LASER (Light Amplificatⁿ by stimulated Emission of Radiation)

Properties of laser beam:

1) unidirectionality

→ Highly directional compared to light from bulb, sodium lamp, etc.

→ It travels in narrow beam.

→ It travels in straight line for a long time.

→ Applications in industry & medicines.

2) Monochromaticity

→ It is highly monochromatic &

(having one colour or, of a very small range of wavelengths)

→ frequency of laser radiatⁿ is highly centred to particular frequency range.

3) Coherent (two sources of waves have the same amplitude, wavelength & constant phase difference)

→ It is highly coherent.

→ Spatially, temperally & directionaly coherent, so it used in many applications.

→ Coherent length of,

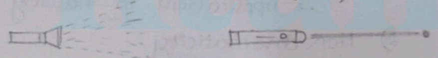
Conventional sources → few centimeters
(LED, halogen lamps, fluorescent tubes ...)
Laser → few kilometers

4) High Intensity (used for cutting & welding in various applications.)

→ laser beam is very narrow & concentrated, ie why it has high intensity.

→ Laser beam can be focused to a very small area, So its density & power can be also increased.

5) Low/negligible divergence

suppose, torch  but for lasers,

6) Brightness

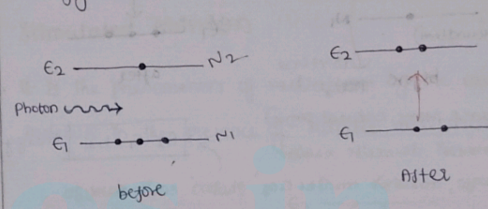
→ power emitted per unit surface area.

→ Brightness of laser of moderate power of several orders are greater than the brightness of brightest conventional sources.
this is due to high directional property.

? What happens when such a beam of light interacts with matter?

① Absorption of Radiation (Induced Absorption)

- It is a phenomenon that occurs when an atom (molecule) absorbs a (external) photon and transitions (excitation/) from a lower energy to higher energy state.



നമ്മൾ ഒരു external stimulus ($E_2 - E_1 = h\nu_{21}$) apply ചെയ്യുമ്പോൾ. E_1 ലെ atoms excite ആയിട്ട് upper level (E_2)-ലേക്ക് പോകും.

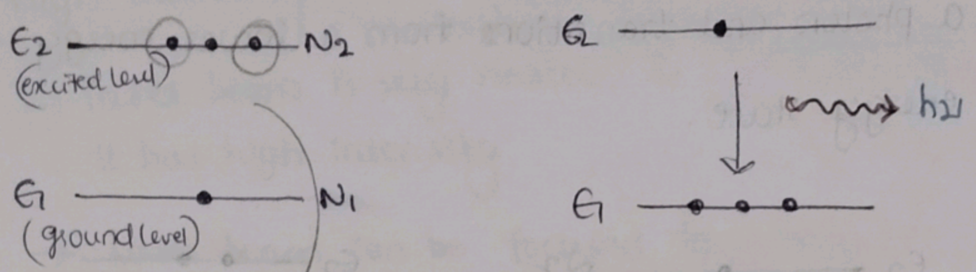
∴ Rate of Absorptn $\propto N_1 \rho(\nu)$ → density of incident photon
(N_1 — no. of atoms in lower energy level)

ie, $P_{12} \propto N_1 \rho(\nu)$

$$\boxed{P_{12} = B_{12}\, \rho(\nu)\, N_1}$$

② Spontaneous emission

- It is the emission of radiatn by natural ~~de-excitatn~~ de-excitation of atoms or molecules from Higher energy level to lower energy level.



before　　　　　　after.

Here,

ഈ 2 Atoms natural ആയി അതേത് de-excite ചെയ്ത് വരും, അപ്പോൾ അതിലെ ഒരു photon emit ചെയ്യും.

$\boxed{E_2 - E_1 = h\nu}$ Energy of photon

* freq. of radiatn emitted due to transition from level 2 to 1

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

Rate of spont. emission $\propto$ no. of atoms in 2^{nd} level.

ie, Rate of spont emission $(N_{sp}) \propto N_2$

$$\therefore \boxed{N_{sp} = A_{21} N_2}$$

E_2 ൽ നിന്ന് E_1 ലേക്കാണ് atoms excited ചെയ്യുന്നത് ചാൻസ്.

(Einstein coeff. for spont emission)

Spontaneous emission rate $\frac{dN_2}{dt}$ is proportional to no. of atoms in higher energy level $E_2 = N_2$

$$\therefore \frac{dN_2}{dt} \propto N_2 \quad \text{or} \quad \boxed{\frac{dN_2}{dt} = A_2 N_2}$$

Features :- (just opposite to laser features)

→ Happens naturally, no ~~exertnal~~ external stimulus is required.

→ Random dxn

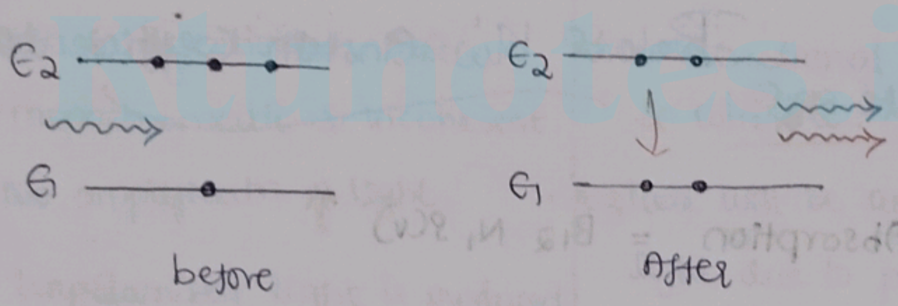
→ lack of coherence

→ Emitted light waves have no phase relation.

eg. Conventional sources.

③ Stimulated emission

- It is the phenomenon of ~~radiation~~ emission by the excited atom or molecule in the presence of suitable radiation.



ഇവിടെ naturally നടക്കുന്നതാണ്, $E_2 - E_1 = h\nu$ or photon of energy $h\nu$ is incident on it. As a result, atoms de-excited from Higher energy level to lower energy level.

And, After → Here two photons (one we incidented photon & other emitted) are moving in same dxn with same phase.

So result beam is coherent.

$\therefore$ Rate of stimulated emission $\propto N_2 \rho(\nu)$

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

Einstein coeff. of stimulated emission.

Features :- (laser features)

→ Emission stimulated ~~emissio~~ by photon of same frequency.

→ Definite phase radiatn & coherent.

→ Directionality

eg. Laser

Relatn b/w Einstein coefficients

Rate eqn

Absorption $= B_{12} N_1 \rho(\nu)$ ↑

Spontaneous $= A_{21} N_2$ ↓

Stimulated $= B_{21} N_2 \rho(\nu)$ ↓

A/c to Einstein, at equilibrium;

upward transition rate = downward transitn rate

$$\underset{\text{absorptn}}{N_{ab}} = \underset{\text{spont}}{N_{sp}} + \underset{\text{stimulated}}{N_{st}}$$

ie, $B_{12} N_1 \rho(\nu) = A_{21} N_2 + B_{21} N_2 \rho(\nu)$

* And here,

Einstein was also able to show that;

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

$$\boxed{\frac{A_{21}}{B_{21}} \propto \nu^3}$$

→ Comparison b/w spontaneous & stimulated emission;

Spont. emission	Stimulated emission
• Random & probabilistic process.	• Not a random process.
• Can't be controlled from outside.	• Can be controlled.
• emitted photons are not same.	• They are identical in all aspects.
• not unidirectional, not-monochromatic & incoherent.	• unidirectional, monochromatic, & coherent.
• No. amplificatn of light.	• There will be amplificatn of light due to process
• Unpolarised light is produced.	• Plane polarised light is produced.

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Requirements for laser action :-

→ Let us, compare the ratio of stimulated emission with spont. emission rate & absorptn rate.

ie, $$\frac{N_{st}}{N_{sp}} = \frac{B_{21}\rho(\nu)\cancel{N_2}}{A_{21}\cancel{N_2}} = \frac{B_{21}}{A_{21}}\rho(\nu)$$

$$\frac{N_{st}}{N_{ab}} = \frac{B_{21}\rho(\nu)N_2}{B_{12}\rho(\nu)N_1} = \frac{N_2}{N_1}$$

N_2 → no. of atoms in excited state

N_1 → " " ground state

($\because B_{21} = B_{12}$)

(N_{ab} = no. of absorptn undergoing per volume per unit time)

→ For laser action, stimulated emission has to dominate over other processes (ie, Absorptn & spont. emission process).

→ To make stimulated emission dominant, the following conditions are required;

(i) large photon density of radiation $\rho(\nu)$.

The presence of large no. of photons is required. This is achieved by enclosing the emitted radiatn in a cavity b/w two reflectors.

(2) large ratio of $\frac{B_{21}}{A_{21}}$

It is necessary to have A_{21} is small, that is lifetime of higher energy state must be large.

This is achieved by choosing upper level as meta stable state.

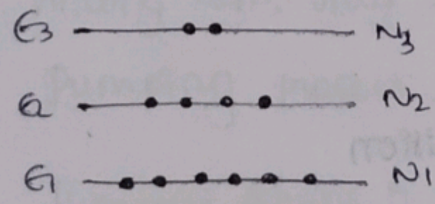
(3) Making $N_2 > N_1$

This condition is called population inversion. It can be achieved by pumping.

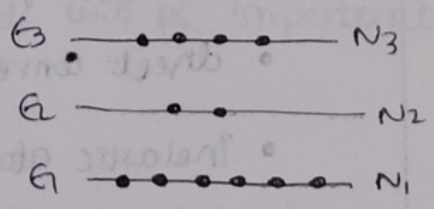
Population inversion:

- When a meterial is in thermal eqbm, the ratio of populatn density of atoms having different energies are given by boltzmann equatn,

$$\frac{N_2}{N_1} = e^{\frac{-(E_2-E_1)}{KT}}$$



$N_1 > N_2 > N_3$



$N_3 > N_2$

Populatn inversion.

→ ∴ Populatn inversion is a situatn in which the no. of atoms in higher energy state is made larger than that of lower energy state. (ie, $N_2 > N_1$)

→ It is a non-eqbm state & exists only for a short time.

Pumping :

→ The process of supplying energy to achieve population inversion is called pumping.

→ For Achieving and maintaining the condition of population inversion, atoms in lower energy level should be ~~equat~~ raised continously to the higher energy level by supplying energy.

→ techniques used in pumping,

- optical pumping
- Electrical pumping
- direct conversion
- inelastic atom-atom collision
- Chemical conversion.

Metastable State :

→ Excited energy states with such long life are called 'metastable states'.

normal state → 10^{-8} sec
metastable state → 10^{-3} sec

→ Even though pumping mechanism, continously raised the atoms to excited level, they undergo spontaneous emission and return to lower energy level very quickly.

→ ~~In certain meterials, this is bcz, atoms in excited states~~

this is bcz, atoms in excited energy ~~level~~ states have very short life time (10^{-8} sec). so here populatn inversion can't established and atoms donot stay long enough at excited state to - undergo stimul. emission

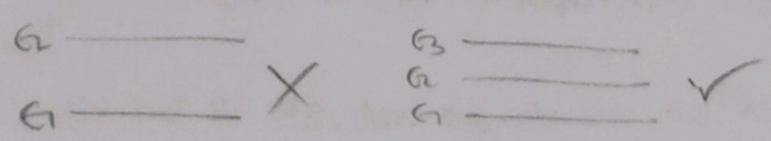
→ In certain meterials, there are excited energy states having life times of the order of 10^{-3} sec.

(which is 10^{5} times higher than the ordinary excited state).

→ In metastable state, establish the conditn of populatn inversion

Principal of pumping schemes

- Atoms have large no. of energy levels.
- Among them, only 3 or 4 levels will be important for pumping process.
- Two-level scheme is not generally used for laser action.



- The reason is that, energy being used to pump the atom to higher energy state has an equal ~~opportunity~~ probability of stimulating them back into lower energy state.

- Three & four level pumping schemes are widely used.

Components of Laser

① Active medium

→ The medium in which laser action takes place.

→ It may be solid, liquid, gas.

→ It placed b/w two reflecting mirrors.

→ It provides amplificatn of light.

→ most important one is we should be able to obtain populatn inversion in it & there should be atoms having metastable states in it.

② Pumping mechanism

→ Pump is an external source.

→ Pumping methods can be optical, electrical, Chemical, etc.

→ It supplies energy needed to transfer the laser medium into state of populatn inversion.

③ <u>optical resonator</u> (Resonant cavity)

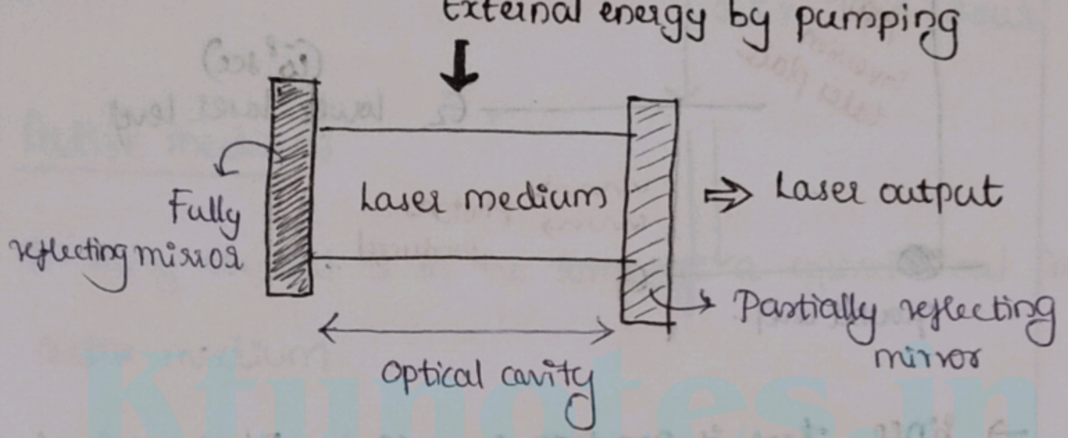
→ It consist of two mirrors b/w the medium.

- one is fully reflecting & other is partially reflecting mirror

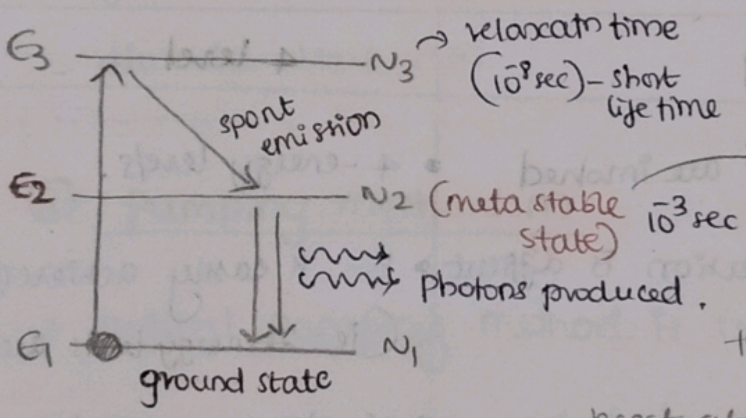
→ optical cavity makes the laser beam unidirectional.

→ It selects & Amplifies only certain frequencies.

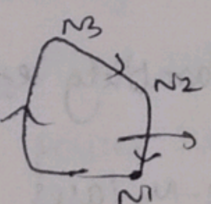
→ Thus the laser output becomes highly monochromatic also.



3-level laser (Ruby eg. laser)



→ populatn is more here, So these actions in E_2 tries come back to E_1 level. And they will be interacting with next atoms i.e, in the excited state and they will be produced photons.



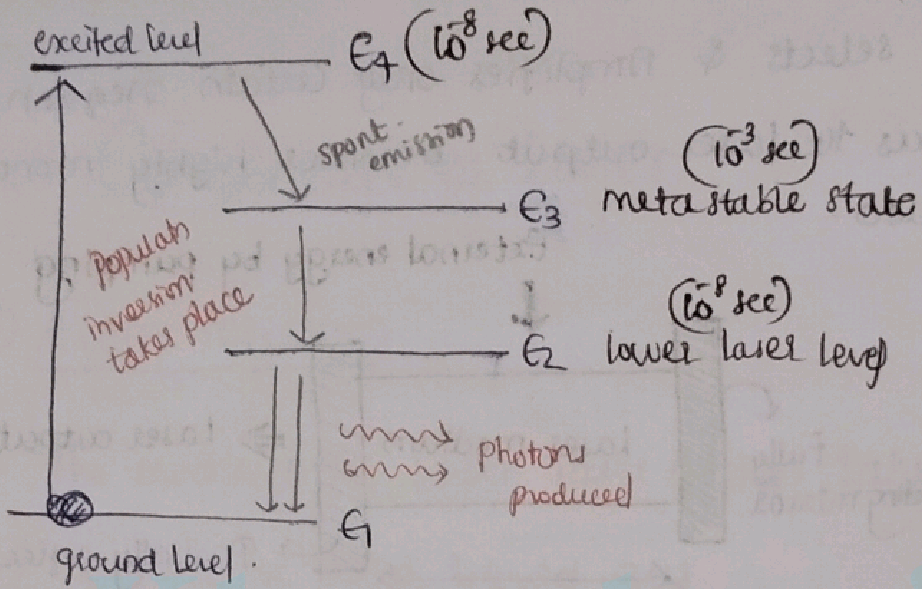
→ ഈ cycle complete ആകുമ്പോഴാണ് photons produced.

i.e (N₁ excited to N3, then N3 de-excited to N2 and N2 de-excited to N₁ And Reapeats)

→ here output is pulsed output. (not continous).

→ more energy is required to pump the particles.

4-level laser



→ here more atoms will accumulate so, de-excited to E_2.

→ since, there is population inversion, photons produced continously and hence a continous beam of light is produced.

→ Efficiency is more.

3-level	4-level
• 3 energy levels are involved	• 4-energy levels.
• populatn inversion is difficult to achieve	• " " easily achieved. (ie, 2-energy levels are involved).
• pulsed output	• Continous output
• Efficiency is very low.	• Comparatively efficiency is high
eg. Ruby laser	eg. He-Ne laser

→ Examples of Laser :-

1. Ruby laser

$\lambda = 6943 A^{0}$.

→ It is a solid laser.

→ It is a three-level laser.

→ Ruby is aluminium oxide ~~Cg~~ crystal (Al_2O_3) doped with 0.05% of chromium oxide (Cr_2O_3). → 0.05% Pink colour
0.5% Red colour.

① Active medium

→ A Ruby crystal is in the form of a cylindrical rod is the active medium.

→ Cr^{3+} ions are the active centres. Which can absorb green & blue light while Al & Oxygen atoms are inert.

→ Cylindrical ~~rod~~ ruby rode will have a length of 4cm & diameter about 1cm.

② Pumping mechanism

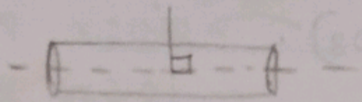
→ Optical pumping method is used here.

→ Ruby rod is surrounded by a helical flash lamp filled with Xenon gas, it emits white light when power supply is given

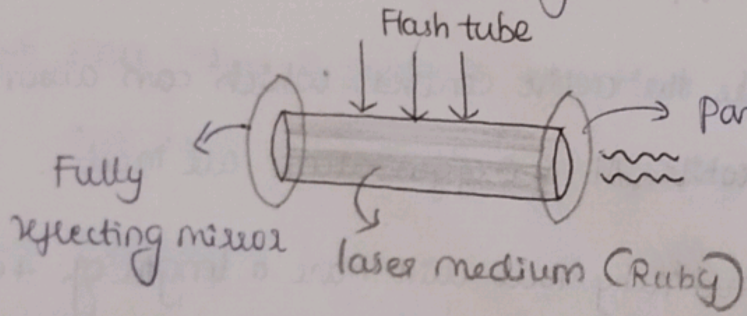
→ A cooling arrangement is required for Ruby laser, bcz the energy level of solid state substances is dependent on temperature, which affects the laser's frequency of operation.

③ optical resonator

→ The end faces of ruby rod are ground & polished such that they are exactly parellel to each other & are also ⊥r to the axis of rod.

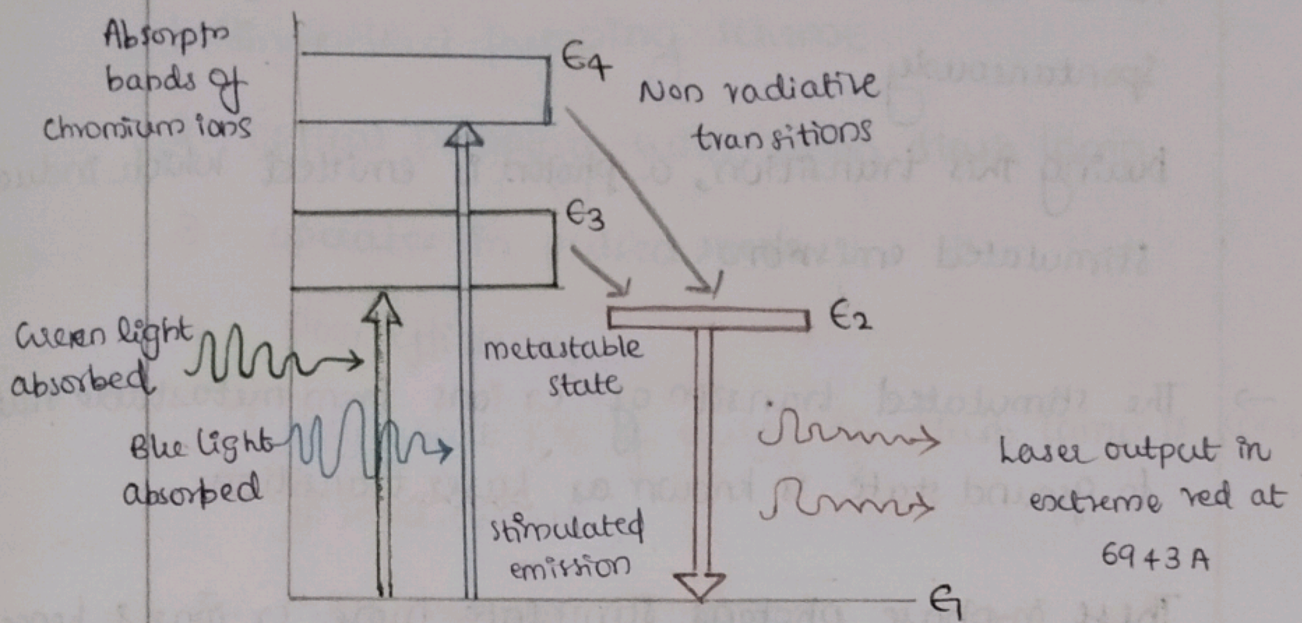


→ Both ends ~~are~~ of ruby rod are silvered (like a mirror). The rear end is made totally reflecting & the front end is made partially reflecting.



→ Photons travelling along axis of rod are repeatedly reflected at the end mirrors, thus becoming an optical resonator.

Working:



→ When the Xenon flash tubes are ON, intense flashes of white light lasting for a few milli-seconds are produced.

→ The Cr^{3+} ions in ground level absorbs & are excited to E_3 & E_4 levels. these are caused by green & blue component of white light.

→ These E_3 & E_4 excited state are unstable (10^{-8} sec), so Cr ions make very fast non-radiative transitions to meta-stable state E_2. -of order→ (10^{-3} sec)

(light radiatn is not emitted but heat radiatn emitted)

→ During these, transitn energy is reduced in form of heat. (so we need for cooling mechanism).

→ As the no. of particles in metastable state ↑ses, there will be a populatn inversion achieved.

→ Since, the state of population inversion is not a stable one, hence the some electrons comes down to ground state spontaneously.

During this transition, a photon is emitted which induces stimulated emission.

→ The stimulated transition of Cr ions from metastable state to ground state is known as 'Laser transition'.

These in-phase photons stimulate more Cr ions & hence the no. of photons emitted increases.

→ This process repeats and hence in-phase photons get multiplied. Thus, a strong and coherent laser beam is obtained through partially reflecting face.

So Ruby laser has a pulse output & hence called 'Pulse Laser'.

- Energy source : Xenon flash tube
- Pumping : optical pumping
- Lasing medium : Ruby Rod
- Optical resonator : Two ends of the ruby rod, one is fully silvered and other is partially silvered.

Salient features

1. Three-level pumping scheme.
2. optical pumping with Xenon flash lamp.
3. operates in pulsed mode.
4. Poor efficiency.
   (only about 1% of energy of flash lamp is converted to laser output)
5. Active medium : Ruby rod
6. Populatn inversion is difficult to achieve.
7. It is a solid laser.

2. Carbon dioxide Laser

→ It is a gas laser.

→ Four-level pumping scheme.

→ Highest power laser continously available.

→ produces Infrared light with wavelength bands centering on 9.6µm & 10.6µm.
(not produces visible light)

→ It is very efficient laser.

Active medium

→ discharge tube is filled with $CO_2 : N_2 : He$ =

→ CO_2 molecules are active centres.

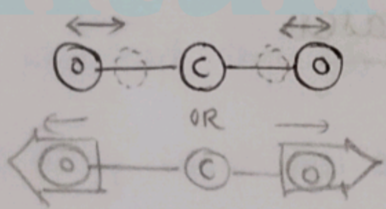
Imp → laser transition occur b/w the vibrational energy states of CO_2 molecules.

↓

A carbon dioxide molecule has a carbon atom at centre with two oxygen atoms attached, one at each sides.

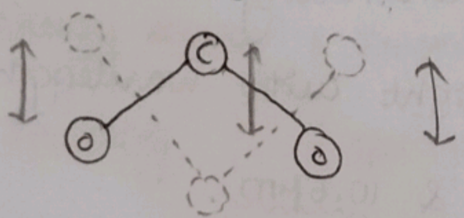
Such a molecule vibrates in 3 independent modes;

(a) Symmetric stretching mode



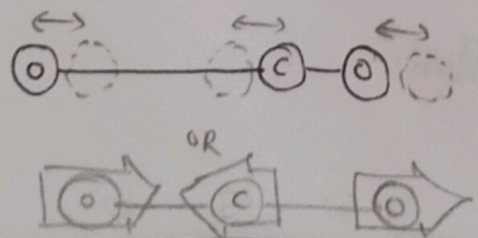
Carbon atom is at rest & both oxygen atoms vibrate such that they are moving away.

(b) Bending mode (degenerate bend)



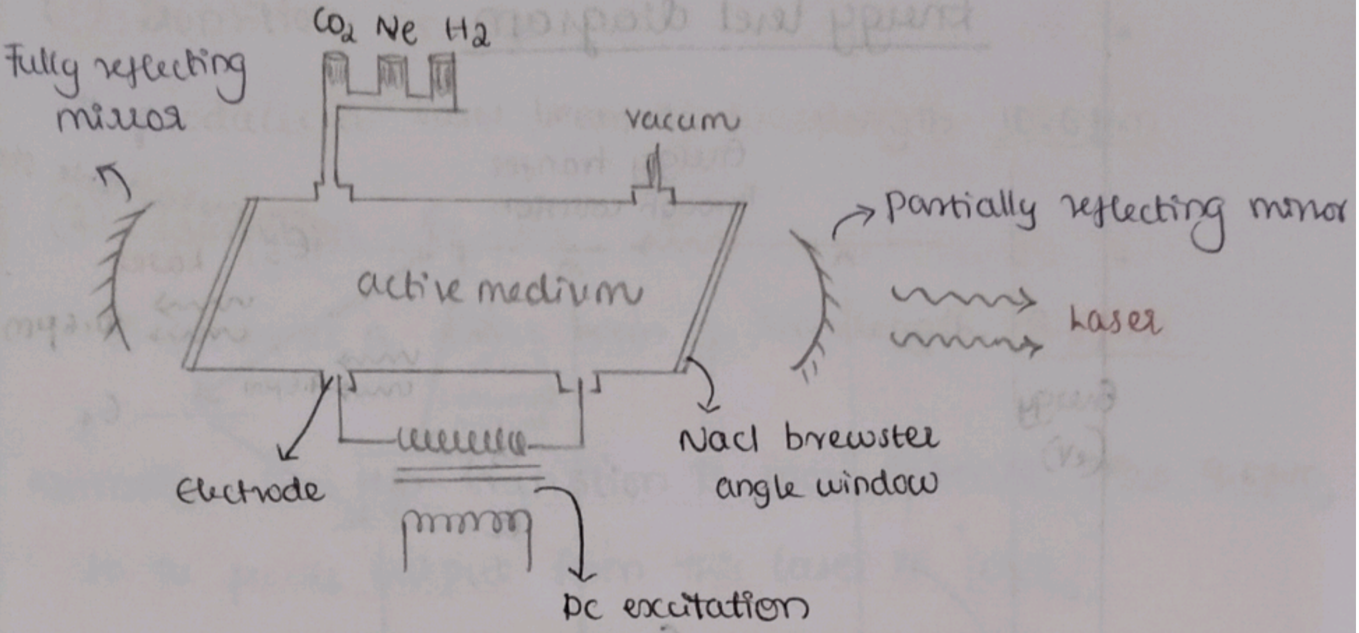
Here, both oxygen-atoms & carbon atom vibrates ⊥r to molecular axis.

(c) Asymmetric stretching mode



both O_2 atoms & C-atom vibrates assymetrically. ie, oxygen atoms move in one dxn & carbon atom moves in oppo dxn.

Construction



→ The Gas mixture ($CO_2 : N_2 : He = 1:4:5$) is the active medium that creates high radiation.

→ Quartz discharge tube is typically 2.5 cm in diameter & about 5 meters long.

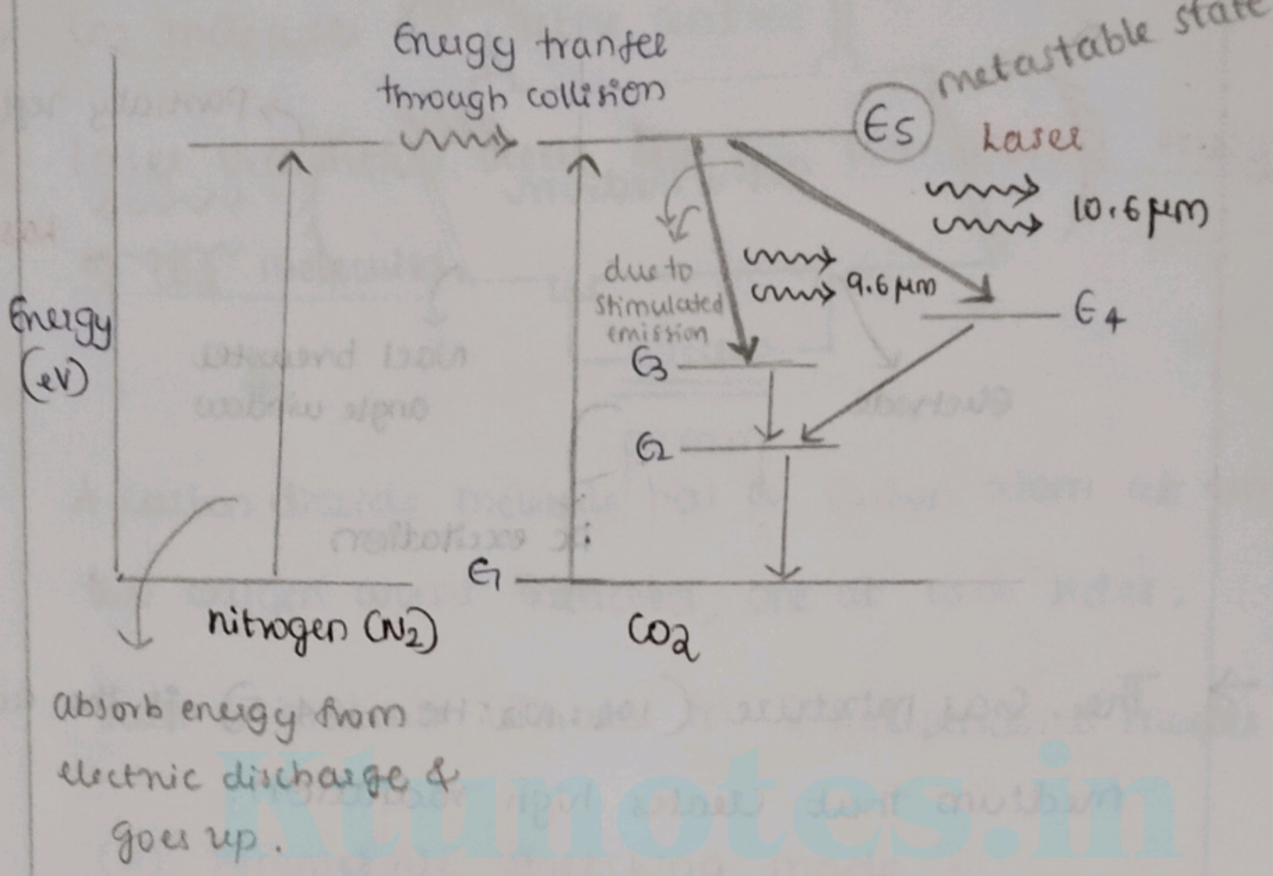
→ Electrodes on either side of the resonator to stimulate the gas.

→ Fully reflecting mirror is at one end of the tube and a partially reflecting mirror is at output end.

→ Brewster windows are fitted at both ends of tube to polarize the laser light.

Working;

Energy level diagram



→ When the electrical discharge occur in gas mixture, the electrons collide with N_2 molecules and they are raised to excited energy states.

→ Since the excited energy level of nitrogen is very close to E_5 energy level of CO_2 molecules. So the CO_2 molecules are excited by energy transfer and population inversion is achieved.

▸ There are two possible types of laser transition;

(1) Transition $E_5 - E_4$

It produces a laser beam of wavelength 10.6 μm.

(2) Transition $E_5 - E_3$

It produces a laser beam of wavelength 9.6 μm.

→ Normally 10.6 μm transition is more intense than 9.6 μm, so the power output from this laser is 10 kW.

Pumping & population inversion

- When current passes through the mixture of gases, N_2 molecules get excited to their metastable state.

- The N_2 molecules undergo inelastic collision with ground state CO_2 molecules and excite them to E_5 level. Some of the CO_2 molecules are excited through direct collisions with electron also.

- As the no. of CO_2 molecules ↑ses at E_5, populatⁿ inversion is achieved b/w E_5 and the levels at E_4 & E_3.

Lasing Action & optical cavity

- Random photons are emitted spontaneously by a few of atoms at energy level E5.
- The spontaneous photons travelling through the gas mixture prompt stimulated emission of photons.
- The laser transition b/w E5 → E4 levels & E5 → E3 level produces Far IR Radiation at the wavelengths 10.6 μm & 9.6 μm respectively.

  (10.6μm is more intense).

- The photons bounce back & forth b/w the end mirrors causing more and more stimulated emissions during each passage through the optical cavity.

De-Excitatn & cooling mechanism

- CO_2 molecules from E_4 and E_3 levels fall to lower level E_2 through inelastic collision with normal CO_2 molecule. (unexcited)
- In addition, E_2 level which is close to ground level is also populated by CO_2 molecules due to thermal excitation from ground level.

- These CO_2 molecules in E2 level have to be de-excited to the ground level. Otherwise it inhibits laser action.
- This de-excitatn takes place by inelastic collisions with He atoms in the tube.
- It also aides cooling the gas mixture heat conduction.

Salient features of CO_2 laser

→ It is a gas laser.

→ Active centres are CO_2 molecules.

→ It is a 4 level laser.

→ High efficiency & High power output.

→ Operates in continous wave (CW) mode.

→ pumping is through electrical discharge and inelastic collisions b/w molecules.

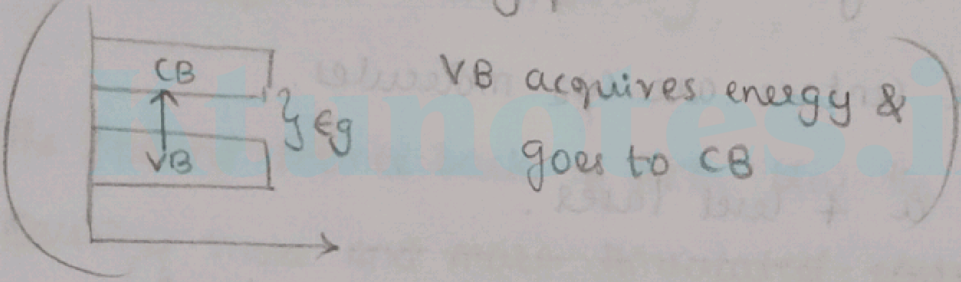
→ Infrared output (10.6 μm & 9.6 μm).

612A 3. Semiconductor laser

→ It is a specifically made p-N junction diode that emits coherent light under forward bias.

→ Materials like Si & Ge which are used to make ordinary semiconductor P-N junction diodes are indirect band gap materials which produce only heat radiations during electron hole recombinatn.

ie, eg). Direct band gap.



→ To produce light during electron hole recombination we must make use of direct band gap materials like GaAs.

→ Hence such materials are used to makes semiconductor diode lasers.

Homojunction & Heterojunction diode lasers

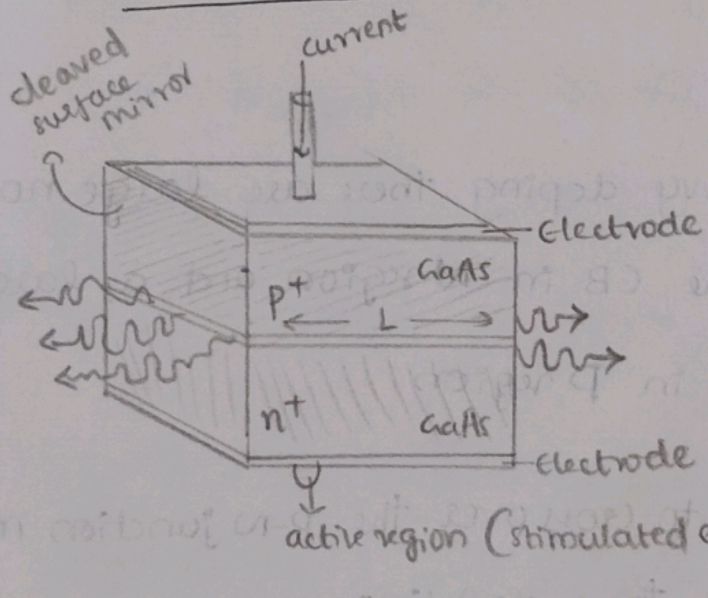
→ A simple diode laser which makes use of the same semiconductor meterial on both sides of the junctn is known as "Homojunctn diode laser".

eg. GaAs laser

→ A diode laser which makes use of different semi-conductor meterials on the two sides of junction is known as "Heterojunction diode laser".

eg. A junctn laser having GaAs on one side & GaAlAs on the other side.

Construction



→ It has a heavily doped N-type GaAs meterial on top of which a p region is formed by diffusing zinc atoms into it.

→ The dimensions of the diode are very small, typically 500 μm x 100μm x 100μm in size.

→ The top and bottom faces are metalized and metal Contacts are provided to pass current through the diode.

→ The front and rear end faces are polished (one partially and the other fully) parellel to each other and ⊥r to the plane of the junction. This is to form the optical resonator.

→ The two remaining sides of the diode are roughened to eliminate lasing action in that dxn.

→ The entire structure is ~~packed~~ packaged in a small case.

Working

→ Due to the heavy doping there are large no. of electrons in the CB in N region and a large no. of holes in the VB in P region.

→ When they try to cross over the P-N junction many of them recombine thus depleting the free charge carriers (conductn electrons & holes) in that region.

Further flow of free charge carriers is prevented by the immobile donor and acceptor ions. Thus a depletion region is formed near the junction, which acts as a potential barrier for further flow of charge carriers. The depletion region acts as the active region for laser action.

→ When the junction is forward biased, electrons & holes are injected into the junction region in high concn. This forms the pumping. pumping is achieved by DC voltage source by direct energy transfer.

→ As a result, there will be a large population of electrons in the CB and a large populatn of holes in the VB.

→ Since a hole represents absence of an $\bar{e}$, we can say that there is populatn inversion of electrons b/w the high energy CB and low energy VB.

→ The narrow region in which populatn inversion ~~occurs~~ occurs is called an inversion region / active region.

→ Chance recombination of electrons and holes will cause spontaneous emission of photons.

→ When the diode current reaches a threshold value, the spontaneous photons propagating in the junctn plane stimulate the conduction electrons to fill the holes of the VB.

→ This stimulated electron-hole recombination produces coherent radiation.

→ GaAs laser emits a wavelength of 9000 Å in the Infra red (IR) region.

Salient features

- High efficiency.
- Simple, compact and small in size.
- Low input power.
- Output power can be controlled by controlling junction current.
- Continous wave laser.

Applications of Laser

→ Industrial applications

→ Communicatn field

→ In computers

→ Holography

→ In defence

→ Scientific applications

→ Medical field

1. Industrial applications :

(a) Laser welding

(b) Laser drilling

(c) Laser cutting

2. Communicatn field :

(a) used in fibre optics communicatn system to send inform-ation.

3. In computers :

(a) used in laser printers, optical disc drives, optical memory cards etc.

4. Holography :

It is the tecnique of recording and reproducing a 3D image of an object without the use of lenses.

5. In defence :

(a) Laser range finders used to find distance of targets.

(b) used to guide missiles.

(c) used to destroy warplanes, missiles, etc by pointing powerful laser beam on them.

6. Scientific applications :

(a) For studying structure of molecules

(b) For accelerating certain chemical rxns

(c) For fabricatn of microelectronic circuit elements in ICs

(d) measurement of atmospheric pollutants and weather forecasting.

7. Medical field :

(a) used for conducting eye surgeries.

(b) for powdering kidney stones & gall stones.

(c) for cutting & sealing small blood vessels in the brain

(d) used in cosmetic plastic surgery for removing tattoos, birth marks, etc.

(e) for diagnosing & treating certain cancers.

(f) For precise, localized surgeries. They are highly sterile, non contact, almost bloodless and almost painless.