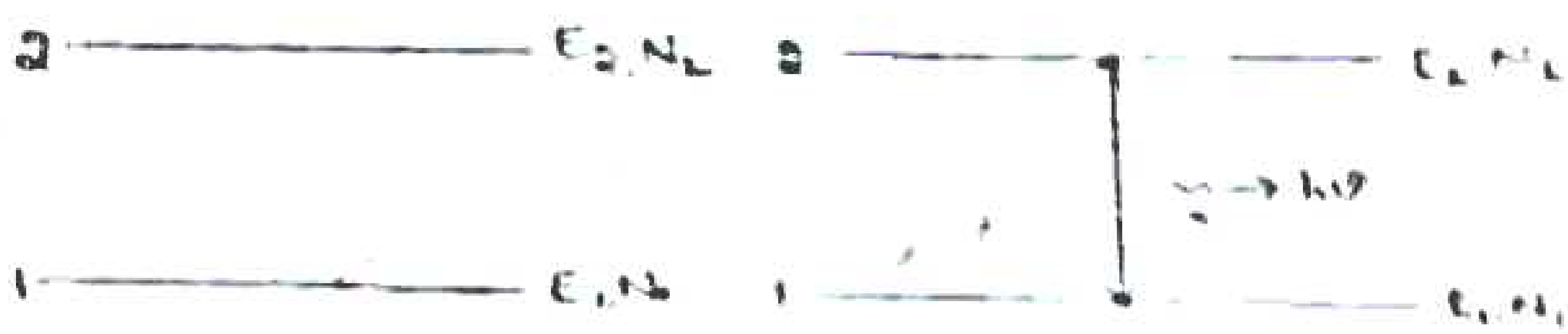


Fig: spontaneous Emission

3. Stimulated Emission of radiation :-

It was proposed by "Einstein". An atom is in excited state, emits the radiation with the application of external ~~agency~~ energy of appropriate frequency

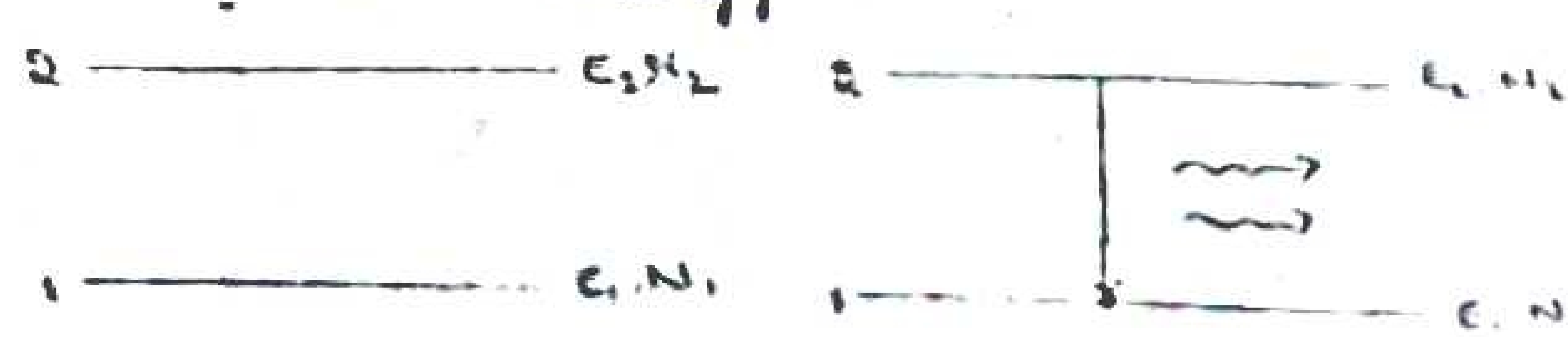


Fig : stimulated . Emission

→ The net stimulated emission depends on the applied field strength and population inversion.

→ By this process the direction of propagation energy phase and state of polarisation of emitted photon is exactly the same as that of the incident radiation

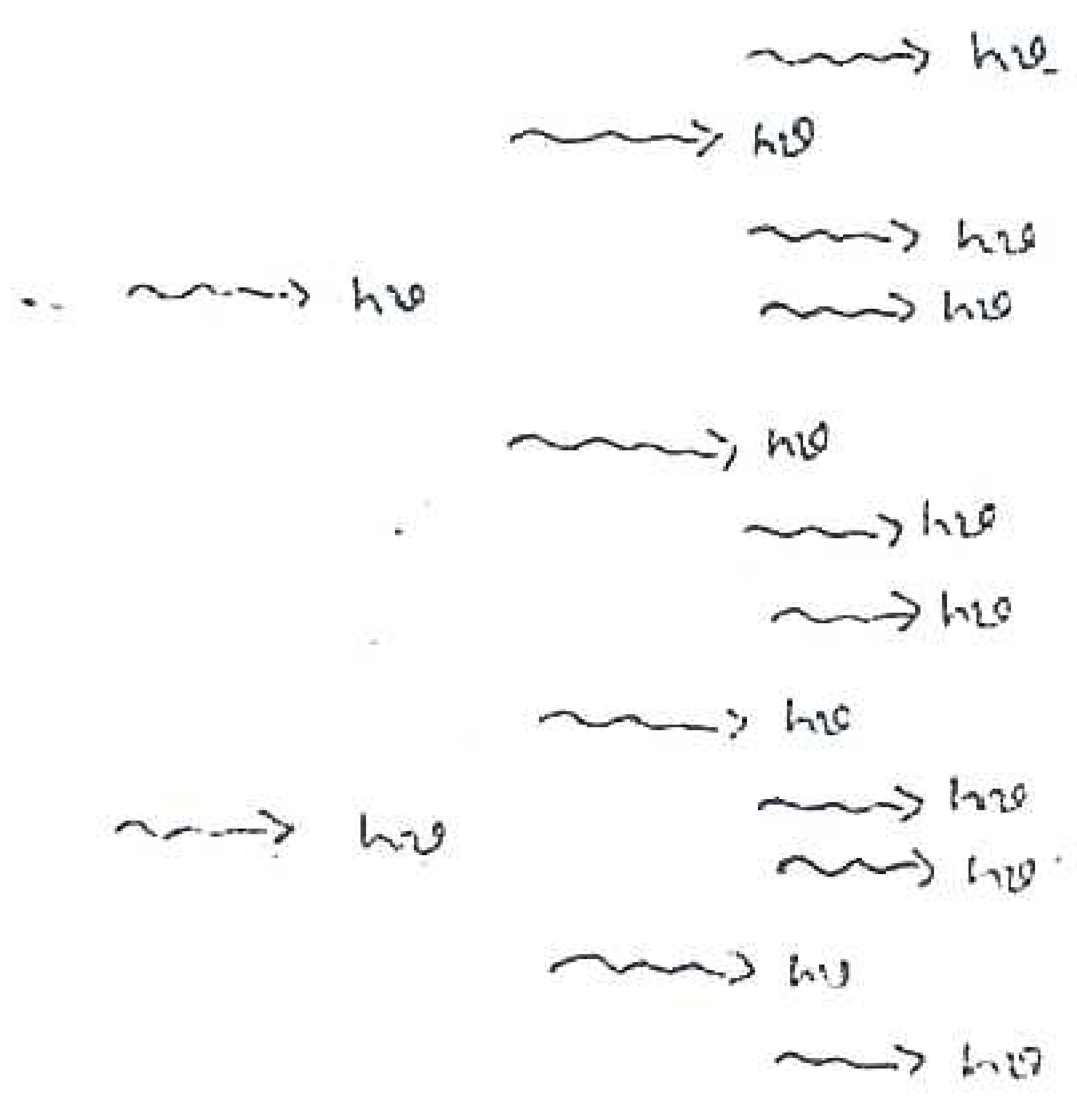
Photon.

→ By this Process the radiation Passing through an assembly of atoms (active medium) is amplified.

Population Inversion :-

Under Normal Circumstances there will be more no. of atoms in the ground state and only a few no. of atoms will be in the Excited state.

For the Productivity of laser beam the no. of atoms in the Excited state must be more i.e to produce stimulated emission. This is called Normal Population distribution.



The above Process continuous and intensity of the light beam increases exponentially and it is known as light amplification.

The Existance of more no. of atoms in the Excited state than that the ground state is called Population inversion for the Production of laser beam Population inversion must be satisfied.

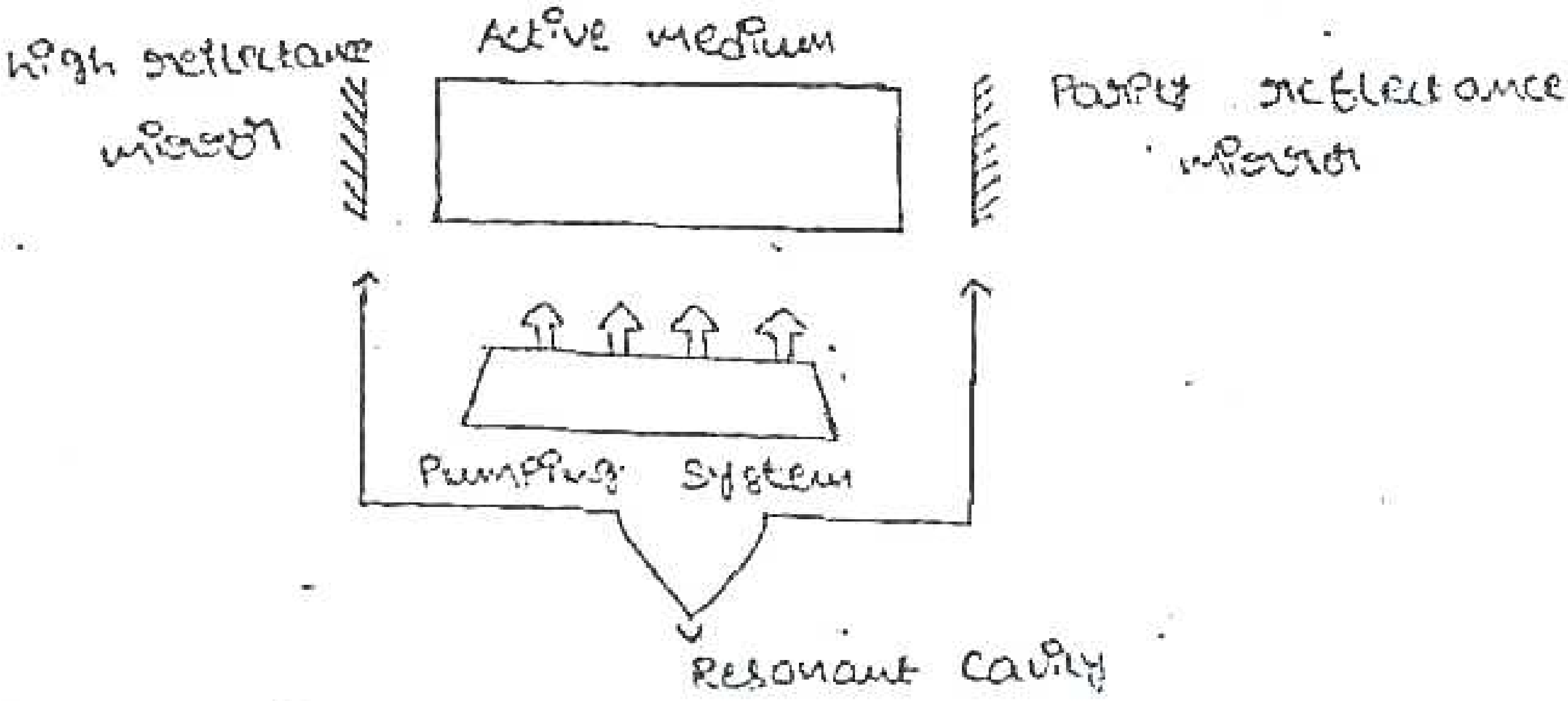
Pumping or achivement of Population inversion :-

The Process by which atoms are raised from a lower to higher energy state is called Pumping of atoms different modes of atomic excitations are some of methods are:

1. Excitation of a strong sources of light (optics Pumping
2. Excitation of chemical reaction (chemical reaction)
3. Excitation of supersonic gas Expansion (gas dynamic Pumping).

Basic Element of laser :-

Four fundamental elements are necessary to produce coherent light stimulated Emission of radiati-n.



Active medium :- A gain medium that can amplifier light that passes through it

Pumping system :- An Energy source to create Population inversion in active medium.

Resonant cavity :- Two mirrors are partially reflector and fully reflector are to produce feed back Mechanics

O/P coupler :- It releases a part of coherent light energy for use.

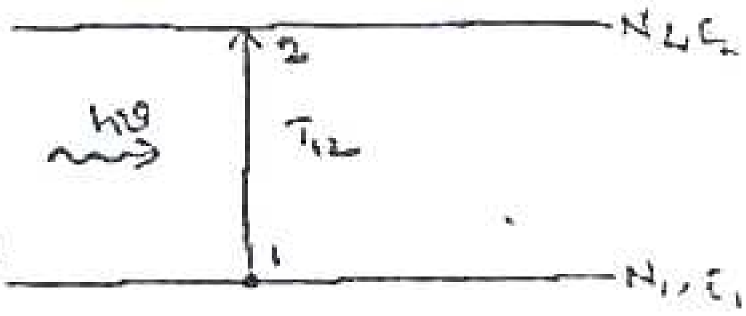
Einstein coefficients :-

Let us consider an assembles of atoms (matter) which is in equilibrium with radiation of frequency "ν" and spectral energy density $u(\nu)$ at temperature "T". Let N_1 & N_2 be the no. of atoms per unit volume in energy state "1 & 2" with energyes "E_1 & E_2" respectively.

The interaction of matter with radiation is determined by as follows process.

1. Stimulated absorption of radiation :-

An atom in the lower energy state "E_1" can absorb radiation and get excited to the state "E_2".



The probability rate of occurance of the absorption transition $1 \rightarrow 2$ would be proportional to N_1 and also to $u(\nu)$

i.e $T_{12} \propto N_1 u(\nu)$

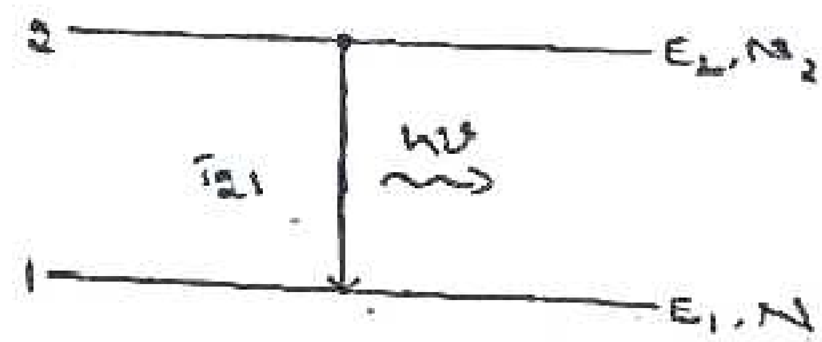
$$\boxed{T_{12} = N_1 B_{12} u(\nu)} \quad - (1)$$

Where "B_{12}" is proportionality constant and is known as Einstein's B- coefficient of absorption of radiation.

2. Spontaneous emission of radiation :-

Let us know consider the emission transition is occurance from energy stat $E_2 \rightarrow E_1$ $(2 \rightarrow 1)$

The Probability rate of Emission transition 2 ⇒ 1 would be proportional to N_2 only.



i.e $T_{21} \propto N_2$

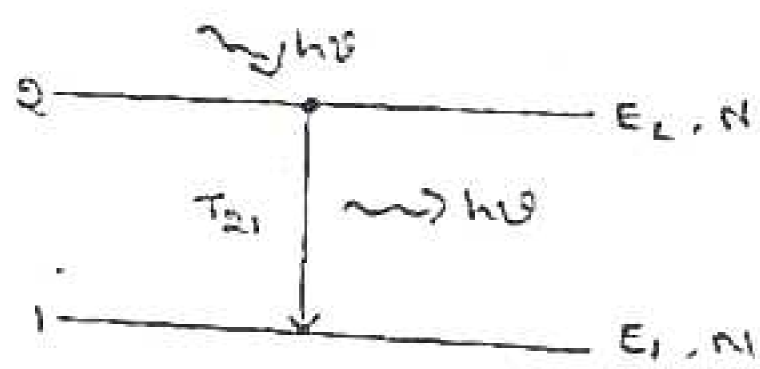
$$\boxed{T_{21} = A_{21} N_2} \quad -(2)$$

Where "A_{21}" : is called proportionality constant 2 & 1 and is known as Einsteins A - coefficient of spontaneous emission of radiation.

3. Stimulated Emission of radiation :-

Let us know consider the emission transition occurance from energy state $E_2 \Rightarrow E_1$ with applicatio of external field.

The Probability rate of stimulated emission transition is 2 → 1 is proportional to the energy density $u(\nu)$ and also N_2.



i.e $T_{21} \propto N_2 u(\nu)$

$$\boxed{T_{21} = B_{21} N_2 u(\nu)} \quad -(3)$$

Where "B_{21}" is Einstein's B- coefficient of stimulated emission of radiation.

At thermal equilibrium the no. of upward transition 1 → 2 should be equal to the no. of down word transition 2 → 1.

i.e from eqns. (1), (2) & (3) becomes

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

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

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

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

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

$$u(\nu) = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{N_1}{N_2}\left[\frac{B_{12}}{B_{21}} - 1\right]}\right] \quad \text{--- (4)}$$

From Boltzmann's law the equilibrium distribution of atoms among different energy states at temperature "T" is given by $\frac{N_1}{N_2} = e^{h\nu/KT}$. Where "K" is Boltzmann's constant.

Equation (4) becomes

$$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\left(e^{h\nu/KT}\left(\frac{B_{12}}{B_{21}} - 1\right)\right)} \quad \text{--- (5)}$$

We comparing above eqn (5) with Planck's radiation formula is

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

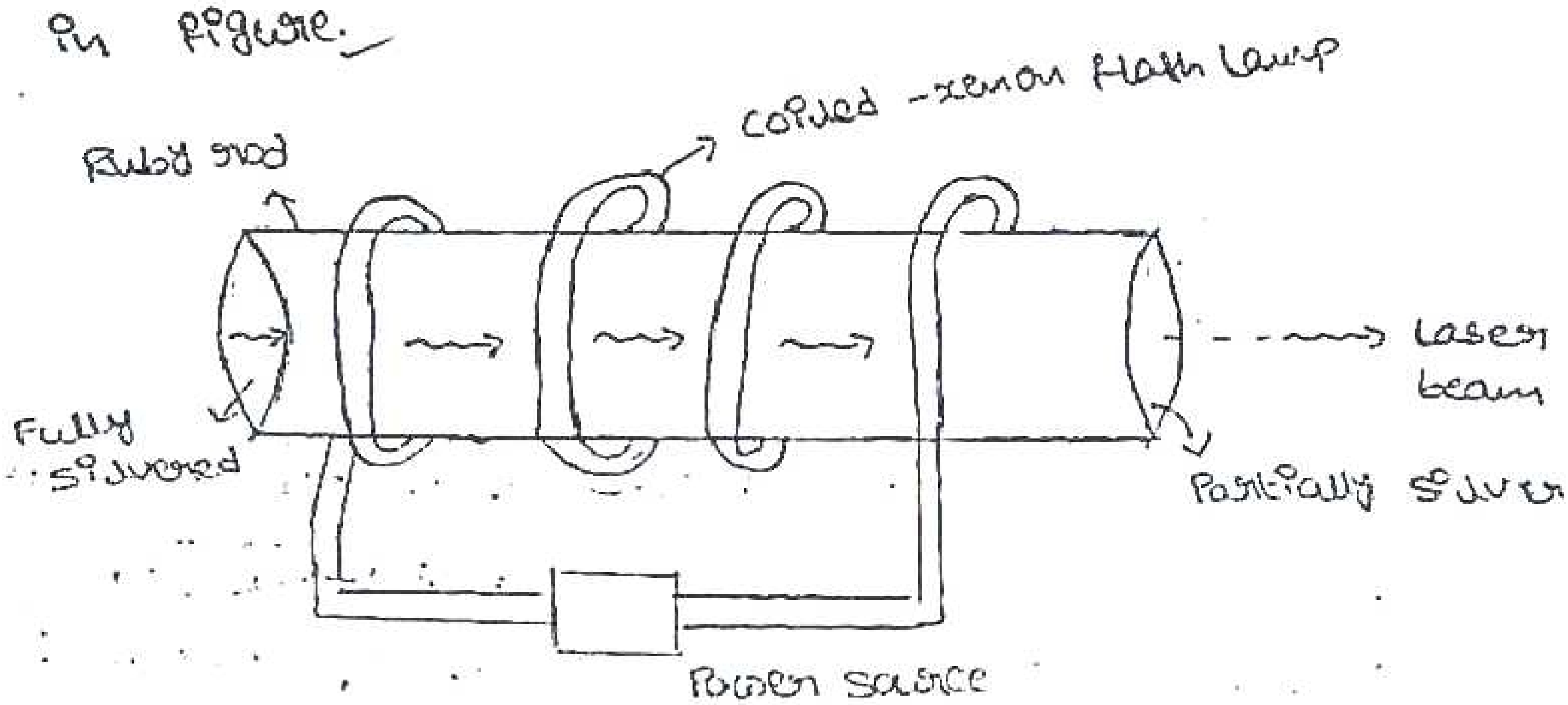
we get $\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$ --- (6)

$$\boxed{\frac{B_{12}}{B_{21}} = 1} \quad \text{--- (7)}$$

From eqn (7) it means the probability of stimulated absorption and stimulated emission is an atom equal from eqn (6) gives (the larger the energy difference btw two states. The much more likely is spontaneous emissions compared to stimulated emission.

Ruby Laser :-

The Ruby laser was the first solid laser developed in 1960. It consists of a pink ruby cylindrical rod whose ends are optically flat and parallel as shown in figure.

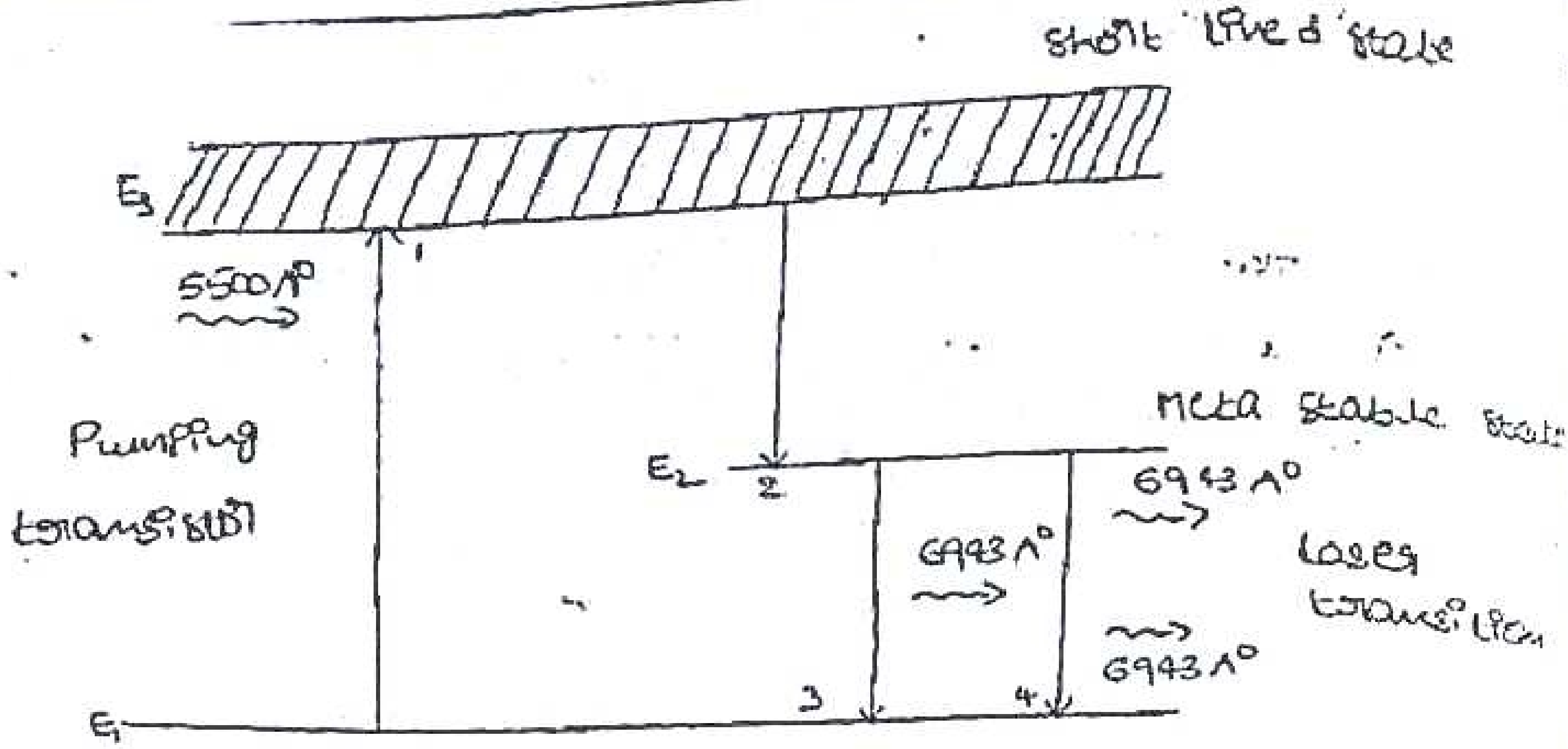


From the figure one end is fully silvered and other is partially silvered. The two ends thus form a resonant cavity. The ruby rod is placed inside a coiled xenon flash lamp. This process is repeated again and again because the photons repeatedly move along the crystal being reflected from 7 to 8 ends part of it emerges crystal through the partially silvered end of the crystal.

Working :-

The ruby rod is a crystal of Aluminium oxide. (Al_2O_3) doped with 0.05 % chromium (Cr_2O_3). so that some of the Al^{+3} ions are replaced by an ions. These impurity chromium ions give pink colour to the ruby and give rise to the laser action.

The 3-level Energy diagram is shown in below.



(A three level laser)

It consists of an upper state short lived energy level "E_3". and ground state energy level "E_1". The energy difference $E_3 - E_1$ corresponding to a wave length of about 5500 A°. There is an intermediate excited state level "E_2". Which is metastable having a life time of 3×10^{-3} sec. This stimulated transition "4" is the laser transition. This process is repeated again and again because the photon's repeatedly move along the crystal being reflected from its end part of it emerges through the partially silvered end of the crystal.

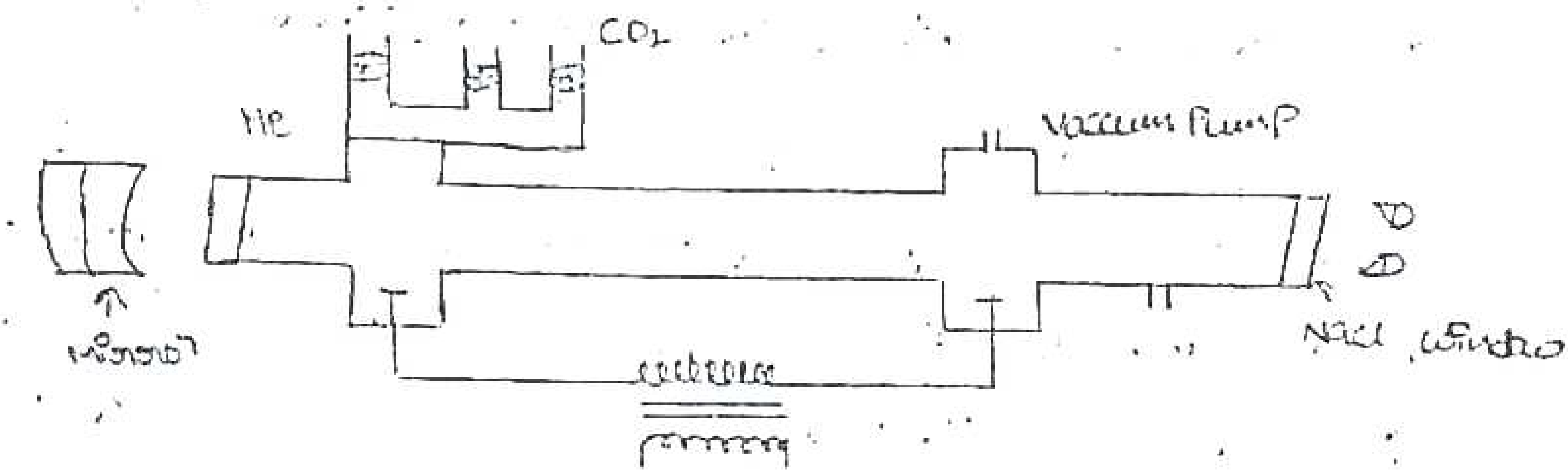
Draw backs:-

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 on to the higher state to achieve population inversion. The ruby laser is a pulsed laser i.e it emits laser light in pulses.

The duration of an individual Pulse of order 0.1 - 1 ms the time interval btw two Pulses is about 1 - 10 us. The Power of each Pulse is as high as $10^4 - 10^5$ W. This phenomenon is known as "spiking" in Ruby laser.

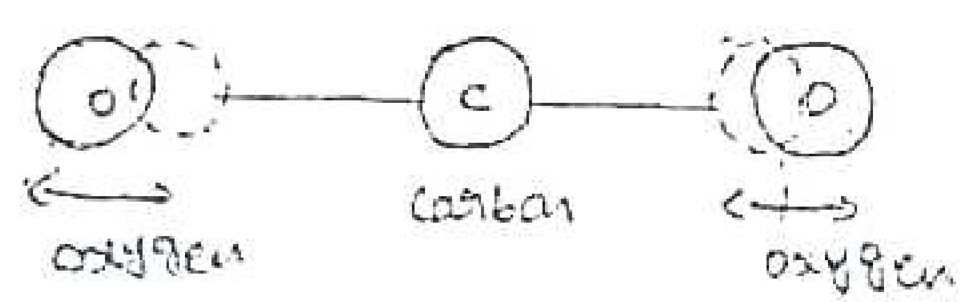
Carbon dioxide laser :-

The carbon dioxide laser is a gas laser. It is a mixture of carbon dioxide, nitrogen and helium gas.

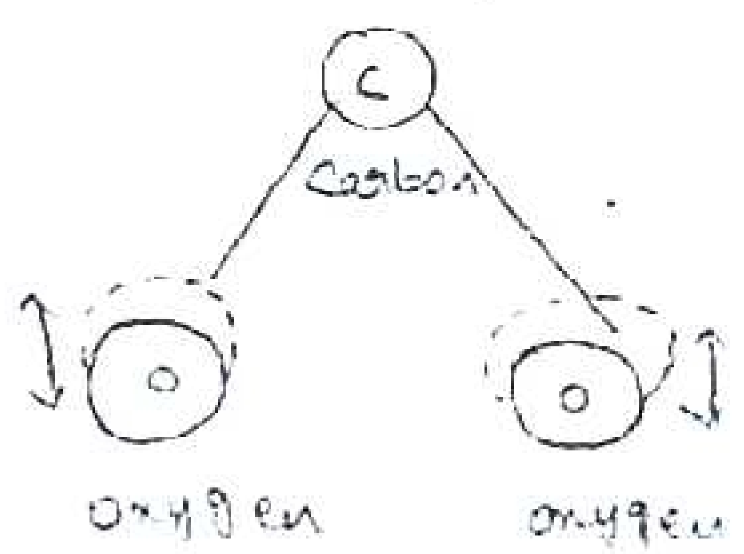


The carbon dioxide molecule consisting of a central atom with two oxygen atoms on either side such a molecule can vibrate in the three independent modes of vibration. S B A — Stretch m, Bending, Asymmetric m

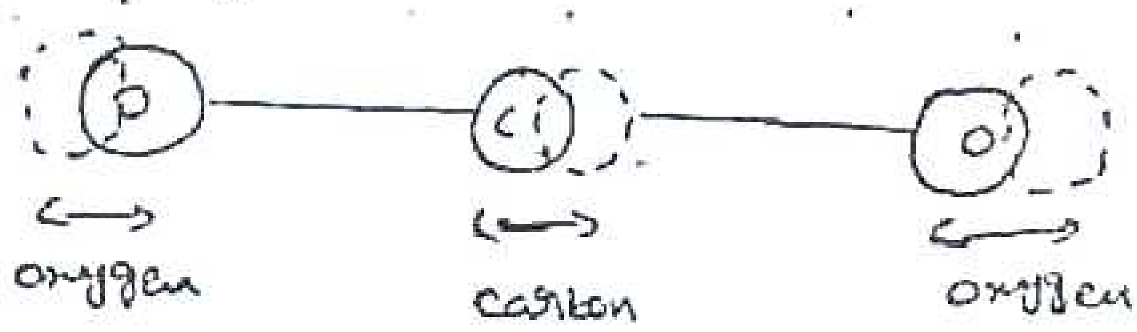
1. Stretch mode :-



2. Bending mode :-



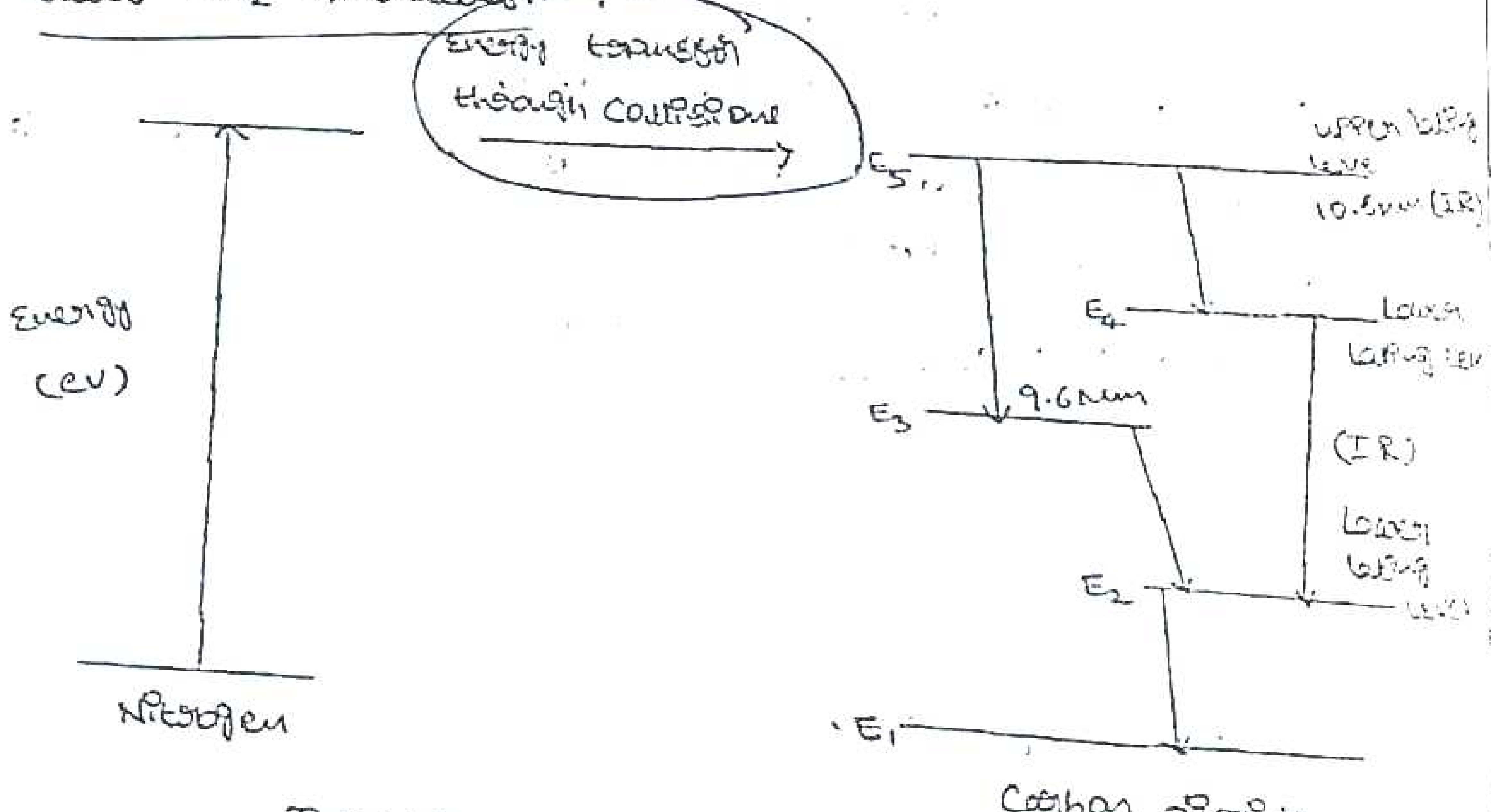
3. Asymmetric mode:-



[The three modes of vibration of a carbon dioxide molecule]

When a molecule vibrates in any of the modes, it can have only a quantized set of energies. When a current passes through the mixture of gases the N_2 molecule get excited to the meta stable state.

The excited N_2 molecules can not spontaneously lose their energy and the no. of N_2 molecules at the level keep on increasing. The N_2 molecules return to ground state through inelastic collisions with ground state CO_2 molecules.



Therefore the CO_2 molecules are excited to E_5 level. The E_5 level in the upper lasing level. while E_4 and E_3 levels act as the lower lasing level

→ Population inversion is achieved b/w E_5 level and the level at E_4 & E_3

→ The laser transition b/w $\boxed{E_5 \rightarrow E_4}$ produces IR radiation at the wave length 10.6 μm.

→ The laser transition b/w $E_5 \rightarrow E_3$ levels produces IR radiation at the wave length 9.6 μm.

→ CO_2 molecules fall to the level E_2 from E_3 and E_4. This leads to the population at E_2 level.

→ The presence of helium along with CO_2 helps to decreases the population at E_2 level. It de excites CO_2 molecules through in elastic collisions and aids cooling the gaseous mixture through heat conduction.

Uses:-

→ CO_2 laser find applications in materials welding hole drilling, cutting and used in communication system.

→ CO_2 laser is used to melting, cladding, alloying, submelting, annealing, hardening and so forth.

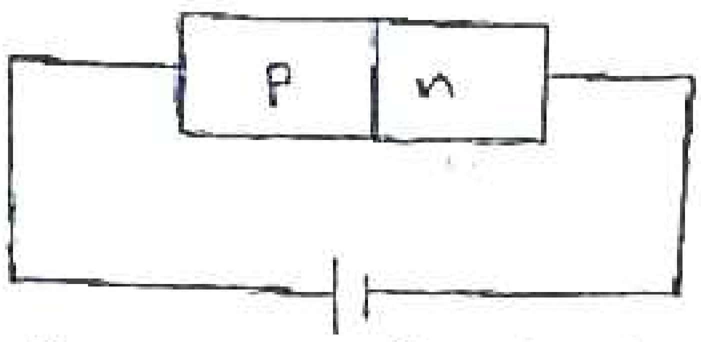
→ For pulsed operations such as the oblation of thin films of material or, drilling of small holes, the laser must reach an intensity on the target of $10^{12}-10^{13}$ w/m²

Semi conductor Lasers or, Diode Laser :-

The semi conductor laser also referred to as the junction laser or, the diode laser. It is a P-n junction device. Which emits coherent light just like in other laser systems. There are three interaction processes.

a). An electron in the valance band can absorb the incident radiation and be excited to the conduction band leaving to the generation of electron - hole

As the current is further increased at some threshold value of current the amplification will begin to emit coherent radiation.



(P-n Junction laser diode)

Uses :-

Semi conductor lasers are used in optical fiber communication in CD players, CD-ROM drivers high speed laser printing etc.

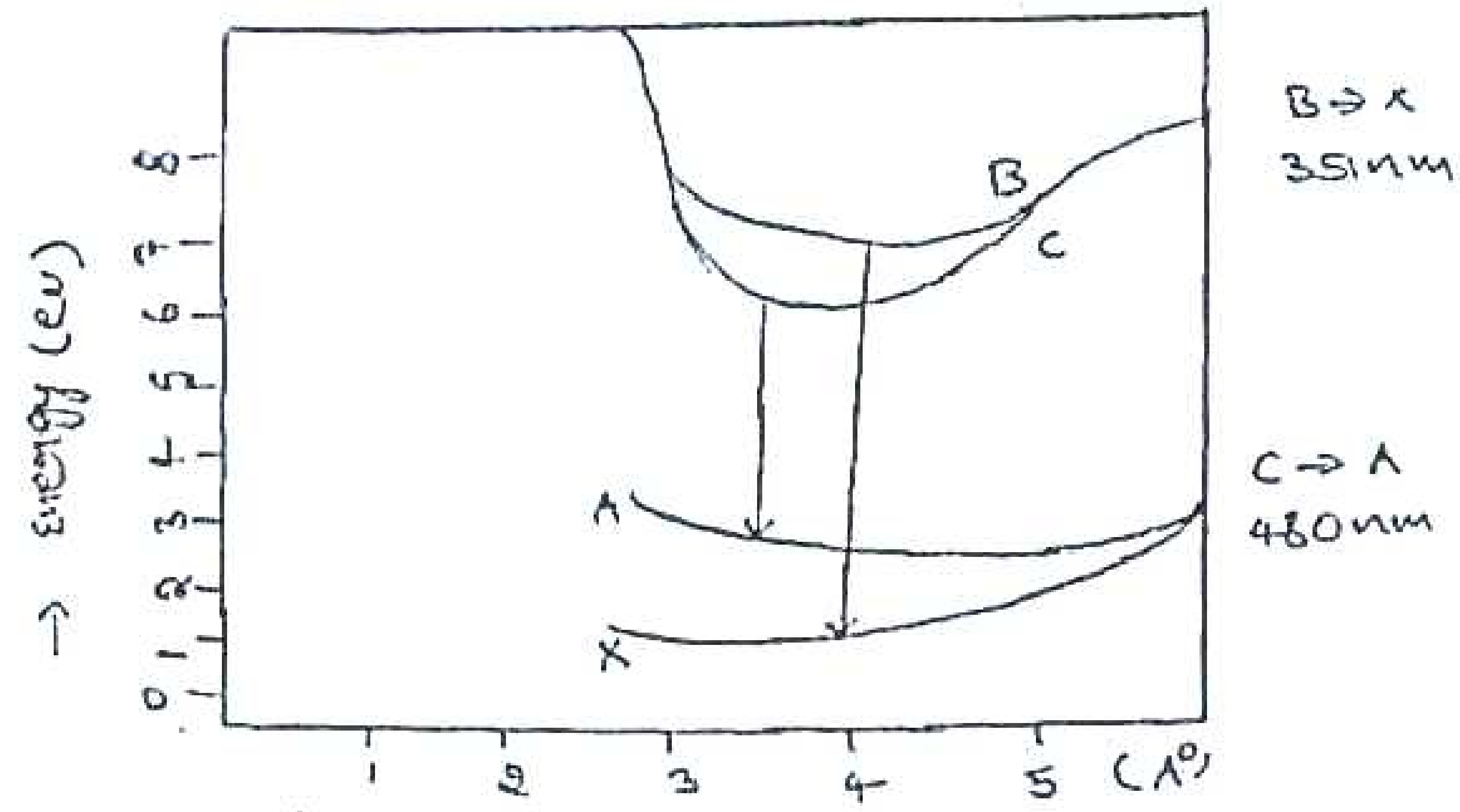
Excimer laser :-

Excimer laser is a gas laser. Excimer lasers are two level lasers. Excimer laser is the mixture of inert gas, halogen gas and helium. Excimer means a compound of two identical species that exist only in excited state.

Excimer lasers employing NeF, ArF, KrF, XeF, ArCl, KrCl, XeCl, ArBr, KrBr, XeBr, KrI and XeI as the active medium have been made.

When the noble gas excited in the laser cavity with electrical discharge method or, electron beam method or, the combination of the two noble gas atoms can be ionized.

When the nobel gas atoms are no longer in the excited state, the compound molecule dissociates and release of binding energy & this released binding energy is in the form of photon energy. This mechanism is used to form excimer lasers. The excimer laser is usually formed in a rectangular resonator cavity and can produce a very high power pulses.



[molecular energy levels involved in a xenon - fluoride Excimer laser]

The average power can be 700 W with rate of 1000 pulses per second. Excimer lasers generate laser weight in u.v region from 0.193 microns to 0.351 microns. Excimer laser have short wave length. the life time of an excimer laser is very short of the order of nano seconds.

Excimer laser are said to be able to do "laser cold cutting" through laser beam less high energy. The energy is used to break chemical bonds, heat generation can be neglected it is truly cold cutting.

Uses :-

1. They are used to remove polymer films from metal substates.
2. used in industry.
3. surgical operation

Dye Lasers (or) Liquid lasers :

Dye Lasers is a liquid laser. Large organi dye molecules as the active lasing medium. Pumping is by another pulsed / continous laser (or) by pulsed lamp a dye laser can be considered as a special device to convert Electro magnetic radiation from one wave length to another wave length. which can be turned.

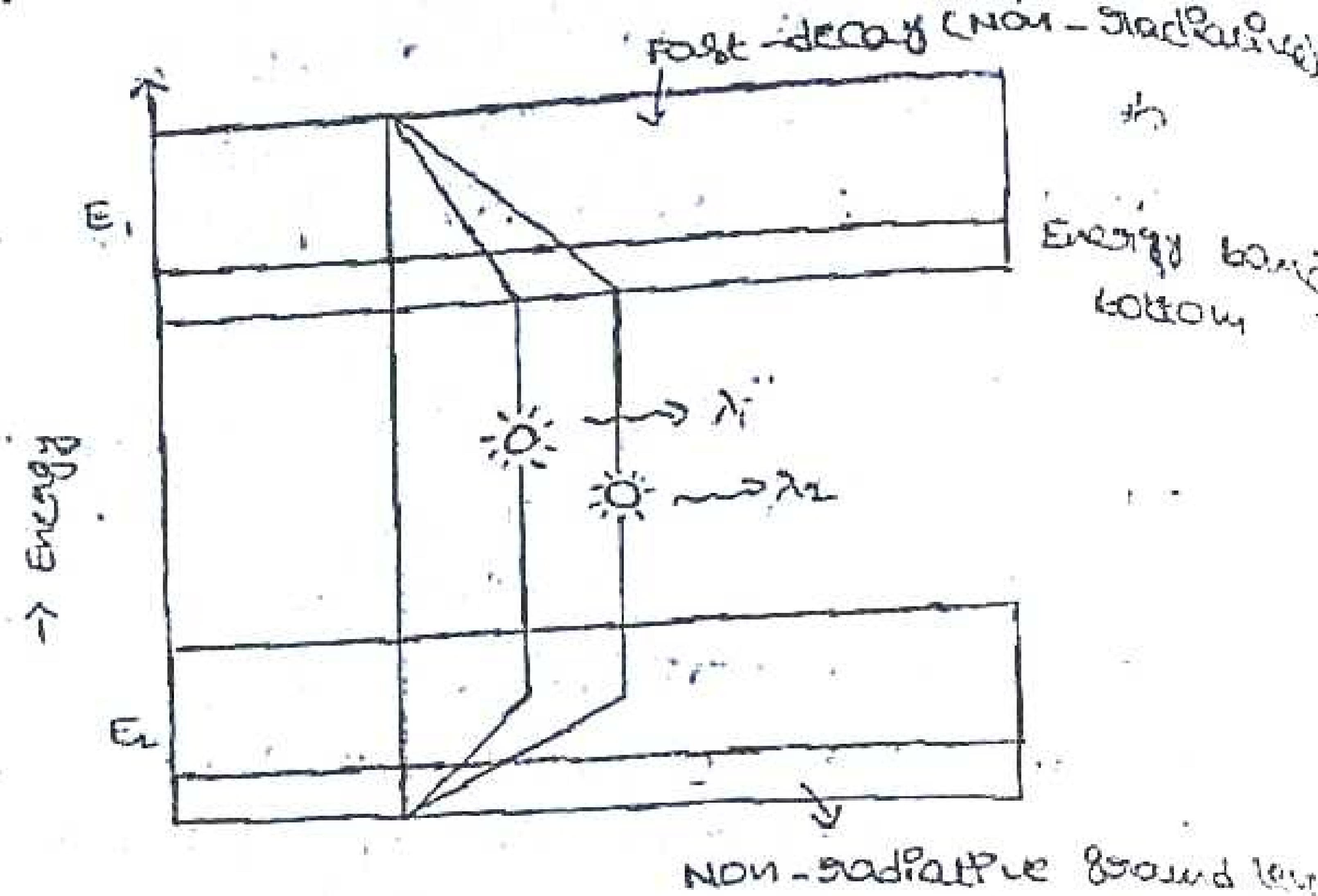
When the colour molecule is optically excit by absorbing a photon. It jumps to an excited stat in a very short time of the order of pico seconds the excited molecule will decay to the bottom of the energy band by a Non radiactive transition from this position the molecule can make lasing transition to any place in the lower band and then by a Non-radiactive transition to the bottom of the ground level.

Population inversion in a dye - laser is done by optical pumping. since each photon carries a certain amount of energy there is some loss of energy. which turn in to heat in the optical pumping process. This the wave length emitted from the laser is longer wave length than the wave length of the pump.

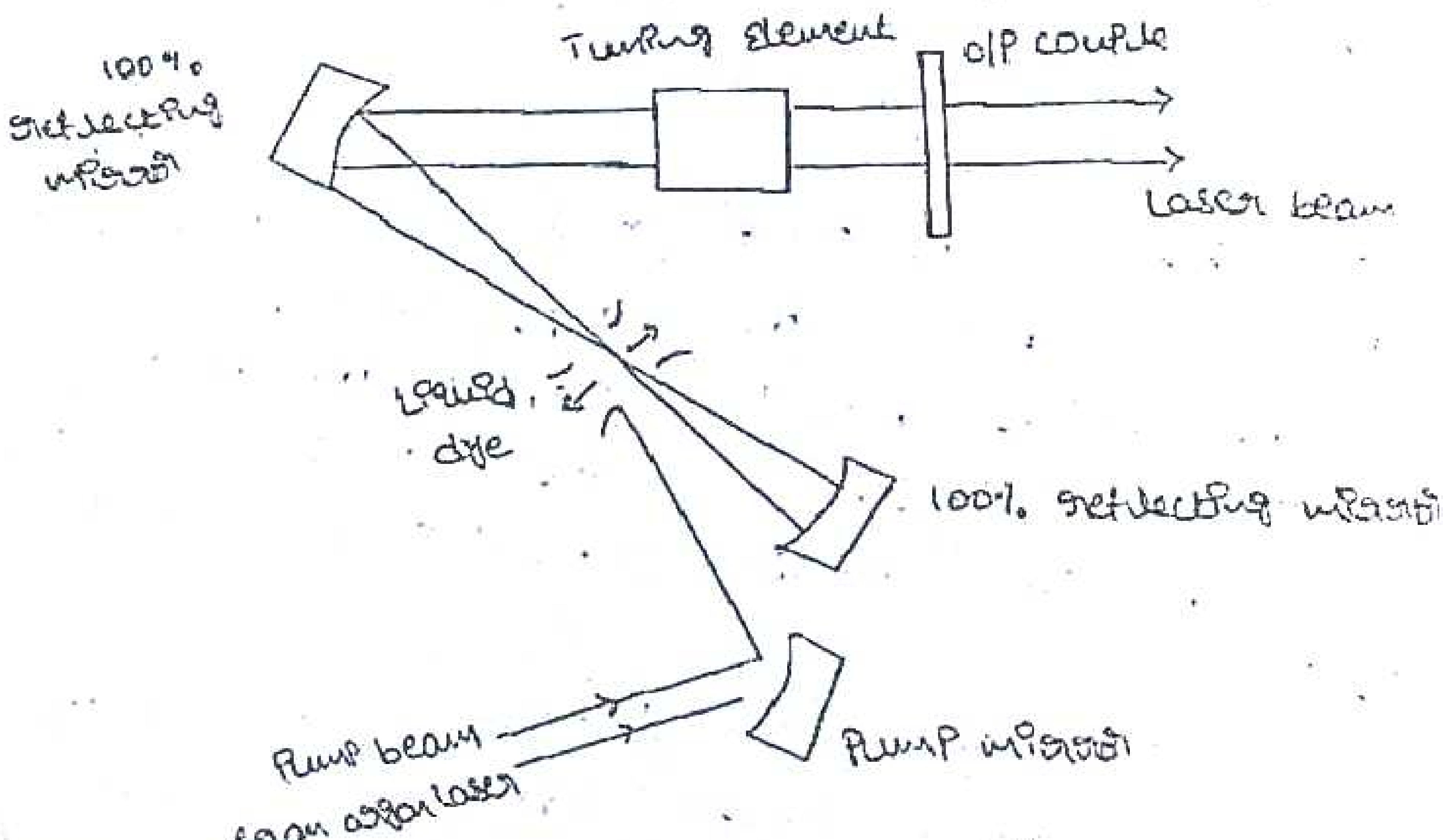
The population inversion occurs in btw the lower part of the upper band and most of the lower band. special properties of the O/P radiation of a dye laser are.

1. very narrow line width
2. very short pulses.

In a dye laser the liquid dye is inside a transparent container and the optical pump energy is coming through the walls of the optical pump energy is struck on it while it flow out of the nozzle.



[Energy level diagram of dye laser]



Uses:-

→ It is used to reduce the band width of the electro magnetic radiation.

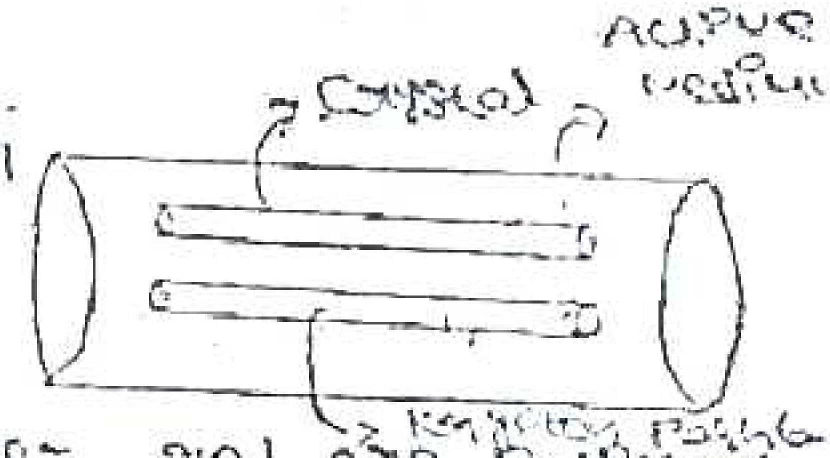
→ In medicine for photo-dynamic theory.

→ In medicine for destroying kidney stones by shock waves created by the short pulses.

Nd : YAG Laser (Neodymium Yttrium aluminium garnet) [$Y_3Al_5O_{12}$] :-

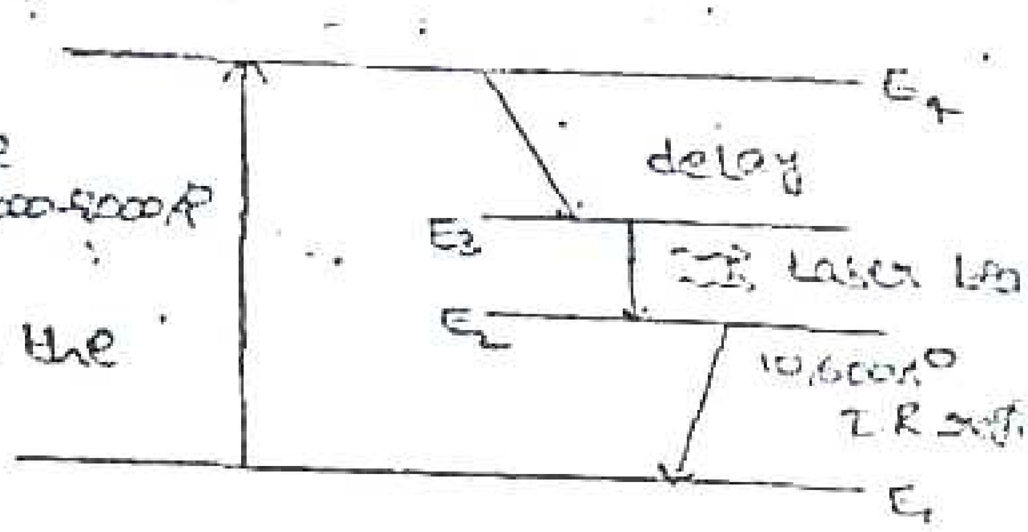
Nd : YAG laser is a synthetic crystalline material of the garnet group. Nd : YAG laser is a solid state laser from the Y^{3+} ions in the crystal are replaced by neodymium ions. Nd^{3+} doping concentration are typically of the order of 0.725% by weight.

The system consists of an Elliptically cylindrical reflector the YAG crystal rods are typically of 10cm in length and 12mm in diameter. the two ends of the laser rod are polished and silvered.



The cylindrical crystal has reflective ends one coated so that it is 100% reflective and the other is sufficiently reflective. The Nd-YAG laser is a four level laser. The pumping of the Nd^{3+} ions to the upper state is done by a krypton arc lamp.

The optical pumping with light of wave length range of 5000 to 8000 A° excites the ground state Nd^{3+} ions to the energy levels at E_4. The meta stable level E_3 is the upper laser level. While the E_2 is the lower lasing level the upper laser level. While the E_2 is the lower lasing level the upper level E_3 will be rapidly populated as the excited Nd^{3+} ions quickly make down ward transitions from the upper band. The population inversion achieved b/w E_3 level and E_2 level. The laser emission occurs in infrared region at a wave length of about 1.06μm. Nd:YAG



lasers find many industrial applications such as resistor trimming, welding, hole drilling etc. They are also used in surgery.

Rate equation for three-level system :-

Three level system:-

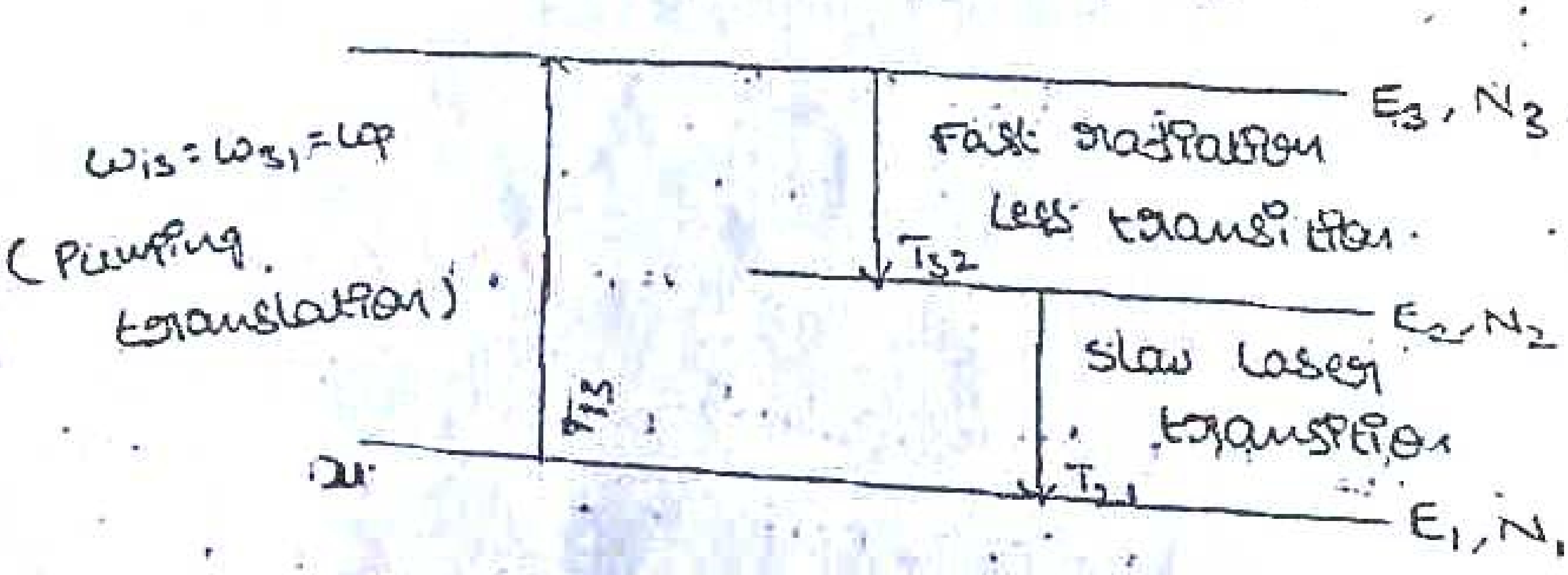
1. In three level system by 1st exciting the particles to an excited state by injecting energy into the gain medium.

2. The particles then quickly decay down into the upper laser state. This decay usually occurs by emitting heat and not photons.

3. It is important for the pumped (Excited) state to have a short life time when compared to the upper level state ($\tau_{21} >> \tau_{32}$). The upper laser state should have a long life time as possible. S.T the particles live along enough to be stimulated & this contribute to gain.

4. Laser transition then occurs btw the upper level laser and the ground state emitting laser light in this process.

Rate equation for laser 3-level system:



By the three-level laser system E_1 is the ground state and lasing is btw E_2 & E_1.

Suppose the pumping process produces a stimula transition probability b/w E_1 & E_3. So atoms at E_3 have fast decay time T_{32}. atoms at E_2 have a relatively slow transition time T_{21}.

We have $W_{13} = W_{31} = W_p$

and $N = N_1 + N_2 + N_3$

The state equations for the three level system

$$\frac{dN_3}{dt} = W_p(N_1 - N_3) - \frac{N_3}{T_{32}}$$

$$\beta = \frac{N_3}{N_2} = \frac{T_{32}}{T_{21}}$$

at steady state the population difference b/w E_2 & E_1 is

$$\frac{N_2 - N_1}{N} = \frac{(1-\beta) W_p T_{21} - 1}{(1+2\beta) W_p T_{21} + 1}$$

If we assume the atoms at E_3 decay to E_2 immediately then $\beta = 0$.

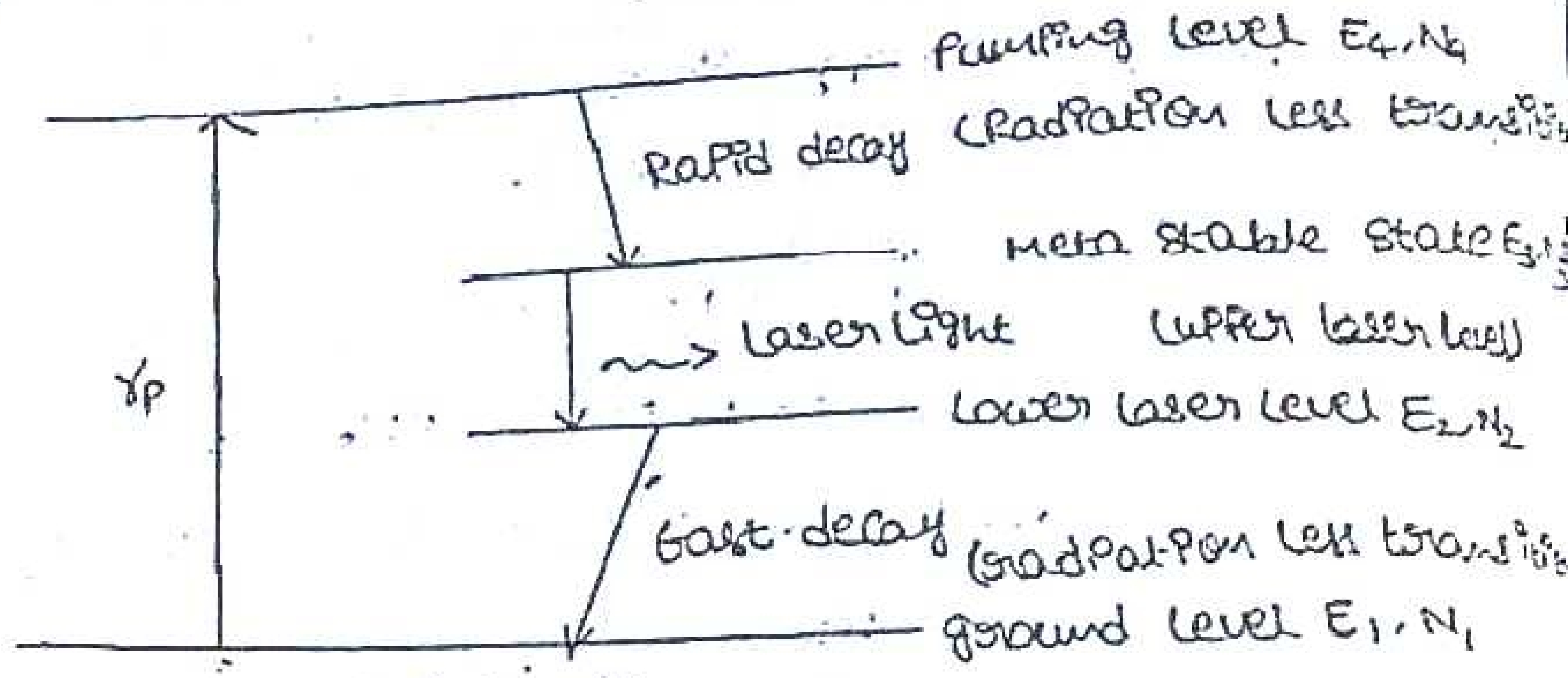
$$\therefore \frac{N_2 - N_1}{N} \sim \frac{W_p T_{21} - 1}{W_p T_{21} + 1}$$

The condition for the 3-level system:-

1. $T_{32} << T_{21}$
2. Pumping rate must be bigger than a positive threshold value.

Eg: Ruby laser: It is a typical three level laser system.

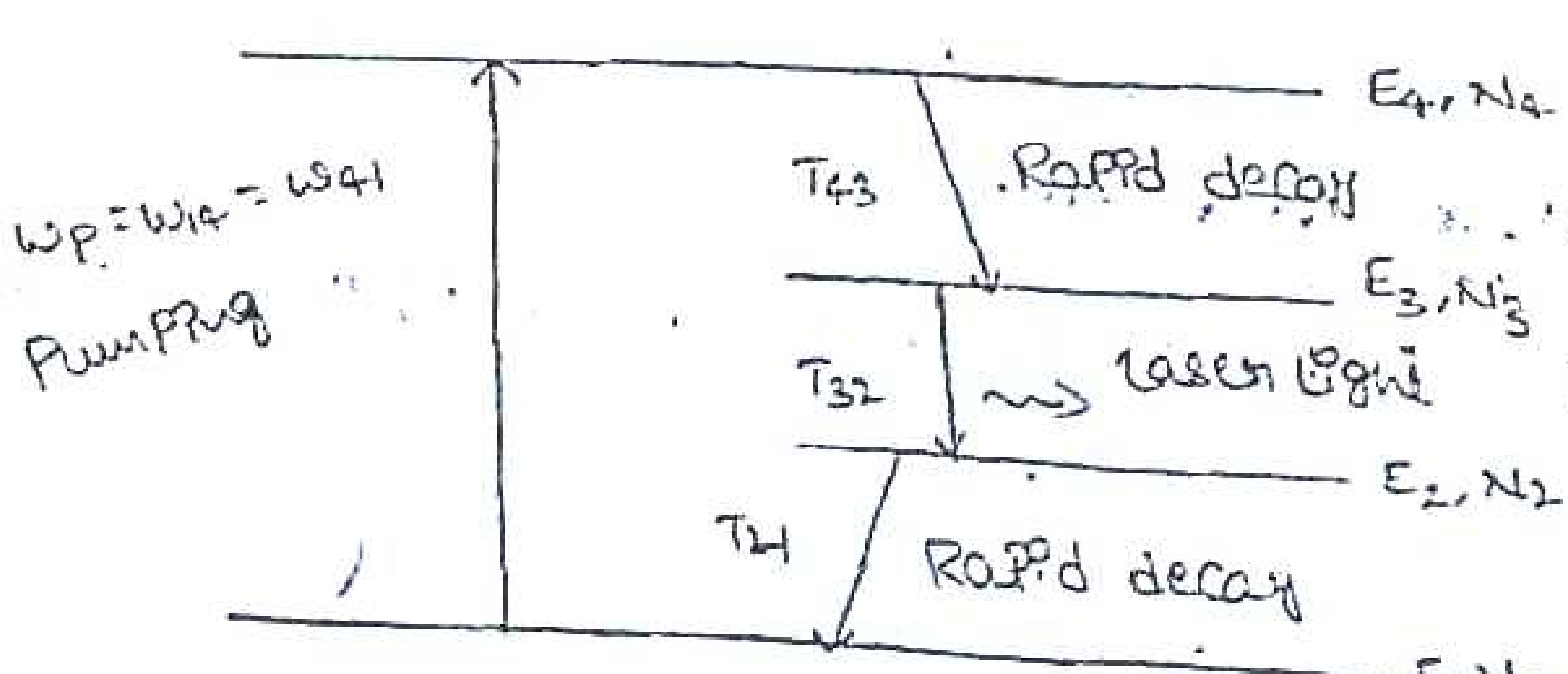
Four level system :-



When light of pump frequency ν_p is incident on the lasing medium atoms are readily excited from the ground level to the pumping level. The atoms get traped at the level E_3. The population at the level "E_3" grows rapidly as a result the level E_2 is empty. a chance of photon of energy $(E_3 - E_2) = h\nu$ emitted spontaneously can fast a chain of stimulated emissions bringing the atoms to the lower layer level E_2.

From the level E_2 the atoms undergo non radiative transitions to the ground level E_1 and will be once again available for excitation.

Rate Equation for the Four-Level Laser System :-



[Four level Laser system]

* We have E_1, N_1 at the ground level, pumping process raises the atom from E_1 to E_4 then the pumping rate is $W_p = W_{14} = W_{41}$
* atoms at E_4 have fast decay to E_3 decay time is T_{43}.
* Lasing happens btw E_2 & E_3 levels the transition time T_{32}.
* atoms at E_2 then decay very fast to E_1 the decay time is T_{21}.
* We have the relation $N = N_1 + N_2 + N_3 + N_4$

The rate equations for 4-level laser system is

$$\frac{dN_4}{dt} = W_p(N_1 - N_4) - \frac{N_4}{T_{43}}$$

$$\frac{dN_3}{dt} = \frac{N_4}{T_{43}} - \frac{N_3}{T_{32}}$$

$$\frac{dN_2}{dt} = \frac{N_3}{T_{32}} - \frac{N_2}{T_{21}}$$

Population $\beta = \frac{N_2}{N_3} = \frac{T_{21}}{T_{32}}$

The population inversion btw N_3 and N_2 is

$$\frac{N_3 - N_2}{N} = \frac{(1-\beta) W_p T_{rad}}{1 + (1+\beta) W_p T_{rad}}$$

since $\beta = 0$ for a four-level system.

$N_3 - N_2$ is bigger than zero.

Eg:-

Nd-YAG laser [Neodymium ytterium aluminium garanet laser] is the example of four-level laser system.