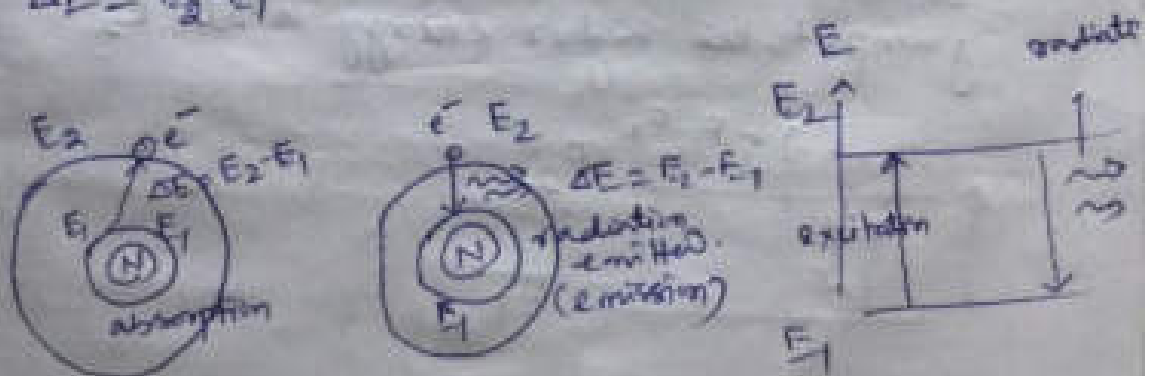


# UNIT - III

## Atomic Excitation and Energy States:

From the fundamentals of atomic structure, it has been established that, in an atom, an electron in a ground state is stable and moves continuously in its orbit without radiating energy. When an electron receives an amount of energy equal to the difference of the energy of the ground state and one of the excited states, it absorbs energy and jumps to the excited state. The electron can stay for a short period ( $10^{-8}$  s) in the excited state, but sometimes spend relatively longer lifetime ( $10^{-3}$  s). It is also interesting to note that, while, de-exciting, it is not necessary to return to the same original state. Let us consider in an atom, an electron absorbs energy equal to the difference of ground-state ( $E_1$ ) & the first excited state ( $E_2$ ) i.e.,  $\Delta E = E_2 - E_1$ . When this excited electron comes to the ground state by the process of de-excitation, then it releases a radiation of energy

$$\Delta E = E_2 - E_1$$



## Interaction of external energy with the atomic energy states.

Generally, three kinds of interactions involved with the atomic energy states. (i)

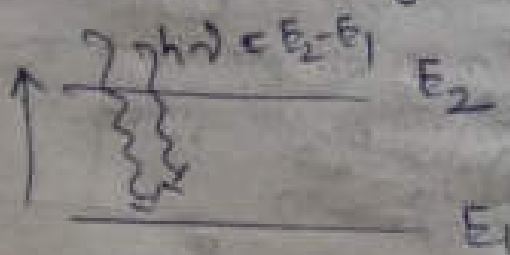
Absorption; in which suitable energy is absorbed by the atoms in the ground state to get excited to the higher energy states. Second, known as

(ii) spontaneous emission, in which the excited atom emits photon and come back to the low energy state without any external impulses.

(iii) Third is known as Stimulated emission, in which atom in the excited state need not wait for the spontaneous emission to occur, but with the influence of an suitable energy impulse, excited atom is triggered to the lower energy state, with the release of appropriate energy.

### (i) Absorption:

Let us consider a sample in which there are two energy levels  $E_1$  &  $E_2$  ( $E_1$  being lower in energy than  $E_2$ ). The atoms residing in the lower energy state  $E_1$  may absorb suitable photon incident upon it to jump to the higher energy state  $E_2$ .



this process of transition is known as induced or stimulated absorption or simply absorption. During each absorption process, one photon disappears from the incident light. If  $A$  is a particular atom which is absorbing the photon energy  $h\nu$  to become a member of the excited energy level  $E_2$ ,



the rate of absorption transition is defined as the number of atoms per unit volume per second which are raised from the lower energy level to the excited energy level.

$$R_{ab} = - \frac{dN_1}{dt}$$

where  $-\frac{dN_1}{dt}$  is the rate of decrease of population at the lower energy level  $E_1$ . If  $\frac{dN_2}{dt}$  is the rate of increase of population at the higher energy level ( $E_2$ ), then the absorption transition rate can be expressed as

$$R_{ab} = \frac{dN_2}{dt}$$

$$R_{ab} = - \frac{dN_1}{dt} = \frac{dN_2}{dt}$$

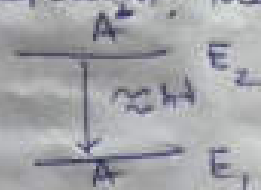
It is clear that, the rate of absorption transition is proportional to the population of atoms in the lower energy state & the energy density of incident light ( $\rho(\nu)$ )

$$R_{ab} = B_{12} \rho(\nu) N_1$$

$B_{12}$  is known as Einstein's coefficient for induced absorption transition, which represents the probability of induced transition from level 1 to 2.

## (2) Spontaneous Emission:

The excited state of atom with higher energy is highly unstable. Without the influence of any external agent, the excited atom can stay in its state for only short average lifetime. The excited atoms are come to lower energy level by emitting the excess of energy as photons. The process in which an excited atom emits a photon itself without any external impulse is known as spontaneous emission. If  $A^*$  is the excited atom, then



the rate of spontaneous transition  $R_{sp}$

$$R_{sp} = -\frac{dN_2}{dt} = \frac{N_2}{T_{sp}}$$

where  $T_{sp}$  is the spontaneous transition lifetime.

Number of photons generated during the process of spontaneous transition will be proportional to the number of excited atoms.

$$R_{sp} = A_{21} N_2$$

$A_{21}$  is known as Einstein's coefficient for spontaneous emission. It gives the probability of spontaneous transition from the level 2 to 1.

$$A_{21} = \frac{1}{T_{sp}}$$

Some features of spontaneous emission.

- (i) It is very difficult to control the process of spontaneous emission from outside.
- (ii) It is essentially probabilistic in nature.
- (iii) The emitted photons during the process of spontaneous emission have different direction of propagation, initial phase, and plane of polarisation.
- (iv) The emitted light is incoherent.

stimulated emission:

Often an photon can trigger an atom in the excited state to go back to lower energy state by emitting photon. The process of emission of radiation from the excited atom under the influence of external impetus is known as induced or stimulated emission.



The rate of stimulated emission

$$R_{st} = B_{21} \rho(\nu) N_2$$

$B_{21}$  is called Einstein coefficient for stimulated emission.

- (i) The process of stimulated emission can be controlled from outside.
- (ii) In the stimulated emission, the incident photon & emitted photon propagate in the same direction.
- (iii) The incident photon & emitted photon have same phase, frequency & polarisation.
- (iv) Produced light is coherent.

## Einstein's coefficient:

Einstein's A & B coefficients give the idea about the relation between spontaneous and stimulated emission probabilities. Let us consider under thermal equilibrium,  $N_1$  &  $N_2$  are the mean population of atoms in the lower energy level  $E_1$  and the upper energy level  $E_2$ , respectively. For the condition of static equilibrium, the number of transitions from  $E_2$  to  $E_1$  must be equal to the transition from  $E_1$  to  $E_2$ . It means the number atoms photons absorbed per unit time must be equal to the number of photons emitted.

If  $\rho(\nu)$  is the photon density, then the number of atoms absorbing photons per unit volume per unit time can be given as

$$B_{12} \rho(\nu) N_1$$

The number of atoms emitting photons per unit time per unit volume can be given as the sum of spontaneous emission and stimulated emission as

$$A_{21} N_2 + B_{21} \rho(\nu) N_2$$

At equilibrium

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

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

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

dividing numerator & denominator of by  $N_2 B_{12}$

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

According to the Boltzmann equation, the population of atoms in the energy states  $E_1$  &  $E_2$  are

$$N_1 = e^{-E_1/KT}$$

$$N_2 = e^{-E_2/KT}$$

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

$$= e^{-\Delta E/KT} \quad \Delta E = E_2 - E_1$$

$$= e^{-h\nu/KT} \quad = h\nu$$

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

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

From Planck's radiation law

$$P(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{h\nu/KT} - 1} \quad \text{--- (2)}$$

For (1) & (2) will be consistent only if  $B_{12} = B_{21}$

$$\frac{A_{21}}{B_{12}} = \frac{8\pi h\nu^3}{c^3}$$

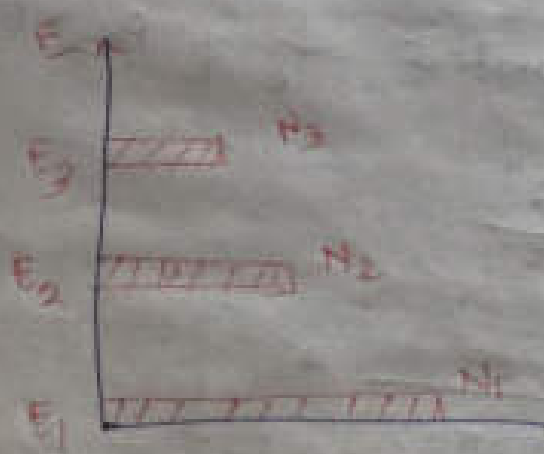
$$B_{12} = B_{21} = \frac{c^3}{8\pi h\nu^3} A_{21}$$



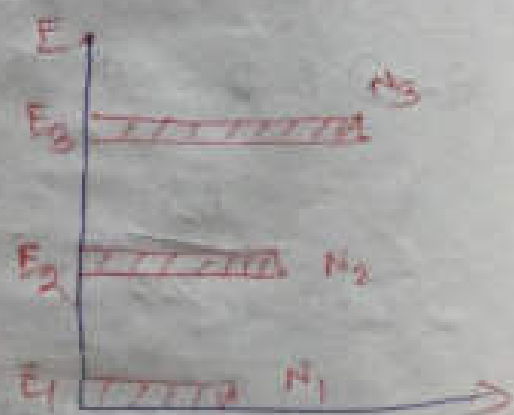
## Population Inversion:

Generally, in thermal equilibrium, the number (population) of atoms in the lower energy level ( $E_1$ ) is more than the population of atoms in the higher energy level ( $E_2$ ). But for laser action, it is essential that the number of excited atoms must be more than the atoms in the ground state. In other words, the number atoms in the higher energy level ( $E_2$ ) must be greater than the number of atoms in the lower energy level ( $E_1$ ). The process by which this condition is achieved is known as the population inversion. This non-equilibrium state in which the population  $N_2$  of the upper energy level exceeds to a large extent the population  $N_1$  of the lower energy level is known as the state of population inversion.

In order to illustrate the phenomenon of population inversion, let us consider a system which has three energy states  $E_1$ ,  $E_2$ , and  $E_3$  in such a way that  $E_3 > E_2 > E_1$ . Let  $N_1$ ,  $N_2$  &  $N_3$  be the number of atoms in the energy state  $E_1$ ,  $E_2$  and  $E_3$  respectively, at the state of equilibrium.



(c) Equilibrium state



(d) Population inversion state.



## Pumping mechanism:

The process by which we can realise and maintain the state of population inversion is known as pumping. In this process, it is necessary that atoms must be continuously promoted from the lower level to the excited level. The pumping energy is to be supplied somewhat to the atoms to raise them from the lower level to the excited level and to ensure that the population at the excited level is at a value greater than that at the lower energy level. There are various methods through which the population inversion is achieved continuously.

### (i) Optical pumping:

In optical pumping, a light source is used to supply luminous energy. Most of the energy is given in the form of short flashes of light. This technique was first used by Maiman in the ruby laser and is also widely used in solid-state lasers. In this method, the laser material is kept inside a helical flash lamp.

### (ii) Electrical pumping:

Here direct electron excitation occurs through an electric discharge. This method is preferred in gaseous ion lasers. In the case of gas laser a high voltage pulse initially ionises the gas so that it conducts electricity. An electric current flowing through the gas excites the atoms to the excited level from where they drop to the metastable state leading to population inversion.

## Main components of LASER

In laser, we obtain very high intense light through the principle of stimulated emission of radiation. The stimulated emission produces completely coherent and intense radiations. There are three essential components of a laser system.

(i) **Pumping:** The method of raising the molecules or atoms from their lower energy state to higher energy state is known as optical pumping. Optical pumping is needed for achieving population inversion. Often electrical pumping method is also utilized for this purpose.

(ii) **Active system:** A system in which the population inversion is to be achieved is called active system or the gain medium for the laser. Laser systems are named based on the makeup of the gain medium, which may be gas, liquid or solid. The energy levels in the gain medium, those participate in the radiation, determine the wavelength of laser radiation.

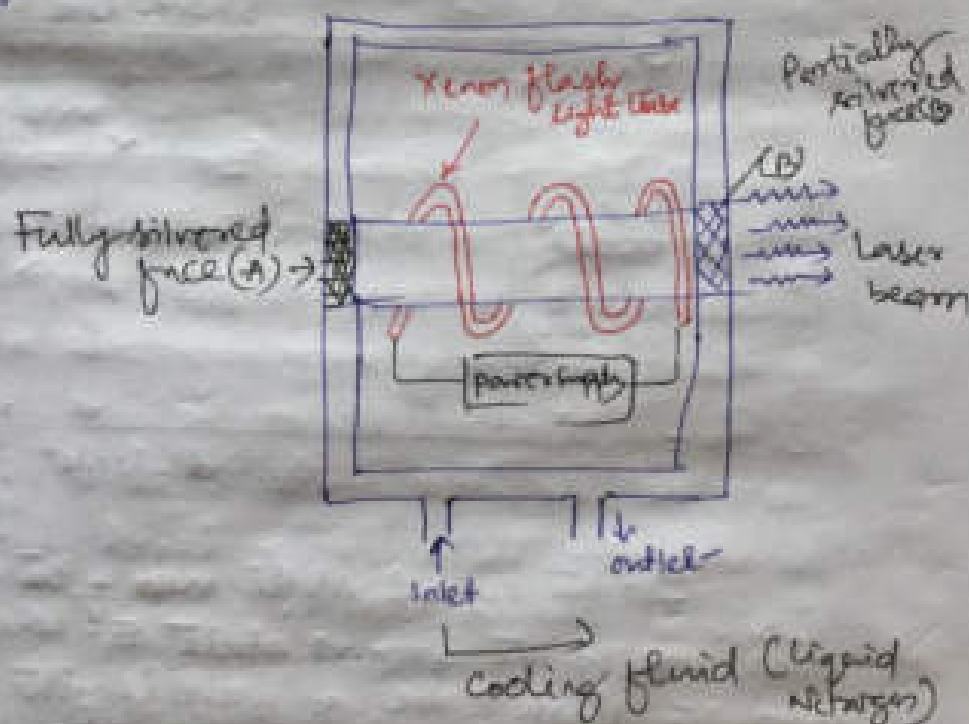
(iii) **Resonant cavity:** In a laser, the active system or the gain medium is enclosed in an optical cavity (or resonant cavity) usually made up of two parallel surfaces one of which is perfectly reflecting reflector and other is partially reflecting reflector. In the resonant cavity, the intensity of photon is raised tremendously through stimulated emission process.

## Ruby laser: Solid state laser:

Ruby laser is a solid state laser which consists of three main parts (1) Working material (2) optical resonant cavity (3) excitation source.

### Working Material:

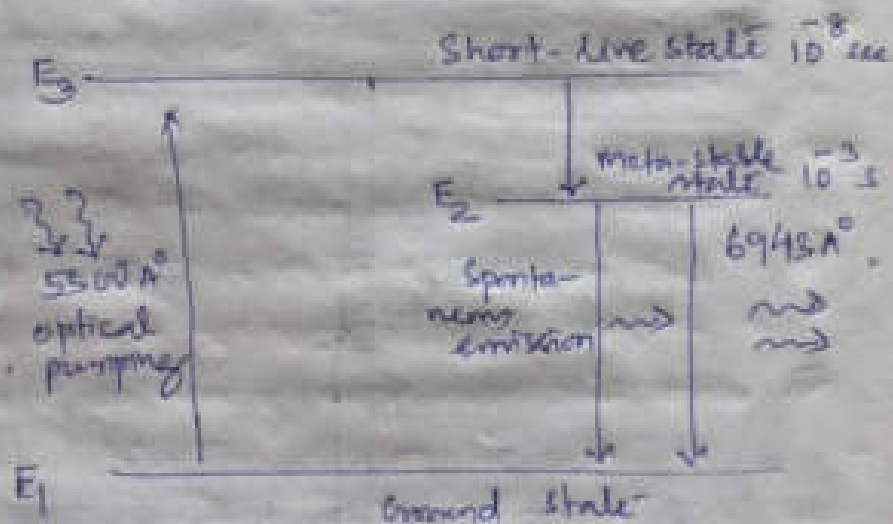
Ruby laser is made up of a crystal of Ruby in the form of cylindrical rod having size 2 to 30 cm in length and 0.5 to 2 cm in diameter whose both ends are optically flat. One of the end is fully silvered & other is partially silvered, so that they can act as fully and partially reflecting surfaces, respectively, as in fig.



Ruby rod is a crystal of  $Al_2O_3$  in which chromium oxide is mixed as impurity so that some of the  $Al^{3+}$  ions are replaced by  $Cr^{3+}$  ions. These 'impurity' chromium ions give rise to the laser action.

The space between the two faces A & B is known as the resonant cavity, in which the light (photons) intensity can be built up multiple reflections and through stimulated emission. The ruby rod is wound by a helical xenon flash light tube with an excitation source in the form of a power supply.

Working principle of Ruby laser: In this laser, chromium ions are active centres which are responsible for the laser transition. A simplified energy level diagram of Chromium ions in ruby crystal is shown in below.



In the normal state most of the chromium ions are in the ground state  $E_1$ . When light from the flash tube of wave length 5500 Å is made to fall upon the ruby rod, these incident photons are absorbed by the Cr ions that rise to the excited state  $E_3$ . Then they give a part of their energy to the crystal

structure and reach the metastable state,  $E_2$ . The ions in metastable state can remain for a longer duration  $10^{-3}$  sec. Therefore, the number of ions in this state goes on increasing while at the same time number of ions in the ground state goes on decreasing due to the optical pumping. Thus the population inversion is established between the metastable state and ground state.

When an excited ion passes spontaneously from the metastable state to the ground state, it emits a photon of wavelength  $6943 \text{ \AA}$ . This photon travels parallel to the axis of ruby rod and stimulates the surrounding ions present in the metastable state then by stimulated emission other photons are emitted which are in the phase with stimulating photons. By successive reflections of these photons at the end of the rod, every time the stimulated emission is achieved, we obtain an intense, coherent and unidirectional laser beam from the partially silvered face B.

The ruby laser operates at about 1% efficiency. It may produce a laser beam of 1 mm to 25 mm in diameter. The beam obtained is in the form of pulses. However, on the advantage side, very strong beam is produced & working & construction is very simple.

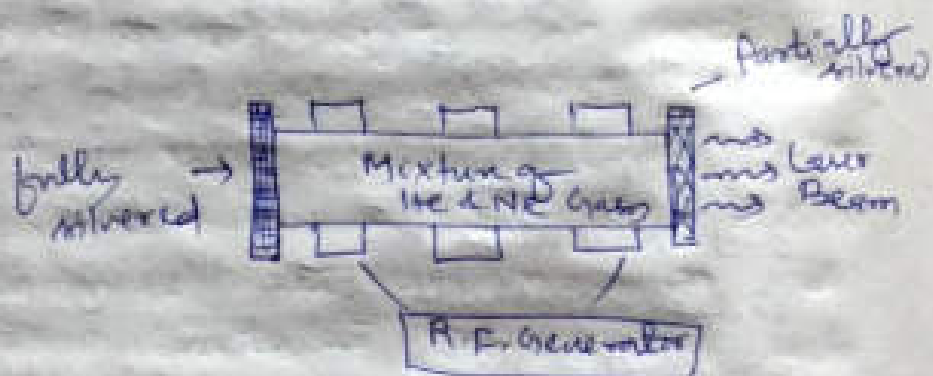
## Helium-Neon Laser: Gas Laser

Gas filled laser was made by

A. Javan, W. Bennet and D. Herriott in 1961.

It consists of a quartz tube having the size of 1.5 cm in diameter and about 1 meter in length.

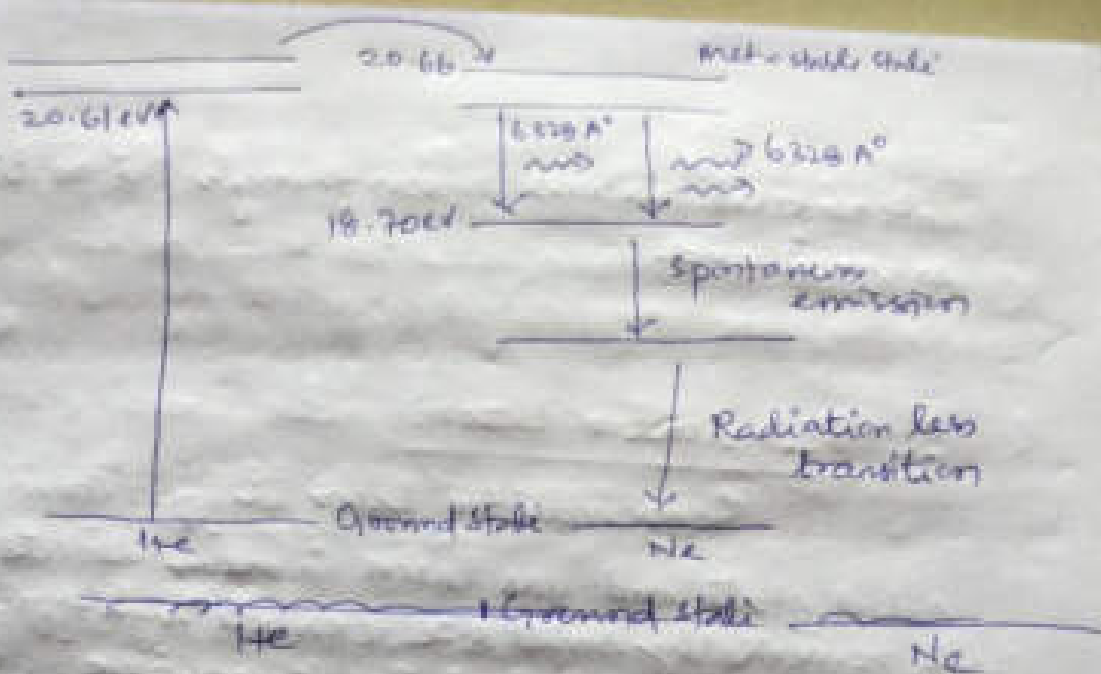
The both ends of the tube are sealed by optically plane and parallel mirrors, one of them being partially silvered (90% reflective) & other one is fully silvered (100% reflective).



In this laser system, a quartz tube is filled with a mixture of helium and neon gas in the ratio of 10:1 respectively, at a pressure of about 0.1 mm of mercury. This mixture acts as the active medium. Helium is pumped up to the excited state of 20.61 eV by the electric discharge. The energy level diagram of He-Ne laser is shown below.

Here, it can be seen that, the excited level of He at 20.61 eV is very close to that of level of Ne at 20.66 eV. It is so close that





upon collision of He & Ne atoms, the energy can be transferred from the He to the Ne atoms. Thus, the excited He atoms do not return to their ground state by spontaneously emitting photons, rather they transfer their energy to Ne atoms through collisions. As mentioned, such an energy transfer can take place when the two colliding atoms identical states. Thus, the He atoms help achieving a population inversion in the Ne atoms. An excited Ne-atom passes spontaneously from the metastable state at 20.66 eV to the excited state at 18.70 eV by emitting a photon of wavelength 6328 Å. The photons travel through the gas mixture parallel to the axis of the tube and stimulates the surrounding Ne atoms present in the metastable state. This way we get other photons that are in phase with the stimulating photons. These photons are reflected back and forth by the silvered ends and the number of stimulated photons get amplified through stimulated emission every time. Finally a portion of these



intensified photons pass through the partially silvered end.

## Semiconductor Laser:

Semiconductor laser differs from the solid state and gas lasers in many aspects. It is remarkably small size, exhibits high efficiency and can be operated at low temperature. When the current passed through a p-n junction diode in forward bias, holes move from the p-region to n-region and the electrons move from n-region to p-region. Then electrons & holes are recombined in the junction region and emit photons due to the transition of electrons from the conduction band to the valence band. This results in stimulated radiation coming from a very narrow region near the junction. The action is intensified by increasing the current and decreasing the junction thickness.

Semiconductor laser is made up of an active layer of (GaAs) of thickness 0.2 microns. This is sandwiched between a n-type GaAs and p-type GaAs layer as in figure. The resonant cavity is provided by polishing opposite faces of the GaAs crystal and the pumping occurs by passing electrical current from a source.

## Advantages & disadvantages of Ruby laser He-Ne laser & Semiconductor laser

### Advantages:

#### Ruby laser

- ① Easy to construct & operate
- ② Very strong & intense beam upto 10 kW
- ③ Beam diameter as large as 25 mm

#### He-Ne laser

- ① Easy to construct & operate
- ② Continuous beam
- ③ Exceptionally monochromatic with high operation duration.

#### Semiconductor laser

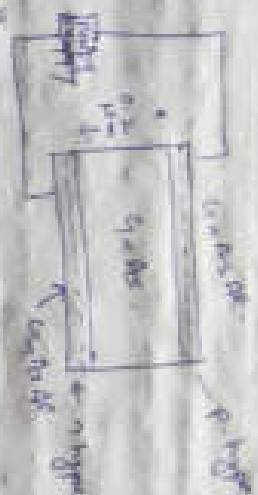
- ① Easy to operate
- ② Long life, highly mechanically tunable & continuous
- ③ Excellent efficiency with very high operation duration

### Disadvantage:

Q-switched laser beam is generated & its operation duration very less.

It has got very low power about 0.5 - 5 mW

It has got low power about 200 mW.



## Applications of LASER:

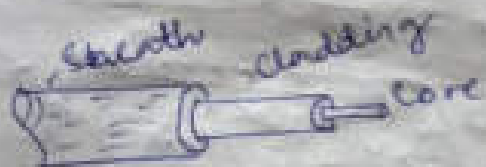
- (i) Lasers have been used to measure long distances, so they are very useful in surveying and ranging.
- (ii) Lasers are electromagnetic waves of very high intensity and can be used to study the laws of interactions of atoms & molecules.
- (iii) Lasers are suitable for communication & they have significant advantages because they are more nearly monochromatic. This allows the pulse shape to be maintained better over long distances. So communication can be sent at higher rates without overlap of pulses.
- (iv) It is used for welding, cutting of materials & drilling holes.
- (v) It has got applications in medical, e.g. eye surgery, dental surgery etc.
- (vi) Laser beam is used in recording of intensity as well as in holography.
- (vii) Laser is used in heat treatment for hardening.
- (viii) Laser is used in barcode scanner, printers.
- (ix) Lasers are used in photodiode detection.
- (x) Lasers are used in holography.

# Optical Fibre

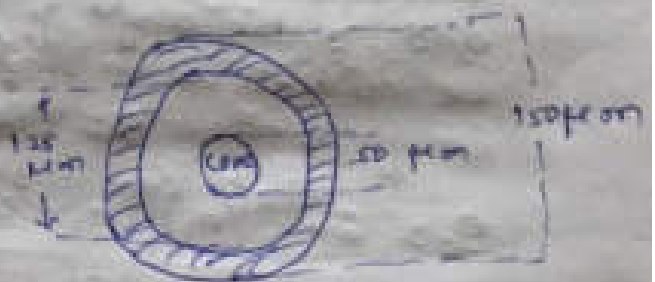
An optical fibre is a flexible cylindrical glass or plastic conduit as thin as human hair designed to guide light waves over a long distance.

**Principle:** It works on the principle of total internal reflection. Light entering at one end of the fibre undergoes successive total internal reflections at side walls and travels down the length along a zigzag path.

**Structure of an optical Fibre:** An optical fibre consists of the following three coaxial sections, viz. (i) the core (ii) the cladding and (iii) the sheath sheath (protective jacket)



(i) **The Core:** It is the innermost region which guides the light through total internal reflection. Its diameter varies from 50 to 100  $\mu\text{m}$  and refractive index  $n_1 > n_2$ , where  $n_2$  is refractive index of the cladding.

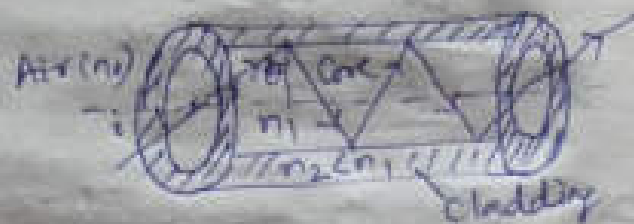


(ii) **The cladding:** The cladding surrounding the core is coaxial with it and its diameter is  $\sim 125 \mu\text{m}$ . The refractive index of cladding is always lower than that of core, i.e.  $n_2 < n_1$ . The purpose of the cladding is to help the light to be confined within the core through total internal reflection.

(iii) The sheath (or jacket) : The outermost part is made of plastic or polymer and is called the sheath. It protects the cladding and core from the harmful influences moisture, contamination, etc. and provides mechanical strength to the fibre. Its diameter is  $\approx 150 \mu\text{m}$ .

### Working Principle of Optical Fibres:

An optical fibre works on the principle of total internal reflections. The light launched inside the core through its one end propagates to the other end due to multiple total internal reflection at the core and cladding interface.



Let a ray of light incident at one end of the fibre making a nearly glancing angle ' $i$ ' (due to small radius of the fibre) with the axis and ' $r$ ' the angle of refraction. If the ray now be incident at an angle  $\theta$  with the core-cladding interface, then  $\theta = (90 - r)$ . If  $\theta > \theta_c$ , where

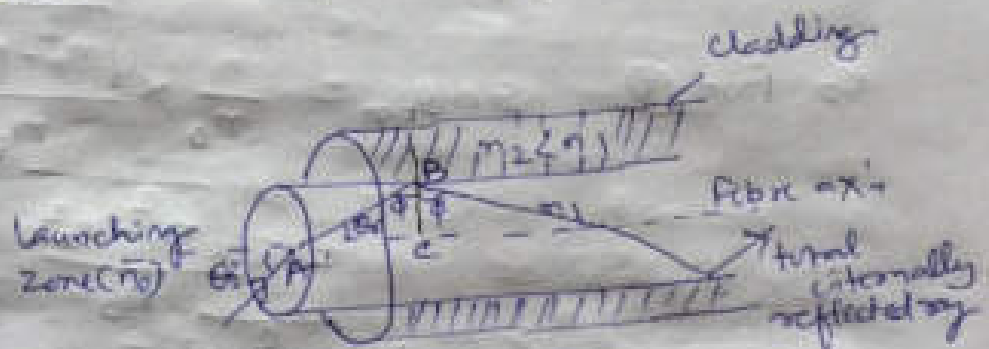
$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right), \quad n_1 \text{ being the refractive index of}$$

core, then ray suffers total internal reflection, until it emerges out at the other end. The ray does not suffer from any loss of energy due to refraction even if it bends.

## Acceptance angle and Acceptance Cone:

When a light beam is launched into a fibre at its one end (called the launching end) using a focussing lens, the entire light pass through the core. Only those rays which are incident at an angle greater than the critical angle at the core-cladding interface undergo total internal reflection and propagate through the core. The rest of the rays are reflected at the interface and lost.

So, there is a maximum value of the launching angle for which entire light passes through the core. This angle is called the acceptance angle.



Let the angle of incidence and refraction of a particular ray at A be  $\theta_i$  and  $\theta_r$ , respectively. The ray is then incident at B at an angle  $\phi$ . We shall find out the value of  $\phi$  for which total internal reflection is possible at B.

Applying Snell's law at A, we get

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_1}{n_0} \quad \text{--- (1)}$$

Let  $\theta_{im}$  be the maximum value of angle of incidence at A for which  $\phi = \phi_c$ ,  $\phi_c$  = the critical angle at B.

$$\text{Now, from } \triangle ABC, \sin \theta_{im} = \sin(90^\circ - \phi) = \cos \phi \quad \text{--- (2)}$$

From equation ① & ②

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

But at  $\theta_i = \theta_{im}$ ,  $\phi = \phi_c$

$$\therefore \sin \theta_{im} = \frac{n_1}{n_0} \cos \phi_c \quad \text{--- ③}$$

Again  $\sin \phi_c = \frac{n_2}{n_1}$ ,  $n_2 = \text{refractive index of cladding}$

$$\cos \phi_c = \sqrt{1 - \sin^2 \phi_c} = \sqrt{1 - \frac{n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \quad \text{--- ④}$$

So from ③  $\sin \theta_{im} = \frac{n_1}{n_0} \times \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$

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

$$\theta_{im} = \sin^{-1} \left[ \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \right] \quad \text{--- ⑤}$$

Generally, the incident ray is launched from air ( $n_0=1$ ), & denoting  $\theta_{im}$  by  $\theta_0$

$$\boxed{\theta_0 = \sin^{-1} \left[ \sqrt{n_1^2 - n_2^2} \right]} \quad \text{--- ⑥}$$

$\theta_0$  is called the acceptance angle of the fibre

The acceptance angle may be the maximum angle of incidence of a ray at the launching end of the fibre, so that it can propagate down the fibre.



Acceptance Cone: The Cone of semi-vertical angle  $\theta_0$  within which the enclosed rays are accepted and transmitted through the fibre is called the acceptance cone.

### Numerical aperture (NA)

Numerical aperture is a number, which defines the light acceptance or light propagating capacity of a fibre. Sometimes, it is also known as figure of merit. Numerical aperture is defined as the sine of the acceptance angle and measures the accepting power of the fibre.

$$NA = \sin \theta_0 \quad \text{from equation (6)}$$

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

$$\text{now } n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2) = \left(\frac{n_1 + n_2}{2}\right) \left(\frac{n_1 - n_2}{n_1}\right) 2n_1$$

$$\text{putting } \frac{n_1 + n_2}{2} \approx n_1 \quad \& \quad \frac{n_1 - n_2}{n_1} = \Delta$$

we get the fractional change of refractive index

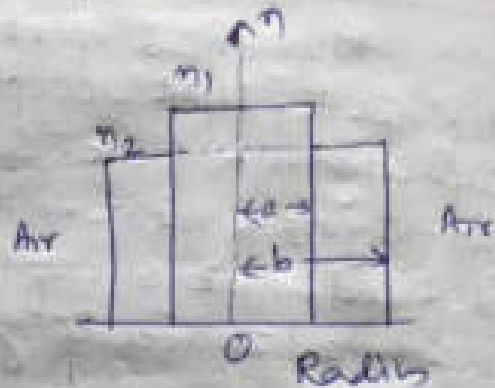
$$NA = n_1 \sqrt{2\Delta}$$

NA provides a measure of light gathering capacity of the fibre. The value of NA ranges from 0.13 to 0.50.

- (i) NA only depends on the refractive index of core ( $n_1$ ) & cladding ( $n_2$ ) materials.
- (ii) The larger the value of NA, larger is the energy gathering gathered by the fibre from source.

## Classification of Optical fibres:

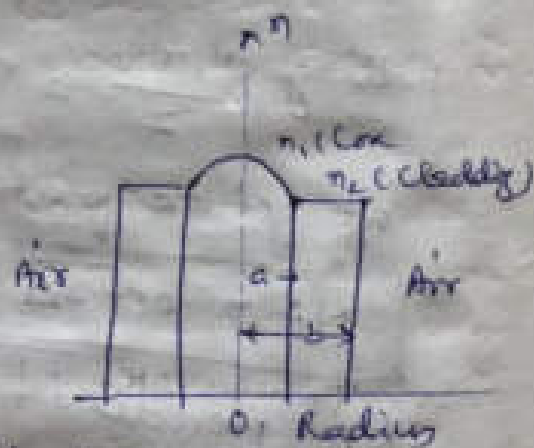
1. Step-index (SI) fibre: A step-index fibre (of radius  $a$ ) has a uniform refractive index  $n_1$  of slightly greater than the refractive index of the cladding (of radius  $b$ )  $n_2$  as shown in figure.



2. Graded-index (GI) fibre: In a graded index multimode fibre the refractive index of the core varies radially as shown in figure. The refractive

index is maximum at the centre and gradually decreases with the increase of radius of the fibre and becomes equal to the refractive

index of the cladding at the core-cladding interface.



In a multimode graded index fibre, the rays are refracted gradually. Due to higher refractive index at the central region, the velocity of light is smaller,

and the velocity of light is greater near the cladding due to smaller refractive index of the core. As a result, the rays spiral around near the axis and travel shorter paths and travel slowly.



Single-mode step index optical fibre: - (SMSI)

Here the diameter of the core is about ten times of the wavelength of the propagating wave or the refractive index difference between core and cladding is made very small. ~~There~~ Due to this condition, only a single mode is propagated through the core of fibre. These fibres are also known as monomode fibres. In general, monomode fibre has a core diameter of 8  $\mu\text{m}$  to 10  $\mu\text{m}$ , and is designed in the infrared region.

Multimode step index optical fibre: (MMSI)

In general, an MMSI optical fibre has longer core diameter than an SMSI optical fibre. The diameter <sup>of core</sup> is about 20 - 100  $\mu\text{m}$  and that of cladding is about 100  $\mu\text{m}$  - 200  $\mu\text{m}$ . In order to achieve the minimum angle for total internal reflection, the refractive index difference between core and cladding is kept relatively large. Due to the special structure,

of these optical fibres, there are many paths available for light signals to travel through the fibre.



### Comparison!

Step index fibre	Graded-index fibre
<p>① The refractive index (<math>n_1</math>) of the core is constant over the entire cross-section with <math>n_1 &gt; n_2</math>, <math>n_2</math> being the refractive index of cladding.</p>	<p>① The refractive index of the core decreases with increase of radius and <math>n_1 = n_2</math> at the core-cladding interface.</p>
<p>② The path of rays is zigzag combination of straight line segment.</p>	<p>② The path of the rays is essentially sinusoidal.</p>
<p>③ Due to inter-modal dispersion, it is not suitable for long distance communication.</p>	<p>③ The inter-modal dispersion being relatively small, it is suitable for long distance communication.</p>
<p>④ It is less expensive.</p>	<p>④ It is medium priced.</p>
<p>⑤ It is suitable for high bandwidth application.</p>	<p>⑤ For high bandwidth application, it is more suitable than step-index fibre.</p>

Single-mode fibre (SMF)

1. SMF has smaller core diameter than MMF
2. Difference between the refractive indices of core and cladding is small.
3. Single mode is propagated through the core.
4. Difficult to launch optical power due to small diameter of the core
5. A single-mode fibre requires more sophisticated light source to launch optical power, usually laser diode is used.
6. More expensive
7. Free from inter-modal dispersion
8. NA of single-mode fibres are small
9. Single mode fibres have high information carrying capability.

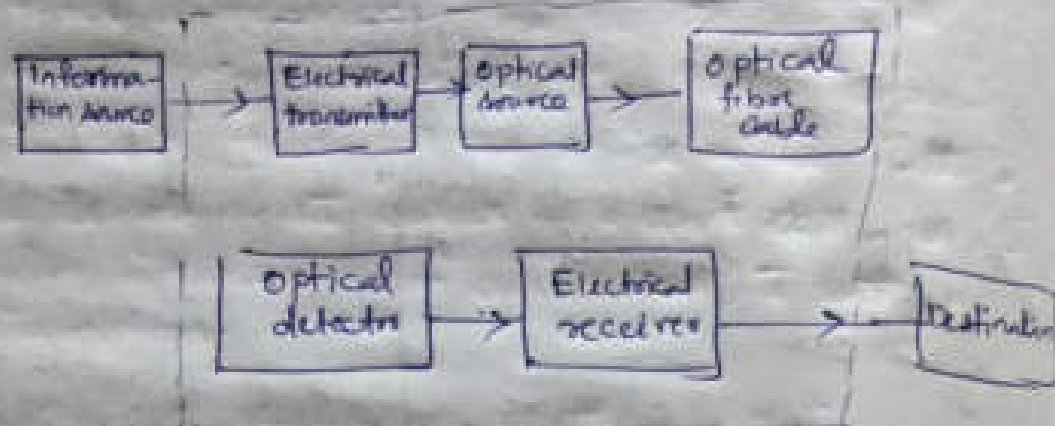
10.

Multimode fibre (MMF)

1. MMF has greater diameter than SMF fibre.
2. Difference between the refractive indices of core and cladding is relatively large.
3. Many modes are propagated.
4. It's easy to launch optical power in the fibre.
5. A multi-mode requires simple source such as LED.
6. Relatively cheaper.
7. Suffers inter-modal dispersion.
8. NA of multi-mode fibres are large
9. Low information carrying capability.

## Optical Fibre transmission link.

For communication of information from one place to other through optical fibre, a standard setup is necessary to avoid loss of information. The various components with block diagram provided below:



- (i) Information source: It is the source of input signals which are to be transmitted through the optical fibre upto the destination.
- (ii) Electrical transmitter: Here the information is produced in the form of electrical signals.
- (iii) Optical source: Optical source is capable of generating an optical signal at desired frequency. Basically LASER or LED are used as the source of light, depending on the selection of the optical fibre.
- (iv) Optical fibre cable: The optical signal is launched into the optical fibre which is contained inside the cable. The cable provides mechanical and environmental protection to the thin optical fibre.

(v) Optical detector: At the receiving end, photodetector is the main component. It is capable of converting the received modulated wave back to the original signal which has the same wave shape as the optical wave envelope.

(vi) Electrical receiver: It is the part of the communication system where original signal is recovered in its suitable form. Usually, electronic amplifiers and signal processors consisting of signal processor circuits are used in this section of communication system.



## Crystal Structure:

A crystal structure is a unique arrangement of atoms. It consists of a set of atoms which are identical in composition, arrangement and orientation, called basis and a lattice. Bases are located upon the points of a lattice which is an array of points repeating periodically in three dimensions. The points can be thought of as forming identical tiny boxes, called unit cells, that fill the space of the lattice. The length of the edges of a unit cell and the angles between them are called the lattice parameters.

Crystal structure = Lattice + Basis

### Crystalline solid:

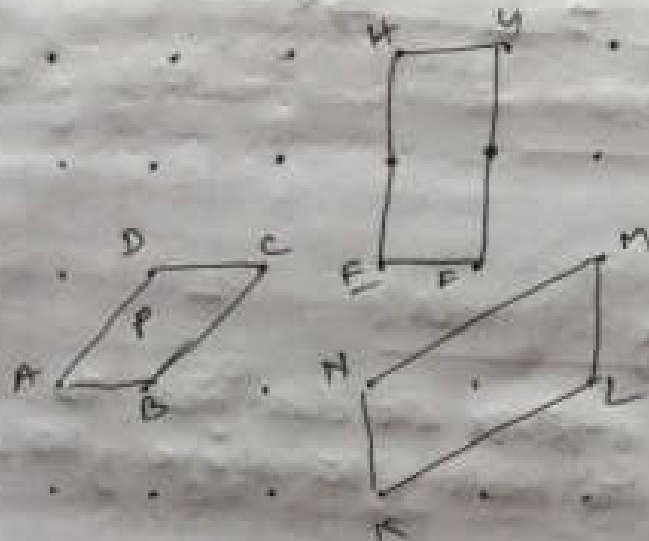
Crystalline solids are arranged in fixed geometric patterns or lattices. They have orderly arranged units and are practically incompressible. Crystalline solids also show a definite melting point. Example, Ice, Sodium chloride

### Amorphous solid:

A material whose structure lacks crystalline periodicity is called an amorphous solid. It means the pattern or its constituent atoms or molecules does not repeat periodically in three dimensions. They do not have definite melting points. Example, glass, plastic.

## Unit cell

A unit cell may be defined as the smallest unit of the lattice which, on continuous repetition, generates the complete lattice. Both primitive and non-primitive translation vectors may be used to construct a unit cell.

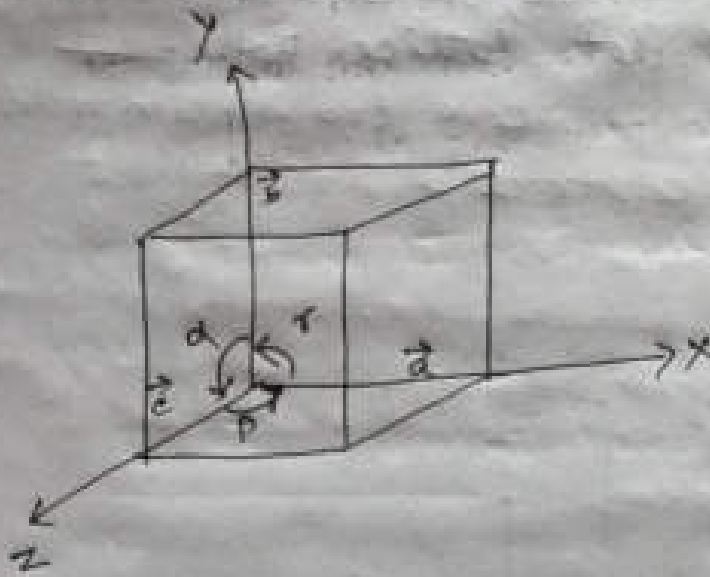


ABCD represents two dimensional primitive cell, whereas, the parallelograms EFGH and KLMN represent non-primitive cells. The smallest volume is known as primitive unit cell. In a primitive cell, all the lattice points belonging to it lie at the corners.

## Lattice parameters:

In a three-dimensional structure, a unit cell is usually represented by a parallelepiped. Vectors  $\vec{a}$ ,  $\vec{b}$ , and  $\vec{c}$  along x-, y- and z-axes, respectively, are called crystallographic axes. The angles between these axes called interfacial angles, which are measured as  $\alpha$ ,  $\beta$ , and  $\gamma$ . Primitive vectors  $\vec{a}$ ,  $\vec{b}$ , and  $\vec{c}$  and the interfacial

angles  $\alpha$ ,  $\beta$  and  $\gamma$  together are known as lattice parameter of the crystal.



### Types of Crystals:

All crystals are classified into seven crystal systems on the basis of the shape of the unit cell.

- |                 |                   |                                                 |
|-----------------|-------------------|-------------------------------------------------|
| 1. Cubic        | $a = b = c$       | $\alpha = \beta = \gamma = 90^\circ$            |
| 2. Trigonal     | $a = b = c$       | $\alpha = \beta = \gamma \neq 90^\circ$         |
| 3. Tetragonal   | $a = b \neq c$    | $\alpha = \beta = \gamma = 90^\circ$            |
| 4. Hexagonal    | $a = b \neq c$    | $\alpha = \beta = 90^\circ, \gamma = 120^\circ$ |
| 5. Orthorhombic | $a \neq b \neq c$ | $\alpha = \beta = \gamma = 90^\circ$            |
| 6. Monoclinic   | $a \neq b \neq c$ | $\alpha = \beta = 90^\circ \neq \gamma$         |
| 7. Triclinic    | $a \neq b \neq c$ | $\alpha \neq \beta \neq \gamma \neq 90^\circ$   |

## Miller Indices

A crystal lattice consists of a large number of parallel equidistant planes passing through the lattice points. These planes are known as lattice planes. For a given crystal, the lattice planes can be chosen in different ways.

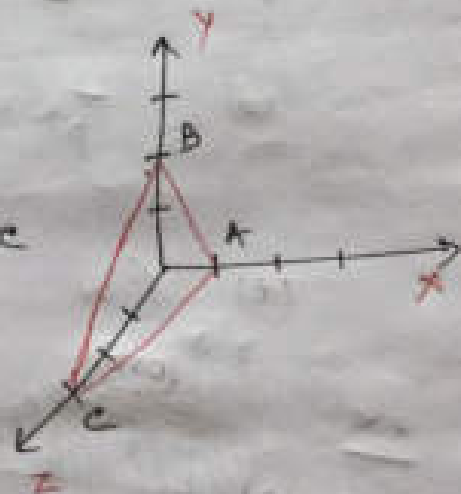


The integers which determine the orientation of a crystal plane in relation to the three crystallographic axes are called Miller indices.

Procedure for finding Miller indices.

Let us assume that  $a, b, c$  are the magnitudes of fundamental translation vectors along the three axes, respectively. Again

we consider that  $ABE$  represents the planes, whose Miller indices are to be obtained. Let  $OA, OB$  &  $OC$  are the intercepts made by this plane along the three axes.



(a) We find the intercepts along the three axis.

(b) We express these intercepts as multiple of lattice parameters.

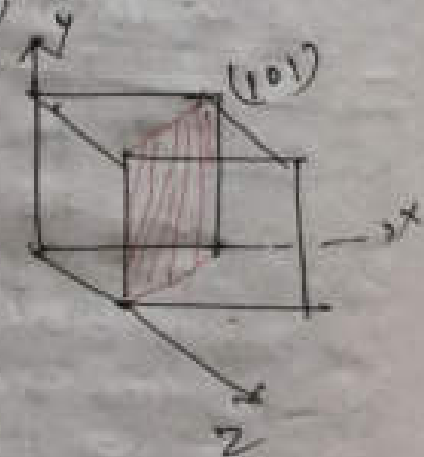
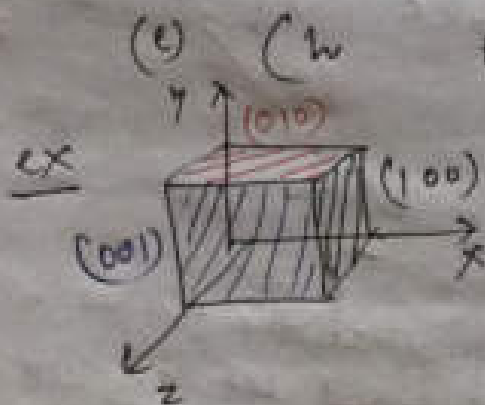
(c) We divide these intercepts by lattice parameters.

(d) We take the reciprocal of these.

(e) We clear these fractions by taking the LCM of the denominators and multiplying it.

ex.

Directions	x	y	z
(a)	OA	OB	OC
(b)	pa	qb	rc
(c)	$\frac{pa}{a}$	$\frac{qb}{b}$	$\frac{rc}{c}$ & p, q, r
(d)	$\frac{1}{p}$	$\frac{1}{q}$	$\frac{1}{r}$



## Important features of Miller Indices

- (i) Equally spaced parallel planes will have the same index numbers.
- (ii) If a plane is parallel to any one of the three coordinate axes, its intercept on that axis is infinity. Hence, the Miller index for that direction is zero.
- (iii) The Miller indices are used to define a set of parallel planes and not to a particular plane.
- (iv) For negative intercept of a plane, negative bar is put on the corresponding Miller index, e.g.  $(\bar{1}00)$
- (v) For cubic crystal system

(a) the distance  $d$  between the adjacent planes of a set of parallel planes of the indices  $(hkl)$  is

$$d = \frac{a}{\sqrt{h^2 + k^2 + l^2}} \quad \text{when } a = \text{the edge of the cube.}$$

(b) the angle  $\theta$  between two crystallographic directions  $(hkl)$  &  $(h'k'l')$  can be calculated as

$$\cos \theta = \frac{hh' + kk' + ll'}{(\sqrt{h^2 + k^2 + l^2}) \sqrt{(h'^2 + k'^2 + l'^2)}}$$

or in general

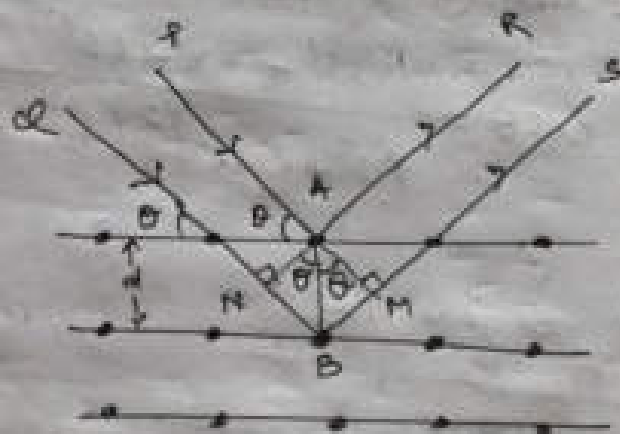
$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

## Reciprocal Lattice

The reciprocal space lattice is a set of imaginary points constructed in such a way that the direction of a vector from one point to another coincides with the direction of a normal to the real space planes and the separation of those points is equal to the reciprocal of the real interplanar distance.

## BRAGG'S LAW

Bragg considered that a crystal is made up of a number of parallel planes on which atoms are arranged in a regular fashion. When X-rays are allowed to fall on the crystal, reflections from different planes take place. These reflected rays interfere and produce diffraction pattern.



Let us consider a narrow beam of X-rays of wavelength  $\lambda$ . It is allowed to incident on a crystal of parallel lattice planes having inter-atomic separation of  $d$ . Let us assume the glancing angle ~~be~~  $\theta$  be  $\theta$ . The incident X-rays get



reflected from various planes of atoms in the crystal. The diffraction pattern of reflected radiation is observed only when reflections from various planes of atoms interfere constructively.

Let us suppose that ray PA is reflected from atom A in the direction AR & ray PB is reflected from atom B in the direction BS. Now, if the path difference between AR & BS satisfies the condition of constructive interference, the diffraction pattern will be observed. Let us draw perpendiculars AN & BM as in figure. Now the path difference between the reflected rays AR & BS is given by  $(NB + BM)$

$$NB = BM = d \sin \theta$$

$$\therefore NB + BM = 2d \sin \theta$$

So get a bright spot (Constructive interference)

$$\boxed{2d \sin \theta = n\lambda} \quad n = 1, 2, 3, \dots$$

When  $n = 1, 2, 3$  etc. for the maxima of first order, second order, third order and so on.

The intensity goes on decreasing as the order of spectrum increases.

## Bosons and Fermions

4. Particles with zero or integral spins are known as Bosons. Bosons do not obey Pauli's exclusion principle and the wave function of a system this kind is not affected by the exchange of any pair of them.

a. Particles with odd half-integral spins ( $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$ ) are called fermions. Fermions obey Pauli's exclusion principle, and the wave function of the fermion change sign upon the exchange of any pair of them.

## Boson

### Maxwell-Boltzmann distribution function:

The Maxwell-Boltzmann distribution function states that the average number of particles  $f_{MB}(\epsilon)$  in a state of energy  $\epsilon$  in a system of particles at the absolute temperature  $T$

$$f_{MB}(\epsilon) = A e^{-\epsilon/k_B T}$$

The value  $A$  depends on the number of particles in the system and play a role here analogous to that of a normalization constant in wave function.

$$k_B \text{ is the Boltzmann Constant } = 1.38 \times 10^{-23} \text{ J/K} \\ \sim 8.617 \times 10^{-5} \text{ eV/K}$$

## Bose-Einstein's & Fermi-Dirac Distribution function:

The probability  $f(E)$  that a boson occupies a state of energy  $E$  is given by

$$f_{BE}(E) = \frac{1}{e^{E/KT} - 1} \quad \text{--- (1)}$$

and the probability for a fermion turns out to be

$$f_{FD}(E) = \frac{1}{e^{E/KT} + 1} \quad \text{--- (2)}$$

The quantity 'd' depends on the properties of the particular system and may be a function of T.

It is clear that, from equation (2)

$f_{FD}(E) = \frac{1}{2}$  for an energy of  $E_f = -dKT$ ,  
this energy is called Fermi energy.

$$f_{FD}(E) = \frac{1}{e^{(E-E_f)/KT} + 1}$$

To get an insight of Fermi energy, let us consider a system of fermions at  $T=0$ ,

$$\text{at } T=0, E < E_f \quad f_{FD}(E) = \frac{1}{e^{-\infty} + 1} = \frac{1}{0+1} = 1$$

$$T=0, E > E_f \quad f_{FD}(E) = \frac{1}{e^{+\infty} + 1} = 0$$

Thus at absolute zero, all energy states upto  $E_f$  are occupied and none above  $E_f$ .

## The three statistical distribution functions:

### Maxwell-Boltzmann

Apply to systems of  $\star$  identical, indistinguishable particles.

category of particles  $\bullet$  classical

Examples  $\bullet$  Molecules of a gas

$$f_{MB}(\epsilon) = A e^{-\epsilon/kT}$$

$\star$  No limit to number of particles per state

### Bose-Einstein

$\star$  Identical, indistinguishable particles that do not obey exclusion principle

$\bullet$  Bosons

$\star$  Photon in a cavity; phonon in a solid

$$f_{BE}(\epsilon) = \frac{1}{e^{\epsilon/kT} - 1}$$

$\bullet$  No limit to number of particles per state

### Fermi-Dirac

$\star$  Identical, indistinguishable particles that obey exclusion principle

$\bullet$  Fermions

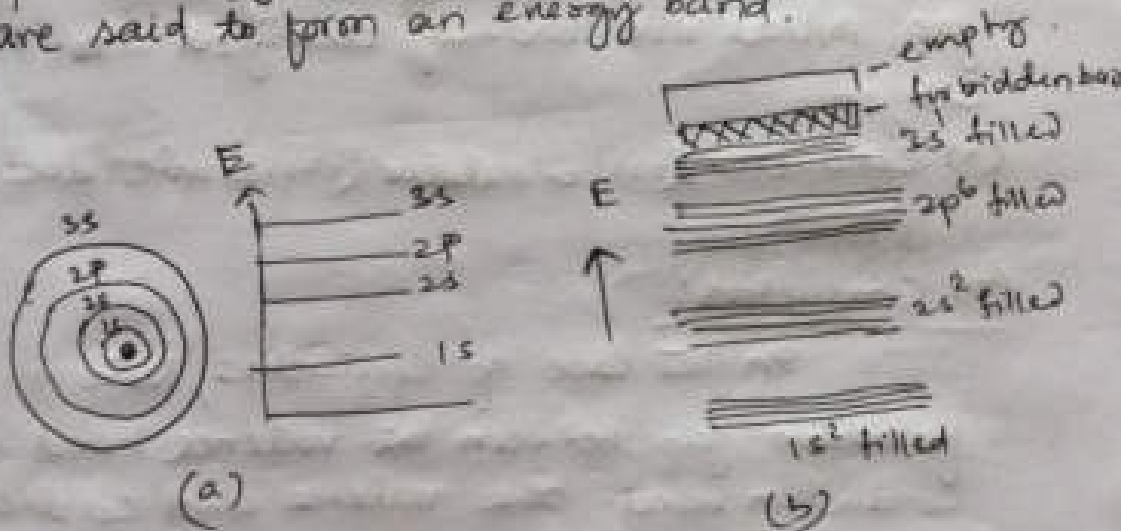
$\star$  Free electrons in metal

$$f_{FD}(\epsilon) = \frac{1}{e^{\epsilon/kT} + 1}$$

$\star$  Never more than one particle per state

## Band theory of solids

In an isolated atom, there are discrete energy levels  $n=1, 2, 3, \dots$  which are occupied by the electrons of the atom. If all the atoms of a solid are assumed to be isolated from one another, then they have completely identical electronic schemes of their energy levels. When these isolated atoms are brought together to form a solid, various interactions occur between the neighbouring atoms. During this interaction, the higher energy levels are affected considerably, and consequently, the energy levels of the outer shells are slightly altered without violating Pauli's exclusion principle. Hence, the single energy levels of atoms split into large number of energy levels. Since there are many atoms in a solid, so the separation between the split energy levels is very small. Hence, the split energy levels are almost continuous and are said to form an energy band.



(a) Electrons in an isolated Na atom

(b) formation of energy band in sodium

There are energy bands in a solid corresponding to the energy levels in an atom. An electron in a solid can have only those discrete

energies that lie within these energy bands. These energy bands are known as the allowed energy bands, which are generally separated by some energy gap known as the forbidden energy bands. Energy bands occupied by the valence electrons is known as the valence band and the energy band which is empty or occupied by the conduction electrons is known as the conduction band. Valence band is also known as the highest occupied band, whereas the conduction band is the lowest unoccupied band. The forbidden energy gap between the conduction band and the valence band is known as the energy band gap.

### Classification of Solids

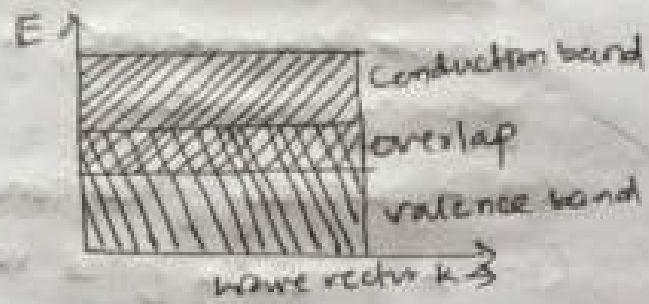
On the basis of the forbidden energy gap, solids are broadly classified into three categories

(i) Conductor (ii) insulator (iii) semiconductor

#### (i) Conductors:

In the case of conductors, there is no forbidden gap between the valence band and the conduction band. The valence and conduction band generally overlap so electrons from valence band can move easily to the conduction band. Since there is no forbidden region between valence band and conduction band there is no chance for the presence of holes.

Hence the total current in the conductor is simply due to the flow of electrons.

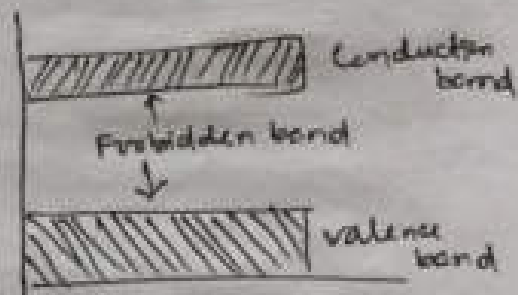


### Insulators.

A class of solids behaves as insulators if it satisfies the following two conditions.

- (i) it has even number of valence electrons per atom
- (ii) the valence band and the conduction band are separated by a large energy gap compared to  $k_B T$ .

Due to the large energy gap, electrons cannot jump from the valence band to the conduction band. In insulators, the valence electrons are bound tightly to their parent atoms.



### Semiconductors.

In case of semiconductors, the energy band gap (forbidden gap) between the filled valence band and the empty conduction band is small as compared to the insulators and more.



as compared to the conductors. Usually, the energy band gap is  $1\text{ eV}$ . At  $0^\circ\text{K}$  temperature, a semiconductor behaves as an insulator, but at room temperature, a semiconductor has the following properties.

- (i) A partially filled conduction band
- (ii) A partially filled valence band
- (iii) A very narrow energy band gap ( $\approx 1\text{ eV}$ )