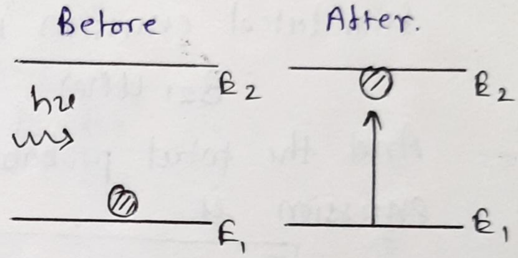
By Vasu Sir physics

* **LASER** - "Light amplification by Stimulated emission of radiation".
It is a device to produce strong, monochromatic, collimated and highly coherent beam of light and depends on the Principle of stimulated emission.

-:- Einstein's theory of matter radiation :-

1) Absorption of Radiation :- A photon incident on the atomic system and excites the atom from lower energy level E_1 to higher level E_2. This process is known as absorption.



The probability of absorption is given by P_{12} and

$$P_{12} \propto U(\nu)$$

or $$\boxed{P_{12} = B_{12}\, U(\nu)}$$

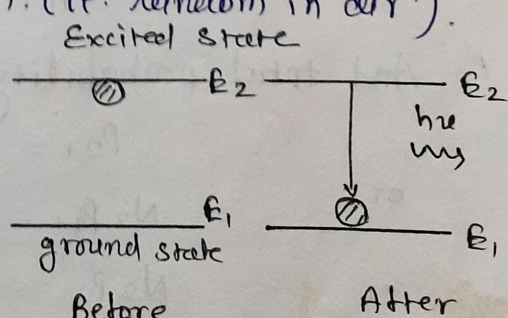
where $U(\nu)$ - Energy density
& B_{12} - Einstein's coeff.

2) Spontaneous Emission :-
After absorption an atom is in higher state, where it does not stay for longer time and jumps to lower state emitting a photon of freq. ν. This ~~phenomen~~ process is called spontaneous emission. In this case emitted photon does not have any fix direction. (ie. random in dir^n).

The probability of spontaneous emission is given by.

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

where - A_{21} - Einstein's coeff^t.



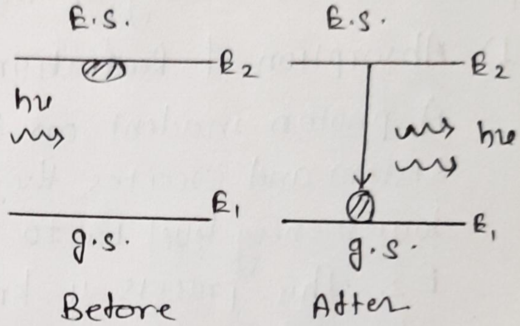
3.) Stimulated (Induced) Emission:-

According to Einstein, an atom in an excited state may under the influence of the electromagnetic field of a photon of freq. ν incident upon it jumps to ground state emitting an additional photon (i.e. two photons) of same freq. (ν). This is called stimulated emission.

In this emission the emitted photons are highly coherent. The probability of stimulated emission is given by

$B_{21}\,u(\nu)$

And the total probability of emission is



$$\boxed{P_{21} = A_{21} + B_{21}\,u(\nu)}$$

where A_{21} & B_{21} called Einstein's A & B coeff^t.

* Relation between Einstein's A & B coeff^t:-

Let us consider a group of atoms in thermal equilibrium at temp. T. with freq. ν & energy density $u(\nu)$. Let N_1 & N_2 be the No. of atoms in ground and excited state resp.

The probability of spontaneous emission is given by

$$P_{12} = B_{12}\,u(\nu)$$

or $$N_1 P_{12} = N_1 B_{12}\,u(\nu) \quad \text{——— (1)}$$

And total probability of emission is given by

$$P_{21} = A_{21} + B_{21}\,u(\nu)$$

or $$N_2 P_{21} = N_2\left[A_{21} + B_{21}\,u(\nu)\right]$$

or $$N_2 P_{21} = N_2 A_{21} + N_2 B_{21}\,u(\nu) \quad \text{——— (2)}$$

At equilibrium condⁿ.

$$N_1 P_{12} = N_2 P_{21}$$

or

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

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

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

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

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

$$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\left(\frac{N_1}{N_2} \cdot \frac{B_{12}}{B_{21}} - 1\right)} \quad \text{--- (3)}$$

But Einstein proved thermodynamically that

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

then eqⁿ (3) becomes.

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

And according to Boltzmann's Distribution law

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

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

from eqⁿ (4)

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

According to Planck's radiation formula energy density of black body radiation is given as

$$u(\nu) = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{(e^{h\nu/kT} - 1)} \quad \text{--- (6)}$$

from eqⁿ (5) & (6)

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}}$$ This is required relⁿ.

or

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

ie. The probability of spontaneous emission increases rapidly with the energy diffᶜ. betⁿ. two states.

* **Population inversion :-** The process of achieving larger number of atoms in higher energy level than the lower energy level is known as population inversion.

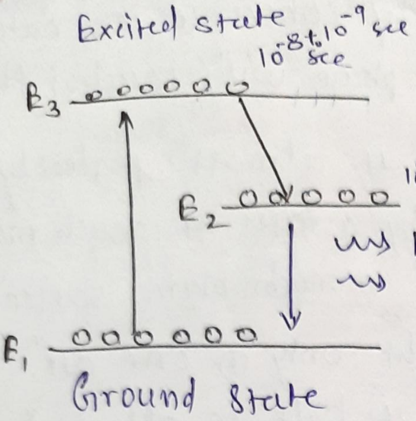
ie $\boxed{N_2 >> N_1}$ or $\boxed{\frac{N_2}{N_1} >> 1}$

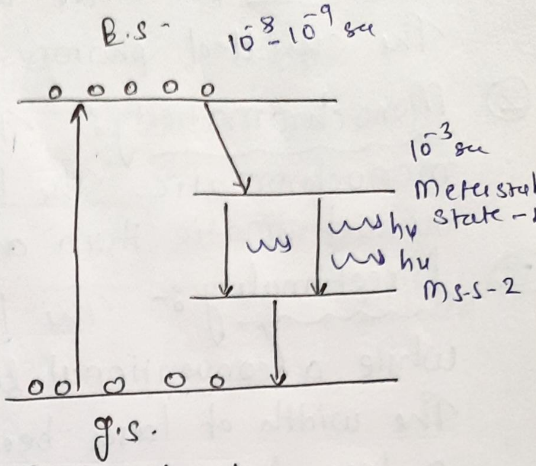
* **Pumping :-** The process of achieving population inversion is known as pumping.

Pumping methods :-

(i) Optical pumping (used in Ruby laser)
(ii) Electric discharge (used in He-Ne laser)
(iii) Direct conversion (used in semi-conductor laser)
(iv) Chemical reaction (used in CO_2 laser)
(v) Inelastic - atom - atom collisions.

Three level and four level pumping :-





① "Three level pumping"

$\boxed{N_2 > N_1}$

(ii) four level pumping.

$\boxed{N_2 >> N_1}$

Between three and four level pumping four level is more efficient because in four level pumping $N_2 >> N_1$ (ie population inversion followed better).

Main Components of laser :-

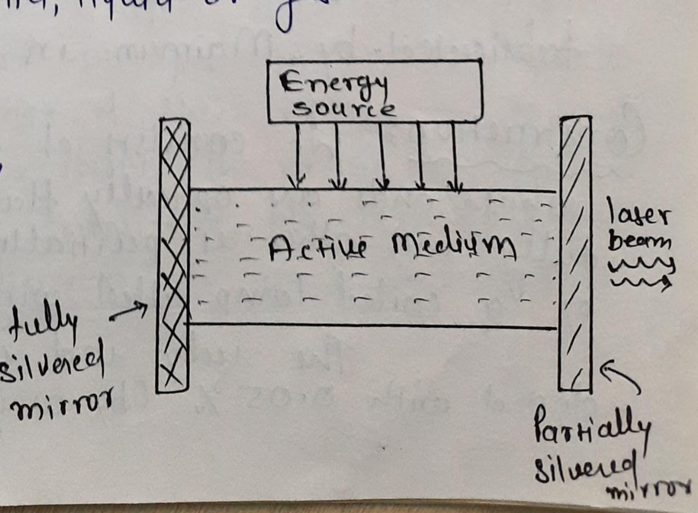
A laser requires three main components:

① Energy source :- that will raise the system to an excited state.

② Active Medium :- which, when excited, achieves population inversion. it may, be solid, liquid or gas.

③ optical Resonator :.

It consists of two mirrors facing each other (one fully and one partially silvered) the active medium is enclosed by this cavity.



Properties of laser beam :-

① **Coherence** :- laser beam is perfectly coherence in nature. The emitted photon is exactly in phase with incident photon.

② **Monochromaticity** :- The laser light is almost perfectly monochromatic. The light emitted by a laser is much more monochromatic than any conventional monochromatic source.

③. **Directionality** :- The laser emits light only in one dir^n while a conventional light source emits light in all dir^n. The width of laser beam is extremely narrow and hence a laser beam can travel to long distances ~~at~~ without spreading.

④. **Brightness** :- laser light is much more bright and intense than any conventional source. This is due to emitted and incident photons are perfectly in phase.

Different types of lasers :-

1. Solid state lasers – (i) Ruby laser
   (ii) Nd- YAG laser
2. Gas lasers – (i) He- Ne laser
   (ii) CO_2 laser.

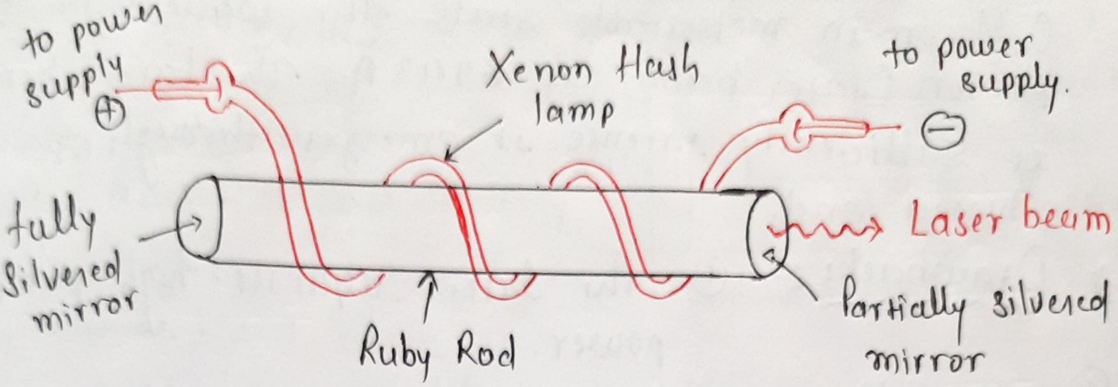
① Ruby laser :-

The solid state Ruby laser is the first laser. It was fabricated by, Maiman in 1960.

Construction:- It consists of a pink ruby cylindrical rod whose ends are optically flat and parallel. One end is fully and other is partially silvered. the rod is wound by a coiled lamp filled with xenon gas.

The ruby rod is basically a Al_2O_3 crystal doped with 0.05% (by weight) of Cr_2O_3. ~~At~~ Aluminium

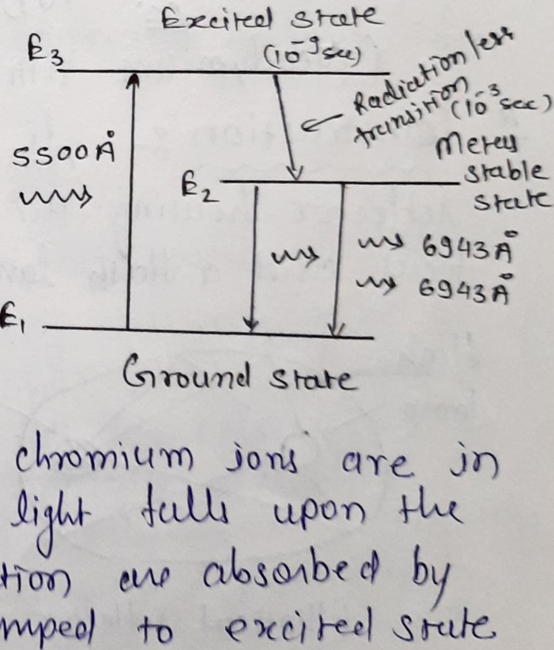
...ons are replaced by Chromium (Cr), which are responsible for the pink colour.



"Ruby laser"

* **Working :-** Ruby laser is based on three level pumping

The upper ~~level~~ energy level E_3 is short lived having life time $10^{-8} - 10^{-9}$ sec. There is an intermediate excited state E_2 - which is meta-stable having life time 10^{-3} sec.



Initially most of the chromium ions are in ground state E_1. When flash light falls upon the ruby rod, the 5500 Å radiation are absorbed by chromium ions, which are pumped to excited state E_3. where they gives a part of their energy to crystal lattice and decay to E_2 level. The transition from $E_3 \rightarrow E_2$ is radiationless transition. Here the population inversion is established between the metastable state E_2 and ground state E_1

A spontaneous photon emitted by a Cr^{3+} ion at level initiates the stimulated emission by the other Cr^{3+} ion in metastable state. The wavelength of the photon (laser beam) is 6943 Å. The laser beam is sufficiently intense. it emerges through partially silvered end.

* **Drawbacks :-** (I) The laser requires high pumping power.

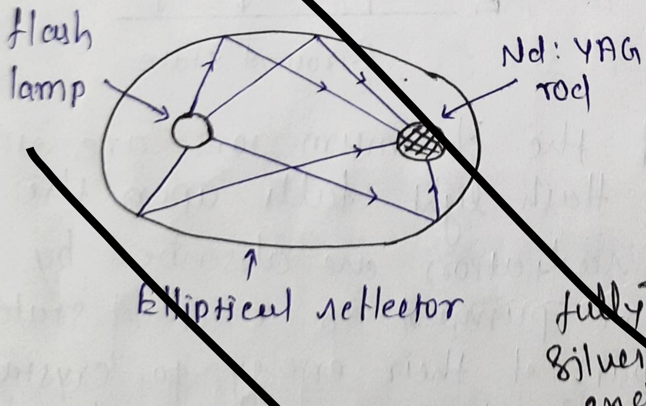
(II) The efficiency of ruby laser is very low.

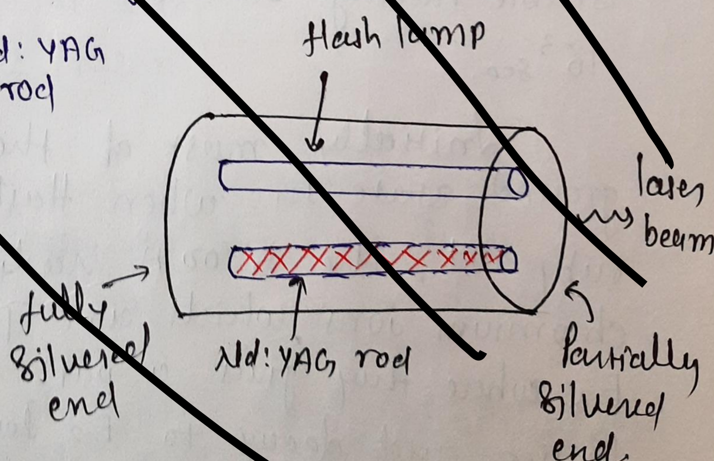
(III) The laser output is not continuous but occurs in the form of microsecond pulses.

2. ND: YAG Laser

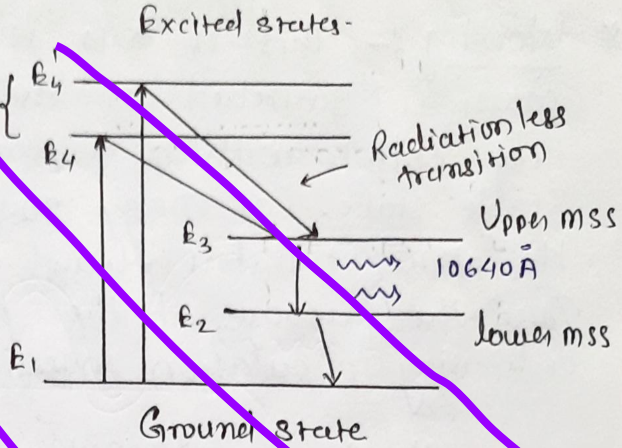
(Neodymium Yittrium aluminium garnet laser)

* **Construction :-** It consists of an elliptically cylindrical reflector housing the laser rod along one of its focus and a flash lamp along the other focus line.





Working :- This is four level pumping based laser. In this laser some yittrium ions replaced by neodymium ions.

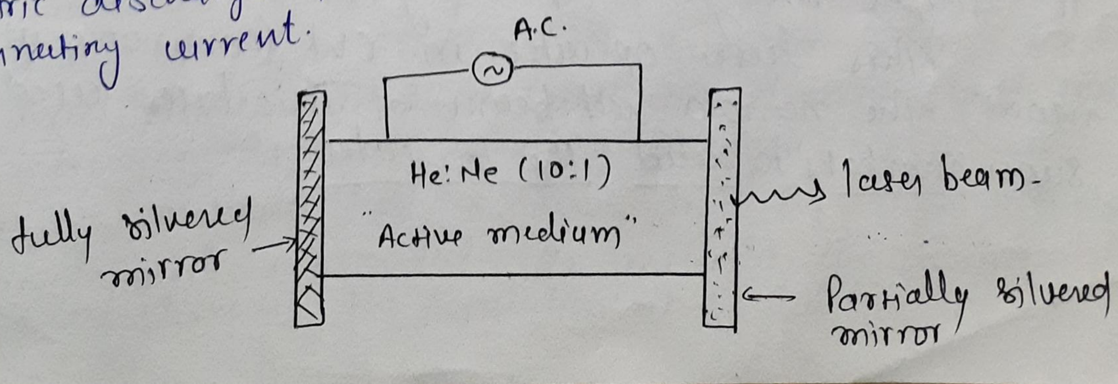


The ground state Nd ions are excited to a higher state by pumping with wavelength 5000 - 8000 Å. As the higher states are short-lived, hence excited Nd ions quickly make downward transitions to upper metastable state E_3. The population inversion is established between E_3 and E_2 level. The laser emission occurs in infrared region at a wavelength of 10640 Å. This laser is operated in CW mode. The efficiency of Nd: YAG laser is high as compared to ruby laser which is about 2%.

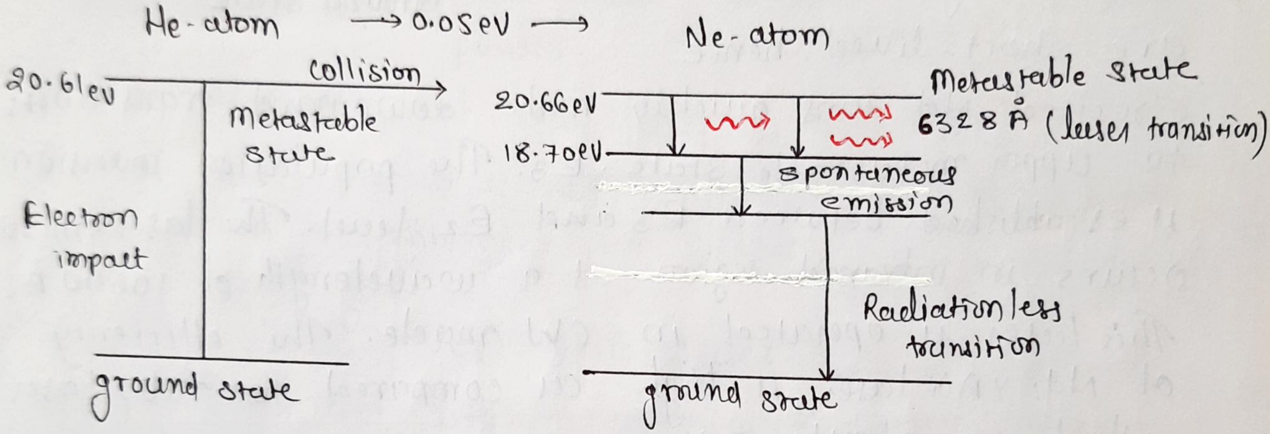
3. He-Ne Laser

He-Ne laser is a four level pumping based gas laser.

Construction :- It consists of a long discharge tube of length about 50 c.m and dia. 1 c.m. filled with He-Ne gas in the ratio 10:1 (He:Ne) at low pressure (~1 torr). Both the ends of the tube are optically flat plane. out of them one is fully silvered and other end is partially silvered. In this laser population inversion is achieved by electric discharge. The tube is connected with high-freq. Alternating current.



★ Working :- This is four level pumping based laser. when power is switched on, the electrons from the discharge tube collide with and pump the He & Ne atoms to meta-stable state. (at energy 20.61 eV) during collision the He atom transfers their 0.05 eV. energy to Ne. atom. Thus the purpose of the He atom is to help in achieving population inversion in the Ne-atoms.



when an excited Ne atom passes from the metastable state at 20.66 eV to an excited state of 18.70 eV it emits a photon of wavelength 6328 Å. This photon travels through the gas-mixture and reflected back and forth by the mirror. ends. until it stimulates an excited Ne-atom and causes it to emit a fresh 6328 Å photon in phase with the stimulating photon. This stimulated transition from 20.66 eV level to 18.70 eV level is the laser transition.

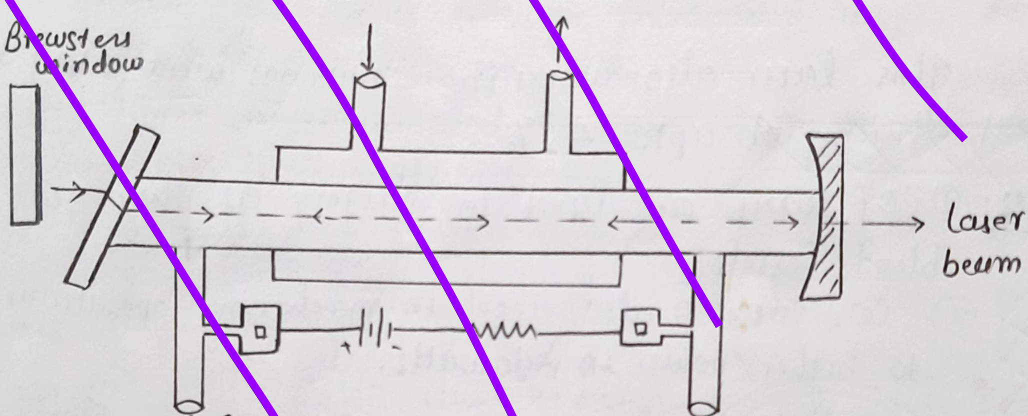
This process is continued and when a beam of coherent radiation becomes sufficiently intens, a portion of it escapes through the partially silvered end.

This laser operates in CW (continuous wave) mode. The narrow red beam of this laser used in super markets to read the bar codes.

4. "Carbon Dioxide (CO_2) Laser"

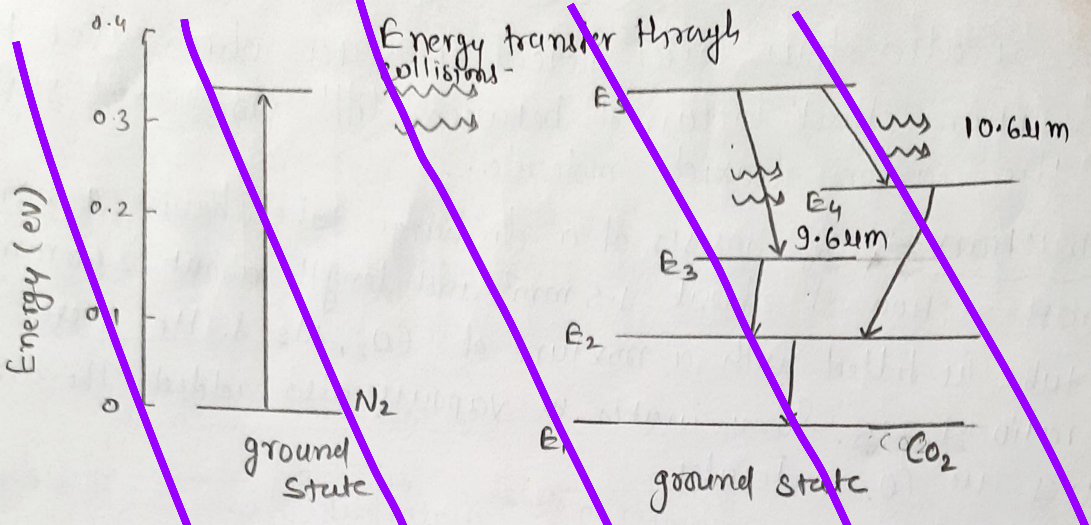
CO_2 is also four level molecular laser which uses the transitions that occurred between diffᵗ. vibrational states of the carbon dioxide molecule.

Construction :- It consists of a discharge tube having a bore of cross-section of about $1.5\ mm^2$ and length about 260 mm. The tube is filled with a mixture of CO_2, N_2 & He gases in the ratio 1:2:3. Some water vapours also added. The active centres are CO_2 molecules



Working :- When current passes through the mixture of gases then N_2 molecules get excited to the metastable state. Here the excited state of N_2 molecule is metastable. These excited N_2 molecules cannot spontaneously lose energy so at that level number of N_2 molecule increases. These N_2 molecules collides with CO_2 molecules. Due to this CO_2 molecules are excited to E_5 level. The E_3 and E_4 level act as lower ~~level~~ laser levels. The population inversion is achieved betⁿ E_5 level and E_4 or E_3 level. The transition from E_5 to E_4 level produces infra-red radiation of wavelength $10.6\mu m$ and between E_5 and E_3 at wavelength $9.6\mu m$. Now the CO_2 molecules fall to lower level E_2 through inelastic collision with unexcited CO_2 molecules. The presence of He with CO_2 decreases the population at E_3 level.

* Energy level diagram:-



This laser also works in continuous wave (CW) mode and has efficiency of upto 45%.

uses:- ① CO_2 lasers are used in surgery as they seal small blood vessels.

② CO_2 laser is also used in machining operations owing to higher power in kilowatts.

* Applications of lasers:-

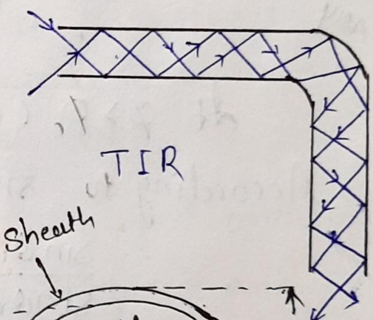
① Metallic rods can be melted and joined by laser welding.
② laser beam is used to vaporise unwanted material during the manufacture of electronic circuits in semiconductor chips.
③ In surgery to seal small blood vessels.
④ lasers are used to detect and destroy enemy missiles during warfare.
⑤ He-Ne. laser used in super-market to read bar-codes.
⑥ In the production of three-dimensional images in Holography technique.
⑦ low power semiconductor lasers are used in CD player, laser printers, laser copiers etc.

Laser Speckles :- Laser ~~speckel~~ speckle is phenomenon ~~with~~ which results from the interference of different reflected portions of incident laser beam with random relative optical phases. Due to this, a random pattern is obtained when light beam is diffusely reflected at a surface having rough structure. If the path diff^c is more than λ, then the phase change will be greater then 2π.

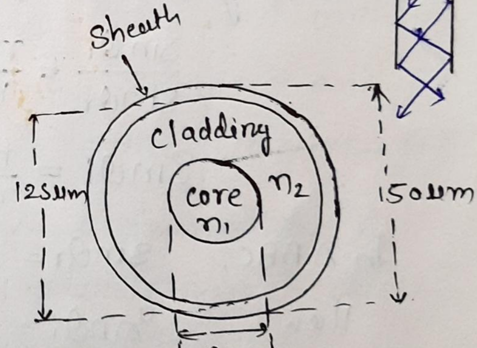
"OPTICAL FIBRE"

Optical fibres are glass or plastic pipes, as thin as human hair, that ~~guided~~ guides light waves through them and works on the principle of Total Internal Reflection (TIR).

Optical fibres are fabricated from glass or plastic, ~~so~~ with these materials three major types of fibres are made:



(i) Plastic core with plastic cladding.
(ii) glass core with glass cladding
(iii) glass core with plastic cladding.



$$\boxed{n_1 > n_2}$$

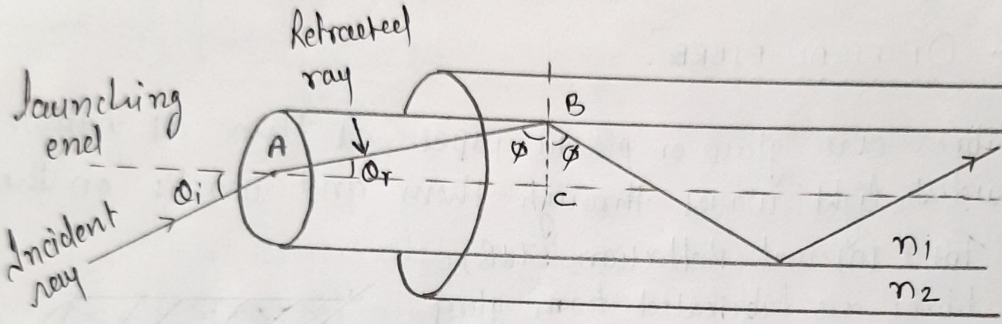
Classification of optical fibre :-

Optical fibres are classified into two types :-

1. Step index optical fibre – (i) Single mode step index fibre
   (ii) Multi mode step index fibre

2. Graded-index fibre (Multi mode).

* Light propagation through an optical fibre :-
(Acceptance angle, acceptance cone and Numerical aperture)
Let light propagates through any optical fibre tube. let n_1, n_2 and n_0 be the refractive index of core, cladding and outer medium resp. let light ray enters the fibre at an angle θ_i & refracted with angle θ_r.



At $\phi > \phi_c$ (critical angle) the ray undergoes TIR.
According to snell's law

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0}$$

$$\sin\theta_i = \frac{n_1}{n_0} . \sin\theta_r$$

In ΔABC, $\sin\theta_r = \sin(90-\phi) = \cos\phi$

then $\sin\theta_i = \frac{n_1}{n_0} . \cos\phi$.

when $\phi = \phi_c$, $\theta_i = \theta_{max}$

$$\sin\theta_{max} = \frac{n_1}{n_0} . \cos\phi_c \quad \text{——} \ (1)$$

But critical angle $\sin\phi_c = \frac{n_2}{n_1}$

$$\cos\phi_c = \sqrt{1-\sin^2\phi_c}$$

$$\cos\phi_c = \sqrt{1-\frac{n_2^2}{n_1^2}}$$

$$\cos\phi_c = \sqrt{\frac{n_1^2-n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2-n_2^2}}{n_1}$$

eqⁿ. 1

$$\sin\theta_{max} = \frac{n_1}{n_0} \cdot \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

$$\boxed{\sin\theta_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}} \quad \text{---} \ (2)$$

for air/vacuum $n_0 = 1$.

$$\sin\theta_{max} = \sqrt{n_1^2 - n_2^2}$$

$$\boxed{\theta_{max} = \sin^{-1}\sqrt{n_1^2 - n_2^2}} \quad \text{---} \ (3)$$

Here the angle θ_{max} is called acceptance angle.

Acceptance angle may be defined as the maximum incident angle that a light ray can have relative to the axis of the fibre and propagates down the fibre.

* Acceptance cone ($2\theta_{max}$) :- The light rays contained within the cone having a full angle $2\theta_{max}$ are accepted and transmitted along the fibre. This cone is called acceptance cone.
* Fractional Refractive Index change :- It is denoted by Δ

$$\boxed{\Delta = \frac{n_1 - n_2}{n_1}}$$

Δ is always +ve because $\boxed{n_1 > n_2}$

* Numerical Aperture :- It is defined as the ~~sign~~ sine of acceptance angle. i.e.

$$NA = \sin\theta_{max} = \sqrt{n_1^2 - n_2^2}$$

$$\boxed{NA = \sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta}}$$

$\because n_1^2 - n_2^2 = \frac{(n_1 + n_2)}{2} \frac{(n_1 - n_2)}{n_1} \times 2n_1 = n_1 \cdot \Delta \cdot 2n_1$

$(n_1 \simeq n_2)$ $= 2n_1^2\Delta$

$$\Rightarrow \sqrt{n_1^2 - n_2^2} = \sqrt{2n_1^2\Delta} = n_1\sqrt{2\Delta}$$

* **V- Number :-** V-number determines the operating fre. or normalized freq. which carry out total internal reflection. It is given by.

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

or

$$V = \frac{2\pi a}{\lambda} . n_1\sqrt{2\Delta}$$

or

$$V = \frac{2\pi a}{\lambda} . N.A$$

where - a - radius of core
λ - wavelength of light used.
n_1, n_2 ref. index of core & cladding

The approximate total number of modes which the fibre will support is

$$N_m = \frac{V^2}{2} \text{ (for step index fibre)}$$

$$N_m = \frac{V^2}{4} \text{ (for graded index fibre)}$$

for single mode fibre $V < 2.405$ and for multimode fibre $V > 2.405$. for $V = 2.405$, the wavelength is known as cut off wavelength - (λ_c).

Attenuation :- When an optical signal propagates through a fibre, it will get progressively attenuated due to several attenuation mechanisms. "The signal attenuation is defined as the ratio of the optical output power from a fibre of length L to the input optical power." The coefficient of attenuation is given by

$$\alpha = \frac{-10}{L} \log \frac{P_o}{P_i}$$

or

$$\boxed{\alpha = \frac{10}{L} \log \frac{P_i}{P_o}} \quad dB/km$$

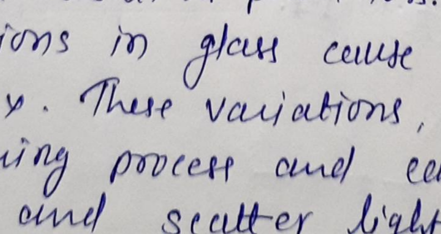
where - P_i, P_o = input and output power

L - fibre length.

* Different mechanisms of attenuation :-

1. Absorption by material :- This includes absorption due to the light interacting with the molecular structure of the material as well as loss because of material impurities. Even a highly pure glass absorbs light in specific wavelength regions.

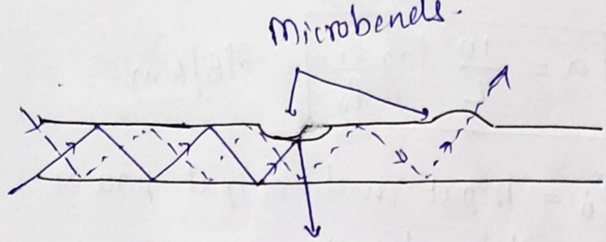
2. Rayleigh Scattering losses :- When light is scattered by an obstruction, the result is power loss. The local microscopic density variations in glass cause local variations in refractive index. These variations, which are inherent in the manufacturing process and cannot be eliminated, act as obstructions and scatter light in all directions. This is known as Rayleigh scattering.



"Rayleigh Scattering"

3. Waveguide losses:- Due to irregularities in the optical fibre geometry, the incident angle becomes less than the critical angle for higher order modes. As a result part of the light ray will be refracted into the cladding. They are known as leaky modes, which are regarded as waveguide losses.

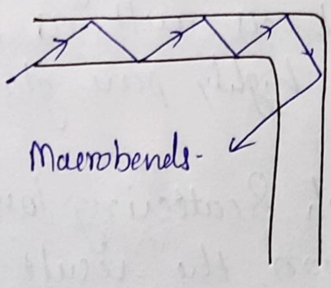
4. Microbending losses:-



These are the fibre losses introduced during manufacturing or installation processes. Structural variations in the fibre or fibre deformation cause radiation of light away from the fibre.

5. Macrobend losses:-

During installation, it happens that the optical fibre cable is bent over larger radius. Such bends lead to loss of light known as macrobending losses.



* Numerical questions.

—x—x—