POOJA PREMNATH
S01

LASER : Light Amplification by Stimulated Emission of Radiation

Characteristics of Lasers

1. High degree of coherence
2. Extraordinary monochromaticity
3. Directionality
4. High Intensity

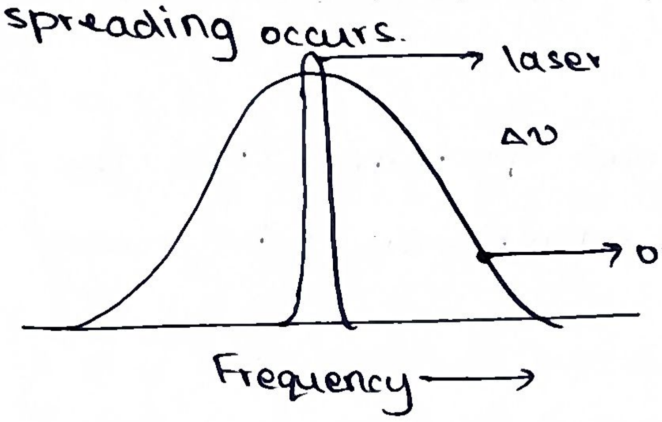
Coherence : Lasers have a high degree of coherence. That is, all the constituent photons have the same energy, same direction and same ~~ext~~ direction of polarization.

Coherence is characterized by 2 parameters, coherence length & coherence time.

Coherence length is the length of the wave train over which there is a fairly sinusoidal character and a predictable phase.

Coherence time is the time ~~to~~ in which the phase of the wave train can be predicted reliably.

Monochromaticity : Ordinary light spreads over a very large frequency of thousands of megacycles per second. On the other hand, lasers have a monochromatic spread having only a single frequency, and thus a very little spreading occurs.



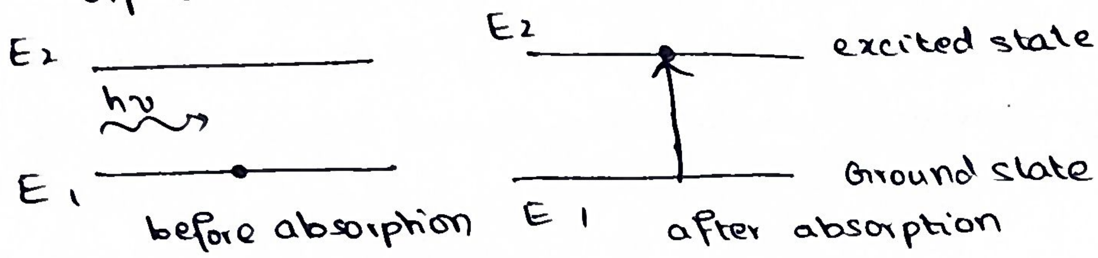
Directionality : Laser beams travel as a parallel beam over very long distances whereas ordinary light emits in all directions. The angular spread is related to the aperture diameter by: $\Delta\theta = \lambda/d$. For a laser, the spread is about only 0.01mm per m, whereas for ordinary light, the spread is 1m for every 1m.

High Intensity : Since the laser beam gives out light in a narrow beam, all its energy is concentrated in a small region. This gives rise to high intensity. It has a very high power radiation of about 5×10^{16} W/m^2.

Spontaneous and Stimulated Emissions

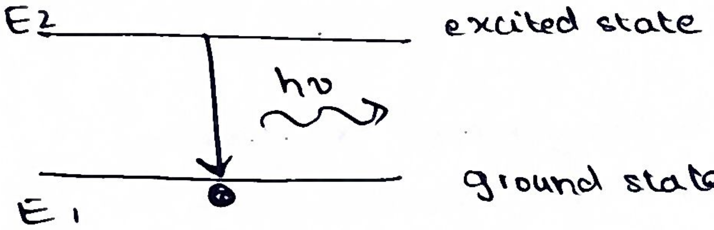
Stimulated absorption

According to quantum theory, light radiation consists of photons of energy $h\nu$. Consider 2 energy states E_1 and E_2 for an atom. The atom can make a transition from a lower energy state E_1 to a higher energy state E_2 by absorbing a photon, provided that the photon energy $h\nu$ = the diff in energy between the 2 states, i.e $E_2 - E_1$. This process is called as stimulated absorption.



Spontaneous and Stimulated Emission

Spontaneous emission: The atom passes from the higher energy state E_2 to the lower energy state E_1, by spontaneously emitting a photon of energy $h\nu$



The spontaneous emission is random in character. The radiation emitted by each atom has a random direction & phase.

Thus, the radiation is incoherent, and has a broad spectrum. It is the process of spontaneous emission that dominates conventional light sources.

Stimulated Emission

According to Einstein, an interaction between an excited atom & a photon, can trigger the atom to make a transition to the ground state.

During this transition, a photon is released, which has the same phase, frequency and direction of propagation as the triggering photon. This process of induced emission of photons, due to the triggering photon is called stimulated emission.

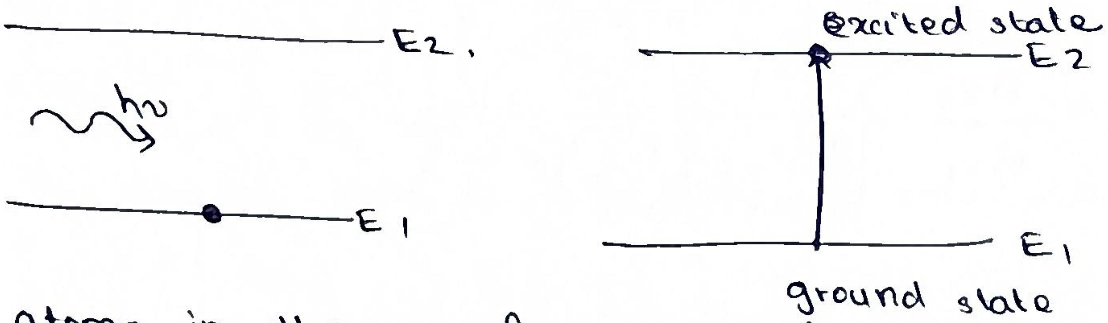
* Basic concept of laser : The photon emitted due to the stimulated radiation and the incident photons have the same phase, frequency. Stimulated emission dominates the laser light source.

* Differences between Spontaneous and stimulated emission

Spontaneous emission	stimulated emission
1. It is a random process, a statistical phenumenon.	1. It occurs due to the inducement of an incident photon.
2. It is incoherent	2. It is coherent
3. dominates the emission in conventional light sources	3. dominates the emission in laser sources
4. ~~was~~ there is radiation of many wavelengths.	4. contains a monochromatic wavelength
5. less directionality, more angular spread.	5. more directionality, less angular spread.

Einstein's Theory (A and B coefficients)

Stimulated absorption



atoms in the ground are excited, and they make a transition from energy levels E_1 to E_2, by absorbing a photon. The energy of the photon $h\nu = E_2 - E_1$.

This is an upward transition. The no. of transitions (N_{ab}) happening per unit volume per unit time depends upon the no. of atoms per unit volume N_1 and the energy density of the incident radiation (Q).

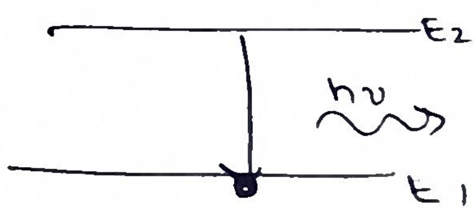
$\boxed{N_{ab} = B_{12} N_1 Q}$ $\qquad B_{12}$ = Einstein's coeff. of absorption.

Spontaneous emission

: Atoms make a spontaneous transition from $E_2 - E_1$

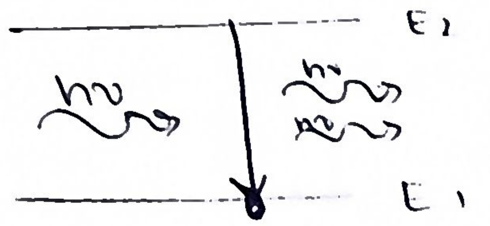
No. of transitions N_{sp} depends on no. of atoms per unit volume in the higher energy level.

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



A_{21} = Einstein's coeff. of spontaneous emission

Stimulated Emission : The presence of an incident photon will cause the atoms in E_2 to make a transition to E_1.



The no. of transitions N_{st} that happen per unit volume per unit second ~~depends on~~ is given by

$$N_{st} = B_{21} N_2 Q$$

B_{21} = Einstein's coeff. of stimulated emission.

At thermal equilibrium, the rate of upward transitions = the rate of downward transitions.

$$B_{12} N_1 Q = A_{21} N_2 + B_{21} N_2 Q$$

$$B_{12} N_1 Q - B_{21} N_2 Q = A_{21} N_2$$

$$Q (B_{12} N_1 - B_{21} N_2) = A_{21} N_2$$

$$Q = \frac{A_{21} N_2}{B_{12} N_1 - B_{21} N_2}$$

$\div$ by $B_{21} N_2$

$$Q = \frac{\dfrac{A_{21} N_2}{B_{21} N_2}}{\dfrac{B_{12} N_1}{B_{21} N_2} - 1} \Rightarrow Q = \frac{A_{21}}{B_{21}} \left\{ \frac{1}{\left(\frac{B_{12}}{B_{21}}\right)\left(\frac{N_1}{N_2}\right) - 1} \right\} \quad (1)$$

According to Boltzmann's law, the no. of atoms per unit volume in any state E is

$$N = N_0 e^{-E/kt}$$

$$\therefore N_1 = N_0 e^{-E_1/kt}$$

$$N_2 = N_0 e^{-E_2/kt}$$

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/kt} \quad (2) \quad = e^{h\nu/kT}$$

Sub (2) in (1)

$$Q = \frac{A_{21}}{B_{21}} \left\{ \frac{1}{\left(\frac{B_{12}}{B_{21}}\right)\left(e^{h\nu/kT}\right) - 1} \right\}$$

This is the formula for the energy density of incident radiation of atoms in energy levels E_1 & E_2.

$$Q = \frac{A_{21}}{B_{21}} \times \frac{1}{\left(\frac{B_{12}}{B_{21}}\right)\left(e^{h\nu/kT}\right) - 1}$$

According to Planck's law of radiation,

$$Q = \frac{8\pi h\nu^3}{c^3} \times \frac{1}{\left(e^{h\nu/kT} - 1\right)}$$

comparing the 2 equations;

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

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

These coefficients are called Einstein's A & B coefficients.

<u>Results</u>: (i) $B_{12} = B_{21}$, i.e stimulated absorption = stimulated ~~absorption~~ emission

(ii) $\frac{A_{21}}{B_{21}} \propto \nu^3 \Rightarrow$ spontaneous emission increases rapidly with energy diff. between the 2 levels.

(iii) $\frac{A_{21}}{B_{21}} << 1$ for stimulated emissions to predominate to produce a laser beam.

Optical Amplification

The ratio of stimulated emission to spontaneous emission is given by:

$$\frac{N_{st}}{N_{sp}} = \frac{B_{21} N_2 Q}{A_{21} N_2}$$

$$= \frac{B_{21}}{A_{21}} \cdot Q$$

$\Rightarrow$ The stimulated emission would increase if the energy density of the incident photons (Q) increases. However, this would to more absorption transitions as well. As a result, mere optical amplification is not enough to increase stimulated emissions.

Population Inversion

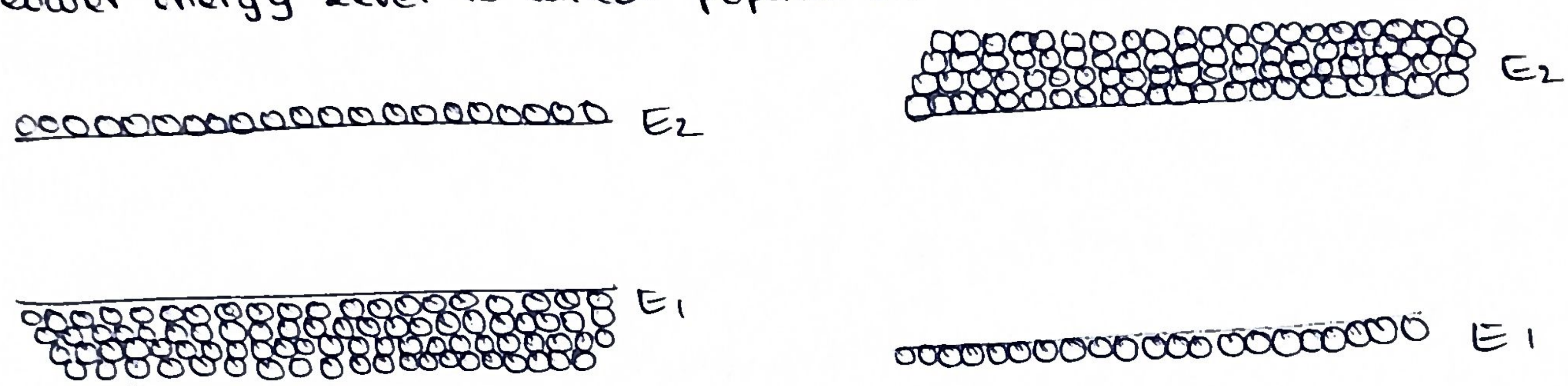
The ratio of stimulated emission to stimulated absorption is given by

$$\frac{N_{st}}{N_{ab}} = \frac{B_{21} N_2 Q}{B_{12} N_1 Q}$$ but $B_{12} = B_{21}$

$$\Rightarrow \frac{N_{st}}{N_{ab}} = \frac{N_2}{N_1}$$

$\Rightarrow$ The stimulated emission would increase if the no. of atoms per unit volume is greater in the higher energy level.

<u>Population Inversion</u>: The establishment of a situation where the no. of atoms in the higher energy level is greater than the no. of atoms in the lower energy level is called population inversion



normal condition

after population inversion

<u>Types of Lasers</u>:

1. solid state laser : ruby, Nd-YAG laser
2. gas laser : He-Ne, CO_2 laser
3. liquid laser : $SeOCl_2$ laser, europium chelate laser
4. chemical & dye lasers : hydrogen fluoride laser
   rhodamine 6G laser
   coumarine laser.
5. semiconductor laser : GaAs, InP laser

<u>Nd-YAG Laser</u>

<u>Principle</u>:
- A four level solid-state laser
- Active medium = Nd-YAG
- When the optical source krypton flash is used neodymium ions are excited.
- A laser beam of wavelength 1064 nm is emitted when there is a transition from E_2 to E_1.

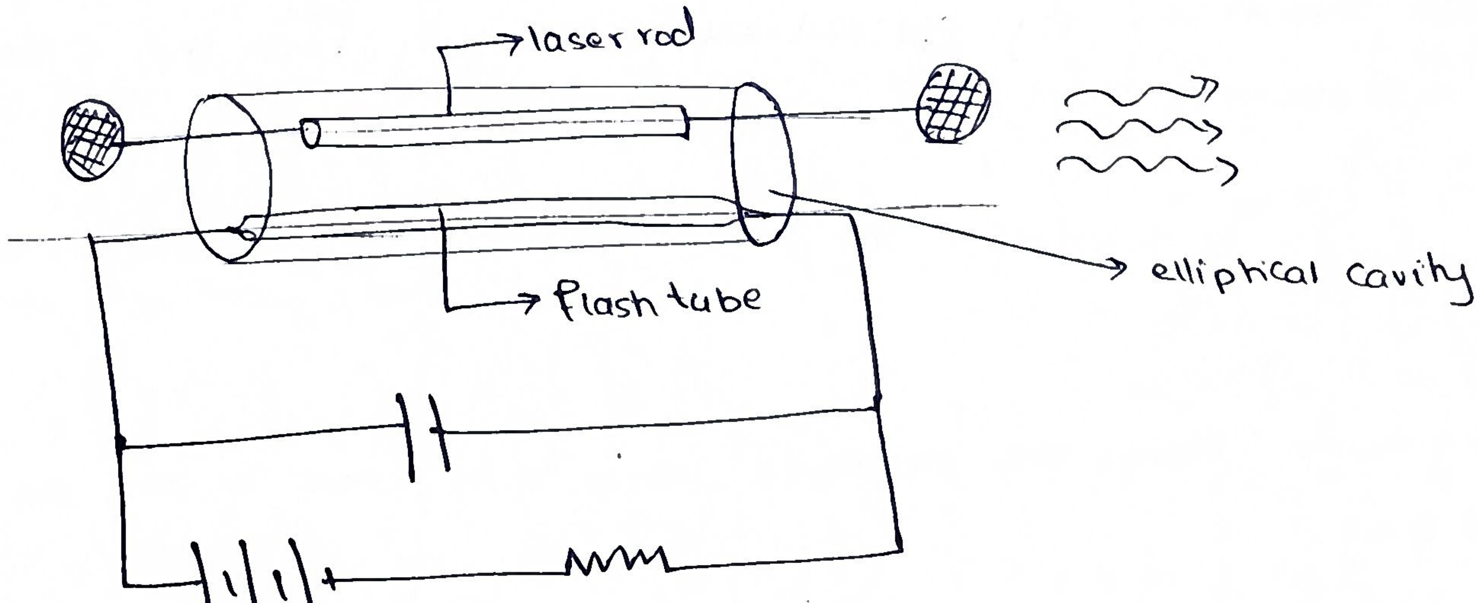
Description : There is an ND - YAG cylindrical rod, made of YAG crystal ($Y_3Al_5O_{12}$). There is also a krypton flash tube. The Nd - YAG rod and the krypton flash tube are placed in a hollow elliptical cavity, with one rod at each foci. ~~The elliptical~~

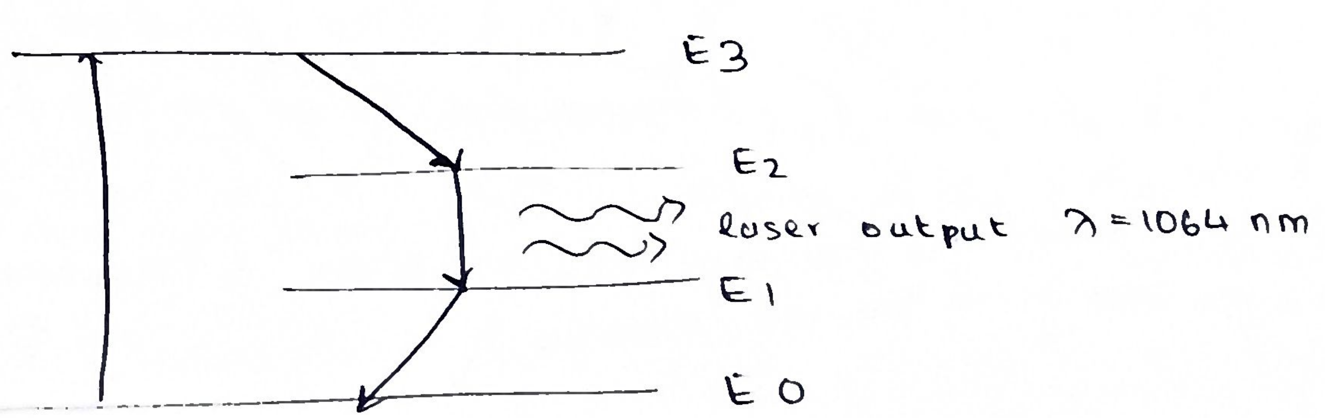
The light coming from the flash tube falls on the other focus, where the Nd-YAG crystal is placed. This ensures that maximum population inversion happens

The flash tube can be switched on & off and can be controlled with a capacitor. The ends of the laser rod and accompanied by 2 mirrors, one is 100% reflecting and the other is partially reflecting. These acts as the optical resonator.

Working : The optical pumping is done by the krypton flash tube. This excites the Nd ions to the E_3 state. The first transition occurs from E_3 to the metastable state E_2. No radiation is emitted. From $E_2 \rightarrow E_1$, radiation of wavelength 1064 nm is emitted. The further transition that occurs from E_1 to E_0 is also non-radiative.

The transition from E_1 to E_0 should be fast so that population inversion is maintained from E_2 to E_1, to yield a continuous out put. A cooling arrangement must also be set up to ~~maintain~~ remove the heat produced during the working of the laser.





applications : (i) resistor trimming

(ii) welding, hole drilling

(iii) surgery

CO_2 Laser

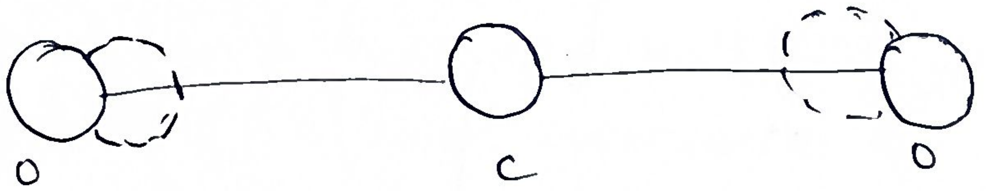
- CO_2 lasers are molecular lasers.
- They are 4 level lasers and operate at 1060nm in the far IR region

Principle :- The active region in the CO_2 laser consists of a mixture of gases like CO_2, He, N_2 and water vapour.

- Besides electronic levels there are also rotational & vibrational levels.
- The vibrations occur as the atoms of the molecules can vibrate w.r.t one another, while the molecule itself can rotate. (The energies associated with rotation are very small compared to that from vibrations).
- The laser operates from the transitions between the vibrational levels in the ground state.

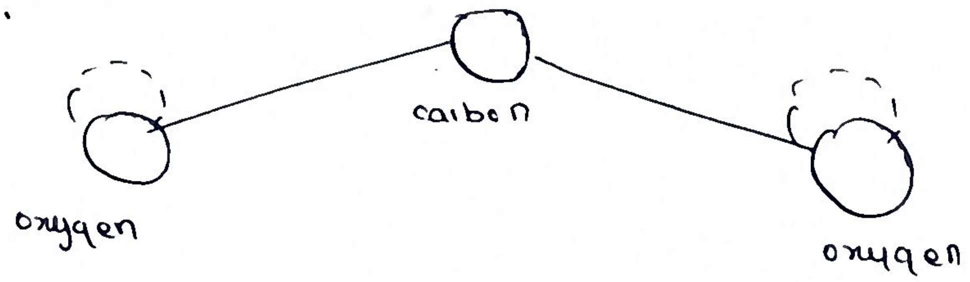
Vibrational modes of CO_2

1. symmetric stretching mode: the oxygen atoms oscillate along the axis with them simultaneously approaching or receding from the C atom. The C atom is stationery.

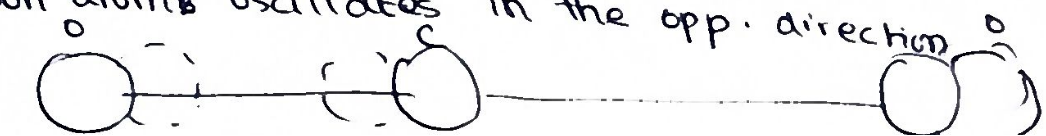


symmetric bending

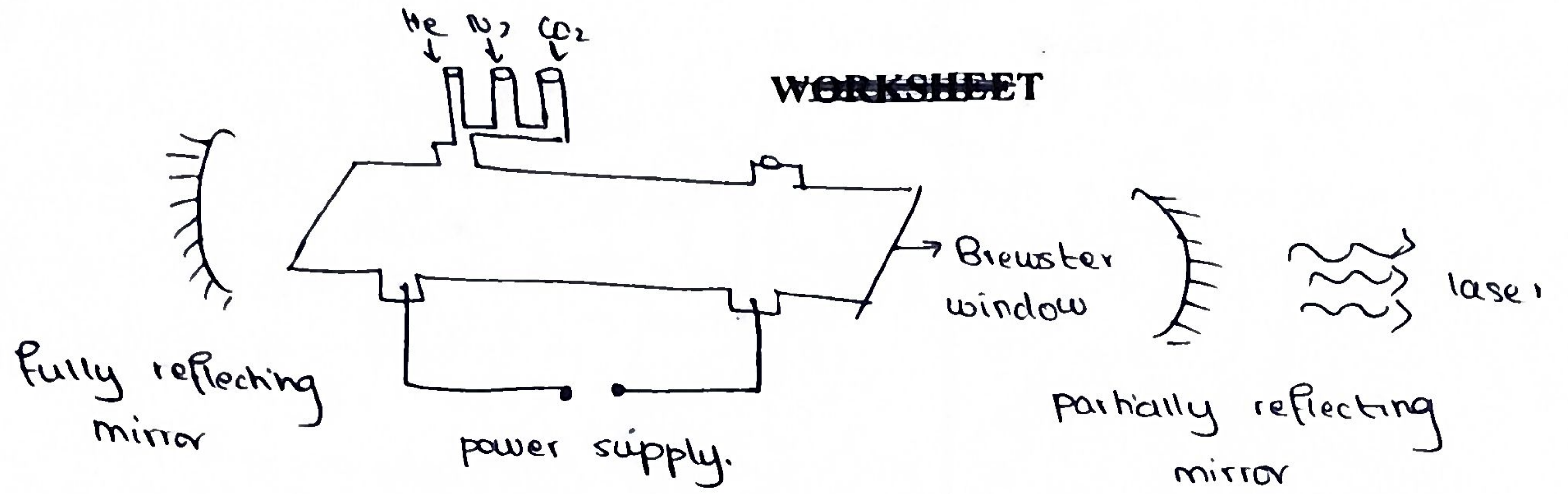
2. bending mode: Here, the molecule ceases to be linear as the atoms oscillate ⊥r to the axis.



3. assymetric stretching mode: here, the oxygen atoms oscillate in 1 direction, while the carbon atoms oscillates in the opp. direction



Design of the CO_2 laser



- There is a discharge tube of diameter 5.5cm and length 5cm. This is connected to a DC power supply.
- A Brewster window is present on one side to obtain a polarized laser
- There are 2 polished confocal mirrors that form the resonant cavity.
- A flow loops enables the pumping of He, Ne & CO_2 into the setup.
- N_2 gas is first pumped in, and then CO_2.

Working

- N_2 gas first pumped in. The nitrogen molecules are raised to an excited state, due to the collision of electrons emitted from the discharge tube with it.

$$N_2 + e^* \rightarrow N_2^* + e$$

- CO_2 gas is then pumped in. The excited N_2 molecules collide with the CO_2 molecules and they are raised to higher electronic, rotational & vibrational levels.

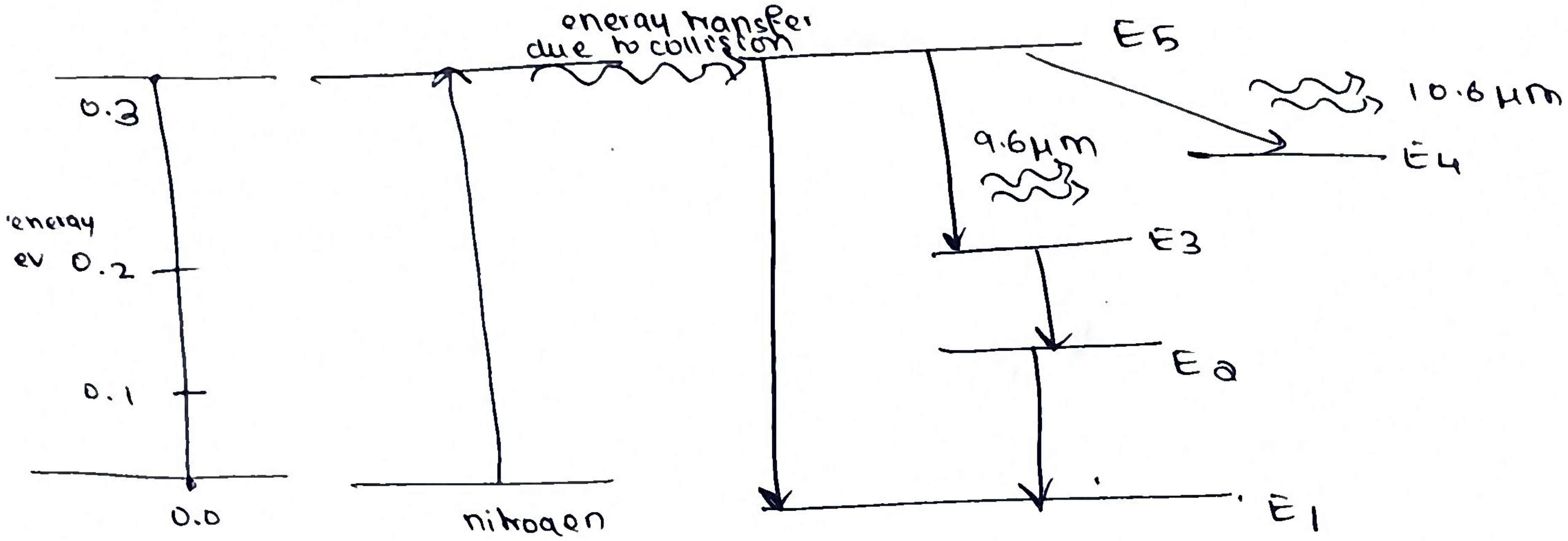
$$CO_2 + N_2^* \rightarrow CO_2^* + N_2$$

- The special feature of the setup is that the discharge electrons excite nitrogen only when they transfer their energy to the active centres of the CO_2 molecules.
- Since the excited state of N_2 is very close to the ~~E_4~~ E_5 level of CO_2, the population level in the E_5 level increases. As soon as population inversion is obtained, one of the triggered photons can cause laser action

• The transition can happen in 2 ways:

(i) From E_5 to E_4 $\rightarrow \lambda = 10.6 \mu m$

(ii) From E_5 to E_3 $\rightarrow \lambda = 9.6 \mu m$



<u>Applications</u> : (i) drilling, welding

(ii) atmospheric attenuation is low for 1060 nm. used for open air communication

(iii) laser remote sensing

(iv) treatment of liver, lungs, neurosurgery.

<u>Semiconductor Lasers</u>

• semiconductors can also be used to produce lasers, they are very compact

• When a forward bias is applied to a p-n junction, there ~~is a~~ holes are injected from the p side → n side and electrons from the n side → p side. This is called minority carrier injection.

• The electrons and holes recombine near the junction region and there is a release of energy. (called activation energy / energy gap.)

• In some semiconductors like Ge, Si, the recombination of holes and electron results in heat being given out. This is because the recombination occurs w/ the interaction of the atoms of the crystal. These are called as Indirect Band Gap Semiconductors.

• In other semiconductors like GaAs, the energy is released as light. This is because the recombination occurs without the interaction with the crystal's constituent atoms. These are called as direct band gap semiconductors.

Semiconductor lasers are classified into 2. Homo-junction laser & hetero-junction laser.

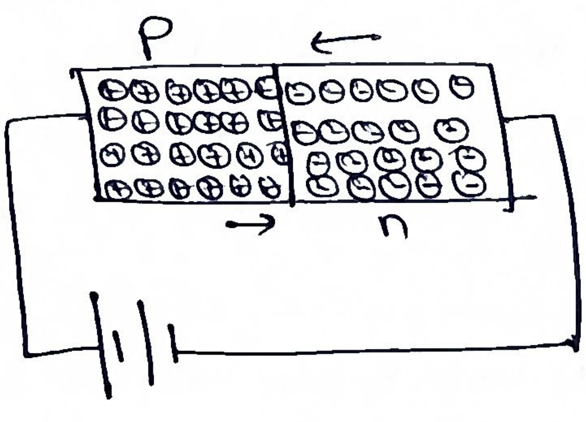
Homo-junction laser: when a p-n junction is formed by a single crystalline structure, eg GaAs

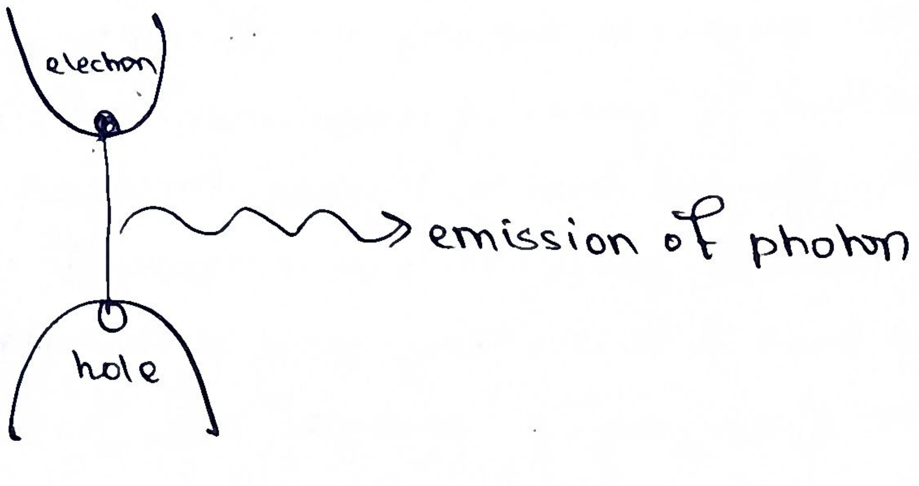
Hetero-junction laser: when the junction has different material on each side, it is called a hetero-junction laser. For eg. a laser w/ GaAs on one side and Ga-Al-As on the other.

Homo-Junction ~~pn~~ Semiconductor Laser

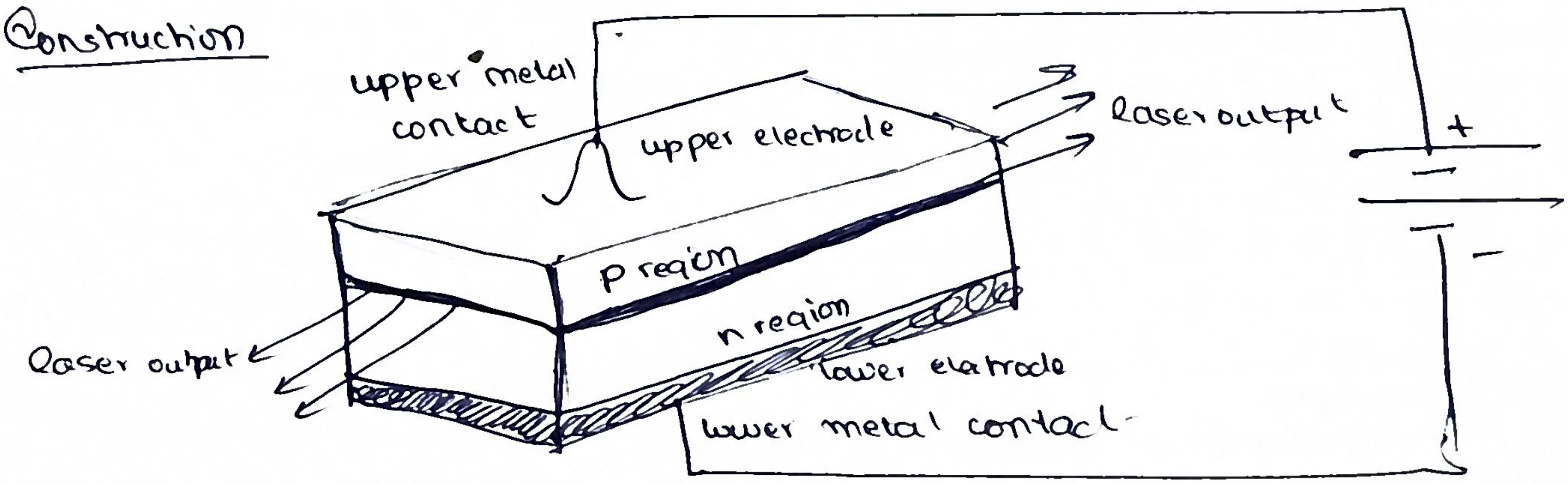
Principle

- When a p-n junction of a homo-junction semiconductor is forward biased, holes move from p→n and electrons from n→p (minority carrier injection)
- The electrons & holes recombine near the junction and they release energy in the form of light. Light energy is released because the recombination does not involve any interaction with the crystal's constituent atoms and ~~nucle~~
- The photons emitted during recombination stimulate the recombination of other charge carriers.
- As a result, there is a chain of stimulated emission required for a laser beam.





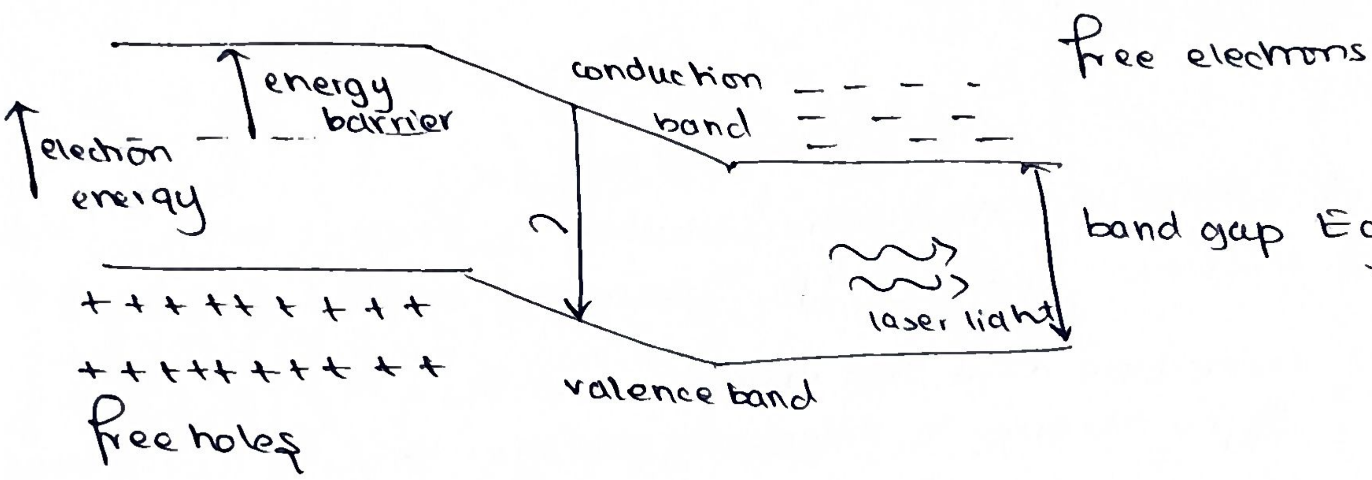
Construction



• A homo-junction semiconductor laser has a single GaAs crystal.
• The crystal is in the form of a platelet of thickness 0.5 mm
It is 2 parts: a region exhibiting electron conductivity (n-region)
a region exhibiting hole conductivity (p-region)

• Forward bias is applied to the junction
• The end faces of the diode are parallel to each other. They act as the optical resonator.

Working



• On applying a forward bias, there is an accumulation of charge carriers near the junction region
• There are free electrons near the conductionband, and free holes near the valence band.
• If the population density is sufficient, population inversion is attained.
• The electrons and holes recombine leading to the emission of light.
• If the forward bias is further increased, the intensity of the laser increases
• The released photons trigger a chain of stimulated emissions, and ~~to~~ as they reflect back & forth, they grow in strength.
• After gaining enough strength, the $\lambda = 8400 \mathring{A}$ which is in the IR region

The wavelength of the laser is given by:

$$E_g = \frac{hc}{\lambda}$$

$$\lambda = \frac{hc}{E_g} \qquad E_g = \text{energy gap}$$

Applications: • Fibre optics
• laser diodes (more powerful than LEDs)
• laser printers, reading CDs
• external pain reliever
• to heal wounds from IR

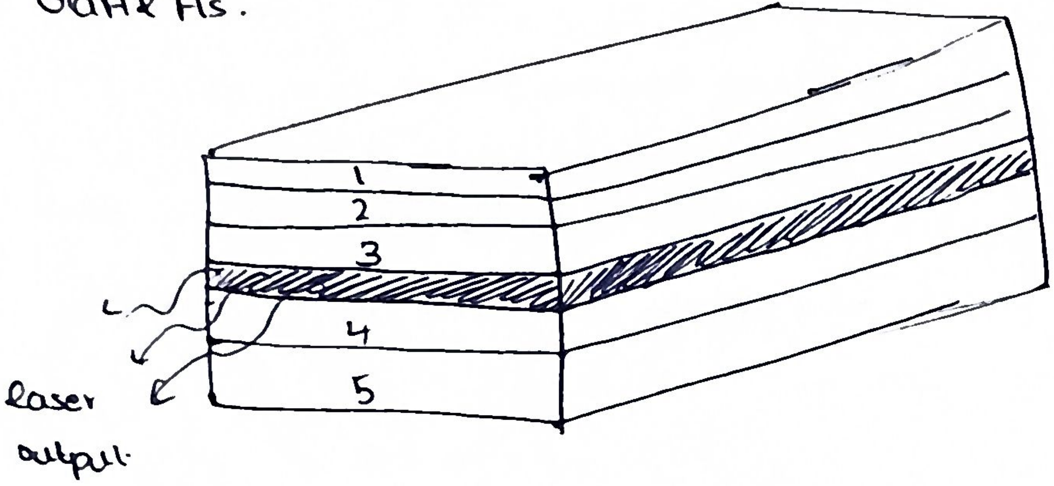
Hetero Junction Semiconductor Laser

Principle

A hetero junction semiconductor laser consists of one material on one side of the junction and another material on the other side. Usually GaAs diode lasers are formed with GaAs on one side and GaAlAs on the other.

Construction

In a GaAs laser diode, a layer of GaAs is sandwiched between 2 layers of GaAlAs.



	laser type	material used
1.	contact	GaAs
2.	p-type wide band gap consignment	GaAlAs
3.	p-type narrow band gap active layer	GaAs
4.	n-type wide band gap consignment	GaAlAs
5.	n-type substrate	GaAs

Working : Under forward biasing, minority carrier injection takes place. This leads to an accumulation of charge, which are available for stimulated emission. Population inversion is attained and photons are ejected. These photons further stimulate more recombination of carriers, and a continuous laser beam is obtained.

- The band gap difference prevents the diffusion of charges
- The difference in the refractive index of the material on either side of the active region keeps the charges localized there (between 3 & 4)
- In hetero-jn. lasers, there is a narrow spectral width, high coherence & high stability

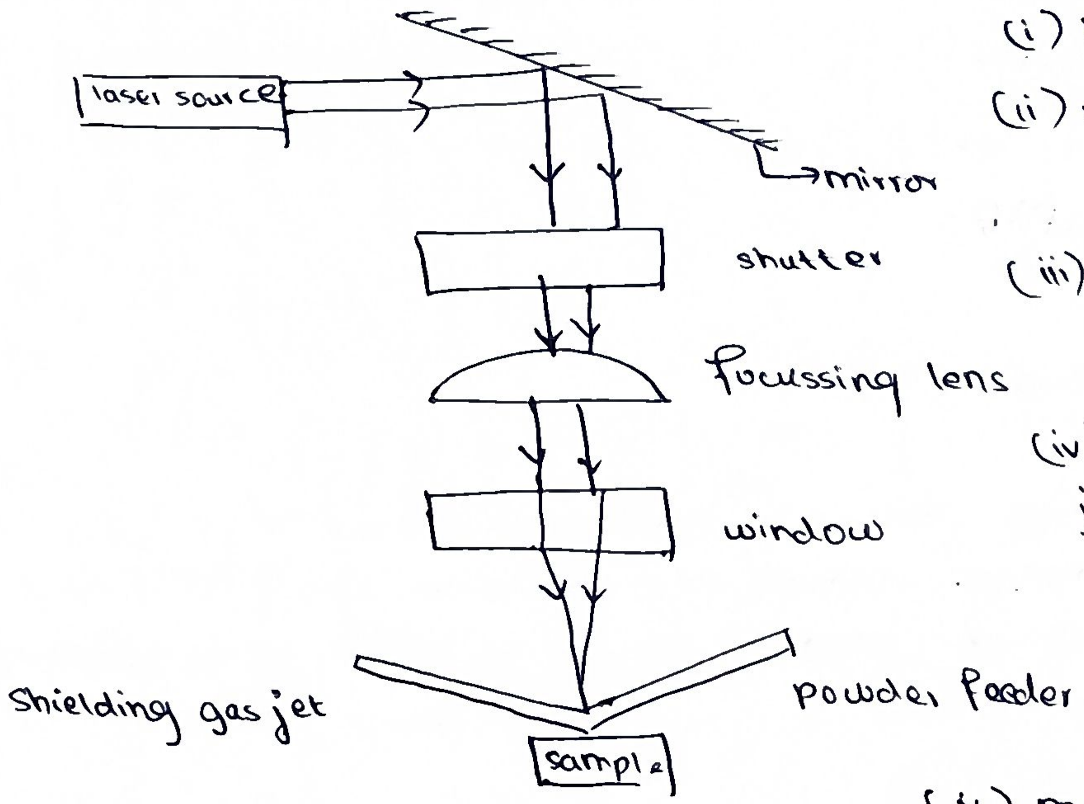
Homo - junction laser diode	Hetero junction laser diode
1. Only a single material is used for fabrication. (GaAs).	1. There is a different material on either side of the junction. (GaAs and GaAlAs).
2. High threshold current density 400 A/m²	2. Low threshold current density 20 A/m²
3. Large beam divergence	3. Very narrow beam divergence
4. Output is in the form of pulses	4. Continuous output
5. Poor coherence, low stability	5. High coherence, high stability

Industrial Applications of Lasers.

1. **Material Processing** - Material processing involves cutting, welding drilling & surface treatment. When a laser beam is focused on a material, light energy is converted into heat energy.

The material is heated, melted and then vapourized.

The set up is as follows:



(i) laser source falls on a mirror

(ii) passes through shutter to control intensity

(iii) & passes through lens to focus the beam

(iv) set up also has a shielding gas jet - cools metal surfaces, protects focussing arrangement against smoke and fumes. increases the absorption energy

(v) powder feeder: sprinkles metal powder on the substrate for cladding / alloying.

Laser Welding : metals can be joined together by means of welding. In order to weld metals, the 2 pieces are held in contact at their edges. Focusing ~~on~~ a laser beam at the edges, raises the temperature till the melting pt, of the metals

On cooling, the 2 pieces fuse together

Advantages : (i) a contactless process, material not contaminated
(ii) no distortion of the work piece
(iii) heat affected area is very small, due to rapid cooling

Heat Treatment Metal surfaces need strength. Certain parts may weaken due to wear and tear. An intense beam of a laser is focussed on the part that needs strengthening. The area is heated, and then the beam is moved to other areas, as the first region cools down. Its strength increases as it cools
It is used in the automobile industry to strengthen certain parts like camshafts gears, cylinder blocks etc.
The process is known for its strengthening efficiency and for causing minimum distortions in the sample material.

Laser Cutting : Fine beams of lasers can be used to cut materials. The heat energy enables this cutting. Oxygen gas is also used in the process to cool down the cutting area, to blow away cutting products & melt from the adjacent areas (to ensure a fine cut)

Advantages / Applications
(i) can make 2D & 3D cuts
(ii) used in the garment & aerospace industry
(iii) fine, precise cuts
(iv) minimum ~~chemic~~ mechanical distortion
(v) chemical purity is maintained
(vi) automated process
(vii) can be used on a wide variety of materials

Medical Applications
(i) treatment of detached retina
(ii) treatment of gastric hemmorhage
(iii) treatment of cancer & tumors

(iv) shatter kidney stones

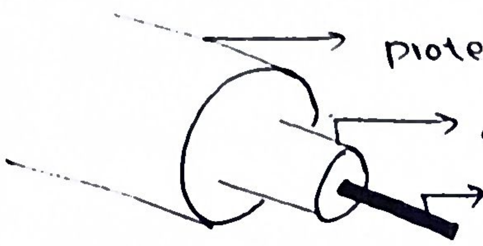
(v) make precise cuts in bones

(vi) used in therapy to heat poorly healing wounds and bone fracture.

Fibre Optics.

Fibre optics: a technology related to the transportation of optical energy through a guiding media. The guiding media is optical fibre

Construction of optical fibre :



$n_1 > n_2$

Total internal reflection : The phenomenon in which a ray of light, travelling at an angle of incidence greater than the critical angle from a denser medium to a rarer medium is totally reflected back into the denser medium is called TIR.

critical angle: The angle of incidence in the denser medium for which the angle of refraction is 90°.

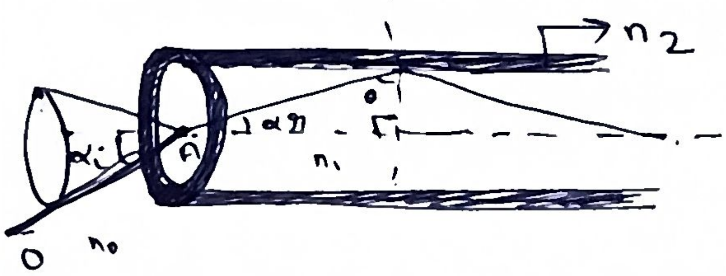
Relation between critical angle angle & refractive index

$$n_1 \sin\theta_c = n_2 \sin 90°$$

$$\sin\theta_c = \frac{n_2}{n_1}$$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \quad (n_1 > n_2)$$

Acceptance angle : The maximum angle of launch for which a ray of light entering the core just undergoes TIR at the core-cladding interface..



By Snell's law:

$$n_0 \sin\alpha_i = n_1 \sin\alpha_r$$

$$\sin\alpha_i = \frac{n_1}{n_0} \sin\alpha_r$$

$$\sin\alpha_i = \frac{n_1}{n_0} \sin(90-\theta)$$

$$\sin\alpha_i = \frac{n_1}{n_0} \cos\theta$$

$$\cancel{\sin\alpha_i = \frac{n_1}{n_0}\sqrt{1-\sin^2\theta}}$$

$$\sin\alpha(max) = \frac{n_1}{n_0} \cos\theta_c$$

$$\sin\alpha(max) = \frac{n_1}{n_0} \cdot \sqrt{1-\sin^2\theta_c}$$

$$= \frac{n_1}{n_0} \sqrt{1 - \frac{n_2^2}{n_1^2}}$$

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

$$\sin\alpha(max) = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$ if the external modium is air

$$\boxed{\sin\alpha(max) = \sqrt{n_1^2 - n_2^2}}$$

or $\boxed{\alpha = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)}$

<u>Numerical</u> <u>Aperture</u> = sine of the acceptance angle.

i.e $\sin\alpha = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} = NA$

condition for propagation : $\theta_i < \alpha$.

$\sin\theta_i < \sin\alpha$

i.e $\boxed{\sin\theta_i' < NA'}$

<u>Fractional Index Change</u> : $\frac{\text{change of refractive index of core \& cladding}}{\text{refractive index of core}}$

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

$$n_1\Delta = n_1 - n_2$$

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

$$NA = \sqrt{(n_1+n_2)\, n_1\Delta}$$ if $n_1 \approx n_2$

$$NA = \sqrt{2n_1^2\Delta}$$

$$\boxed{NA = n_1\sqrt{2\Delta}}$$

Types of optical Fibres

(1) On the basis of material

(a) Glass Fibre: made up of metal ores and silicon glass

eg. $GeO_2 - SiO_5$ - core SiO_2 cladding

(b) Plastic fibre: made of plastic, tough & durable, need not be handled w/ care like glass fibers.

eq. polystyrene-core , methylmethacrylate-cladding

Modes: • Light, once it enters the optical fibre, is trapped inside due to TIR. However, all the light waves do not propagate. The ones which propagate are called modes.

• The path of light inside the optical fibre is zig-zag. Some paths are in phase due to constructive interference, others are out of phase due to destructive interference. (due to phase changes during multiple reflection)

• The paths which interfere constructively are called modes.

• The no. of modes is dependent on the ratio $\frac{d}{\lambda}$, where d = diameter of the core.

note: higher modes = smaller angles

Classification the basis of modes

single mode fibres

(i) d is very small (~~8~~ 4 μm)

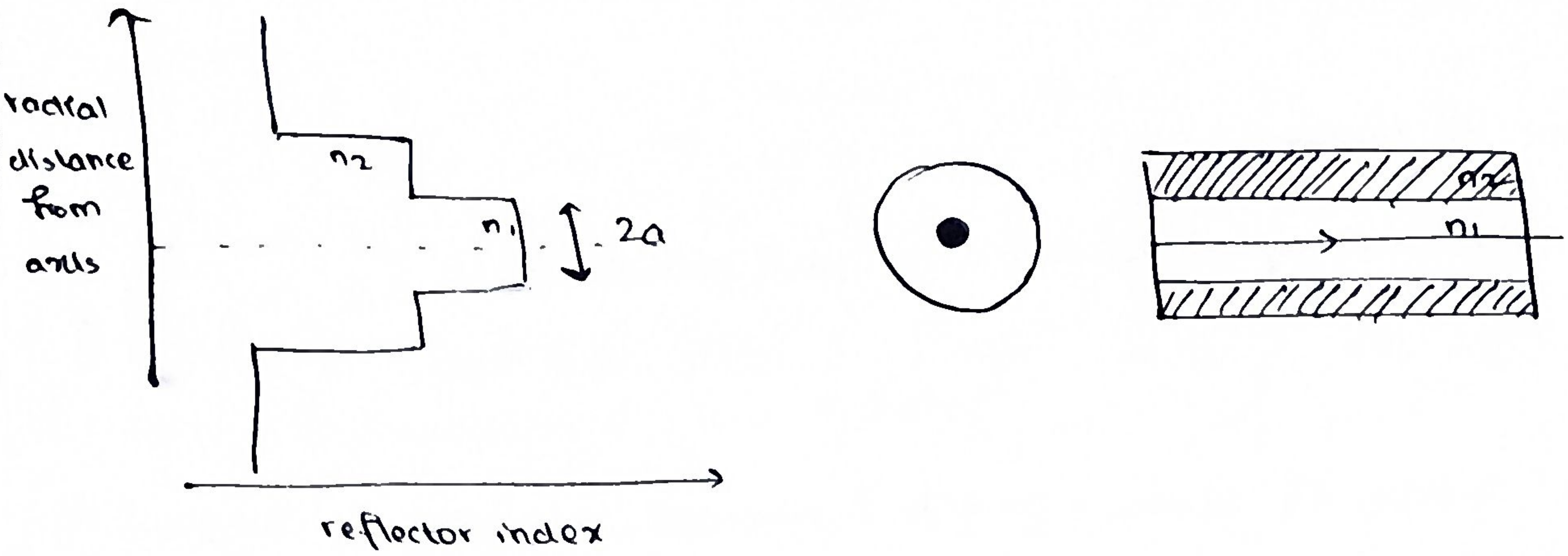
(ii) the only mode that exists is along the axial line

(iii) intermodal dispersion does not occur

(iv) has a very small value of Δ (Fractional index change)

(v) since d is small, light is launched using lasers

(vi) used for long distance communication.



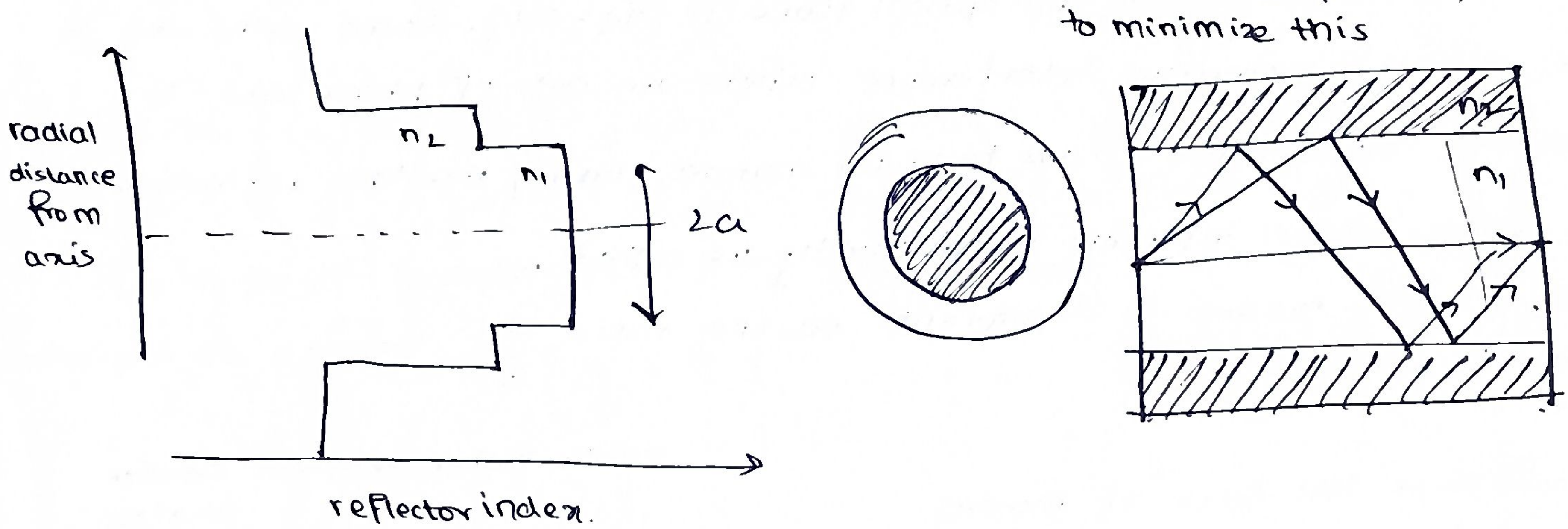
multimode fibres

(i) have a much larger diameter (50 – 100μm)

(ii) multiple modes are present apart from the axial mode's

(iii) used in short distance communication

(iv) intermodal dispersion is present (use graded index fibres to minimize this)



Step Index Fibres : The core has a refractive index of n_1 and the cladding n_2. There is an abrupt change in refractive index at the core cladding interface ⇒ they are called step index fibres.

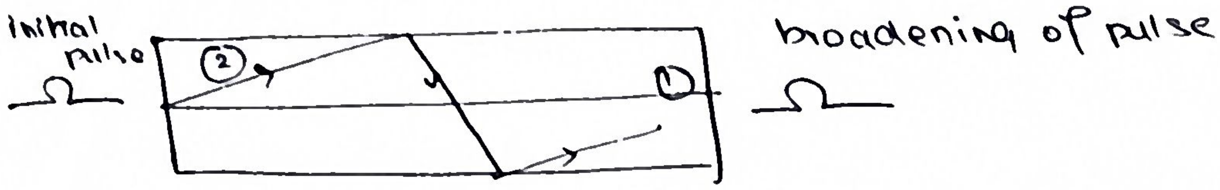
They are classified as:

(i) single mode step index fibres

(ii) multimode step index fibres

} For explanations, write the same as single mode & multimode fibres.

Transmission of signal in a multimode step index fibre



- Signals are sent through the fibre in digital form.
- Consider the propagation of 2 pulses, 1 & 2
- 1 travels along the axial line, and reaches the other end first
- 2 travels in a zig-zag path and reaches the other end after a while since it has to travel a longer distance
- This leads to the broadening of the pulse ⇒ called intermodal dispersion.
- This reduces the transmission capacity

Graded Index Fibre (GRIN)

- A multimode fibre with a core consisting of concentric layers of different refractive indices.
- The RI is max. at the core, and decreases gradually w/ radial distance, till it matches the refractive index of the cladding.
- The variation of the refractive index is given by

$$n(x) = n_1 \left[1 - 2\Delta \left(\frac{x}{a} \right)^{P} \right]^{2}$$

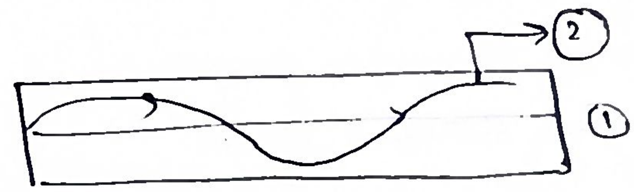
n_1 = RI at core

P = graded index profile no.

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

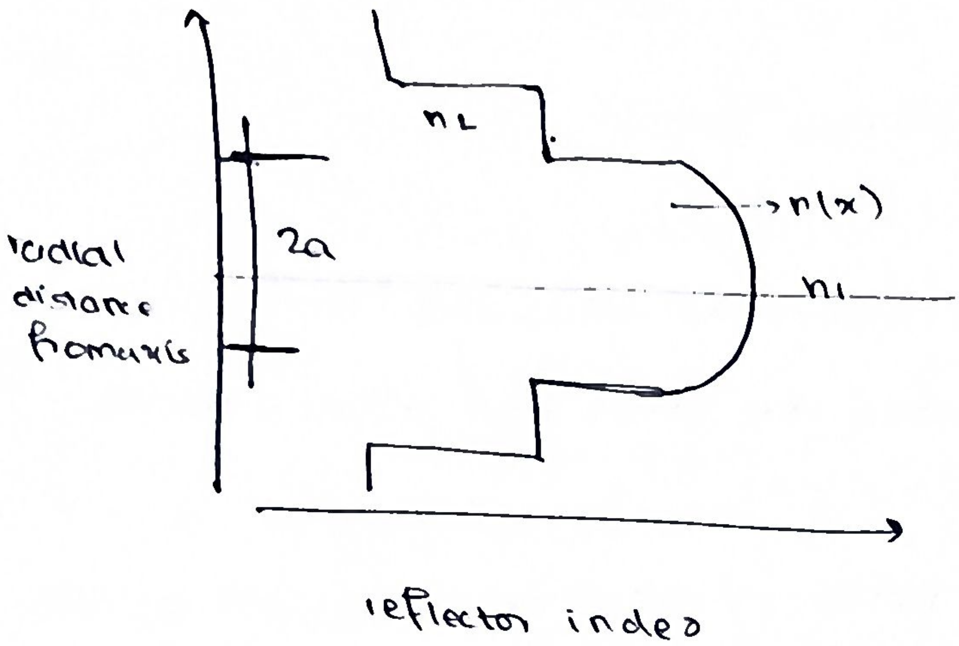
- The core has a large diameter (50 – 100 μm)

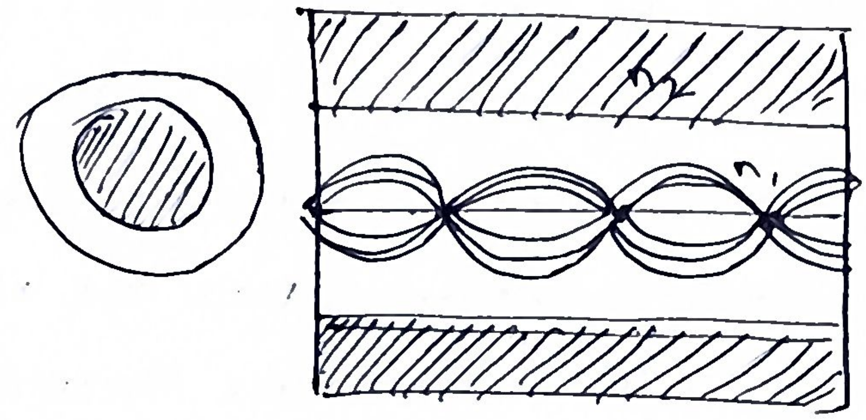
Transmission of signals in GRIN



- 1 is along the axial line. It travels a shorter distance, but its velocity is less, as it propagates in a region of high RI.
- 2 travels along a longer path, but w/ a greater velocity as the RI is less.

- As a result, both 1, 2 reach the other end at the same time.
- Intermodal dispersion can be overcome.





V Frequency (Normalized Frequency)

- $V = \frac{2\pi a}{\lambda}\left(\sqrt{n_1^2 - n_2^2}\right)$
- The no. of modes is given by - $N_m \simeq \frac{V^2}{2}$ (For GRIN : $N_m = \frac{V^2}{4}$)
- The value of λ corresponding to $V = 2.405$ is called the cutoff wavelength.

$$\lambda_c = \frac{\lambda V}{2.405}$$

* Differences between single mode & multimode fibres

Single mode Fibre	Multimode Fibre
1. Only a single mode along axial line	1. mode along axial line + zigzag modes (meridonial → step index, skew rays → GRIN)
2. diameter → 4 μm	2. diameter → 50 - 100 μm
3. Intermodal dispersion absent	3. Intermodal dispersion present
4. used in long distance comm	4. used in short distance comm.
5. Difficult to launch light, connect	5. easy to launch light, connect
6. Lenses used as sources	6. LEDs used as sources
7. Difficult & expensive to install	7. Easy & inexpensive to install
8. Draw RI diagram	8. Draw RI diagram

* Differences between step index fibre and graded index fibre

Step Index Fibre	Graded Index Fibre
1. change in refractive index in the form of a step (draw RI diagram)	1. Refractive index max. at core, decreases as we move towards cladding. (draw RI diagram)
2. apart from axial ray, light travels in a zig-zag path (called meridonial rays) pass through axis of fibre (diagram)	2. Rays undergo repeated refraction at each core layer, finally undergo TIR at cladding. (called skew rays), do not pass through the axis of fibre (diagram)
3. Intermodal dispersion present	3. Intermodal dispersion absent (self focussing effect)
4. High attenuation	4. Low attenuation
5. Easy to manufacture	5. Difficult to manufacture
6. Low bandwidth	6. High bandwidth
7. no. of modes: $N_m = \frac{V^2}{2}$	7. no. of modes: $N_m = \frac{V^2}{4}$.

Losses in optical Fibres

Attenuation: The signal attenuation for a fibre of length L, is defined as the ratio of the power output to the power input.

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

unit: decibel/km

- For an ideal optical fibre $P_o = P_i \Rightarrow \alpha = 0$

The 3 fundamental mechanisms responsible for attenuation are:
(i) Absorption
(ii) Scattering
(iii) Bending losses or radiative losses

Absorption: • happens due to impurities/defects at the atomic level in the glass structure.

- There may be atomic defects like oxygen defects, increase in density due to a cluster of atoms, missing molecules etc. The impact of these defects are negligible though.

• Hydroxyl ions & transition metals like nickel, copper, chromium etc. have electronic absorption in the visible region.

• This leads to heavy losses, but they can be minimized by certain manufacturing processes.

• In improved fibres, metal ions are almost negligible. Losses still occur due to the absorption of light by OH^- ions. These is called extrinsic absorption

• Intrinsic absorption is associated with the very basic material of the fibre. Even if all the impurities are removed, the material still has the tendency to absorb light.

Scattering

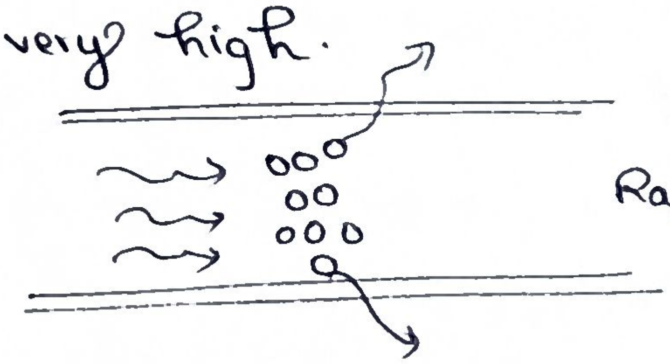
• When light is scattered by an ~~powe~~ obstruction, there are power losses.

• There are microscopic variations in density which cannot be rectified/ eliminated.

• These lead to a variation in refractive index, and thereby cause scattering.

• This is known as Rayleigh scattering. It varies by $1/\lambda^4$.

• The lower limit for wavelength is set at 0.8 μm below which scattering losses are very high.



Rayleigh scattering

Radiative and Bending Losses

• This occurs due to a change in the angle of incidence at the microscopic/ macroscopic level ~~due to~~ at the core-cladding interface.

• At the macroscopic level, it happens when the radius of curvature is greater than the diameter of the fibre.

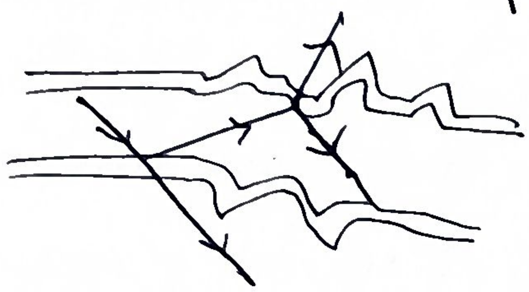
• The conditions for TIR are no longer satisfied.

: It can be minimized by bending the cable in a larger radius of curvature.

Microscopic Bending: This sort of loss occurs when there are irregularities at the core-cladding interface.

It may be due to non-uniform pressure applied during cabling or during manufacture.

- It can be minimized by squeezing a compressible jacket over the fibre.



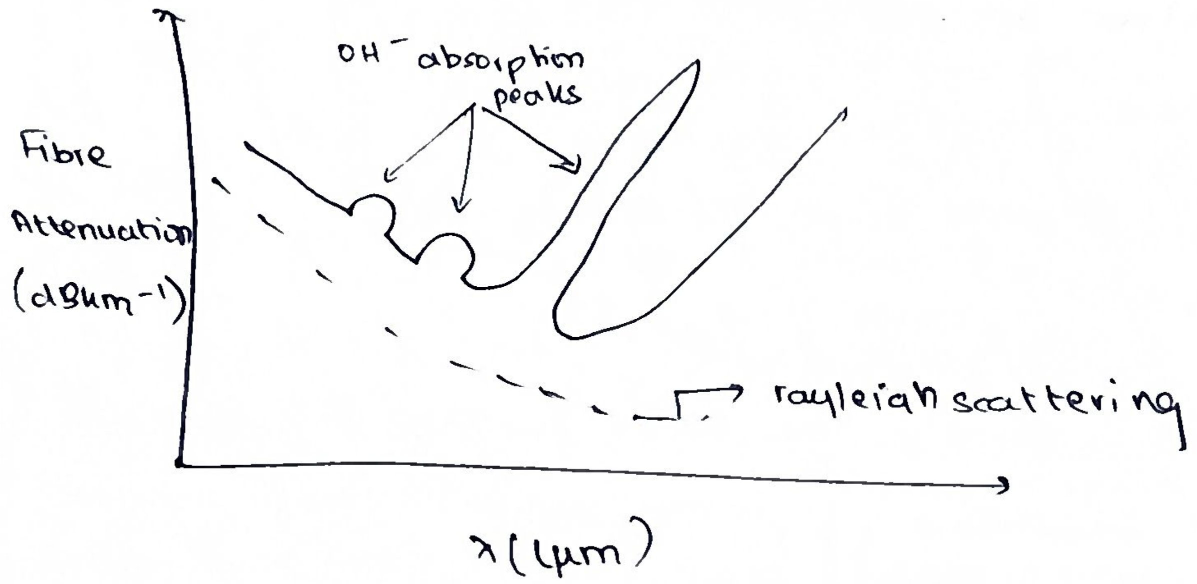
- If an external force is applied, the fibre tends to stay relatively straight.

Absorption Losses : can be ultraviolet absorption
ion resonance absorption
infrared absorption

Ultraviolet absorption : In pure fused silica, the absorption of ultraviolet rays of wavelength 0.14μm, leads to ionization of valence electrons. This leads to a loss of light energy.

Infrared absorption: The absorption of infrared photons leads to an increase of random mechanical vibrations and heating.

There are also OH^- ions present in the material, due to the minute amounts of water that may have got stuck during manufacturing.



Dispersion : The broodening of the output pulse in comparison to the input pulse is called dispersion. It can happen in three ways:

(i) Intermodal Dispersion

(ii) Material / Chromatic Dispersion

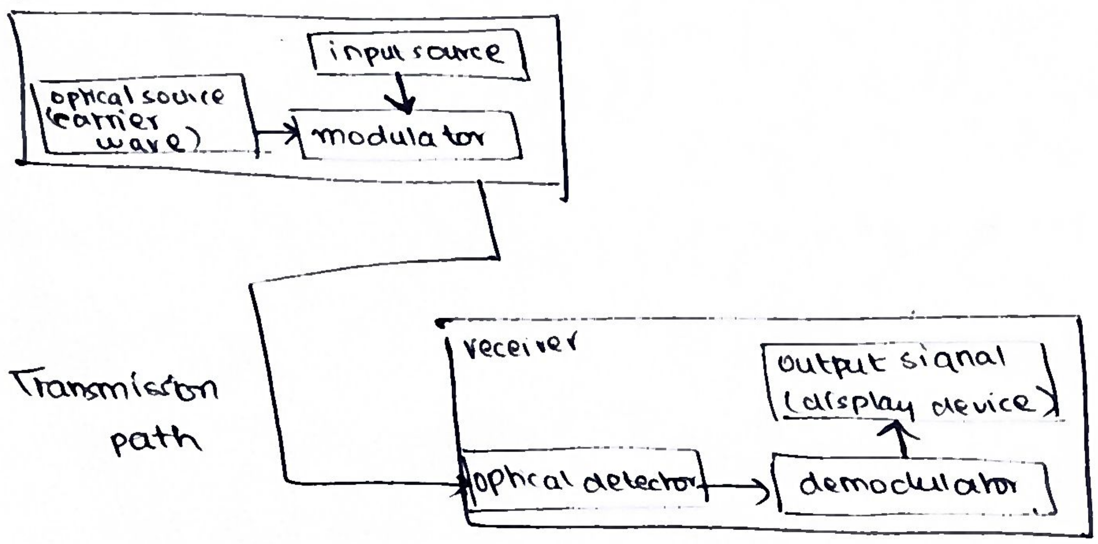
(iii) Wave Guide Dispersion

① **Inter modal Dispersion** : The rays reflected a larger angles, higher order modes, travel a greater distance, than lower order modes. The higherorder modes reach the ~~lower order~~ end later than the lower order modes. This leads to the broadening of the pulse and thereby, the distortion of the signal.

② **Material / Chromatic Dispersion** : The input light source consists of many wavelengths. The shorter wavelength components travel slower than the longer ~~input~~ wave components, which eventually causes the light pulse to broaden.

③ **Waveguide Dispersion** : It arises due to the guiding property of the fibre and the diff. angles of incidence at the core - cladding interface. It is significant only for single mode fibres. This is because of the fact that some of the light travels through the cladding as well. The cladding has a lower refractive index, so these light rays travel faster. Thus, the light pulse broodens in time.

Fibre Optic Communication System



Transmitter

1. Conversion of ~~optic~~ input into electrical signal: done using transducers & associated electronic circuits
2. Light source: The transmitter has an optical source such as an LED / semiconductor that can act as a carrier wave
3. Modulator: mixing the input electrical signal & carrier wave, which is coupled with the optical fibre.

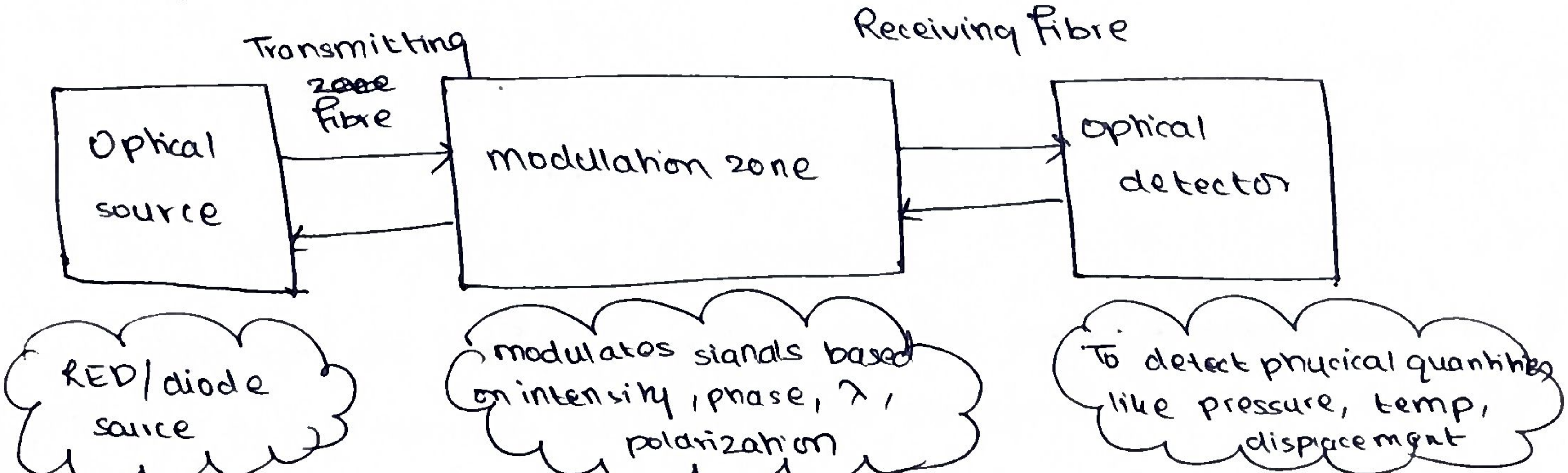
Optical Fibre: many fibres joined over a long distance using connectors. If the distance is large, signal repeaters are used. The signal is reshaped & retimed at the repeaters.

Receiver:

1. Conversion of optical signal to electrical signal: w/ photodetectors and electronic circuits
2. Amplification: done w/ minimum noise and distortion
3. Demodulation: the pulses are demodulated into their original wave form.

The demodulated signal is fed into the display unit.

Fibre Optic Sensors: converts any signal into an optical signal using a transducer



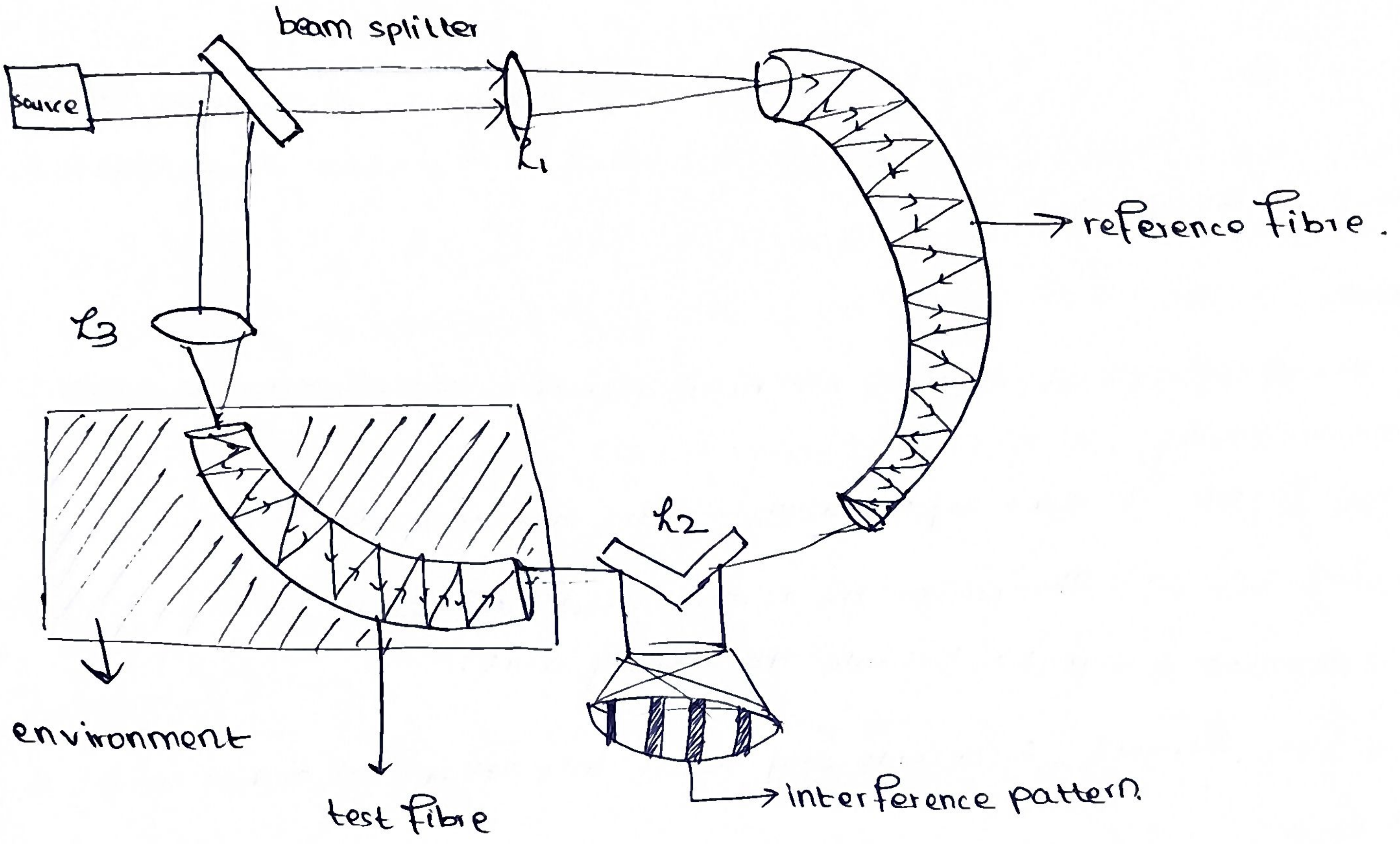
There are 2 types of fibre optic sensors:

Intrinsic sensors / active sensors: the physical parameter to be checked acts on the fibre itself causing changes in the transmission & receiving pulses eg. pressure sensors

Extrinsic sensors / passive sensors : there is a separate sensing element the fibre acts as the guiding media to carry the transmitting & receiving pulses. eg. displacement sensors.

Intrinsic sensor : Measurement of pressure

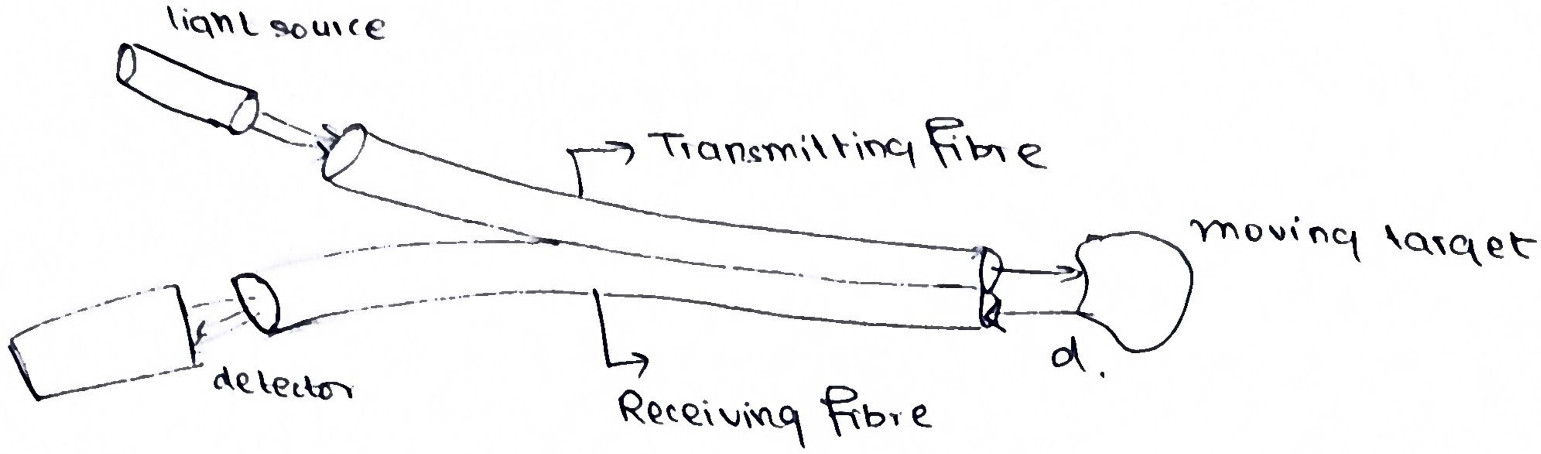
Principle : interference from the beams coming from the test fibre and the reference fibre.



Working :- A power laser source is split into 2 using a beam splitter.

- The transmitted beam is focussed on the reference fibre with lens L_1
- After passing through the reference fibre, it falls on the lens L_2.
- The reflected beam is focussed w/ lens L_3.
- It passes through the test fibre placed in the environment.
- There is a change in transmission, i.e a path diff. because of the pressure in the environment.
- The beam is made to fall on L_2.
- The path diff. causes an interference pattern, and the pressure can be measured

• Extrinsic Sensor - Displacement sensor



• Laser light is focussed on the moving target through the transmitting fibre

• The reflected light is focussed on the detector w/ the receiving fibre.

• The axis of transmitting fibre is aligned with the laser source and moving source, and the axis of the receiving fibre is aligned w/ the moving target & the detector. This is done to ~~the~~ increase the sensitivity of the sensor

• If the ~~sensor~~ target is moving away from the sensor ⇒ intensity ↓
If the target is moving towards the sensor ⇒ intensity ↑

• Based on the changes in intensity, the displacement can be calculated

Applications

Engineering applications: (i) send signals
(ii) measure physical quantities like tem, pressure
(iii) connect computers in a network
(iv) long distance comm

Medical applications
(i) endoscopy
(ii) investigation of heart & respiratory systems
(iii) absorption of light by blood, to measure haemoglobin count.