(20A56201T) Applied Physics

- **PREPARED BY**

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COURSE OUTCOMES

- **CO1:** Identify the wave properties of light and the interaction of energy with the matter .
- **CO2:** Understands the response of dielectric and magnetic materials to the applied electric and
magnetic fields.
- **CO3:** Study the quantum mechanical picture of subatomic world along with the discrepancies
between the classical estimates and laboratory observations of electron transportation
- **CO4:** phenomena by free electron theory and band theory.
- **CO5:** Elaborate the physical properties exhibited by materials through the understanding of properties of semiconductors and superconductors.

APPLIED PHYSICS

Unit – I:	Wave Optics
Interference- Principle of superposition – Interference of light – Conditions for sustained interference - Interference in thin films (Reflection Geometry) – Colors in thin films – Newton's Rings – Determination of wavelength and refractive index. **Diffraction-** Introduction – Fresnel and Fraunhofer diffraction – Fraunhofer diffraction due to single slit, double slit and N-slits (qualitative) – Grating spectrum. **Polarization-** Introduction – Types of polarization – Polarization by reflection, refraction and double refraction - Nicol's Prism - Half wave and Quarter wave plates with applications.	

Unit – II:	Lasers & Fiber Optics
Lasers- Introduction – Characteristics of laser – Spontaneous and Stimulated emission of radiation – Einstein's coefficients – Population inversion – Lasing action – Pumping mechanisms – Nd-YAG laser – He-Ne laser – Applications of lasers. **Fiber optics-** Introduction – Principle of optical fiber – Acceptance Angle – Numerical Aperture – Classification of optical fibers based on refractive index profile and modes – Propagation of electromagnetic wave through optical fibers – Propagation Losses (qualitative) – Applications.	

APPLIED PHYSICS

Unit – III:	**Dielectric and Magnetic Materials**

Dielectric Materials- Introduction – Dielectric polarization – Dielectric polarizability, Susceptibility and Dielectric constant – Types of polarizations: Electronic, Ionic and Orientation polarizations (Qualitative) – Lorentz internal field – Clausius-Mossotti equation.
Magnetic Materials- Introduction – Magnetic dipole moment – Magnetization – Magnetic susceptibility and Permeability – Origin of permanent magnetic moment – Classification of magnetic materials: Dia, para & Ferro-Domain concept of Ferromagnetism (Qualitative) – Hysteresis – Soft and Hard magnetic materials.

Unit – IV:	**Quantum Mechanics, Free Electron Theory and Band theory of Solids**

Quantum Mechanics- Dual nature of matter – Schrodinger's time independent and dependent wave equation – Significance of wave function – Particle in a one-dimensional infinite potential well.
Free Electron Theory- Classical free electron theory (Merits and demerits only) – Quantum free electron theory – Equation for electrical conductivity based on quantum free electron theory – Fermi-Dirac distribution – Density of states – Fermi energy.
Band theory of Solids- Bloch's Theorem (Qualitative) – Kronig-Penney model (Qualitative) – E vs K diagram – Classification of crystalline solids – Effective mass of electron – m* vs K diagram – Concept of hole.

APPLIED PHYSICS

Unit – V:	Semiconductors and Superconductors
Semiconductors- Introduction – Intrinsic semiconductors – Density of charge carriers – Electrical conductivity – Fermi level – Extrinsic semiconductors – Density of charge carriers – Dependence of Fermi energy on carrier concentration and temperature – Drift and diffusion currents – Einstein's equation – Direct and indirect band gap semiconductors – Hall effect – Hall coefficient – Applications of Hall effect. **Superconductors-** Introduction – Properties of superconductors – Meissner effect – Type I and Type II superconductors – BCS theory – Josephson effects (AC and DC) – High Tc superconductors – Applications of superconductors.	

Textbooks:
1. Engineering Physics – Dr. M.N. Avadhanulu & Dr. P.G. Kshirsagar, S. Chand and Company 2. Engineering Physics – B.K. Pandey and S. Chaturvedi, Cengage Learning.
Reference Books:
1. Engineering Physics – Shatendra Sharma, Jyotsna Sharma, Pearson Education, 2018 2. Engineering Physics – K. Thyagarajan, McGraw Hill Publishers 3. Engineering Physics - Sanjay D. Jain, D. Sahasrambudhe and Girish, University Press 4. Semiconductor physics and devices- Basic principle – Donald A, Neamen, Mc Graw Hill

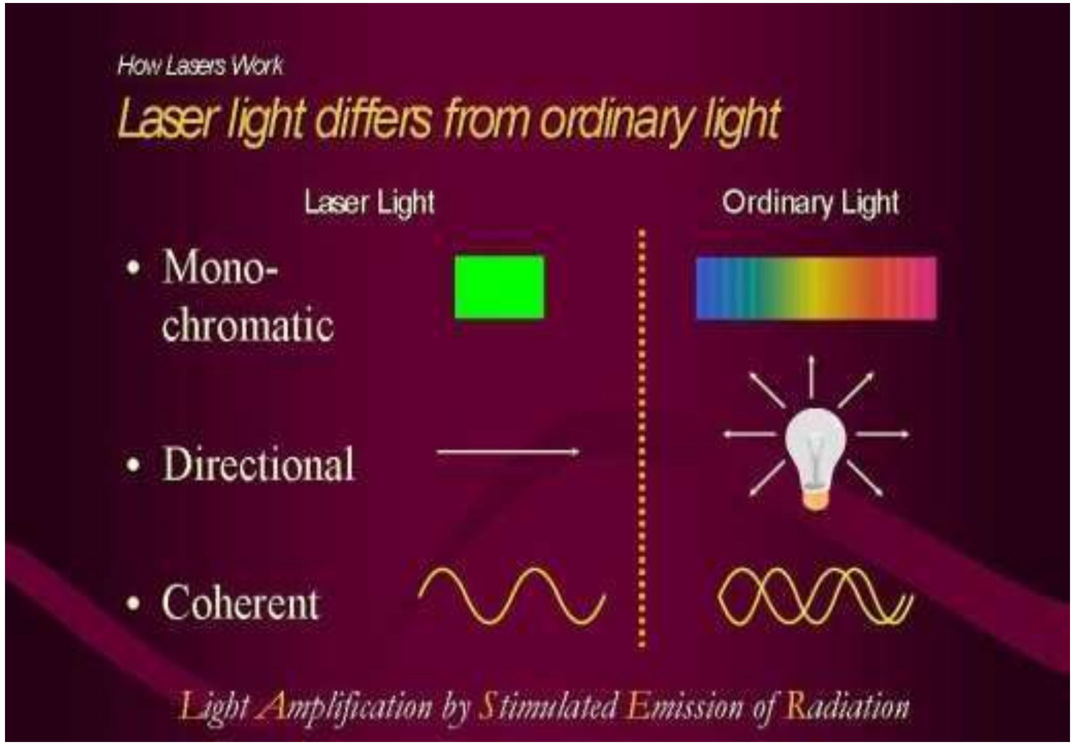
2.1 Introduction

- Laser is one of the outstanding inventions of the 20th century.
- A laser is a ***photonic device*** that emits light(electromagnetic radiation)through a process of optical amplification based on the ***Stimulated Emission of Radiation.***
- The term "LASER" originated as an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- In 1960 An American Scientist T.H .Maiman was first invented solid state laser (Ruby LASER)
- In 1961, A.Javan and associates developed the first gas laser (He-Ne gas LASER).Further many lasers was invented based on their applications.
- In now days, laser is a important tool in a wide variety of fields such as optical communication systems, metal working, entertainment, surgery and weapon guidance in wars.

2.2. Characteristics of Lasers

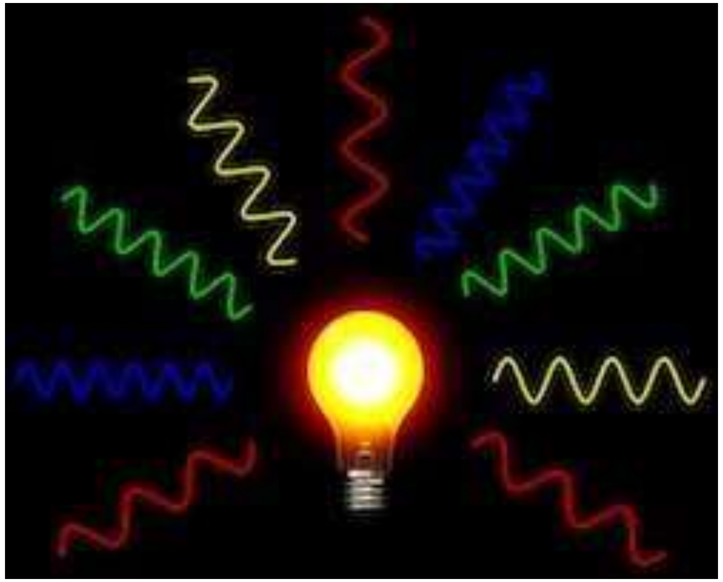
Laser has certain unique properties when compared to ordinary sources of light. They are

1. Monochromaticity
2. Coherence
3. Directionality
4. Intensity



2.2.1. Monochromaticity

- Monochromatic light means a light containing a single color or wavelength.
- The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors. Hence, ordinary light sources emit polychromatic light.
- On the other hand, the photons emitted from laser light sources have same energies,frequencies, wavelengths, or colors. Hence, laser emits a single wavelength or color light.



a) Ordinary Light

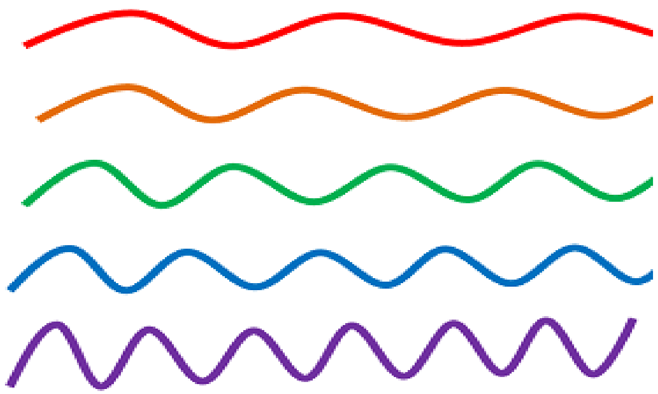
b) Laser light

2.2.2. Coherence

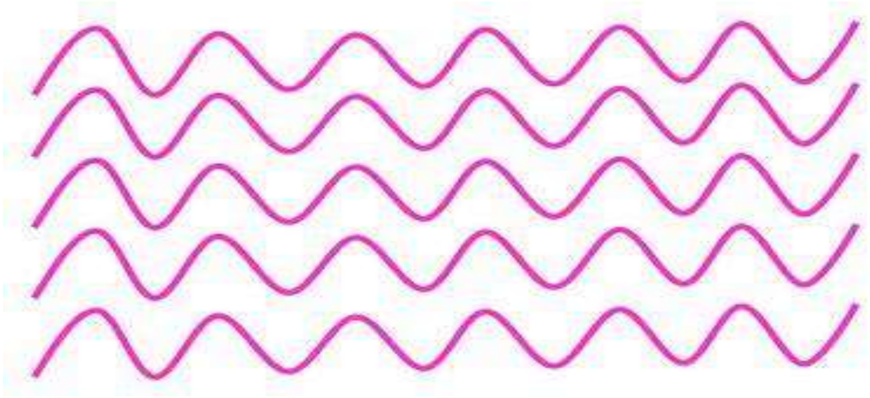
❖The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors and are out of phase. Therefore, ordinary light sources produce incoherent light.

❖The photons emitted from laser light sources have same energies, frequencies, wavelengths, or colors and are in phase. Therefore, a laser light source produces coherent light.

❖To produce coherent light in a laser, a new technique used called stimulated emission of radiation.



Incoherent light

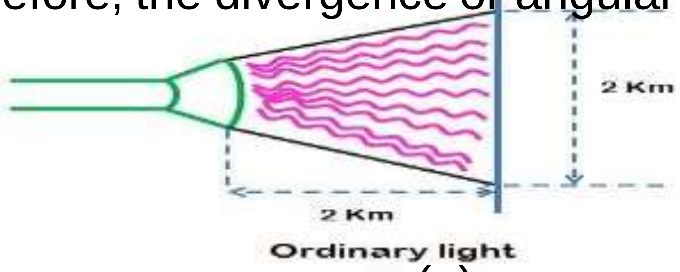


Coherent light waves

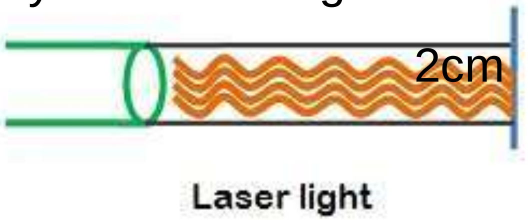
2.2.3. Directionality

- ❖Directional means that the beam is well collimated (very parallel) and travels over long distances with very little spread.
- ❖In conventional light sources (lamp, sodium lamp and torchlight), photons will travel in random direction. Therefore, these light sources emit light in all directions and is highly divergent.
- ❖On the other hand, in laser, all photons will travel in same direction. Therefore, laser emits light only in one direction. This is called directionality of laser light.
- ❖The width of a laser beam is extremely narrow. Hence, a laser beam can travel to long distances without spreading.

- For example, if an ordinary light travels a distance of 2 km, it spreads to about 2 km in diameter.
- On the other hand, if a laser light travels a distance of 2 km, it spreads to a diameter less than 2 cm.
- Therefore, the divergence or angular spread of a laser is very small and high directional.



(a)



(b)

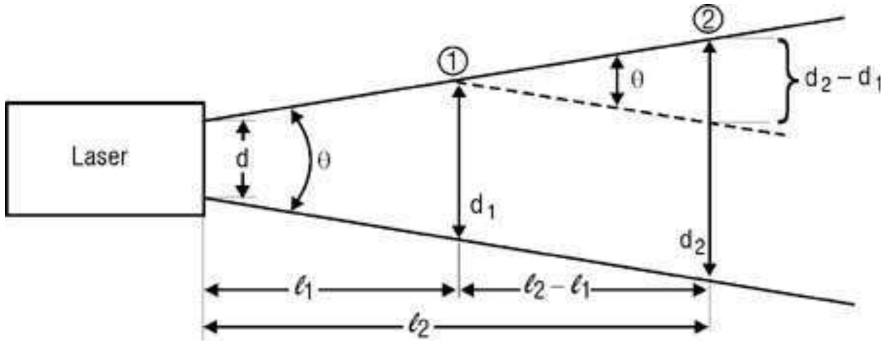
The angular spread or divergence $(\theta) = \frac{d_2 - d_1}{l_2 - l_1}$ degrees

Where: d_1 = Beam diameter at point 1.

d_2 = Beam diameter at point 2.

l_1 = Distance from laser to point 1

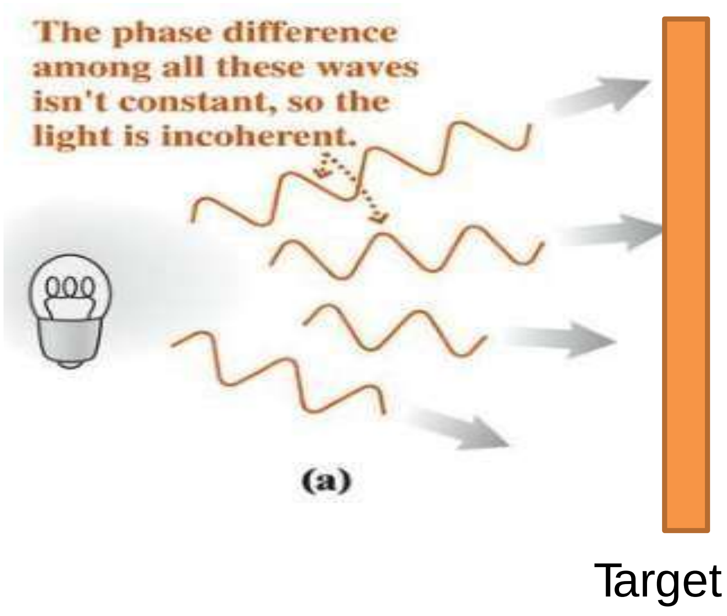
l_2 = Distance from laser to point 2.

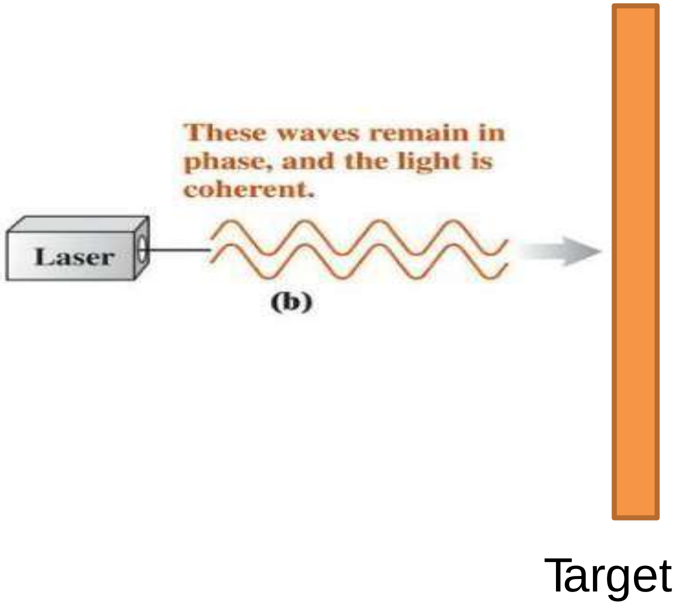


(c)

2.2.4. Intensity

- ❖The intensity of a light is defined as the light energy per unit time flowing thriugh a unit area
- ❖In an ordinary light spreads in all directions; the intensity reaching the target is very less.
- ❖But in the case of laser, due to high directionality many beams of light incident in small area,therefore the intensity of light high.





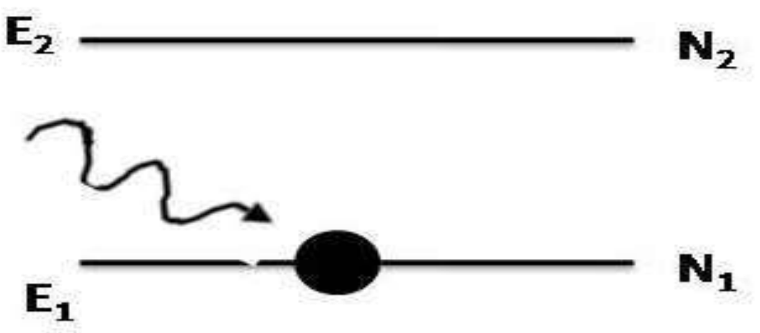
2.3. Interaction of radiation with matter

When the incident radiation (Photon) interacts with atoms in the energy levels then three distinct processes can takes place.

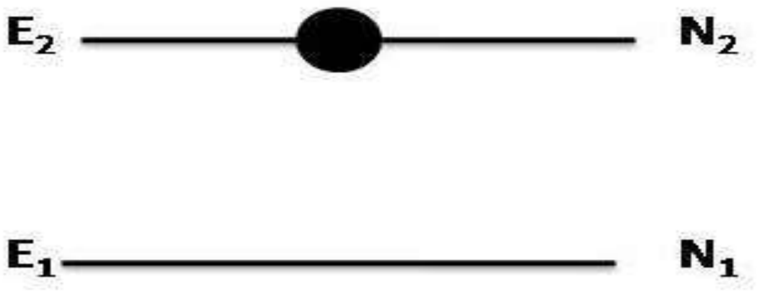
1. Absorption of radiation
2. Spontaneous emission of radiation
3. Stimulated emission of radiation

2.3.1. Absorption of radiation

Suppose if an atom in the lower energy level (or) ground state energy level E_1 and absorbs the incident photon radiation of energy then it goes to the higher energy level (or) excited state E_2 as shown in Fig. This process is called absorption of radiation



(a) Before absorption of radiation



(b) After absorption of radiation

The number of absorptions depend upon the number of atoms per unit volume (N_1) in lower energy level (E_1) and the number of photons per unit volume of radiation i.e. incident radiation density ρ_υ.

The rate of absorption (R_{12}) is proportional to the following factors

i.e., $R_{12} \propto$ incident radiation density (ρ_υ)

$\propto$ No. of atoms in the ground state (N_1)

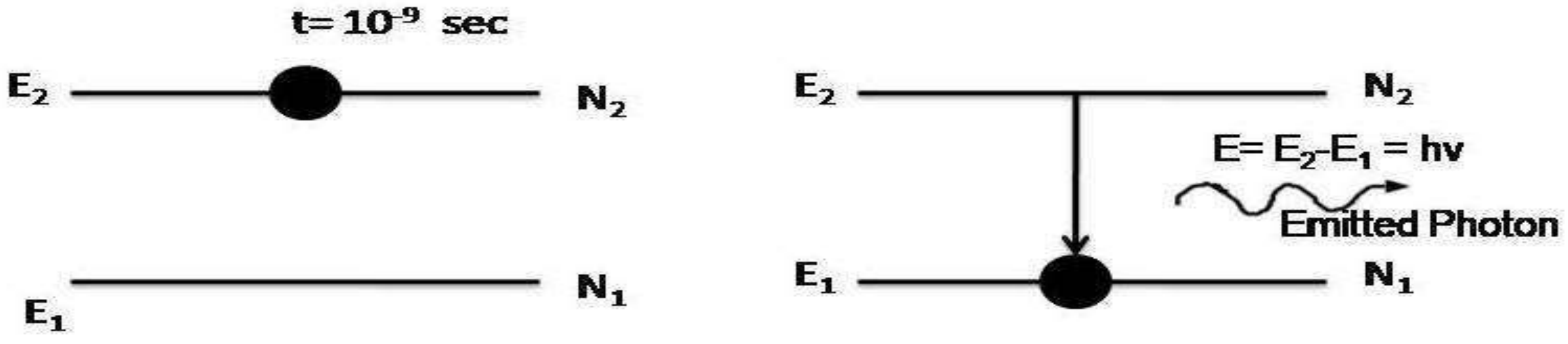
$$\therefore \quad \boxed{R_{12} = B_{12}\, \rho_\upsilon\, N_1} \quad \longrightarrow \quad (2.1)$$

Where B_{12} is a constant and is known as Einstein's coefficient of absorption of radiation.

2.3.2. Spontaneous emission of radiation

Normally the atom in the excited state will not stay there, for a long time i.e., it can stay up to 10^{-9} second. This called life time of atom. After the life time of the excited atom, it returns to the ground state by emitting photon energy $E = E_2 - E_1 = h\nu$, spontaneously without any external energy as shown in Fig .

This process is known as Spontaneous emission of radiation



(a) Before spontaneous emission of radiation (b) After spontaneous emission of radiation

The number of spontaneous emission of radiation depends on the number of atoms per unit volume in higher energy level E_2 i.e. N_2

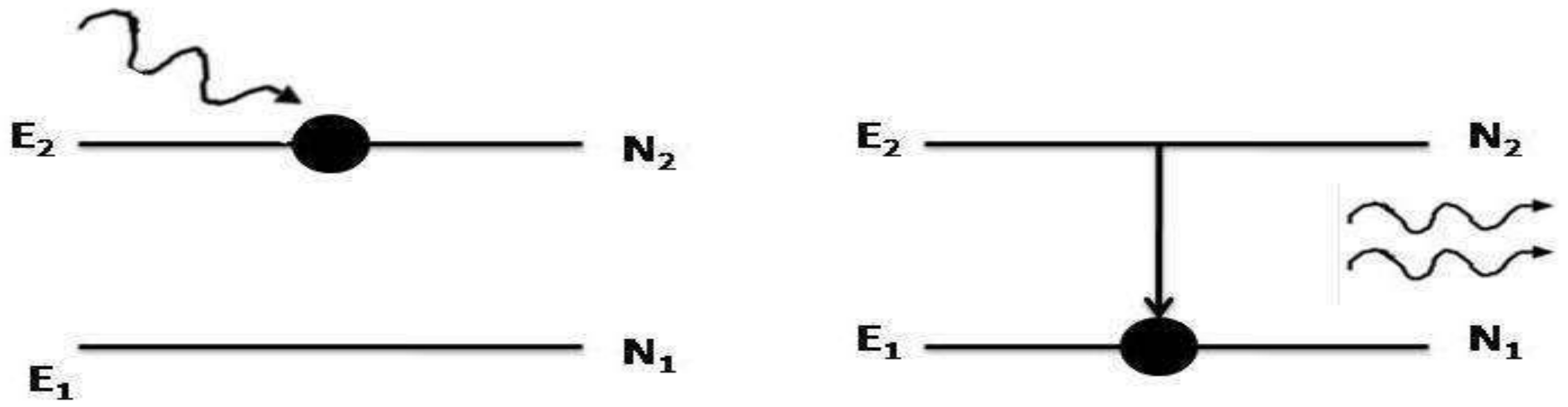
∴The rate of spontaneous emission is $R_{21(SP)} \propto N_2$

$$\therefore \quad \boxed{R_{21(SP)} = A_{21}N_2} \quad \longrightarrow (2.2)$$

Where A_{21} is a constant called Einstein's coefficient of spontaneous emission of radiation.

2.3.3. Stimulated emission of radiation

Suppose if we incident some suitable form of energy on the atom in the excited state, then it can also return to the ground by emitting a photon, known as stimulated emission. In this process two photons are released. They have same frequency, wavelength and in phase difference and of same directionality as shown in Fig.



(a) Before stimulated emission of radiation

(b) After stimulated emission of radiation

The number of stimulated emission depends on the number of atoms in the E_2 energy level N_2 and the incident radiation density ρ_υ.

∴ The rate of stimulated emission R_{21} is given by

$$R_{21(St)} \propto N_2$$

$$\propto \rho_\upsilon$$

$$R_{21(St)} \propto N_2 \rho_\upsilon$$

$$\therefore \boxed{R_{21(St)} = B_{21} \rho_\upsilon N_2} \longrightarrow (2.3)$$

Where B_{21} is a constant called Einstein coefficient of stimulated emission of radiation

2.4. Difference between spontaneous and stimulated emission of radiation

Spontaneous Emission of radiation	Stimulated Emission of radiation
1. This emission is postulated by Bhor	1. This emission is postulated by Einstein.
2. Emission of radiation takes place without any external energy.	2. Emission of radiation takes place with help of inducement or stimulus energy.
3. The emitted photons move in all directions and are random.	3. The emitted photons move in same direction and is highly direction
4.Incoherent radiation	4.Coherent radiation
5. Low intense and less directional	5. High intense and more directional
6.Polychromatic radiation	6.Monochromatic radiation
7.It is an uncontrollable process	7.It is controllable process
8.The rate of spontaneous emission is $R_{12(SP)} = A_{21}N_2$	8. The rate of stimulated emission is $R_{21(St)} = B_{21}\ \rho_{\upsilon}\ N_2$
9. Example: Light from sodium vapor lamp and mercury vapor lamp	9. Example: Light from Ruby laser, He-Ne laser,and GaAs laser etc.

2.5. Important Factors affecting interaction of radiation with matter

The absorption of radiation and emission of radiation manly depends on the two factors

1. Population(N)
2. Incident Radiation density (ρ_{υ})

2.5.1. Population

The number of atoms per unit volume in an energy level is known as population of that energy level.

According to Boltzmann`s distribution law; if N is the number of atoms per unit volume in an energy state E, at temperature T , then the population of that energy level E is given by

$$N = N_O \exp^{\frac{-E}{K_B T}} \longrightarrow (2.4)$$

Where, N_O is the population of lower energy level and K_B is Boltzmann`s constant ($1.3807 \times 10{-}23$ J K^{-1})

2.5.2. Incident Radiation density (ρ_{υ})

The number of photon incident present per unit volume is known as incident Radiation density. According to Planck's quantum theory of radiation, the incident radiation density is given by,

$$\rho_{\upsilon} = \frac{8\pi h\nu^3}{C^3} \left[\frac{1}{\exp^{\frac{h\nu}{K_B T}} - 1}\right] \rightarrow (2.5)$$

2.6. Einstein's coefficients and their relations

In 1917 Einstein proposed a mathematical relation between absorption and emission of radiation based on Boltzmann's distribution law and Planck's theory of radiation.

Consider two energy levels of energies E_1 and E_2 ($E_2 > E_1$) . Let N_1 and N_2 be the number of atoms per unit volume of E_1 and E_2.

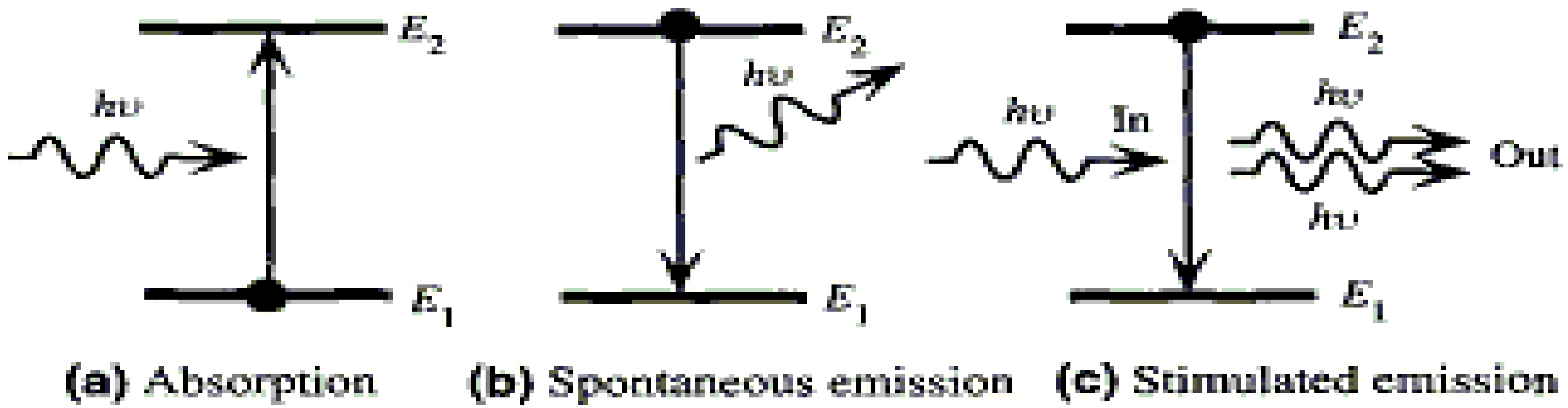


Fig. Three different processes during the interaction of light with matter

We know that when the incident radiation (photon) interacts with atoms in the energy levels then three distinct processes takes place.

1) **Absorption :-**

   The rate of absorption is given by R_{12} (ab) $= B_{12}\ \rho_{\upsilon}\ N_1$

2) **Spontaneous emission :-**

   The rate of spontaneous emission is given by $R_{21\,(SP)} = A_{21} N_2$

3) **Stimulated Emission:-**

   The rate of stimulate emission is given by $R_{21(St)} = B_{21}\ \rho_{\upsilon}\ N_2$

Under thermal equilibrium,

The rate of absorption = The rate of emission

i.e., $R_{12(ab)} = R_{21\,(SP)} + R_{21(St)}$

$B_{12}\ \rho_{\upsilon}\ N_1 = A_{21}N_2 + B_{21}\ \rho_{\upsilon}\ N_2$

$B_{12}\ \rho_{\upsilon}\ N_1 - B_{21}\ \rho_{\upsilon}\ N_2 = A_{21}N_2$

$\rho_{\upsilon}(B_{12}\ N_1 - B_{21}\ N_2) = A_{21}N_2$

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

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

$$= \frac{A_{21}}{B_{12}\ \left(\frac{N_1}{N_2}\right) - B_{21}} \quad \rightarrow (2.6)$$

$$= \frac{A_{21}}{B_{12}\left[\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}}\right]} \quad \rightarrow (2.7)$$

We know that; Boltzmann distribution law

$$N_1 = N_0 \exp\frac{-E_1}{K_BT} \quad \rightarrow (2.8)$$

Similarly $$N_2 = N_0 \exp\frac{-E_2}{K_BT} \quad \rightarrow (2.9)$$

And $$\frac{N_1}{N_2} = \exp\frac{-E_1}{K_BT} \cdot \exp\frac{E_2}{K_BT}$$

i.e., $$\frac{N_1}{N_2} = \exp\frac{(E_2 - E_1)}{K_BT}$$

Since $E_2 - E_1 = h\upsilon$, we have

$$\frac{N_1}{N_2} = \exp\frac{h\upsilon}{K_BT} \quad \rightarrow (2.10)$$

Substituting Eq (2.10) in Eq (2.6) we have

$$\rho_\upsilon = \frac{A_{21}}{B_{21}\left[\exp\frac{h\upsilon}{K_BT} - \frac{B_{21}}{B_{12}}\right]} \quad \rightarrow (2.11)$$

According to Planck's quantum theory of radiation, the incident radiation density is given by,

$$\rho_{\upsilon} = \frac{8\pi h\nu^3}{C^3}\left[\frac{1}{\exp^{\frac{h\nu}{k_BT}} - 1}\right] \rightarrow (2.5)$$

Therefore comparing equations (2.11) and (2.5), we can write

$$\frac{B_{21}}{B_{12}} = 1 \text{ or } B_{21}=B_{12}=1 \text{ and} \rightarrow (2.12)$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{C^3} \rightarrow (2.13)$$

From eq. (2.12), we conclude that the coefficient of absorption B_{12} is equal to the coefficient of stimulated emission B_{21}.

From eq. (2.13), we conclude that the coefficient of spontaneous versus stimulated emission is proportional to the third power of frequency of the radiation.

i.e., $\frac{A_{21}}{B_{21}} \alpha \nu^3$

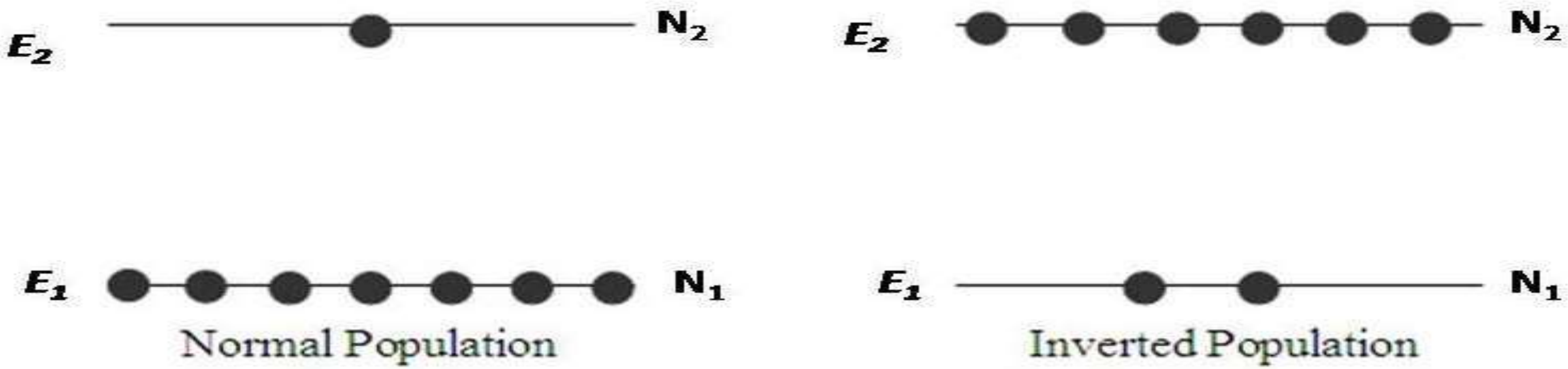
Thus, the spontaneous emission of radiation dominates the stimulated emission of radiation at normal conditions. This is why it is difficult to achieve laser action.

The spontaneous emission produces incoherent light, while stimulated emission produces coherent light. In an ordinary conventional light source, the spontaneous emission is dominated. For, laser action stimulated emission should be predominant over spontaneous emission and absorption. To achieve this, an artificial condition is required, known as population inversion.

2.7. Population Inversion

In general, the population of lower energy level will be greater than that of the higher energy level. To get stimulated emission of radiation, the population of higher energy level (E_2) should be greater than the population of the lower energy level (E_1).i.e., $N_2>N_1$.

The process of making a state in which the population of higher energy level (E_2) is greater than the population of the lower energy level (E_1) is known as population inversion.



$N_1>N_2$ $N_2>N_1$

Explanation

❖In general, a two energy level diagram is suitable for spontaneous emission of radiation the life time of higher energy level is in the order of 10^{-9}sec. But, to attain population inversion the life time of higher energy level must be longer. Hence population inversion cannot be attained in a two energy level diagram.

❖To explain Population Inversion, let us Consider a there energy level system in which three energy levels E_1, E_2 and E_3 are present and populations in those energy levels are N_1, N_2 and N_3 respectively.

❖ In normal conditions $E_1 < E_2 < E_3$ and $N_1 > N_2 > N_3$ obeying Boltzmann's distribution law.

❖E_1 is the lower energy state with more time of an atom, E_3 is the higher energy state with less lifetime of an atom (10^{-9}sec) and E_2 is the intermediate energy state with more life time of an atom (10^{-3}sec) compare to that of E_3.

❖This intermediate energy state with more life time of atoms is known as metastable state.

❖ This state provides necessary population inversion for the laser action.

❖ When suitable form of energy is supplied to the system, then the atoms excite from ground state E_1 to higher energy state E_3 and E_2.

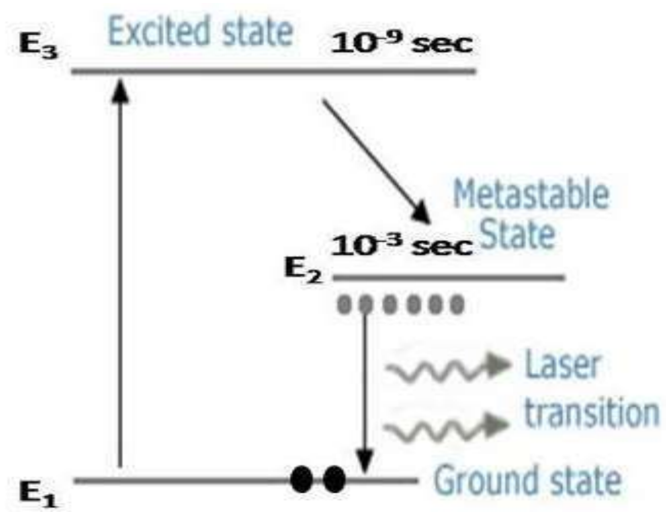
❖ Graphically this has been as shown in Fig.

❖ Let the atoms in the system be excited from E_1 state to E_3 state by supplying energy equal to E_3-E_1= hv from an external source.

❖ The atoms in E_3 state are unstable; they can stay up to 10^{-9} s. This called life time of atoms. After the life time of the excited atoms, they can returns to the meta stable state E_2 without emission of any radiation .This process is called *non-radiative transition. In* E_2 state, the atoms can stay for a very long time (10^{-3}s).

❖ As atoms in E_1 state are continuously exciting to E_3 , so the population in E_1 energy state goes decreasing.

❖ A state will reach at which the population in E_2 State is greater than E_1 state (i.e.N_2>N_1). This situation is known as population inversion.



Non radiative transsion

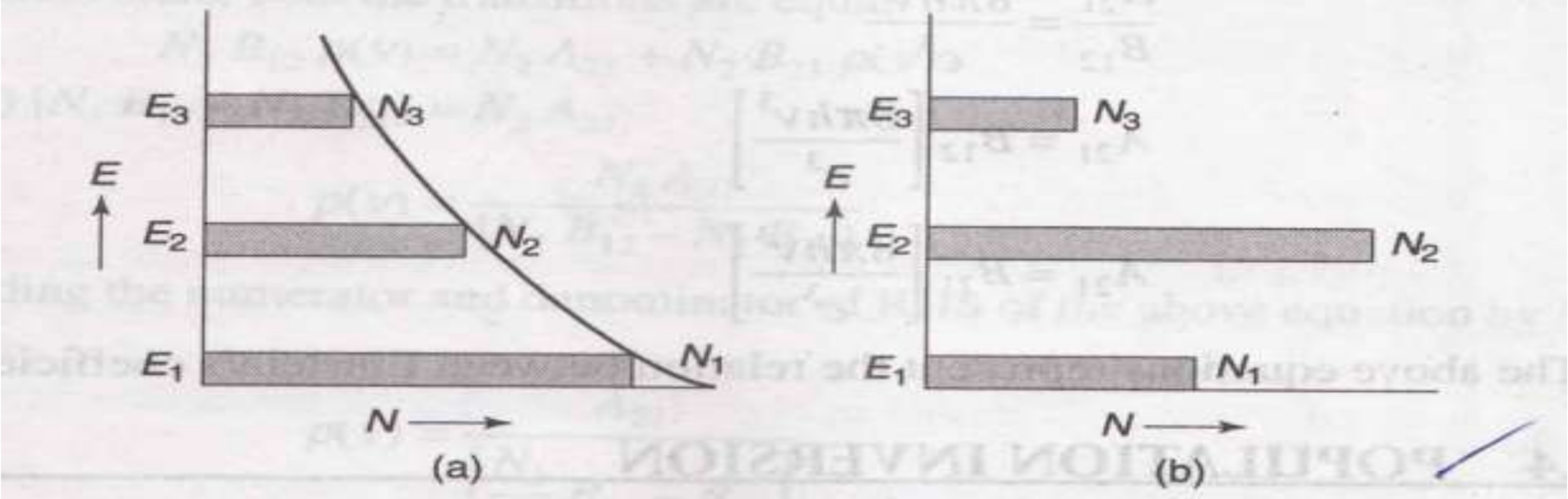


Fig.(a) Boltzmann's distribution (b) Population inversion between E_1 and E_2

2.8 EXCITATION MECHANISMS: PUMPING

The population inversion cannot be achieved thermally. To achieve population inversion suitable form of energy must be supplied. The process of supplying suitable form of energy to a system to achieve population inversion is called pumping.

There're several methods for achieving the condition of population inversion necessary for laser action. Some of the most commonly used pumping methods are,

(i) Optical pumping

(ii) Electrical discharge(Direct electron excitation)

(iii) Inelastic atom-atom collision

(iv) Direct conversion

(v) Chemical reaction.

2.8.1 OPTICAL PUMPING METHOD

- The process of supplying suitable form of optical energy to a system to achieve population inversion is called optical pumping.
- In this method, light source is used to supply suitable form of optical energy to excite the atoms to higher energy level to achieve population inversion.
- This type of pumping is used in solid state lasers (Ex: Ruby laser and Nd-YAG Laser).

2.8.2 ELECTRICAL DISCHARGE (DIRECT ELECTRON EXCITATION) PUMPING METHOD

- In this method, a high voltage or electric field is applying to electrodes at both sides of the discharge tube containing the gas causes Electrons are ejected from the cathode, accelerated toward the anode, and collide with the gas molecules along the way.
- During the collision, the mechanical kinetic energy of the electrons is transferred to the gas molecules, and excites them. (This same method of energy transfer is used in common fluorescent lights).
- This type of pumping is used in gaseous ion lasers (Ex: He-Ne laser and co_2 Laser).

2.8.3 INELASTIC ATOM-ATOM COLLISION PUMPING METHOD

- **In this method a combination of two types of gases are used say A and B, both having same or nearly coinciding excited states A* and B*.**
- **In the first step, during electric discharge, A gets excited to A* (meta stable state) due to collision with electrons. The excited atom now colloid with the B atoms so that B goes to excited state B*.**
- **For example, in the helium-neon laser the electrons from the discharge collide with the helium atoms, exciting them. The excited helium atoms then collide with neon atoms, transferring energy so that Ne atoms go the excited state.**

2.8.4 DIRECT CONVERSION PUMPING METHOD

when a p-n junction diode is forward biased and then the recombination of electrons and holes across the junction emits the radiation.

Electron + hole $\longrightarrow$ photon

This method is used in semiconductor lasers.

2.8.5 CHEMICAL REACTIONS PUMPING METHOD

In this method, due to some chemical reactions, the atoms may be raised to excited state.

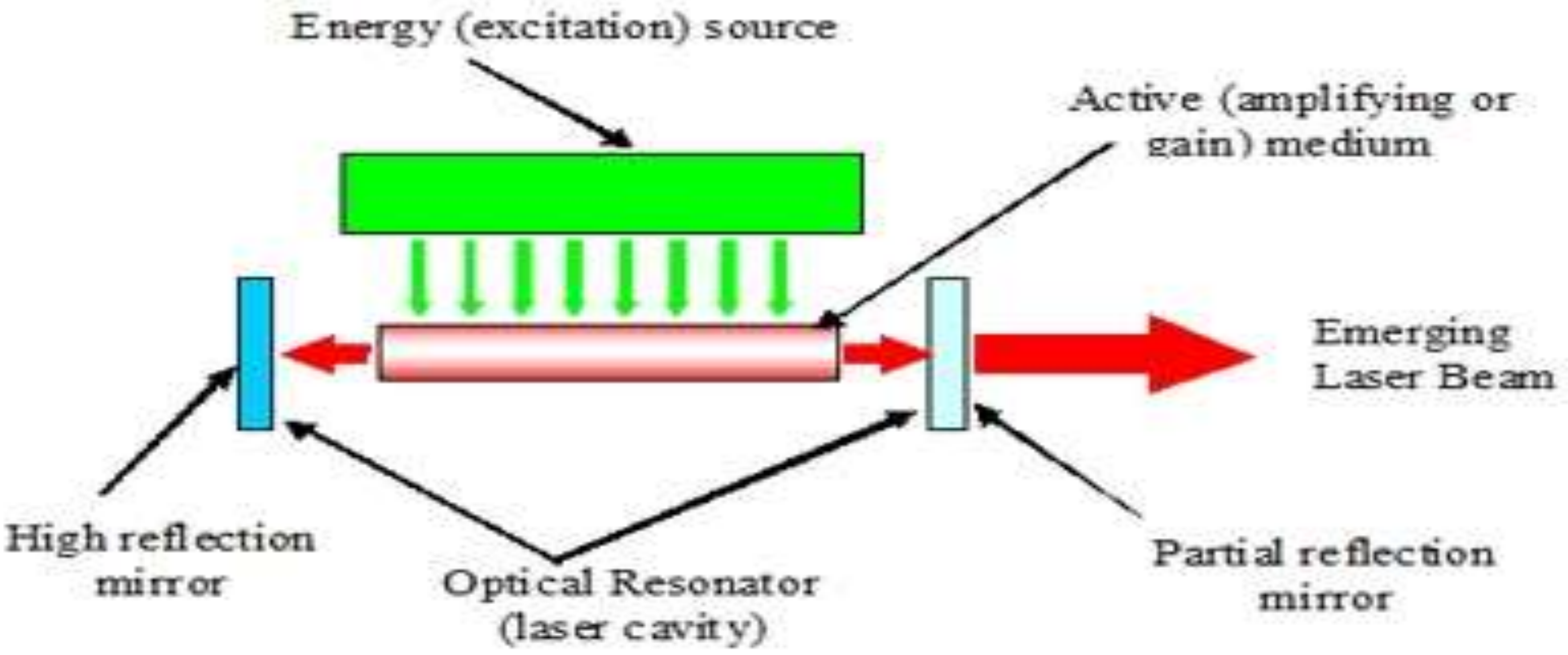
For example, hydrogen fluoride chemical laser, in which hydrogen can react with fluorine to produce hydrogen fluoride liberating heat energy. This heat energy will try to excite the atoms to higher energy level.

$$H_2 + F_2 \longrightarrow 2HF + \text{Heat energy}$$

2.9 BLOCK DIAGRAM OF A LASER SYSTEM

The block diagram of laser system contains three parts, they are

1. Source of energy
2. Active medium and
3. Optical resonator.



2.9.1 SOURCE OF ENERGY

- **To achieve population inversion suitable form of energy must be supplied. It supplies suitable form of energy by using any one of the pumping methods.**

  For example in ruby laser, helical xenon flash tube used as pumping source.

- **In helium-neon laser, electrical discharge tube used as pumping source.**

2.9.2 ACTIVE MEDIUM

- **To achieve population inversion medium is necessary.**
- **The material medium in which population inversion takes place is called as active medium. In which metastable state is present.**
- **In metastable state only the population inversion takes place. It can be a solid, liquid, gas or semiconductor diode junction.**

2.9.2 ACTIVE MEDIUM

- **To achieve population inversion medium is necessary.**
- **The material medium in which population inversion takes place is called as active medium. In which metastable state is present.**
- **In metastable state only the population inversion takes place. It can be a solid, liquid, gas or semiconductor diode junction.**
- **The material medium in which the atoms are raised to exited state to achieve population inversion is called as active centers.**

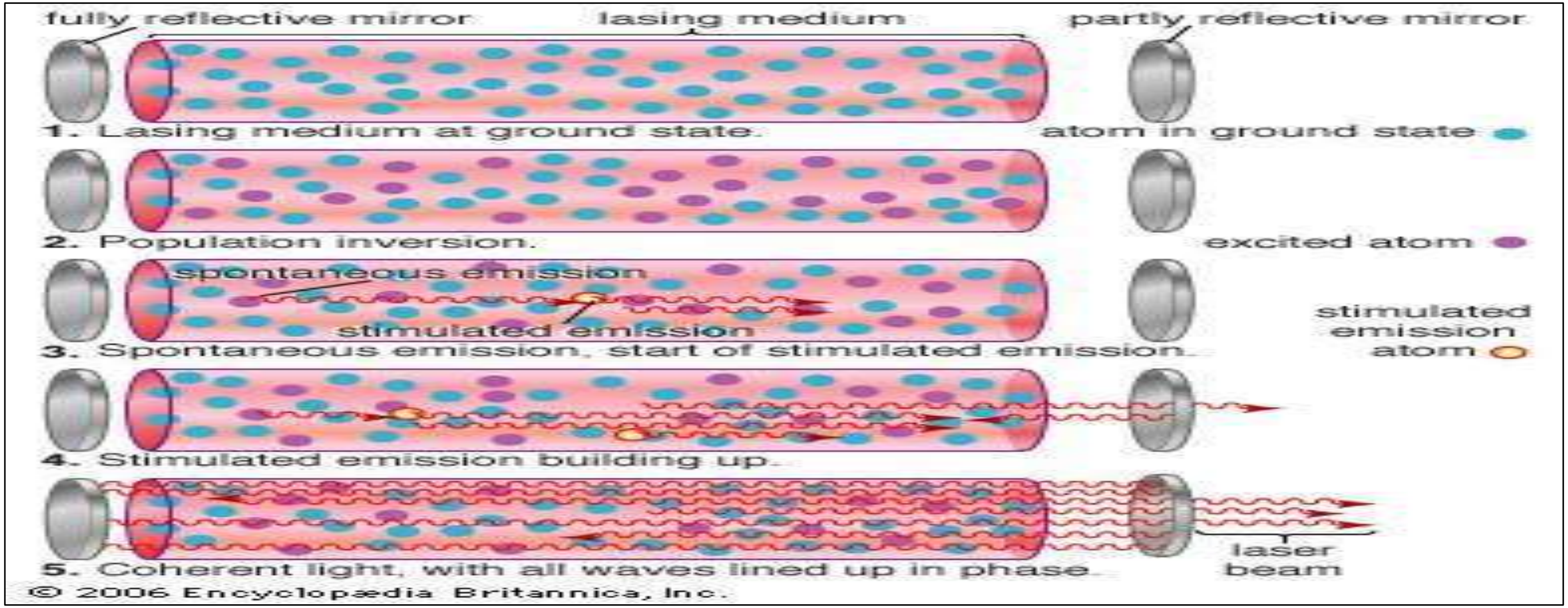
- **The material medium in which the atoms are raised to exited state to achieve population inversion is called as active centers.**
- **For example, in ruby laser, the active medium is aluminum oxide (Al_2O_3) doped with chromium oxide (Cr_2O_3). In which chromium ions (Cr^{3+}) act as active centers.**
- **In helium -neon laser it is the combination of helium and neon in the ratio of 10:1 in which Ne atoms act as active centers.**

2.9.3 OPTICAL RESONATOR

- An optical resonator which consists of two mirrors. One mirror is fully reflective and other is partially reflective.
- An active medium is kept between in them. The light emitted due to the stimulated emission of radiation bounces back and forth between the two mirrors and hence the intensity of the light is increased enormously.
- Finally the intense, amplified beam called laser is allowed to come out through the partial mirror

PRINCIPLE OF LASER ACTION

Due to stimulated emission the photons multiply in each step giving rise to an intense beam of photons that are coherent and moving in the same direction . Hence the Light Is Amplified by Stimulated Emission of Radiation



2.10 Nd-YAG [Neodymium-Yttrium Aluminum Garnet] Laser

Characteristics of Laser

Type : Solid state laser (4-level solid state laser)

Active medium : Yttrium Aluminum Garnet [$Y_3Al_5O_{12}$]

Active center : $Nd3^+$ ions

Pumping method : Optical pumping

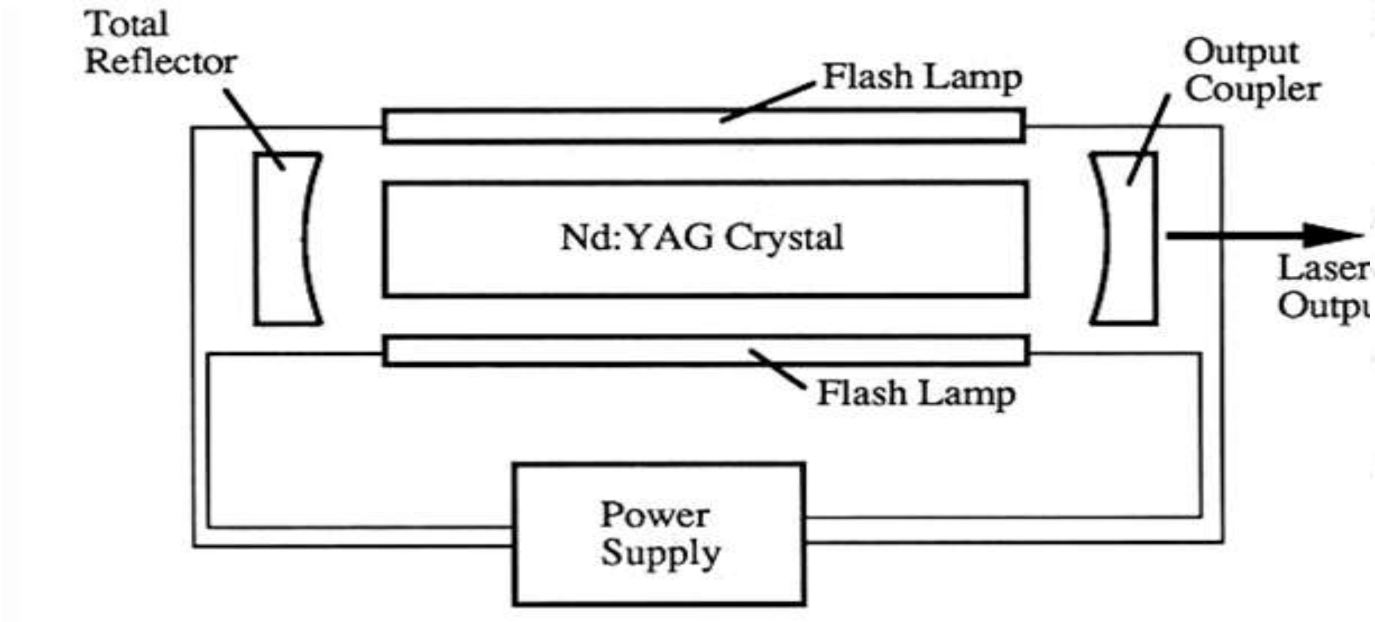
Pumping source : Xenon flash lamp

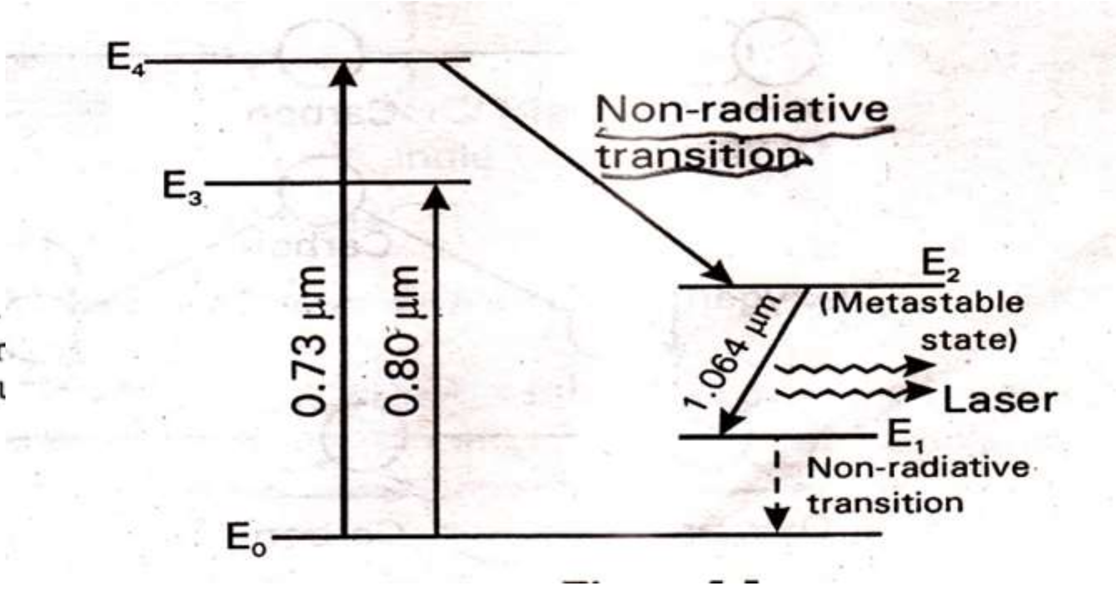
Optical resonator : Two ends of the rod polished with silver

Wave length : 1.064 µm.

Principle: The neodymium ions are raised to exited states by using optical pumping. Then the ions are accumulated at Meta stable state by non radiative transition. Due to stimulated emission the transition of ions takes place from Meta stable state to ground state, the laser beam of wavelength1.064 μm emitted.

- **Construction:**
- **A Nd-YAG laser consists of a cylindrical Nd-YAG rod [$Y_3Al_5 0_{12}$].**
- **In the Nd-YAG rod, Nd^{3+} ions are the active ions taking part in the laser action.**
- **The Nd-YAG rod will act as an active medium.**
- **One end of the Nd-YAG rod is fully silvered and the other end is partially silvered so that the two ends will act as optical resonator (or) cavity.**
- **The Nd-YAG rod surrounded by elliptical glass cavity which in turn is enclosed by xenon flash lamp filled with xenon gas shown in Fig.**





Energy level diagram of Nd-YAG laser

Construction of Nd-YAG laser

2.10.1 WORKING

- **The xenon flash lamp is switched on.**
- **A few thousand joules of light energy is discharged in a few milliseconds.**
- **A part of this light energy will be flashes on the Nd-YAG rod.**
- **Then the Nd^{3++} ions in the rod absorbs the particular wavelength of the incident light energy and are excited to higher energy states as shown in fig(2).**
- **The Nd^{3+} ions absorbs the light of photon of wavelength 0.73 μm and go to E_4 excited state and by absorbing wavelength 0.80 μm they go to E_3 excited state as shown in the energy level diagram.**
- **The excited Nd^{3+} ions then make a transition from these energy levels.**
- **The Nd^{3+} ions remain for about 10^{-8} second in these energy levels and makes non-radiative transition to the Meta stable state (E_2).**

- **In Meta stable state, the Nd^{3+} ions remain for longer duration of the order 10^{-3} second, so population inversion takes place between Meta stable and ground state.**
- **As a result, stimulated emission takes place and Nd^{3+} ions transmitted from Meta stable state to ground state.**
- **Hence, pulsed form of laser beam of wavelength 1.064 μm is emitted during transition from E_2 to E_1.**

2.10.2 APPLICATIONS OF Nd-YAG LASER

- **These lasers are widely used for cutting, drilling, welding in the industrial products.**
- **It is used in long haul communication systems.**
- **It is also used in the endoscopic applications.**

2.11 HELIUM-NEON LASER

This laser is discovered by Ali Javan an USA Scientist. He-Ne stands for Helium-Neon. The He-Ne laser active medium consists of two gases which do not interact form a molecule. Therefore He-Ne laser is one type of atomic gas lasers.

Characteristics of laser

Type	**:**	**Gas laser**
Active medium	**:**	**Mixture of Helium and Neon in the ratio10:1**
Active Centre	**:**	**Neon**
Pumping method	**:**	**Electrical pumping**
Optical resonator	**:**	**Pair of concave mirrors**
Wavelength	**:**	**632.8 nm**

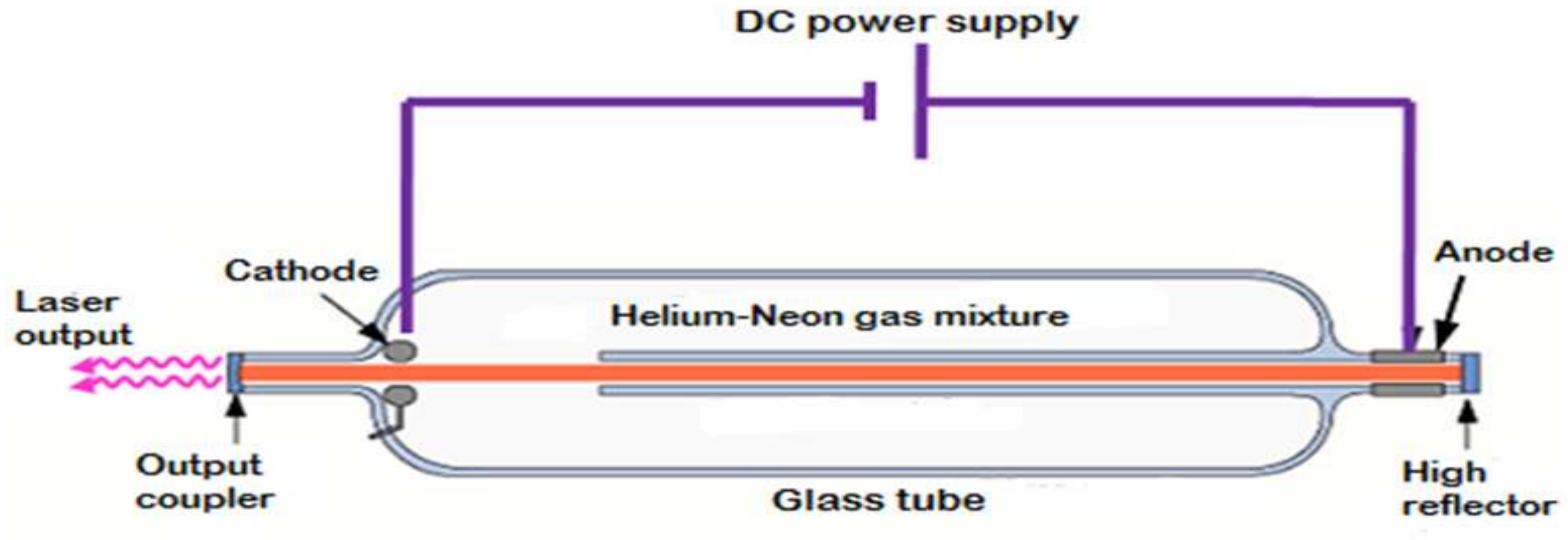
Principle

This laser is based on principle of stimulation emission, produced in the active medium of gas. Here, the population inversion is achieved due to the interaction between two gases which have closed higher energy levels.

Construction

- It consists of a gas discharge tube, which made up of quartz and is filled with the mixture of helium under a pressure of 1mm of hg and neon under the pressure of 0.1mm of hg. The ratio of the He-Ne mixture is 10:1. i.e., the number of Helium atoms is greater than the number of Ne atoms.
- The electrons at the ends of the discharge tube are connected to the radio frequency oscillator to produce electrical discharge in the He-Ne mixture as shown in Fig.

The end faces of the discharge tube are tilted at the Brewster angle and are called as Brewster windows. It is used to produce plane polarized light by reflecting the perpendicularly polarized light .A fully reflecting and partial reflective concave mirror is placed at the left and right ends of the discharge tube respectively which acts as a resonant cavity.

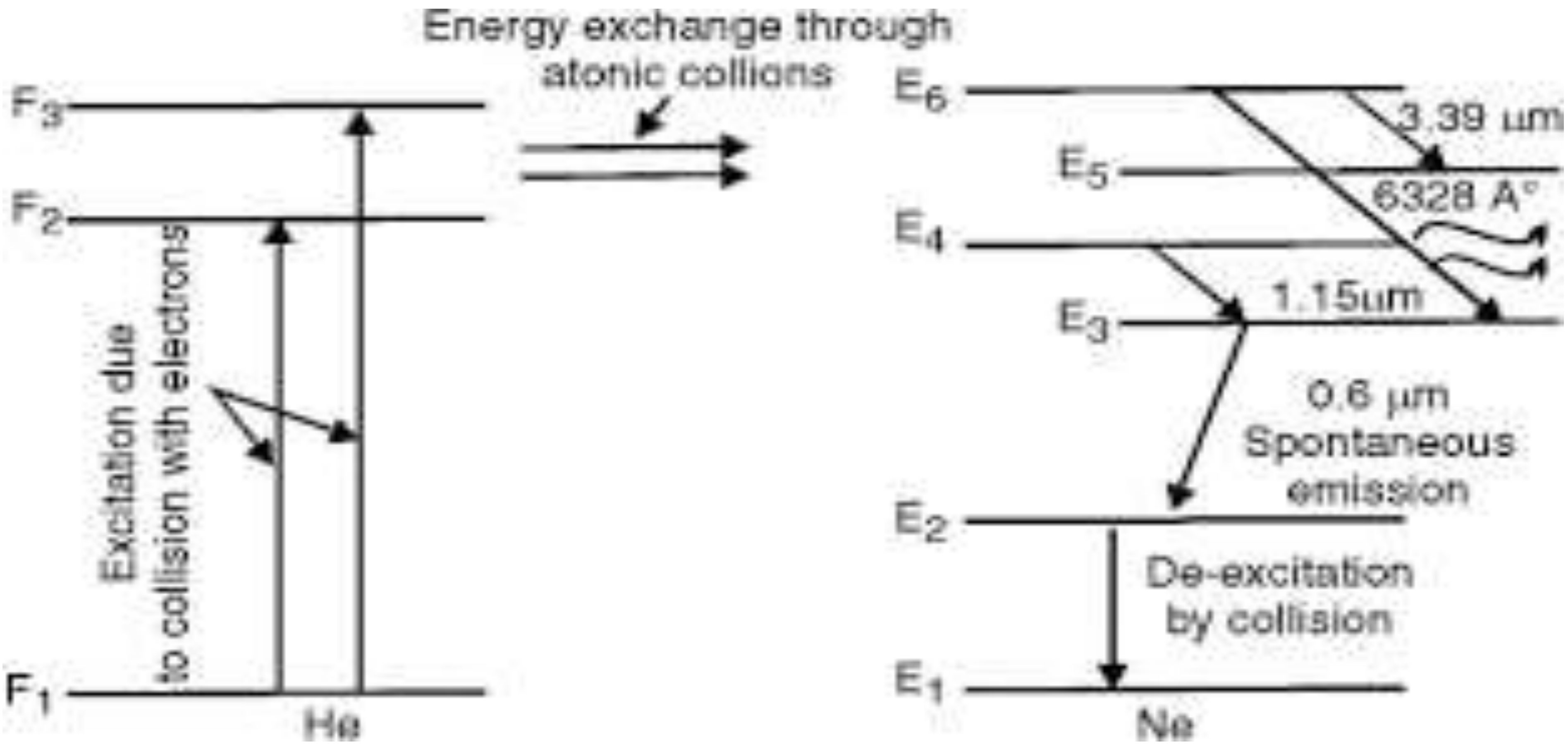


Construction of He-Ne Laser

WORKING

- **By electrical discharge in a tube, the ground state helium atoms are excited to higher energy levels.**
- **The excitation occurs due to the collision of discharged electrons with helium atoms.**
- **The excited He atoms colloid inelastically with the neon atoms which have close energy level as that of helium energy level.**
- **Therefore the helium atoms deliver its energy to neon atoms by the process known as resonant collision energy transfer.**
- **This resonant energy transfer takes place because the corresponding energy levels of Helium atoms ($2s^1$ and $2s^2$) are almost closer to the neon energy levels (2s and 3s).**

ENERGY LEVEL DIAGRAM OF He-Ne LASER



Applications of He-Ne Laser

The Helium-Neon gas laser is one of the most commonly used laser today because of the following applications.

- **He-Ne lasers are produced in large quantities from many years.**
- **Many schools / colleges / universities use this type of laser in their science programs and experiments.**
- **He-Ne lasers also used in super market checkout counters to read bar codes and QR codes.**
- **He-Ne lasers also used by newspapers for reproducing transmitted photographs.**
- **He-Ne lasers can be use as an alignment tool.**
- **It is also used in Guns for targeting.**

Advantages of He-Ne Laser

- He-Ne laser has very good coherence property
- He-Ne laser can produce three wavelengths that are 1.152μm, 3.391 μm and 632.8nm, in which the 632.8nm is most common because it is visible usually in red color.
- He-Ne laser tube has very small length approximately from 10 to 100cm and best life time of 20.000 hours.
- Cost of He-Ne laser is less from most of other lasers.
- Construction of He-Ne laser is also not very complex.

Disadvantages of He-Ne Laser

- **It is relatively low power device means its output power is low.**
- **He-Ne laser is low gain system/ device.**
- **To obtain single wavelength laser light, the other two wavelengths of laser need suppression, which is done by many techniques and devices. So it requires extra technical skill and increases the cast also.**
- **High voltage requirement can be considered its disadvantage.**
- **Escaping of gas from laser plasma tube is also its disadvantage.**

2.13 APPLICATIONS OF LASERS

Lasers find applications in various fields of science technology. They are described below.

Medical applications

- **Lasers are used in eye surgery.**
- **Lasers are used for treatments such as plastic surgery, skin injuries and to remove moles and tumors developed in skin tissue.**
- **Lasers are used in cancer diagnosis and therapy.**

Scientific field

- Lasers are used in counting of isotopes separation and to separate isotopes of uranium.
- Lasers are used to estimate size and shape of biological cells such as erythrocytes.
- Lasers are used to create plasma.
- Lasers are used to produce chemical reaction
- Lasers are used in recording and reconstruction of a hologram.

Industry applications

- Lasers are used to cut glass and quartz.
- Lasers are used to drill holes in ceramics.
- Lasers are used to drill aerosol nozzles.
- Lasers are used for heat treatment in the tooling and automotive industry.

Fibre Optics

Communication from Womb to Tomb

Contents

The Evolution of Communication through the Centuries

Communication :

➢The English word "communication" derived from the greek word *Comminicare* which mean exchange of information.

➢For as long as humans have been on this planet, we've invented forms of communication—from Cave Paintings, Symbols, Smoke Signals, Carrier Pigeon, Postal System, Newspapers, Radio, Telegraph ,Telephone, Television, Internet, E-mail, Text Message, Social Media like Face book, Messenger, Whats Up , Twitter , Instagram and Telegram etc., that have constantly evolved how we interact with each other

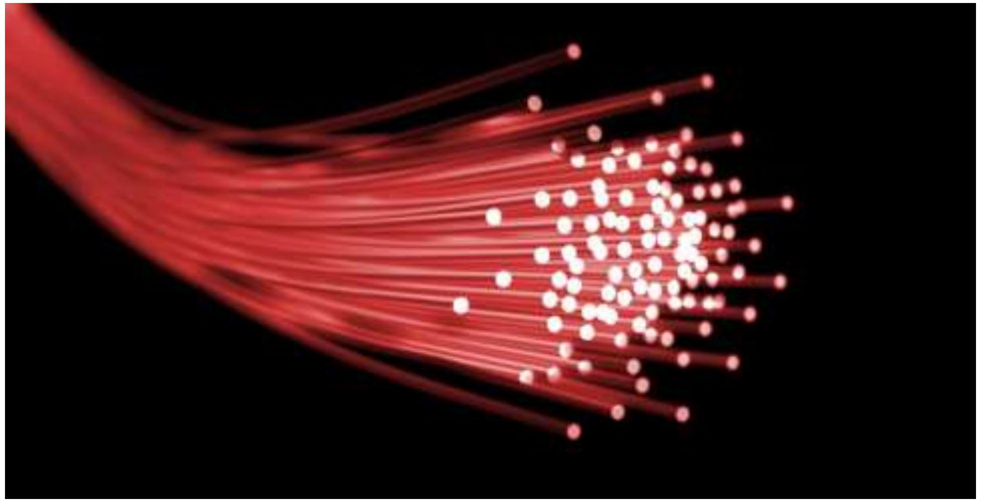
➢Technology has indeed redefined communication. People no longer have to wait for years, months, weeks, and days to receive an information or message. Today, texts, e-mails, tweets, and personal messages can reach the recipient in just a matter of seconds. *i.e.,****we communicate in a fingersnap.***

Now, we can send information in forms : 1)Audio, 2) Video, 3) Data

- Now, optical fibers became on of the greatest communicating media in the world.
- Everywhere on this planet optical fibers carry vast quantities of information from place to place.

What is Fiber Optics ?

Fiber optics is a branch of optics which deals with the study of propagation of information in the form of light (rays or modes) through transparent dielectric optical fibers.



Optical fiber

Optical fiber is a thin and transparent guiding dielectric medium or material which guides or transmits the information as light waves, using principle of total internal refection.

Optical fiber

Optical fiber is a thin and transparent guiding dielectric medium or material which guides or transmits the information as light waves, using principle of total internal refection.

Optical fiber cable

A bundle of optical fibers consists of thousands of individual fiber wires as thin as human hair, measuring 0.004mm in diameter is known as optical fiber cable.

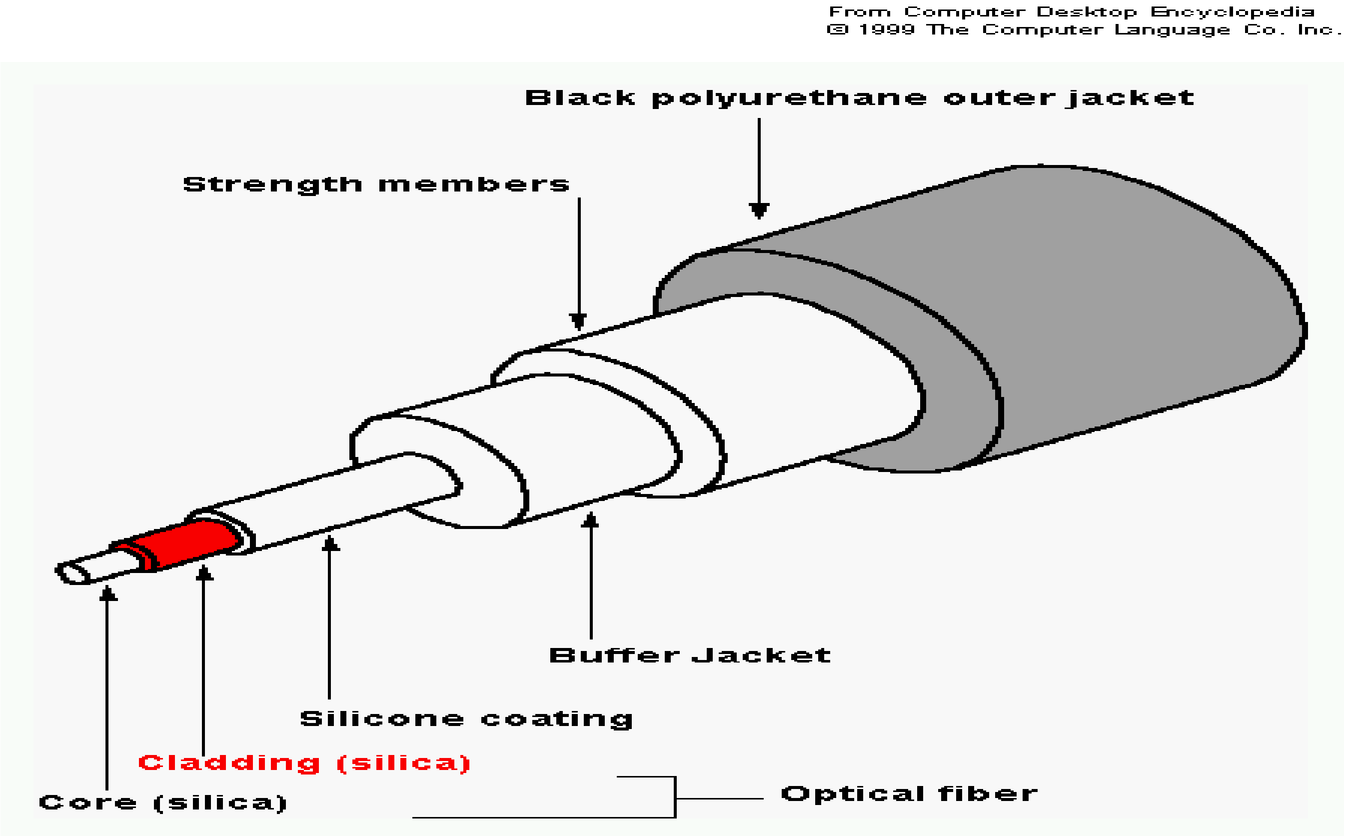
History of Fiber Optics

John Tyndall demonstration in 1870

Total Internal reflection is the basic idea of fiber optics

Optical fiber structure and construction:

A typical structure of optical fiber as shown in fig.



Optical Fiber dimensions:

Core diameter : 5µm to 600µm.
Cladding diameter : 125µm to 750µm
Protective layer : 250µm to 1500µm.
Numerical aperture : 0.1 to 0.5.
Acceptance angle : 20^0 t0 50^0.
Band width : 50MHZ.

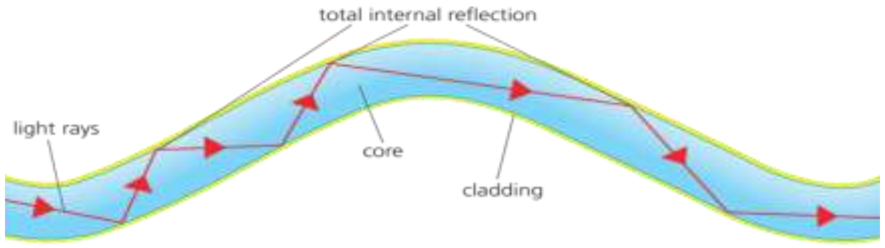
Principle of optical fiber:

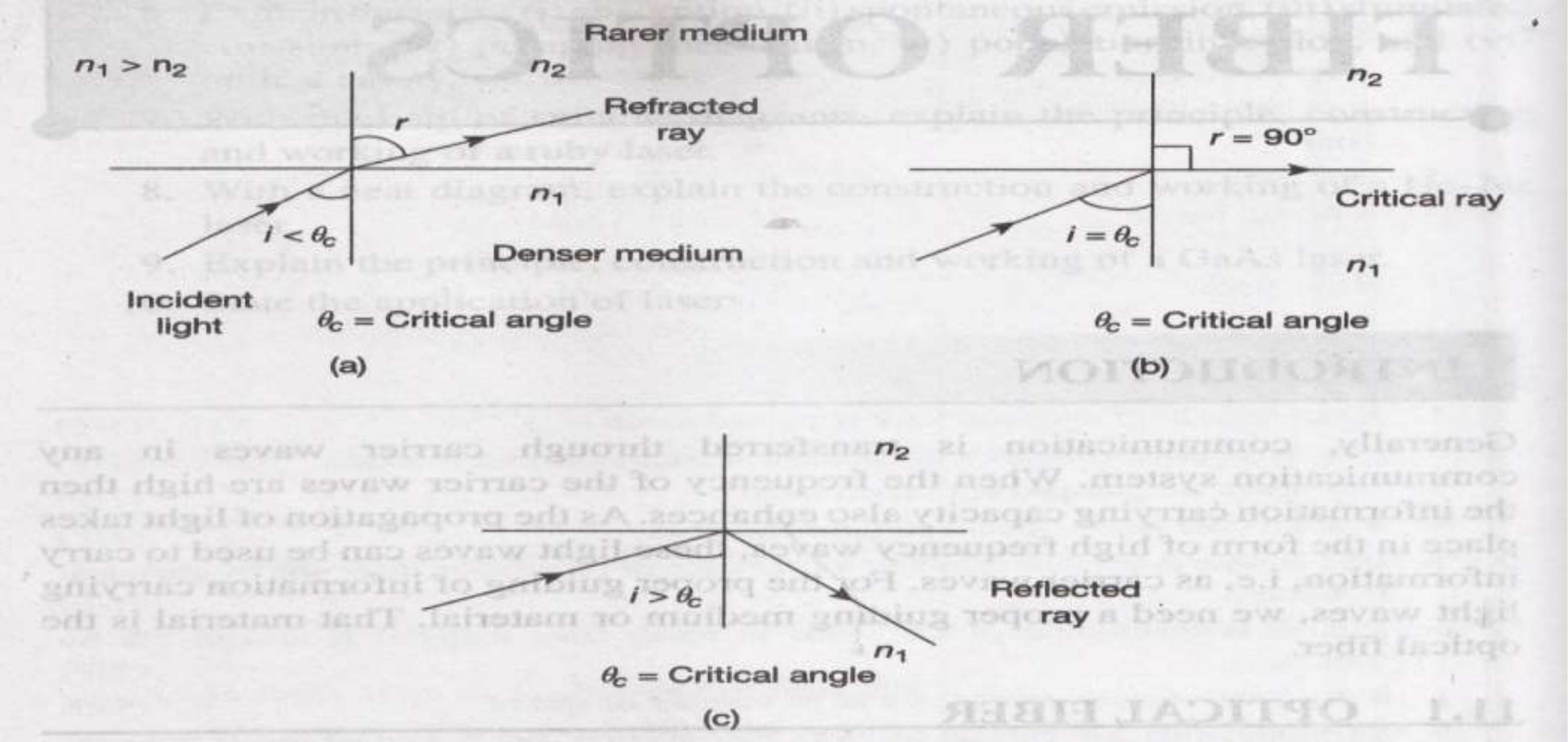
➢An optical fiber works on the principle of total internal reflection.

➢John Tyndall observed that the propagation of light through the optical fiber will be in the form of multiple total internal reflections.

Definition:

when a light ray travels from denser medium to rarer medium and angle of incidence is greater than the critical angle, then the light ray reflects totally, this phenomenon is known as total internal reflection.





Principle of Optical Fiber

Derivation for Critical Angle:

If n1 and n2 are the refractive indices of denser and rarer medium

According to Snell's law, $n_1 \sin i = n_2 \sin r$.

When $i = \Theta_c$ then $r = \quad = 90^0$.

Therefore; $n_1 \sin \Theta_c = n_2 \sin 90^0$.

$n_1 \sin \Theta_c = n_2$.

$\sin \Theta_c = n_2/n_1$

$\boldsymbol{\Theta_c = \sin^{-1}(n_2/n_1)}$

If the rarer medium is air, then $n_2=1$.

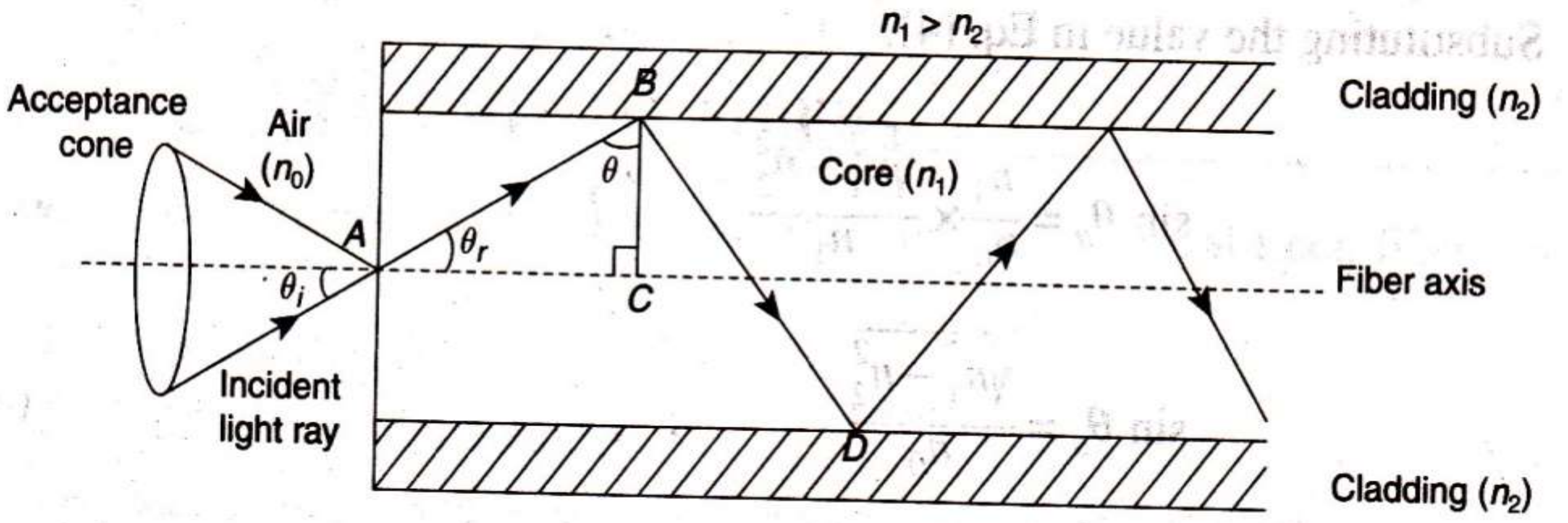
$\boldsymbol{\Theta_c = \sin^{-1}(1/n_1)}$

Conditions for total internal reflection:

1. The light ray should move from denser to rarer medium.
2. When $i < \Theta_c$,then the light ray refracts into rarer medium.
3. When $i = \Theta_c$,then the refracted light ray passes along interface of the two media.
4. When $i > \Theta_c$,then the light ray is reflected back into the denser medium and we get total internal reflection.

Acceptance angle and acceptance cone:

The maximum angle at which the light can suffers total internal refection is called as acceptance angle. The acceptance cone is derived by rotating the Acceptance Angle about the fiber axis.



Numerical aperture (N.A):

❖Numerical aperture represents the light gathering power of an optical fiber. It is a measure of the amount of light that can be accepted by a fiber.

❖The value of NA ranges from 0.13 to 0.50.

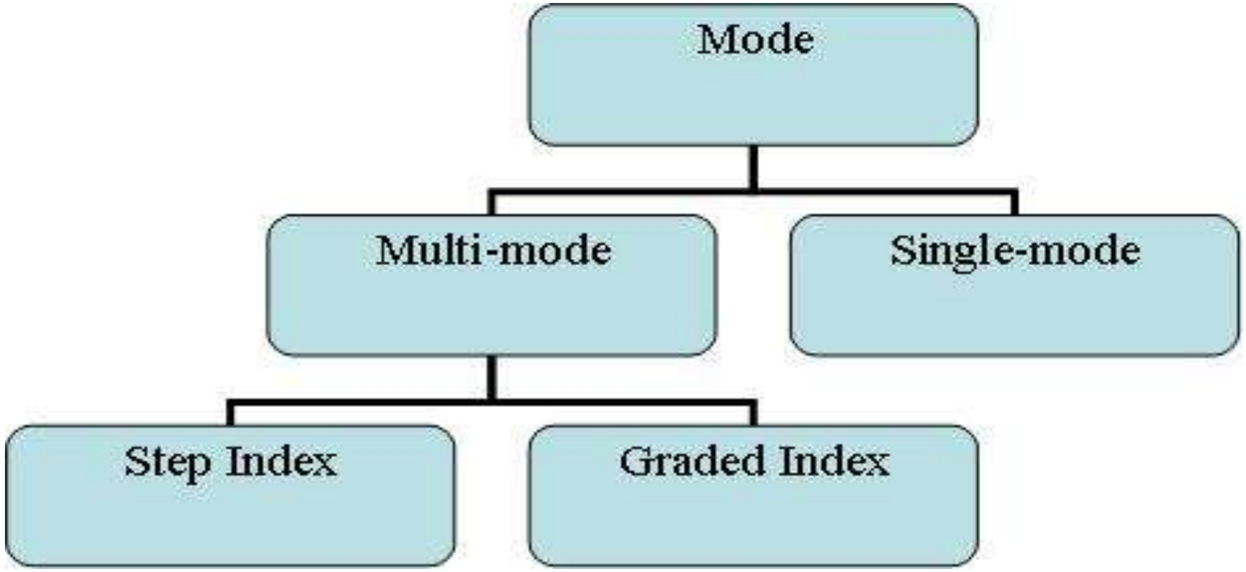
❖Numerical aperture is proportional to acceptance angle. So, numerical aperture is equal to the sine of acceptance angle.

Types of optical fibers:

Optical fibers are classified into 2 major categories based on

1. Number of modes transmitted into the optical fibers and
2. Refractive index profile of the fibers.

According to the mode of propagation, optical fiber is classified into two: single-mode and multi-mode optical fibers

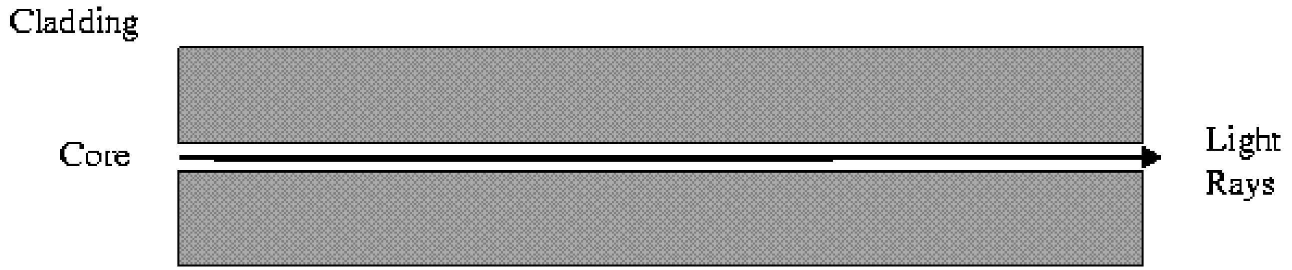


Single mode optical fibers:

- If the optical fiber which allows one mode of light propagation, then it is known as single mode optical fiber. Because it has very small core diameter so that it can allow only one mode of light propagation as shown fig.
- In general single mode optical fibers are step index optical fibers.
- They are made from doped silica with mixtures of metal oxides.
- The ray travels along the **axis** of the fiber

Single mode Optical Fiber dimensions:

Core diameter : 5µm to 10µm.
Cladding diameter : around 125µm.
Protective layer : 250µm to 1000µm.
Numerical aperture : 0.08 to 0.10.
Acceptance angle : 20^0 t0 30^0.
Band width : more than 50MHz.



Multi mode optical fibers:

•The core diameter is very large compared to single mode fibers, so that it can allow many modes of light propagation and hence, it is called multi- mode optical fiber as shown in fig.

•**The multi mode optical fibers are useful manufacturing both for step index and graded index optical fibers.**

•**They are made by multi-component glass compounds such as Glass-clad silica, Silica-clad silica, doped silica etc.,**

Multi mode Optical Fiber dimensions:

Core diameter : 50μm to 350μm.

Cladding diameter : 125μm to 500μm.

Protective layer : 250μm to 1100μm.

Numerical aperture : 0.12 to 0.5.

Acceptance angle : 20^0 t0 30^0.

Band width : Less than 50MHz.

<u>Step index optical fibers and graded index optical fibers:</u>

Based on the variation in the refractive index of the core and the cladding, the fibers are classified into two types. They are.

1) **Step index optical fibers** (multimode, single mode) **and**
2) **Graded index optical fibers** (multimode)**.**

<u>Step index optical fibers:</u>

•In the step index fiber, the refractive index of the core is uniform throughout and undergoes an abrupt or step change at the core-cladding boundary.

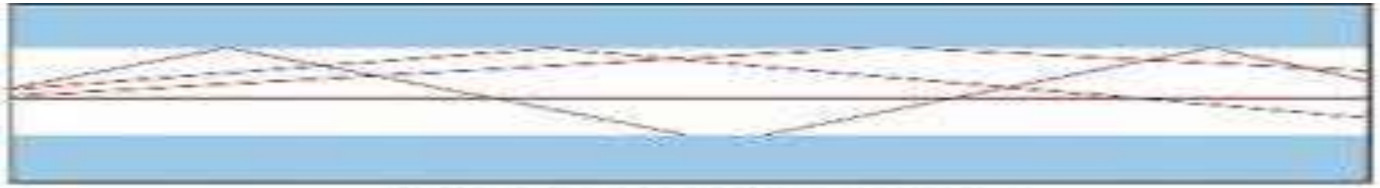
•The refractive indices of air, core and cladding varies step by step with increase radial distance from the axis of the fiber and hence, it is known as step index optical fiber as shown in fig.

•The path of light propagation is in zigzag manner.

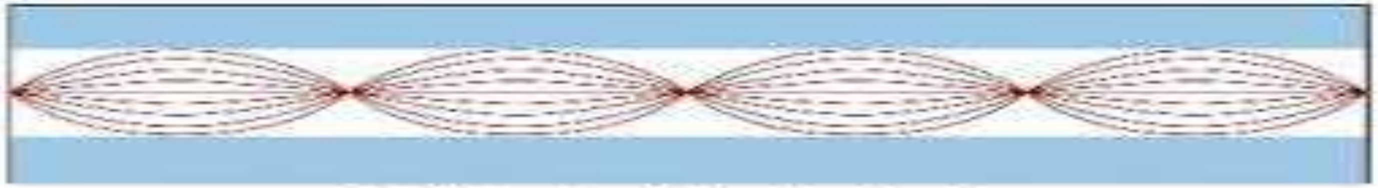
• Step index fiber can be single mode step index fiber or multimode step index fiber.

•The single mode step index fiber has low intermodal dispersion compared to multimode step index fiber.

•It is used widely as data link cables.



Multimode, Step-Index



Multimode, Graded Index

Applications:

Because of its less band width, they are used in short haul communication systems (data and audio/video applications in LANs)

A **local area network (LAN)** is a computer network that interconnects computers in a limited area such as a home, school, computer laboratory, or office building using network media

Advantages:

- **Launching of light is easy.**
- **Connecting two fibers is easy.**
- **Fabrication is easy.**
- **Cost is low.**

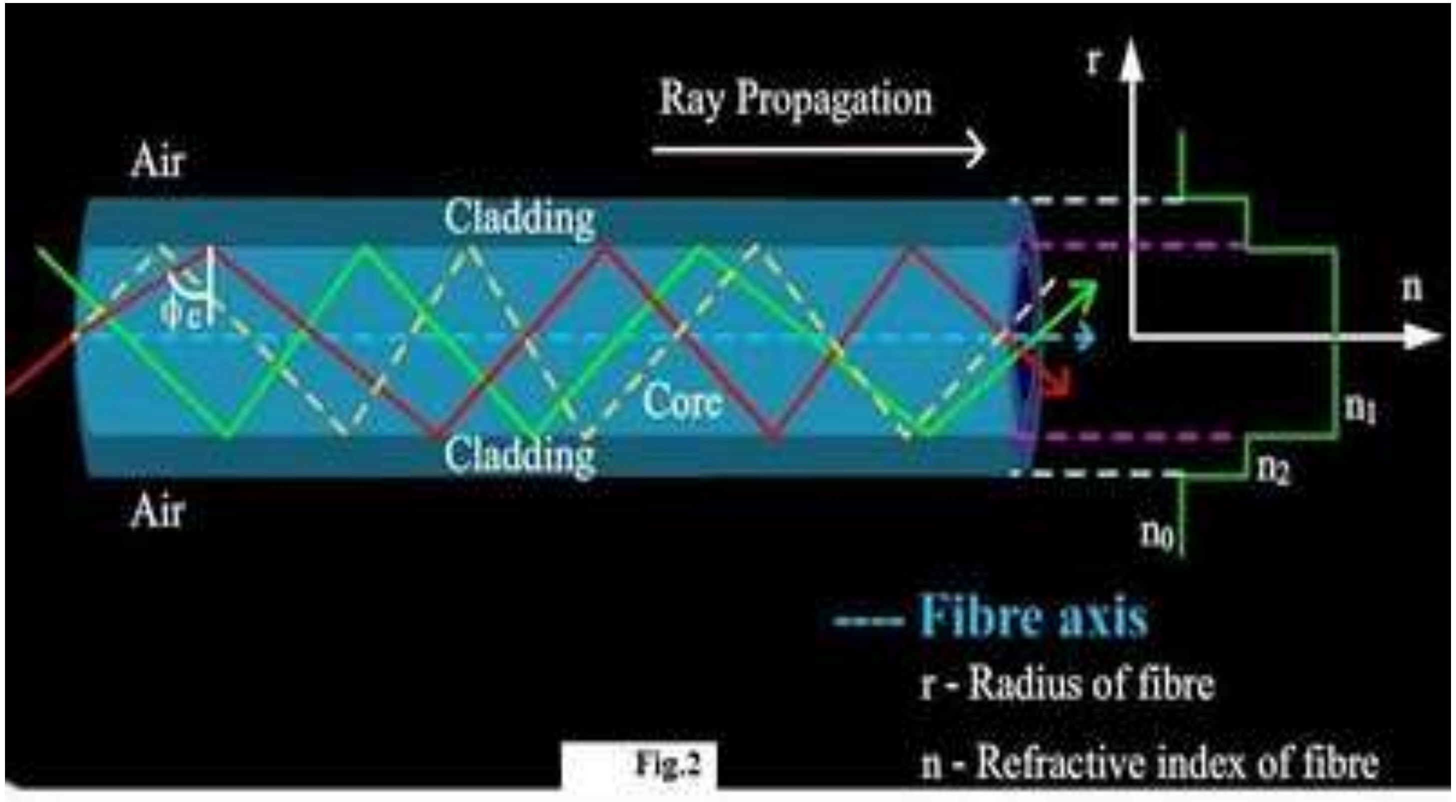


Fig: 2) Multimode step index optical fiber

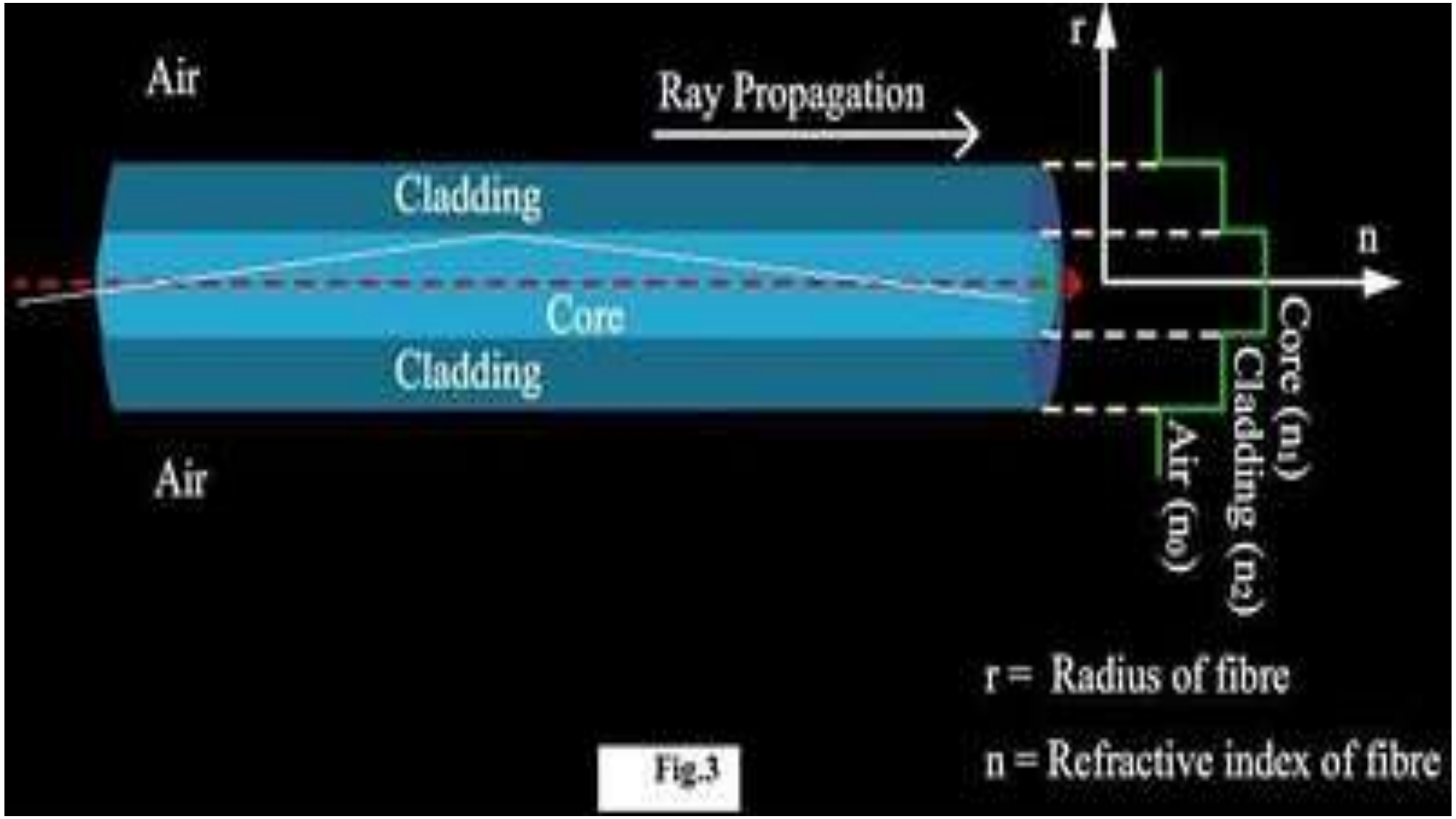


Fig: 3) single mode step index optical fiber.

Graded index optical fiber:

Graded index fibers do not have a constant refractive index in the core but the refractive index decreases gradually with increase in radial distance from the axis of fiber, hence the name "graded-index as sown in fig.

The path of light propagation is in a helical or spiral manner.

Graded index fibers are multimode fibers.

The multimode graded index fiber has very less intermodal dispersion compared to multimode step index fiber.

It is used in medium range communications, medical field and in industries.

Multi mode graded index Optical Fiber dimensions:

Core diameter : 50µm to 350µm.

Cladding diameter : 125µm to 500µm.

Protective layer : 250µm to 1100µm.

Numerical aperture : 0.12 to 0.5.

Acceptance angle : 18^0 t0 30^0.

Band width : Less than 50MHz.

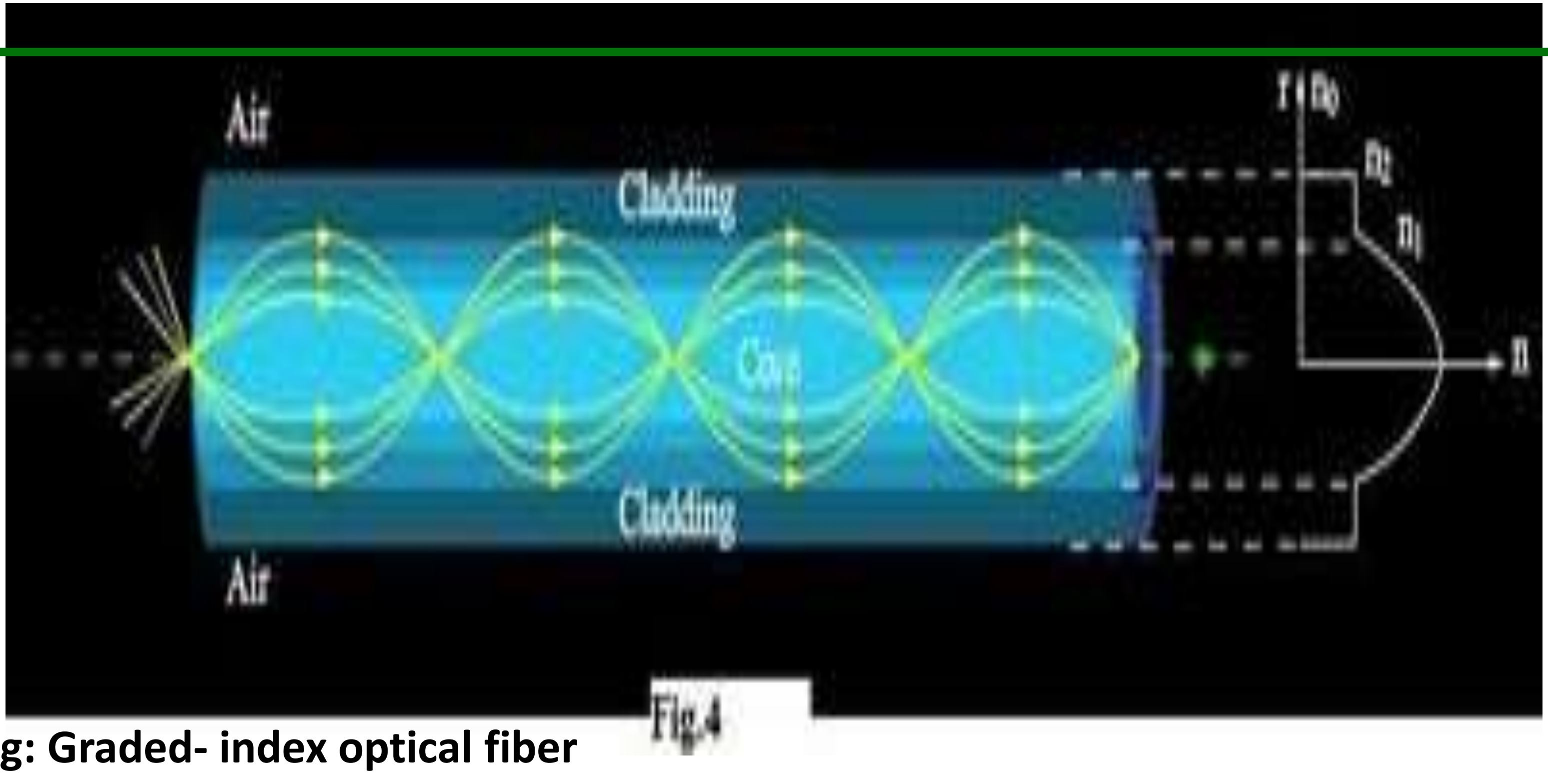


Fig: Graded- index optical fiber

Note:

Inter-modal dispersion: When more than one mode is propagating through a fiber, then the inter-modal dispersion will occur. Since, many modes are propagating; they will have different wavelengths and will take different time to propagate through the fiber, this results in elongation or stretching of data in the pulse. This is known as inter-modal dispersion.

Optical fiber communication system:

An optical fiber communication system mainly consists of three parts viz., (1) transmitter section (2) optical fiber (3) receiver section as shown in fig.

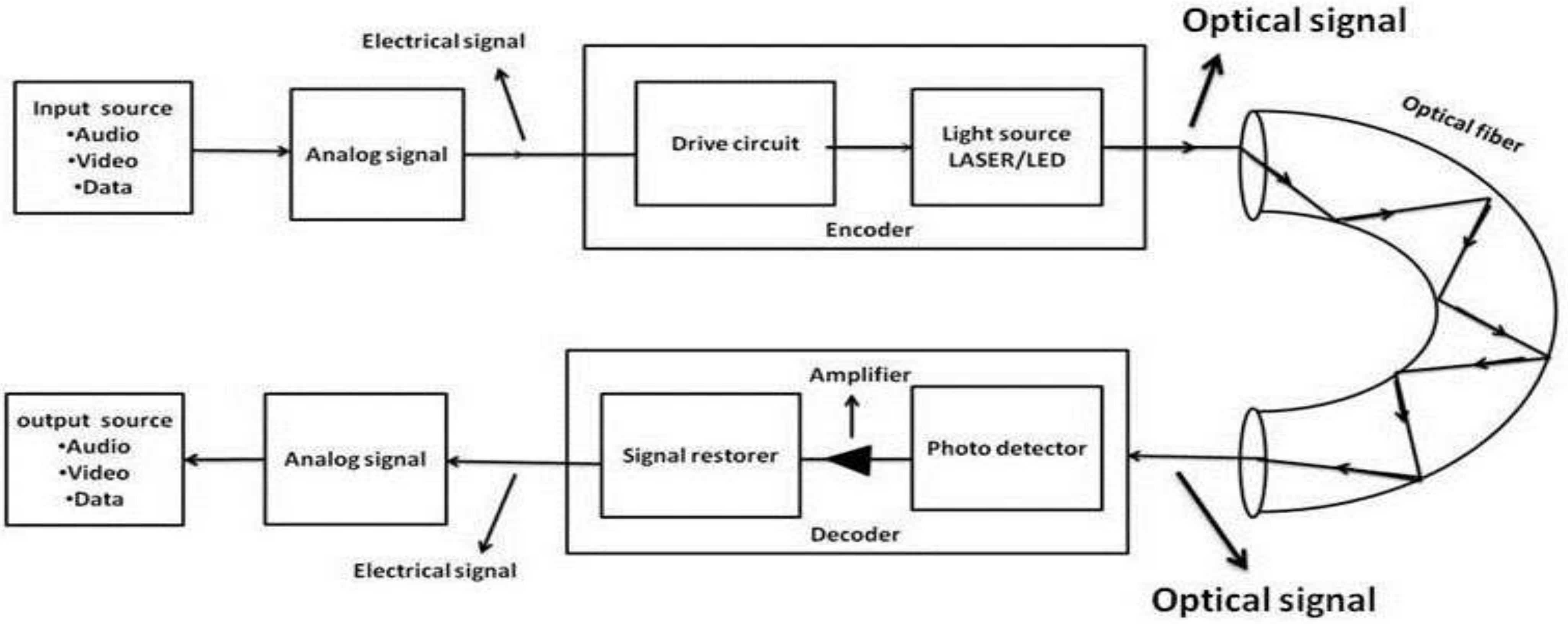
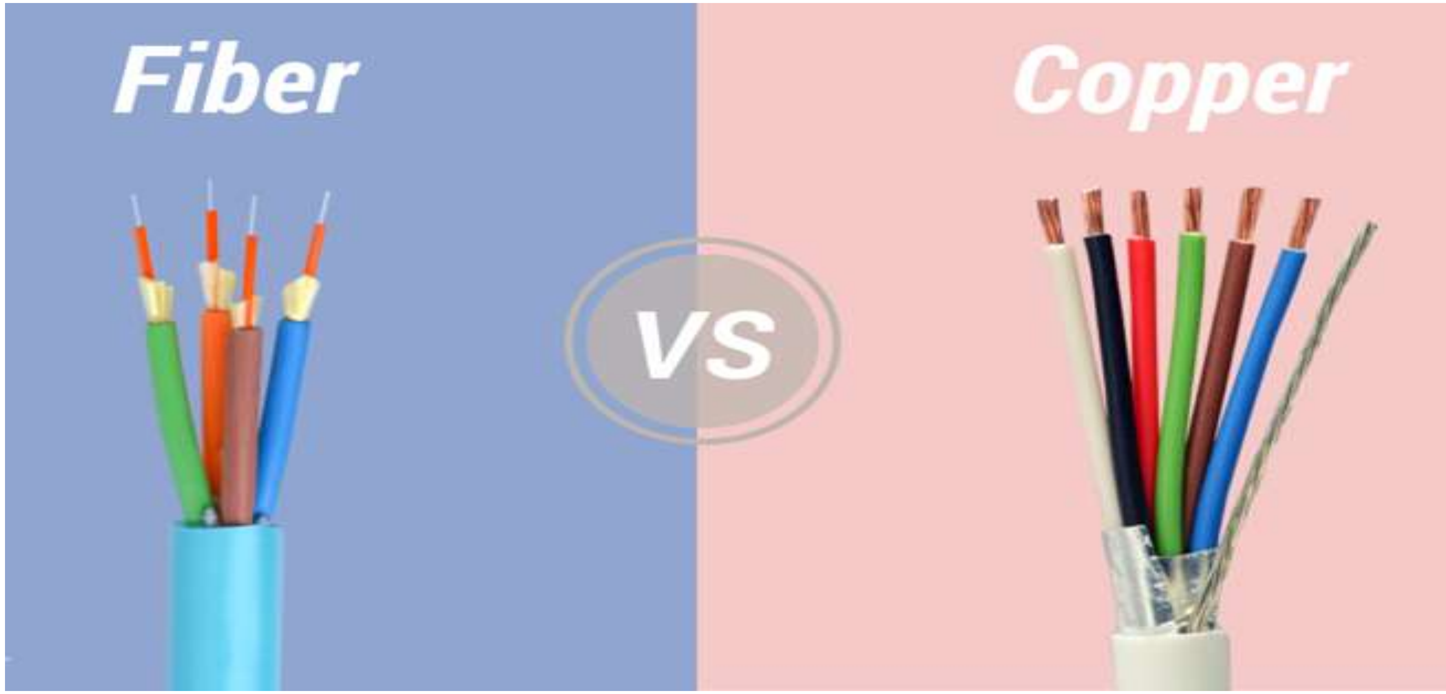


Fig: Fiber optical communication system

Advantages of optical fiber communication:

Optical fibers have largely replaced copper wire communications in core networks in the developed world, because of its advantages over electrical transmission. Here are the main advantages of fiber optic transmission.



Safety

- The fiber is non-conducting, and is therefore safe in all environments.
- It uses light waves for communication hence it is shockproof.
- Since it is shockproof, it is very useful in sensitive areas like petroleum industries, oil and natural gas industries, cotton industries etc.

Weight

Fiber optic cables are made of glass or plastic, and they are thinner than copper cables. These make them lighter weight and easy to install.

Low Power Loss

An optical fiber offers low power loss, which allows for longer transmission distances than comparison to copper cable.

Bandwidth

Fiber optic cables have a much greater bandwidth than metal cables. The amount of information that can be transmitted per unit time of fiber over other transmission media is far greater than copper cables.

Security :

- It CANNOT be tapped unlike copper cables.
- There is NO any leakage of signals so communication is secured.
- It is very strong, flexible and can work on high temperature.
- It does NOT have corrosion due to water, chemicals and high humidity etc.
- It is cost effective and maintenance free.
- It is very easy to install. It does NOT require skilled labor.

Losses in Fiber Optics

Attenuation

Dispersion-intermodel, Intramodel,

Bending loss-micro ,macro

scattering losses-Linear, Non linear,

Absorption- Intrinsic, Extrinsic

Coupling

Attenuation

Attenuation means loss of light energy as the light pulse travels from one end of the cable to the other.

It is also called as signal loss or fiber loss.

It also decides the the number of repeaters required between transmitter and receiver.

Attenuation is directly proportional to the length of the cable.

Attenuation

Attenuation is defined as the ratio of optical output power to the input power in the fiber of length L.

$\alpha = 10\log_{10} Pi/Po$ [in db/km]

where, Pi= Input Power

Po= Output Power, α is attenuation constant

The various losses in the cable are due to

Absorption

Scattering

Dispersion

Bending

Bending losses

The loss which exists when an optical fiber undergoes bending is called bending losses.

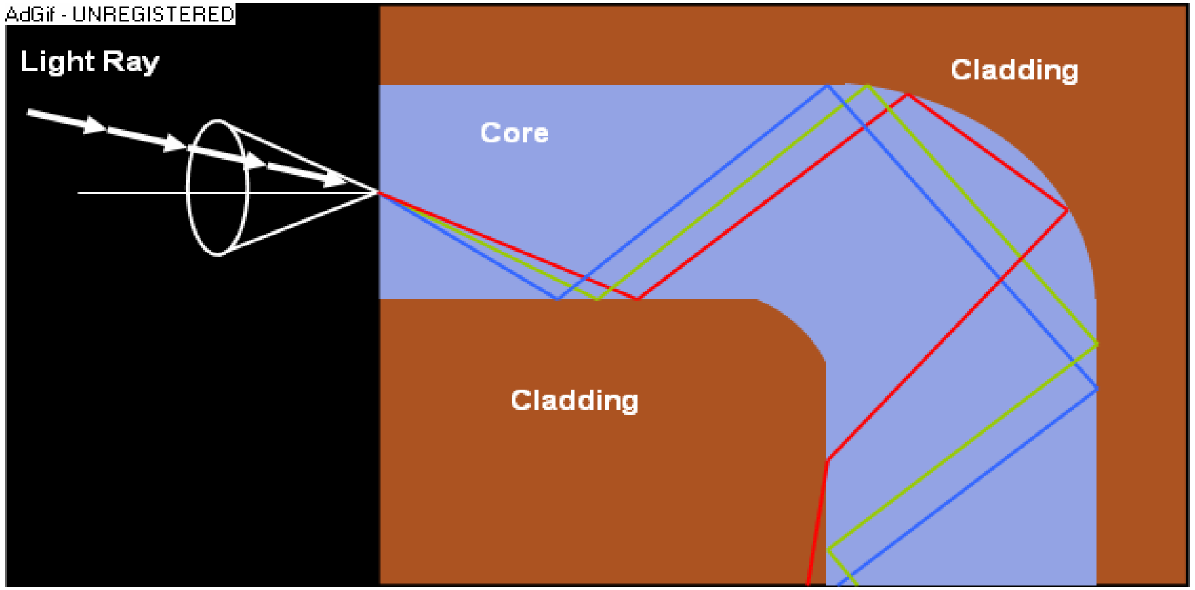
There are two types of bending

i) Macroscopic bending

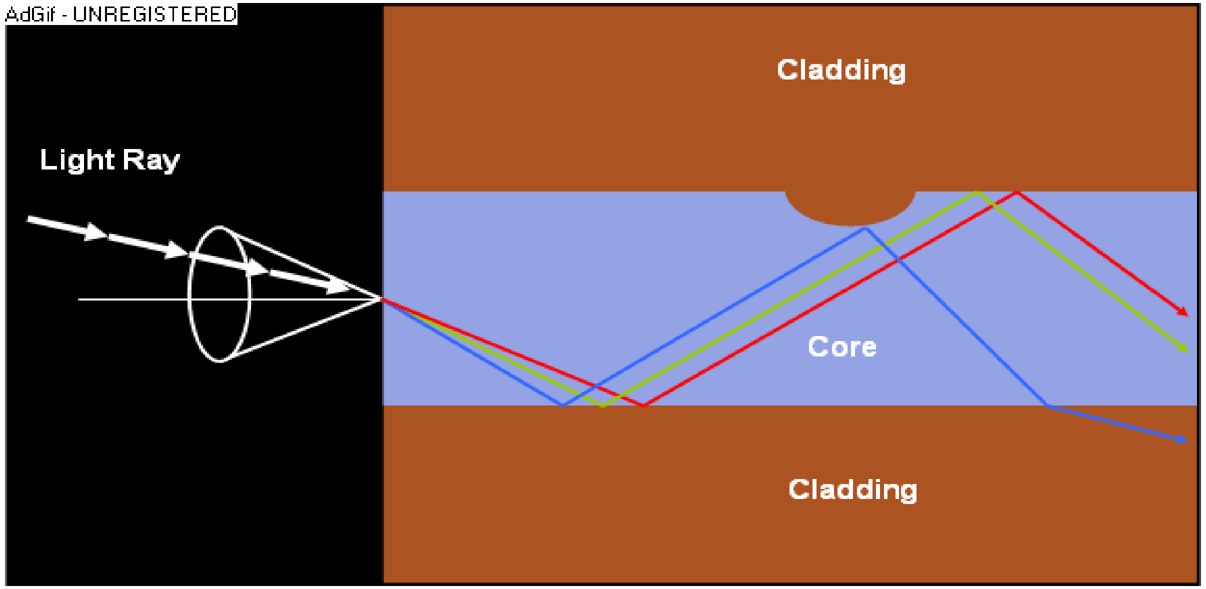
Bending in which complete fiber undergoes bends which causes certain modes not to be reflected and therefore causes loss to the cladding.

ii) Microscopic Bending

Either the core or cladding undergoes slight bends at its surface. It causes light to be reflected at angles when there is no further reflection.



Macroscopic Bending



Microscopic Bending

Absorption Loss

Absorption of light energy due to heating of ion impurities results in dimming of light at the end of the fiber.

Two types:

1. Intrinsic Absorption
2. Extrinsic Absorption

Intrinsic Absorption:

Caused by the interaction with one or more components of the glass

Occurs when photon interacts with an electron in the valence band & excites it to a higher energy level near the UV region.

Extrinsic Absorption:

Also called impurity absorption.

Results from the presence of transition metal ions like iron, chromium, cobalt, copper & from OH ions i.e. from water

Dispersion Loss

As an optical signal travels along the fiber, it becomes increasingly distorted.
This distortion is a sequence of intermodal and intramodal dispersion.
Two types:
1.Intermodal Dispersion
2.Intramodal Dispersion

Intermodal Dispersion:
Pulse broadening due to intermodal dispersion results from the propagation delay differences between modes within a multimode fiber.
Intramodal Dispersion:
It is the pulse spreading that occurs within a single mode.
Material Dispersion
Waveguide Dispersion

1) **Material Dispersion**:

Also known as spectral dispersion or chromatic dispersion.

Results because of variation due to Refractive Index of core as a function of wavelength, because of which pulse spreading occurs even when different wavelengths follow the same path.

2) **Waveguide Dispersion:**

Whenever any optical signal is passed through the optical fiber, practically 80% of optical power is confined to core & rest 20% optical power into cladding.

Scattering Losses

It occurs due to microscopic variations in the material density, compositional fluctuations, structural in homogeneities and manufacturing defects.

Coupling Losses

The machanical losses due to the coupling of optical fiber cables is called coupling losses

Applications of optical fibers:

1. Communication:

Optical fibres are used in exchange of information between different networks of computers.

For example, A **local area network (LAN)** is a computer network that interconnects computers in a limited area such as a home, school, computer laboratory, or office building using network media to exchange the information.**. They are used for short distances about 1to 2 km.**

Long haul communication: they are used for long distances, 10 km or more. Tele phone cables in which Optical fibres are used in to exchange of information between various places.

They are used for exchange of information in cable television, space vehicles, submarines, etc.

2. Medical field:

Fibre optic technology is used in medical diagnostics. Optical fibres are used in medicine, in the fabrication of fiberscope in endoscopy to view internal body parts without having to perform surgery.

Gastroscope is used to examine the stomach.

Bronchoscope is used to see upper passages of lungs.

Orthoscope is used to see the small spaces within joints.

Peritoneoscope is used to test the abdominal cavity, lower parts of liver and gall bladder.

DIELECTRICS

A Dam with full of Power

According to band theory of solids, solids can be classified into conductors, semiconductors and insulators. In insulators, the valence band is full while the conduction band is empty. Further the energy gap between valence band and conduction band is very large .i.e., greater than 3eV. So electrons cannot jump from the valence band into the conduction band. This means that there are no free electrons available for conduction in the insulators under normal conditions.

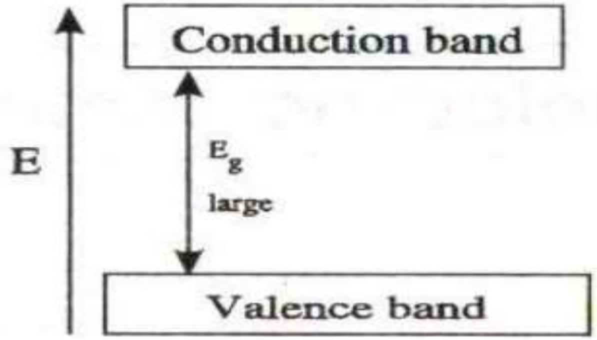


Fig 2.1 Energy band diagram of dielectrics

For this reason, the electrical conductivity is extremely small and may be nil under ordinary conditions. Though some of the insulators exhibit behavior of electric polarization when they placed in an electric field such insulators are known as dielectrics. Therefore, a dielectric is an electrical insulator that can be polarized by an applied electric field.

In other words, if the main function of non- conducting materials is to provide electrical insulation, then they are called as *insulators*. On the other hand, if the main function of non- conducting materials is to store electrical charges, then they are called as *dielectrics*. Dielectrics are widely used in electrical applications.

3.1 Dielectrics

Dielectrics are non-conductors of electricity which do not contain free charge carriers.

Examples: air, mica, rubber, ceramics, glass, wood and plastic etc.

Properties

1. They are insulators.
2. Theyhaveaverylargeenergygap(morethan3eV)
3. Alltheelectronsinthedielectricsaretightlyboundtotheirparentnucleus.
4. Astherearenofreeelectronstocarrythecurrent,theelectricalconductivity of dielectrics is verylow.
5. They have high specific resistance.
6. They have negative temperature of coefficient of resistance.
7. They can be polarized by an electric field.
8. The main function of dielectric materials is to store electric energy.

3.2 Types of Dielectrics

Each atom/molecule of a dielectric is neutral. Depending on the atomic/molecular structure, dielectrics are classified into two types. They are

i) Non-polar Molecules

ii) Polar Molecules

Non-polar Molecules

If the centers of gravity of positive and negative charges in the molecules coincide; so that no electric dipoles are formed, the molecules of the dielectrics are said to be non-polar molecules.The examples of non-polar molecules are H_2, N_2, O_2, CH_4 and CO_2etc

Polar Molecules

If the centers of gravity of positive and negative charges in the molecules do not coincide, so that electric dipoles are formed, the molecules of the dielectrics are said to be polar molecules.The examples of polar molecules are H_2O, HCl, NH_3, CH_3Cl and CO etc.

Though each molecules of a polar dielectric has its own dipole moment; but the molecular dipoles are randomly oriented in all directions, so that the net dipole moment as a whole is zero.

3.3 Basic definitions

1. Electric dipole

Two equal and opposite electric charges are separated by a small distance is called an electric dipole.

Consider two opposite charges of magnitudes +q and -q are separated by a small distance d as shown in Fig.2.1. These two electric charges constitute electric dipole. Some of the examples of the electric dipoles are HCl, CO_2 andWater etc.

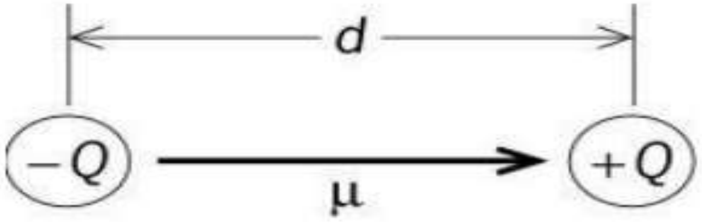


Fig.2.2. Electric dipole

2. Electric dipole moment (μ)

If two opposite charges are separated by a certain distance, a dipole moment μ arises. Mathematically, it isthe product of magnitude of charge & distance of separation between the charges.

$$\boxed{\mu = q.d} \quad \longrightarrow (3.1)$$

It is vector quantity pointing from a negative charge towards positive charge.

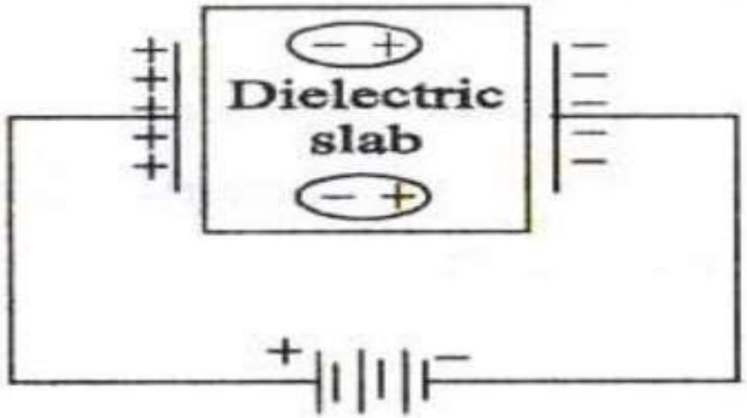
The S.I. unit of Dipole moment is coulomb-meter(C-meter) or Debye.

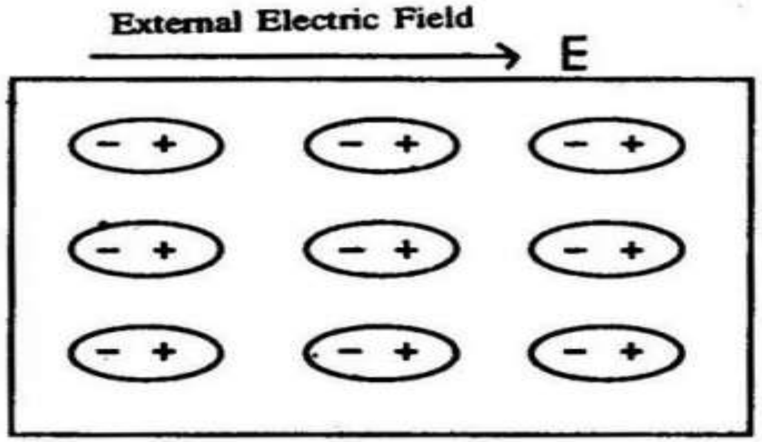
$$1\text{debye}=3.3\text{x}10^{-30}\text{c-m}$$

3. Polarization in dielectrics

The process of producing electric dipoles by an electric field is called polarization in dielectrics.

When an electric field is applied to the dielectrics, the field exerts a force on each positive charge in its own direction, as result the positive charges are displaced in the direction of field while negative charges are displaced in the opposite direction. Consequently, the displacement of these charges produces electric dipoles throughout the dielectric material. This process is known as polarization in dielectrics.





4. Polarizability(α)

If the strength of the electric field E is increases, the strength of the induced dipole moment also increases. The induced dipole moment is proportional to the intensity of electric field.

$$\vec{\mu} \alpha E$$

$$\vec{\mu} = \alpha E \longrightarrow (3.2)$$

Where $\boldsymbol{\alpha}$ is the proportionality constant, called Polarizability.

5. Polarisation vector ($\vec{P}$)

If μ is the average dipole moment per molecule and N is the number of molecules per unit volume, the polarization vector ($\vec{P}$) is defined as dipole moment per unit volume of the dielectric material.

$$\vec{P} = N\vec{\mu} \qquad \longrightarrow (3.3)$$

Units: Coulomb/m^2

6. Electric susceptibility (χ_e)

The electric susceptibility χ_e of a dielectric material is a measure of how easily it polarizes in response to an electric field.

When a dielectric material is placed in an electric field E, then polarization takes place. The polarization vector $\vec{P}$ is proportional to the electric field E.

$$\vec{P} \alpha E$$

$$\vec{P} = \chi_e E \longrightarrow (3.4)$$

Where χ_e is called electric susceptibility.

Units: No units

7. Permittivity

It is defined as the ability of the material to permit the passage of electric field through it. The permittivity of any dielectric material can be represented as $\varepsilon = \varepsilon_r \varepsilon_0$.

Where ε_r is called the relative permittivity or dielectric constant of the dielectric material and ε_0 is permittivity of free spaceand is equal to 8.85×10^{-12} F/m.

It is a dimensionless quantity.

8. Dielectric constant

It is defined as the ratio of permittivity of medium to permittivity of free space.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \longrightarrow (3.5)$$

The dielectric constant can also be obtained from electric flux density (D) and an applied electric field (E). The number of electric force lines passing per unit area perpendicular to field is called electric flux density (D). It is proportional to the applied electric field (E).

$$D \alpha E$$

$$D = \varepsilon\, E \text{ (in medium) } \longrightarrow (3.6)$$

Where ε is the proportionality constant, called permittivity of medium.

$$D = \varepsilon_o\, E \text{ (in a free space) } \longrightarrow (3.7)$$

3.4. Types of polarization mechanisms:

When a dielectric material is place in an external dc electric field, it gets polarized. The four types of polarization which occur in dielectrics are:

1. Electronic polarization,
2. Ionic polarization,
3. Orientation or dipole polarization,
4. Space charge or interfacial polarization

3.4.1. Electronic polarization

When electric field applied is applied on dielectric material then all the positive nuclei of atoms move in the field direction and the negative electron cloud of atoms move in opposite direction, hence dipoles will be formed. This phenomenon is known as electronic polarization.

Examples: Mono atomic gases exhibit only electronic polarization: Helium (He), Neon (Ne), Argon (Ar), Krypton (Kr), Xenon (Xe) and Radon (Rn).

The induced dipole moment (μ_e) is proportional to the electrical field strength (E).

$$\text{i.e., } \mu_e \alpha\ E$$

$$\mu_e = \alpha_e\ E \qquad \longrightarrow (3.8)$$

Whereα_e isproportionalityconstantanditisknownaselectronicpolarizability.

The electronicpolarizability for a rare or noble gas atom is given by

$$\boxed{\alpha_e = 4\pi\varepsilon_0 R^3}$$

(i) Without electric field (E=0)

Let us consider an atom of dielectric material with atomic number Z, then the charge on its nucleus is +Ze. The nucleus is surrounded by electron cloud of charge –Ze which is distributed over a sphere of radius R as shown in Fig .2.4. Thecentersoftheelectroncloudandthepositivenucleusareatthesamepointandhenc ethereisno dipole moment

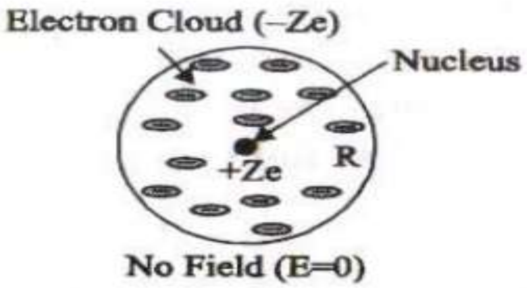


Fig.2.4. Atom without any electric field.

Therefore, the charge density for electron cloud is given by

$$\rho = \frac{\text{Total negative charge of electron cloud}}{\text{Volume of the atom}} = \frac{-Ze}{\frac{4}{3}\pi R^3} = \frac{-3}{4}\frac{Ze}{\pi R^3} \longrightarrow (3.9)$$

(ii) With field ($E \neq 0$)

When the atom of dielectric material is subjected to electric field, two types of phenomena occur.

(i) Lorentz force arises due to the electric field which separates the nucleus and the electron cloud from their equilibrium positions in opposite directions. Therefore, due to the Lorenz force theelectroncloudandthenucleusmoveinoppositedirectionsandtheyareseparatedb ya distance'x'wherethereisaformationofelectricaldipoleintheatom as shown in Fig.2.4 (b).

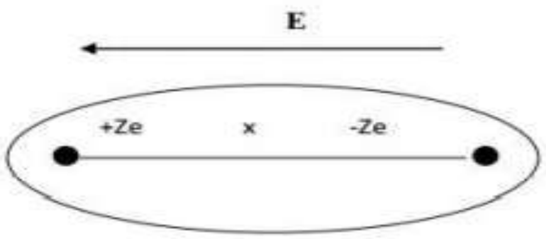


Fig.2.4. Atom with an electric field ($E \neq 0$).

(ii) Coulomb attractive force arises between the nucleus and the electron cloud after separation which tries to maintain the original equilibrium position. When these two forces are equal and opposite, there will be a new equilibrium between the nucleus and electron cloud of the atom.

*Lorentzforce*betweenthenucleusandtheelectron F_L=chargexelectricalfield

$$= -ZeE \longrightarrow (3.10)$$

Coulombattractiveforce (F_C)

betweenthenucleusandtheelectroncloudbeingseparated at a distance$x$ is

$$= +Ze \text{ X } \frac{\text{Total negative charges(Q)enclosed in the sphere of radius x}}{4\pi\varepsilon_0 x^2} \longrightarrow (3.11)$$

The total negative charge enclosed in the sphere of radius x

=Charge density of electrons (ρ) X Volume of the sphere.

$$= \frac{-3}{4}\frac{Ze}{\pi R^3} \text{ X } \frac{4}{3}\pi x^3$$

$$= -\frac{Zex^3}{R^3} \longrightarrow (3.12)$$

Substituting equation (2.11) in equation (2.10), we have

$$\text{Coulombattractiveforce } (F_C) = +Ze \text{ X } \frac{\frac{Zex^3}{R^3}}{4\pi\varepsilon_0 x^2}$$

At equilibrium, the Coulomb force and Lorentz force are equal and opposite. Hence

i.e., $F_L = F_C$

$$-ZeE = \frac{Z^2e^2x}{4\pi\varepsilon_0 R^3}$$

$$x = \frac{4\pi\varepsilon_0 R^3 E}{Ze} \longrightarrow (3.14)$$

Therefore, the displacement of electron cloud(x) is proportional to the applied electric filed E.

Due to this displacement atom act as dipole.

Therefore, the induced dipole moment μ_e is the product of magnitude of charge (Ze) & distance of separation between the charges (x).

$$\mu_e = Ze.x \longrightarrow (3.15)$$

Substituting equation (2.13) in equation (2.14), we have

$$\mu_e = Ze.\frac{4\pi\varepsilon_0 R^3 E}{Ze}$$

$$\mu_e = 4\pi\varepsilon_0 R^3 E$$

$$(or) \mu_e \alpha\ E$$

$$\mu_e = \alpha_e E \longrightarrow (3.16)$$

Where $\alpha_e = 4\pi\varepsilon_0 R^3$ is called electronic polarizability, which is depending on the volume of the atom and is independent of temperature.

3.4.2. Ionic polarization

When an electric field is applied on ionic dielectric material then positive ions move in the field direction where as negative ions move in the opposite direction, hence dipoles will be formed. This phenomenon is known as ionic polarization.

Examples: Ionic solids (NaCl) exhibit ionic polarization.

The induced dipole moment (μ_i) due to ionic polarization is proportional to the electrical field strength (E).

$$\text{i.e., } \mu_i \alpha\ E$$

$$\mu_i = \alpha_i\ E$$

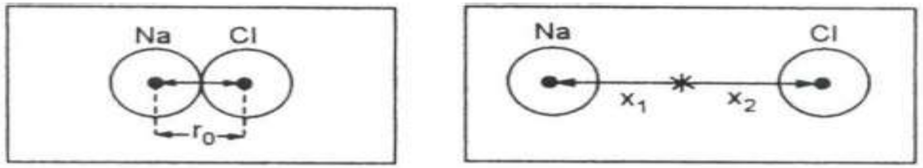
Whereα_e isproportionalityconstantanditisknownaselectronicpolarizability.

The ionicpolarizability for an ionic solid is given by

$$\boxed{\alpha_i = \frac{e^2}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right)}$$

Calculation for ionicpolarizability(α_i)

Let us consider there are one cation and one anion present in each unit cell of NaCl ionic crystal.Whenanelectricalfield(E)isappliedonanionicdielectric crystal,thereisashiftofoneionwith respecttoanotherfromtheirmeanpositions.Thepositiveionsdisplaceinthedirectionofapplied electricalfieldthroughthedistancex_1. The negative ions displace in opposite direction through the distance x_2 as shown in Fig.2.5.



(a) Without filed (b) With filed

Fig 4.5. Ionic polarization of NaCl crystal

From Fig 4.5, thenetdistancebetweentwoions $x = x_1 + x_2$

Therefore, the resultant dipole moment per unit cell is $\mu_i = e(x_1 + x_2) \longrightarrow (3.17)$

Whentheionsaredisplacedfromtheirmeanpositionsintheirrespectivedirections then therestoring forces appear on the ions which tend to move the ions back to their mean position. The restoring force produced is proportional to the displacement.

For Positive ion

The restoring force acting on the positive ion $F \alpha x_1$

$F = \beta_1 x_1 \longrightarrow (3.18)$

For Negative ion

The restoring force acting on the negative ion $F \alpha x_2$

$F = \beta_1 x_2 \longrightarrow (3.19)$

Whereβ_1 and $\beta_2$arerestoringforceconstantswhichdependuponthemassesofionsandangular frequencyofthemoleculeinwhichionsarepresent.

If 'm' isthemassofpositiveion and 'M'isthemassofnegativeion and $\omega_0$is the angular frequency,then

$$\beta_1 = m\omega_0^2 \text{ and } \beta_2 = M\omega_0^2 \longrightarrow (3.20)$$

At equilibrium the force and restoring force will be equal and opposite. Hence

$$F = \beta_1 x_1 = \beta_2 x_2$$

Hence, $x_1 = \frac{F}{\beta_1}$ *and* $x_2 = \frac{F}{\beta_2} \longrightarrow (3.21)$

We know that, F = eE⟶(3.22)

Substituting equation (2.24) in equation (2.23), we have

Thus, $x_1 = \frac{eE}{m\omega_0^2}$ and $x_2 = \frac{eE}{M\omega_0^2} \longrightarrow (3.23)$

Therefore, the resultant dipole moment per unit cell is $\mu_i = e(x_1 + x_2)$

$$= e\left(\frac{eE}{m\omega_0^2} + \frac{eE}{M\omega_0^2}\right)$$

$$= \frac{e^2 E}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right) \longrightarrow (3.24)$$

But $\mu_i = \alpha_i E \longrightarrow (3.25)$

Comparing equations (2.26) and (2.27) we get

$$\alpha_i E = \frac{e^2 E}{\omega_0^2}\left(\frac{1}{\mathrm{m}} + \frac{1}{M}\right)$$

$$\boxed{\alpha_i = \frac{e^2}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right)} \quad \longrightarrow (3.26)$$

Thus, ionic polarisability is inversely proportional to the square of the natural frequency of the ionic molecule and directly proportional to its reduced mass $\left(\frac{1}{m} + \frac{1}{M}\right)$.

3.4.3 Orientation polarization (Dipolar polarization)

Orientation polarization arises in dielectric materials which possess molecules with permanent dipole moment (i.e., in polar molecules).

Examples: Dipolar polarization or orientation takes place only in polar molecules such asH_2O, HCl, NH_3, CH_3Cl and CO etc.

The induced dipole moment (μ_0) due to orientation polarization is proportional to the electrical field strength (E).

$$\text{i.e., } \mu_0 \alpha\ E$$

$$\mu_0 = \alpha_0\ E$$

Whereα_0 isproportionalityconstantanditisknownasorientationpolarizability.

The orientationpolarizability for polar dielectric medium is given by

$$\boxed{\alpha_0 = \frac{\mu^2}{3K_BT}}$$

Explanation

(i) Without electric field (E=0)

Polar Molecules have permanent dipole moments even in the absence of an electric field and yet they have net zero dipole moment due to the random orientation of dipoles as shown in Fig 4.6.

(ii) With field ($E \neq 0$)

When an electric field is applied on the dielectric medium with polar molecules, the electric field tries to align the dipoles along its direction (Fig.4.6).Due to this there is a resultant dipole moment in the dielectric medium and this process is called orientation polarization. Orientation polarization depends on temperature, when the temperature is increased, thermal energy tends to disturb the alignment.

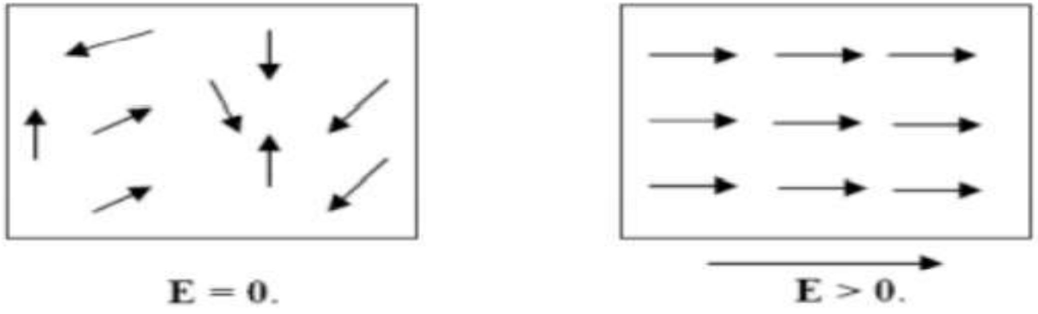


Fig.4.6.Orientation polarization

3.4.6 Total polarization

The total polarization is the sum of electronic polarization, ionic polarization, orientation polarization and space-charge polarization. But space-charge polarization is very small when compared to other polarization mechanisms and it is not common in most of the dielectrics. So, it can be neglected.

Therefore, The total polarizability $\alpha_T = \alpha_e + \alpha_i + \alpha_o$

$$= 4\pi\varepsilon_0\ R^3 + \frac{e^2}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right) + \frac{\mu^2}{3K_BT}$$

We know that total polarization $P = NE\alpha$

$$\therefore P = NE\left[4\pi\varepsilon_0\ R^3 + \frac{e^2}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right) + \frac{\mu^2}{3K_BT}\right] \longrightarrow (3.28)$$

This equation is called as Langevin-Debye equation.

3.5. Local (internal) field or Lorentz relation

Definition

When a dielectric material is subjected to an external electric field, each of the atoms develops a dipole moment and act as a electric dipole. Hence the resultant field at a given atom will be the sum of applied electric field and the electric field due to surrounding dipoles. This resultant field acting atanatominadielectric is called local field (or) internal field E_{int} and is different from the applied external field E_{app}.This was first calculated by Lorentz.

Calculation of local field (or) internal field (E_{int})

To calculate an expression for local electric field on a dielectric molecule or an atom, we consider a dielectric material in the electric field of intensity E, between the capacitor plates so that the material is uniformly polarized, as a result opposite type of charges are induced on the surface of the dielectric near the capacitor plates as shown in Fig.4.9.

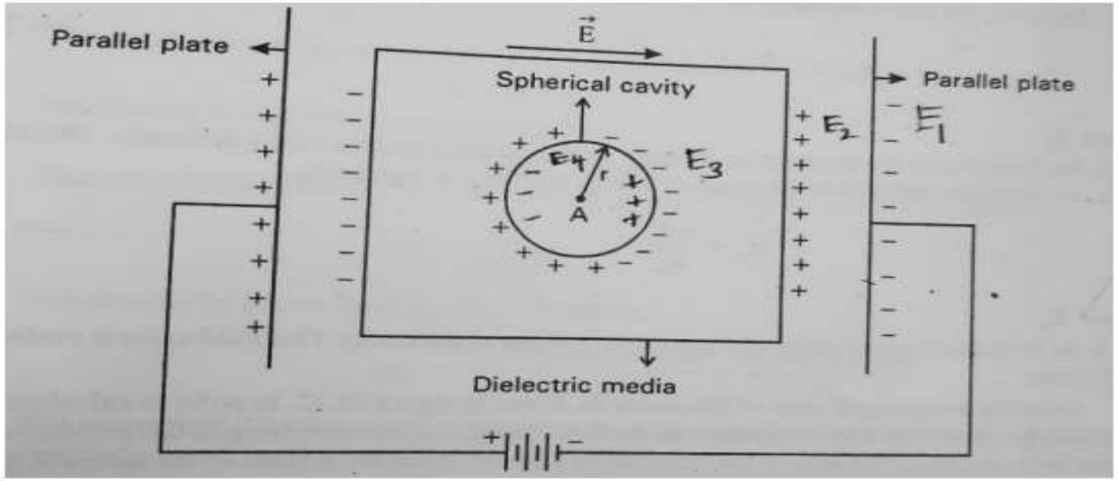


Fig.4.9. Local field (or) Internal field E_{int}

Let us assume a small sphere region or cavity of radius 'r' around the atom A inside the dielectric at which the local field is to be calculated. It is also assumed that the radius of the cavity is large compared to the radius of the atom. i.e., there are many atomic dipoles within the sphere.

The electric field acting on the central atom of the sphere is called local field (or) internal field, which is arises due to sum of following fields.

$$E_{int} = E_1+E_2+E_3+E_4 \longrightarrow (2.29)$$

Where,

E_1 = Field at A due to the charges on the plates (externally applied).

E_2 = Field at A due to the polarized charges induced on the two sides of dielectric.

E_3 = Field at A due to the polarized charges induced on the surface of the spherical cavity.

E_4 = Field at A due to the atomic dipoles inside the spherical cavity.

Now, let us calculate E_1, E_2, E_3, E_4 values one by one as follows.

Field E_1

When a dielectric medium is polarized due to an electric field E, the displacement vector D is given by

$$D = \varepsilon_0 E + P \longrightarrow (3.30)$$

From the field theory, the filed at A due to the charges on the plates is given by

$$D = \varepsilon_0 E_1 \longrightarrow (3.31)$$

∴ Equating equation (2.31) and (2.32), we get

$$\varepsilon_0 E_1 = \varepsilon_0 E + P$$

Dividing the above equation by ε_0, we get

$$E_1 = E + \frac{P}{\varepsilon_0} \longrightarrow (3.32)$$

Field E_2

E_2 is the field at A due to the polarized charges induced on the two sides of dielectric. This field acts in a direction opposite to the external field. Fromthefieldtheory,wehave

$$E_2 = -\frac{P}{\varepsilon_0} \longrightarrow (3.33)$$

Field E_3

E_3 is the field at A due to the polarized charges induced on the surface of the spherical cavity. This field value was calculated by Lorentz as given below.

Consider a magnified or enlarged view of the imagined spherical cavity as shown in Fig.4.10. A small elemental ring is cut with area 'dA' perpendicular to the field direction and is making between θ and θ+dθ, where θ represents the direction with respect to the applied field direction.

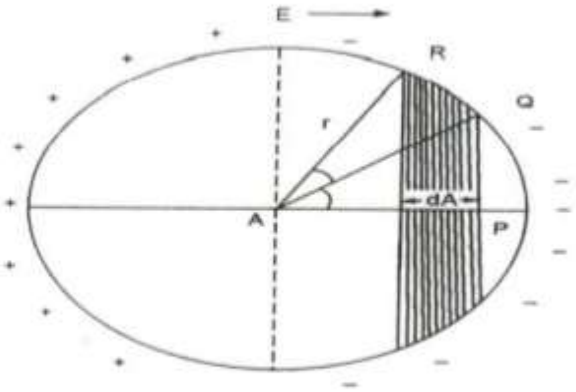


Fig.4.10. Enlarged view of the imagined spherical cavity

From the figure, the area of the small elemental ring along the surface of the sphere is given by

$$dA = 2\pi(PQ)(QR) \longrightarrow (3.34)$$

From the triangle APQ, $\sin\theta = \frac{PQ}{r}$ or $PQ = r\sin\theta \longrightarrow (3.35)$

and from the sector AQR, $d\theta = \frac{QR}{r}$ or $QR = rd\theta \longrightarrow (3.36)$

Substituting equations (3.35) and (3.36) in equation (3.34)

$$dA = 2\pi(r\sin\theta)(rd\theta)$$

$$dA = 2\pi r^2 \sin\theta\, d\theta \longrightarrow (3.37)$$

From the definition of polarization (i.e., $P = \frac{q}{A}$),The charge dq on the surface dA is equal to the product of the normal component of the polarization and the surface area.

$$\text{i.e., } dq = P_N .dA \longrightarrow (3.38)$$

The polarization P is parllel to E. Its component normal to dA is $P_N = P\cos\theta$.

$$dq = P\cos\theta\, dA \quad \longrightarrow (3.39)$$

Substuting dA value in equation (3.39)

$$dq = P\cos\theta .\ 2\pi r^2 \sin\theta d\theta \longrightarrow (3.40)$$

The field due to the charge dq is denoted by dE_3 at 'A' is given by (Coulomb's law)

$$dE_3 = \frac{dq\, Cos\theta}{4\pi\varepsilon_0 r^2} \qquad \longrightarrow (3.41)$$

Substuting equation (3.40) in equation (3.41)

$$dE_3 = \frac{(P\cos\theta.2\pi r^2\sin\theta d\theta)\cos\theta}{4\pi\varepsilon_0 r^2} = \frac{P\cos^2\theta\sin\theta d\theta}{2\varepsilon_0} \longrightarrow (3.42)$$

Therefore, the field at a due to the surface charge on the cavity is obtained by integrating over the whole surface of the sphere.

$$\int_0^{\pi} dE_3 = \frac{P}{2\varepsilon_0}\int_0^{\pi}\cos^2\theta\,\sin\theta d\theta \longrightarrow (3.43)$$

$$E_3 = \frac{P}{2\varepsilon_0}\int_0^{\pi}\cos^2\theta\,\sin\theta d\theta \longrightarrow (3.44)$$

$$= \frac{P}{2\varepsilon_0}.\frac{2}{3} = \frac{P}{3\varepsilon_0}\left(\because \int_0^{\pi}\cos^2\theta\,\sin\theta d\theta = \frac{2}{3}\right)$$

$$\therefore E_3 = \frac{P}{3\varepsilon_0},, \longrightarrow (3.45)$$

Field E4

E_4 is the field at A due to the atomic dipoles inside the spherical cavity which depends on the crystal structure. This field E_4 is zero for spherically symmetric system (cubic structure) because the dipoles will cancel with each other.

$$\therefore E_4 = 0 \longrightarrow (3.46)$$

Hence, substituting all the four field values from the equations (3.32), (3.33), (3.45) and (3.46) in equation (3.29)

$$E_{int} = E + \frac{P}{\varepsilon_0} - \frac{P}{\varepsilon_0} + \frac{P}{3\varepsilon_0} + 0 \qquad \longrightarrow (3.47)$$

or

$$\boxed{E_{int} = E + \frac{P}{3\varepsilon_0}} \qquad \longrightarrow (3.48)$$

This equation is known as Local filed or internal field. Thus, it is observed that the local field is greater than the electric field applied by an additional factor $\frac{P}{3\varepsilon_0}$.

3.6. Claussius-Mosotti Equation

The relation between dielectric constant ε_r (macroscopic quantity) and polarizability α (microscopic quantity) of atoms in a dielectric is known as Claussius-Mosotti Equation.

$$\boxed{\frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2}}$$

This relation is known as Claussius-Mosotti Equation.

Proof

When a dielectric material is place in an external electric field E, it gets polarized .ie., dipole moments are induced. If the strength of the electric field E is increased, the strength of the induced dipole moment also increases. The induced dipole moment is proportional to the intensity of electric field.

$$\vec{\mu} \alpha E_{int}$$

$$\vec{\mu} = \alpha\, E_{int} \longrightarrow (3.49)$$

Where α is the proportionality constant, called Polarizability and E_{int} is the local field.

If $\boldsymbol{\mu}$ is the average dipole moment per molecule and N is the number of molecules per unit volume, the polarization vector $(\vec{\boldsymbol{P}})$ is defined as dipole moment per unit volume of the dielectric material

$$P = N\vec{\mu} \longrightarrow (3.50)$$

Substuting equation (2.49) in equation (2.50),we have

$$P = N\alpha E_{int} \longrightarrow (3.51)$$

We know that

$$E_i = E + \frac{P}{3\varepsilon_0}$$

$$P = N\alpha(E + \frac{P}{3\varepsilon_0})$$

$$P = N\alpha E + N\alpha\frac{P}{3\varepsilon_0}$$

$$P - N\alpha\frac{P}{3\varepsilon_0} = N\alpha E$$

$$\left(1 - \frac{N\alpha}{3\varepsilon_0}\right)P = N\alpha E$$

$$P = \frac{N\alpha E}{\left(1 - \frac{N\alpha}{3\varepsilon_0}\right)} \longrightarrow (3.52)$$

We also know that

$$P = \varepsilon_0 E(\varepsilon_r - 1) \longrightarrow (3.53)$$

Equating the equations (3.53) and (3.54)

$$\varepsilon_0 E(\varepsilon_r - 1) = \frac{N\alpha E}{\left(1 - \frac{N\alpha}{3\varepsilon_0}\right)}$$

$$1 - \frac{N\alpha}{3\varepsilon_0} = \frac{N\alpha E}{\varepsilon_0 E(\varepsilon_r - 1)}$$

$$1 = \frac{N\alpha E}{\varepsilon_0 E(\varepsilon_r - 1)} + \frac{N\alpha}{3\varepsilon_0}$$

$$1 = \frac{N\alpha}{3\varepsilon_0}\left[\frac{3}{(\varepsilon_r - 1)} + 1\right]$$

$$\frac{N\alpha}{3\varepsilon_0} = \frac{1}{\frac{3}{(\varepsilon_r - 1)} + 1}$$

$$\frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{3 + \varepsilon_r - 1}$$

$$\frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \longrightarrow (3.54)$$

The above relation is known as Claussius-Mosotti equation.

MAGNETISM

The origin of infatuation between the materials

Basic Definitions

Magnetism

A substance that attracts pieces of iron (or) steel is called "Magnet". This property of a substance is called "magnetism.

Magnetic Poles:

Poles of magnet are regions near the two ends of a magnet with maximum power of attraction.

The strength of the pole is called **pole strength** denoted by ***m*.** The **S.I. unit of pole strength is *Ampere-Meter.***

The distance between two magnetic poles is called "magnetic length" (2*l*).

Magnetic Dipole

Two equal and opposite charges separated by a small distance is called an electric dipole. Similarly a north pole and south pole separated by a small distance 2*l* **(magnetic length)** constitute a magnetic dipole.

For example: A bar magnet, a compass needle etc. are the magnetic dipoles. And also a current loop behaves as a magnetic dipole.

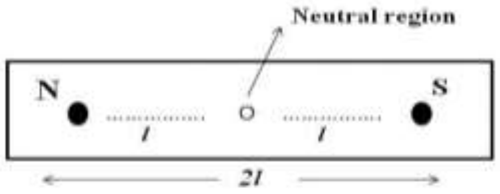


Fig : Magnetic dipole

Magnetic Dipole Moment:

The behavior of magnetic dipole is described by the magnetic dipole moment.

(a)In the case of bar magnet:

It is defined as the product of pole strength (m) and magnetic length (2*l*).

$$\mu_m = m\,(2l)$$

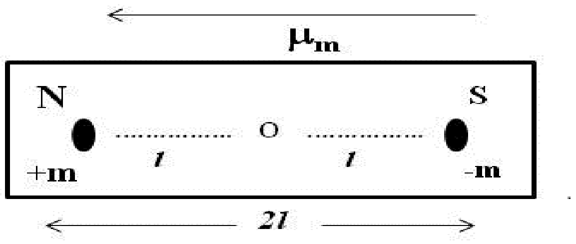


Fig : Magnetic dipole moment

It is a vector quantity. It is directed from South Pole to North Pole.

The S.I.Unit of magnetic dipole moment: Ampere – meter ^{2} (A-m^2).

(b) In the case of current loop:

A current carrying loop behaves as a magnetic dipole.

Consider a current carrying conductor loop of wire as shown fig.

The current (I) establishes a magnetic field around the loop.

By right hand palm rule, the upper face of the loop acts a S- pole and the lower face act as N- pole.

The magnitude of dipole moment of current loop (μ_m) is

- Directly proportional to current (I) through the loop.
- Directly proportional to the area of cross –section (A).

$\mu_m \rightarrow I.A$

$\mu_m = K\ IA$

$\mu_m = IA$

Where K is a proportionality whose value is one

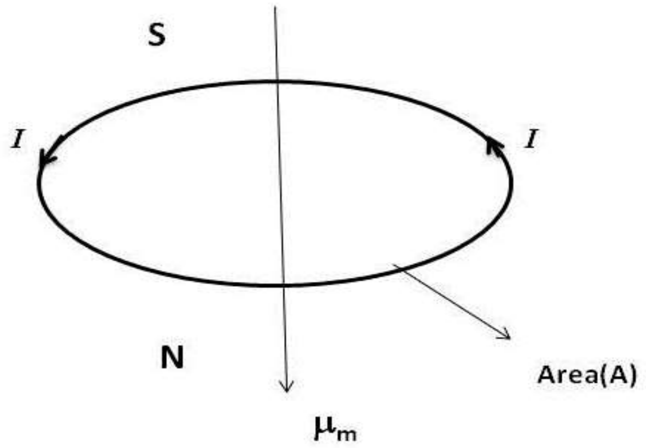


Fig : Current carrying conductor loop

Magnetic Field:

The space surrounding a magnet where magnetic force is experienced is called a magnetic field.
A magnetic field can be represented by drawing lines called “magnetic lines of force”. The lines go from North to South on the magnet.

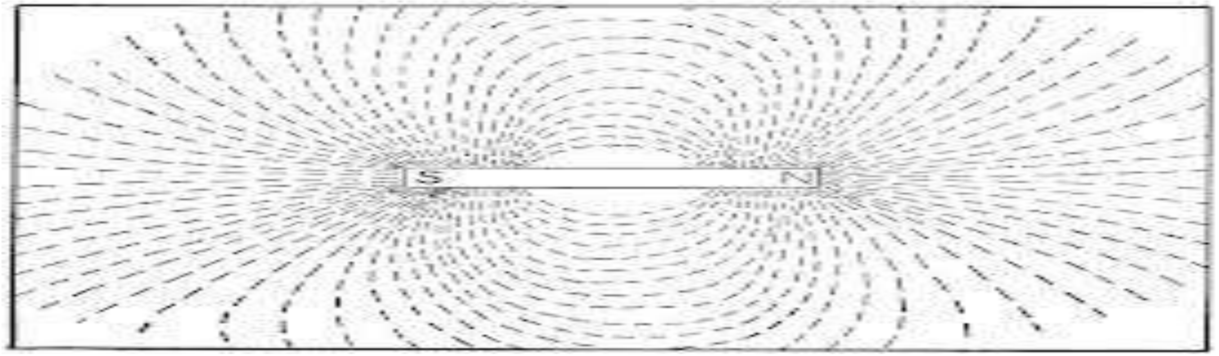
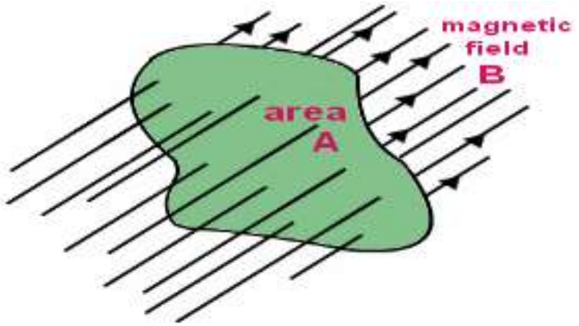


Fig: Magnetic field.

Magnetic Flux:

A group of magnetic lines of force is called “magnetic flux”.



The symbol for magnetic flux is Φ (phi).

The SI unit of magnetic flux is the Weber (Wb).

One Weber is equal to 1 x 10^8 magnetic field lines

Magnetic Flux Density:

Magnetic flux density is the amount of magnetic flux per unit area of a section, perpendicular to the direction of flux.

Magnetic flux density (B) = $\frac{\text{Magneticflux (Weber)}}{\text{Area } (m^2)}$ $\frac{\emptyset}{A}$

B = Tesla

Magnetization:

Magnetization in magnetic field is analogues to polarization of dielectric material in electrostatic field.

The process of converting a non-magnetic material into a magnetic material is known as “magnetization” or the process of producing magnetic dipoles by magnetic field is called magnetization.

Intensity of Magnetization (I or M)

When a material medium is placed in a magnetic field, it gets magnetized. To magnetize a material medium is to create magnetic dipole moments.

The magnetic dipole moment per unit volume of the material is called the intensity of magnetization I (or simply magnetization).

$$I = \frac{\text{Magnetic dipole moment}(\mu_m)}{\text{Volume (V)}} = \frac{\text{Length of magnet } (2l) \times \text{Pole Strength (m)}}{\text{Length of Magnet } (2l) \times \text{Area of cross –section (A)}}$$

$$= \frac{\text{Pole Strength (m)}}{\text{Area of Cross Section (A)}}$$

The S.I. Unit of magnetization is ampere / meter

Magnetic Field Strength (H):

The ability of magnetic field to magnetize a material medium is called its magnetic intensity or field strength. It is denoted by **H**.

The S.I. Unit of magnetic field strength is ampere / meter.

Magnetic Susceptibility (χ_m):

The word Susceptibility comes from the Latin word "susceptible" means the easily affected

The magnetic susceptibility of a material medium indicates how easily a material medium can be magnetized in the presence of magnetic field..

The intensity of Magnetization is directly related to the applied field strength H.

$$M \quad H$$

$$M = \chi_m H$$

Magnetic Susceptibility (χ_m) = $\frac{M}{H}$

Therefore; the magnetic susceptibility of a material is defined as the ratio of intensity of magnetization (I) developed in the material to the applied magnetic field (H).

=

Magnetic Permeability (μ):

In Latin, *per* means *through* and *meare* means *to pass.*

It is defined as the ability of the material to permit the passage of magnetic lines of force through it.

The Magnetic induction B is proportional to the applied Magnetic field intensity H.

$$B = \mu H$$

Magnetic Permeability(μ) = $\frac{B}{H}$

Where "μ" is the permeability of a medium.

$B = \mu_0 H$

For vacuum,

Where μ_0 is the proportionality constant and is also called permeability of the free space and its value is $4\pi \times 10^{-7}$ H m^{-1}.

Relative permeability (μ_r):

The ratio of permeability of medium to the permeability of free space is called relative permeability μ_r of the medium

$$\mu_r = \frac{\mu}{\mu_0}$$

It has no units.

The Relation between Relative Permeability and Magnetic Susceptibility:

When a magnetic material is magnetized by placing it in a magnetic field, the resultant field inside the material is the sum of the field due to the magnetization of the material and the original magnetizing field. The resultant field is called magnetic induction or magnetic flux density **B.**

$B = \mu_0(H+M)$

$\mu H = \mu_0(H+M)$ ($B=\mu H$ and $\mu = \mu_0\mu_r$)

$\mu_0\mu_r H = \mu_0 H(1+M/H)$

$\mu_r = (1+\chi_m)$

Where $\chi_m = M/H$

This is the relation between Relative Permeability and Magnetic Susceptibility.

Origin of Magnetism:

Magnetism originates from magnetic dipole moment. This magnetic dipole moment arises due to the rotational motion of charged particles.

According to modern view;

- All substances are made of atoms or molecules. An atom which consists of '+' vely charged nucleus at the centre and negatively charged electrons revolving around the nucleus in different orbits. This motion of electrons is called orbital motion as shown in fig. The orbiting elections constitute tiny current loops. These loops behave as the magnetic dipoles.
- The orbital motion of electrons around the nucleus gives rise to the orbital magnetic dipole moment (μ_{orbit}).
- The electrons also rotate around their own axes. This motion of electrons is called spin motion as shown fig. The spinning motion of electrons around their axes gives rise to the spin magnetic dipole m oment (μ_{spin}).
- The motion of the protons and neutrons within the nucleus also contributes to the total magnetic moment (($\mu_{nucleus}$). But the magnitude of the nuclear magnetic moment is (about 10^{-3} times) very small compared with the magnetic moment of electron and is usually neglected.

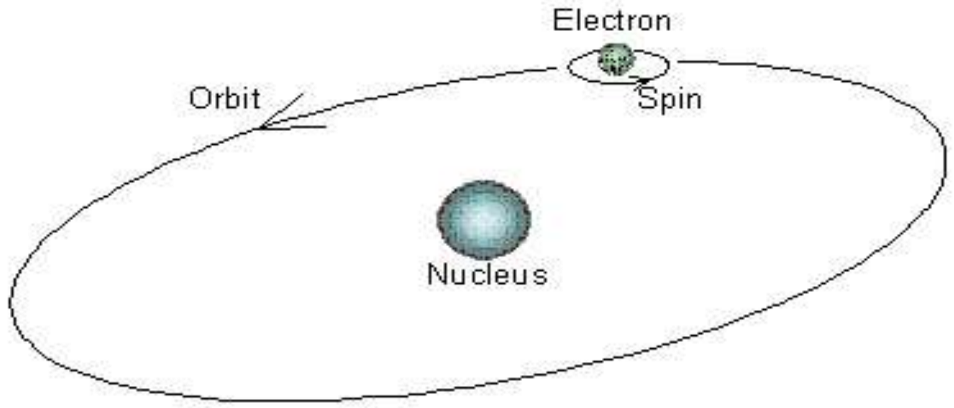


Fig: Motion of electron

Orbital magnetic dipole moment of electron (μ_{orbit}):

The magnetic dipole moment arises due to the orbital motion of electrons around the nucleus is called orbital magnetic dipole moment (μ_{orbit}) .

$$\mu_{Orbit,z} = - \mu_B .m_l$$

Proof:

Let us consider an electron of mass '**m**' and charge e revolving around the nucleus in a circular orbit o radius '**r**' with linear velocity '**v**' as shown in fig.

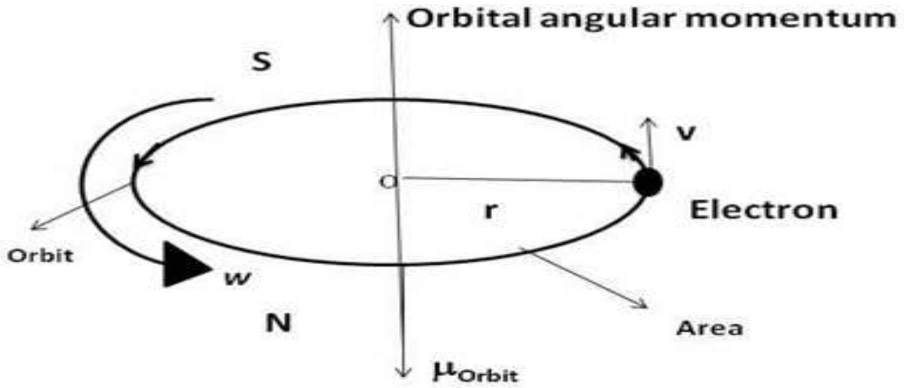


Fig : Orbital motion of electron

The revolving electron in circular orbit establishes a current is given by

$$I = \frac{\text{Charge of electron}}{\text{time period}} = \frac{-e}{T} \longrightarrow (1)$$

Where 'T' is the time taken by the electron to make one revolution around the nucleus

$$\text{i.e., } T = \frac{2\pi}{w} \longrightarrow (2)$$

Where *'w'* is the angular frequency of the electron

But relation between linear velocity 'v' and angular velocity can be written as

$$v = r\,w$$

$$\text{and } w = \frac{v}{r} \longrightarrow (3)$$

Substituting the equation (3) in (2),

$$T = \frac{2\pi r}{v} \longrightarrow (4)$$

Further, substituting the equation (4) in (1),

$$I = \frac{-ve}{2\pi r} \longrightarrow (5)$$

The current 'I' establishes a magnetic field around the circular orbit, so that the upper surface acts as South Pole and the lower surface acts as North Pole.

The Area of the orbit is $A = \pi r^2 \longrightarrow (6)$

Then the corresponding magnetic dipole moment is given by

$$\mu_{Orbit} = IA$$

$$= \frac{-ve}{2\pi r} x \pi r^2$$

$$= \frac{-evr}{2} \longrightarrow (7)$$

Dividing and multiplying the equation (7) by the mass "m' of electron.

$$\mu_{Orbit} = \frac{-evr}{2} \, x \, \frac{m}{m}$$

$$= \frac{-e(mvr)}{2m}$$

$$= \frac{-e\,(\vec{L})}{2m} \qquad \text{(But } L = \vec{mvr}\text{)}$$

$$\mu_{Orbit} = \frac{-e}{2m}\vec{L} \text{ (Orbital angular momentum)}$$

The – ve sign indicates that the orbital angular momentum and orbital magnetic dipole moment are in opposite directions.

Let us assume that the component of orbital angular momentum (L) is measured along the z- axis of a coordinate system. Then the measured component $L_Z$can have only the values is given by

$$L_Z = m_l \frac{h}{2\pi}$$

Where m_s is called orbital magnetic quantum number = 0, $\pm$1, $\pm$2, $\pm$3 ....

The orbital magnetic dipole moment (μ_{Orbit}) of electron itself also cannot be measured. Only; its component along any axis can be measured.

Let us assume that the component of orbital magnetic dipole moment (μ_{Orbit}) of electron is measured along the z- axis of a coordinate system. Then the measured component $\mu_{orbit,z}$can have only the two values is given by

$$\mu_{Orbit,z} = \frac{-e}{2m} L_z$$

$$\mu_{Orbit,z} = -\left(\frac{e}{2m}\right) m_l \frac{h}{2\pi}$$

$$\mu_{Orbit,z} = -\left(\frac{eh}{4\pi m}\right) m_l$$

$$\boxed{\mu_{Orbit,z} = -\mu_B . m_l}$$

Where $\mu_B = \frac{eh}{4m\pi}$ is known as Bohr magneton and its value is 9.27x 10^{-24} A-m^2.

Spin magnetic dipole moment of electron (μ_{spin}):

The magnetic dipole moment arises due to its spin motion is called spin magnetic moment (μ_{spin}) and is given by

$\mu_{Spin} = -g\left(\frac{e}{2m}\right)\vec{S}$ (Spin angular momentum)

The – ve sign indicates that the spin angular momentum and spin magnetic dipole moment are in opposite directions.

Where g is called land's g factor or Spectroscopic splitting factor

$$g = \frac{1+J(J+1)+S(S+1)-L(L+1)}{J(J+1)}$$

g_l=1 for orbital motion

g_s =2 for spin motion

An electron has an intrinsic spin angular momentum($\vec{S}$) itself cannot be measured. However, its component along any axis can be measured..

Let us assume that the component of spin angular momentum ($\vec{S}$) is measured along the z- axis of a coordinate system. Then the measured component $S_Z$can have only the values is given by

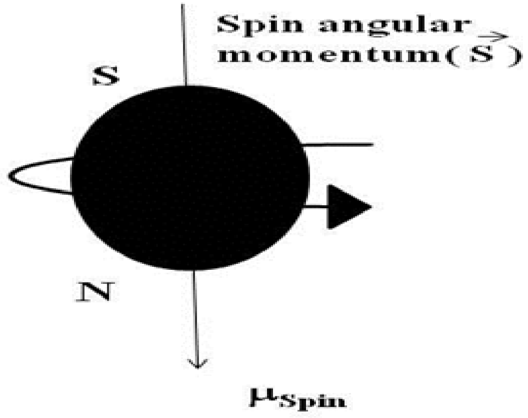


Fig: Spin motion of electron

$$S_Z = m_s \frac{h}{2\pi}$$

Where m_s is called magnetic spin quantum number $= \pm \frac{1}{2}$

$m_s = +\frac{1}{2}$ for spin up and

$m_s = -\frac{1}{2}$ for spin down

The spin magnetic dipole moment (μ_{Spin}) of electron itself also cannot itself be measured. Only; its component along any axis can be measured. Let us assume that the component of spin magnetic dipole moment ((μ_{Spin}) of electron is measured along the z- axis of a coordinate system. Then the measured component $\mu_{spin, z}$ can have only the two values is given by

$$\mu_{Spin,\,z} = -g\left(\frac{e}{2m}\right) S_z$$

$$\mu_{Spin,\,z} = -g\left(\frac{e}{2m}\right) m_s \frac{h}{2\pi}$$

$$\mu_{Spin,\,z} = -2\left(\frac{eh}{4\pi m}\right) m_s$$

$$\mu_{Spin,\,z} = -2\,(\mu_B)\, m_s$$

Where $\mu_B = \frac{eh}{4m\pi}$ is known as Bohr magneton and its value is 9.27×10^{-24} A-m^2.

Nuclear spin magnetic dipole moment ($\mu_{Nuclear}$):

The atomic nucleus contains protons and neutrons. They have intrinsic spin.

The spin motion of the protons and neutrons within the nucleus also contributes to the total spin magnetic dipole moment and is given by

$$\mu_{nuclear,\ spin} = \frac{eh}{4\pi M_N} = 5.525 \times 10^{-27}\ A\text{-}m^2$$

Where M_N is the Mass of the proton

But the magnitude of the nuclear magnetic dipole moment is(about 10^{-3} times) very small compared with the magnetic dipole moment of electron and is usually neglected.

Therefore, the magnetism mainly arises due to the orbital and spin magnetic dipole moments of electron.

Classification magnetic materials:

Magnetic materials are classified based on presence or absences of the permanent magnetic dipoles in a material. They are

1. Dia magnetic material
2. Para magnetic material
3. Ferro magnetic material
4. Anti Ferro magnetic material and
5. Ferri magnetic material

Diamagnetic materials:

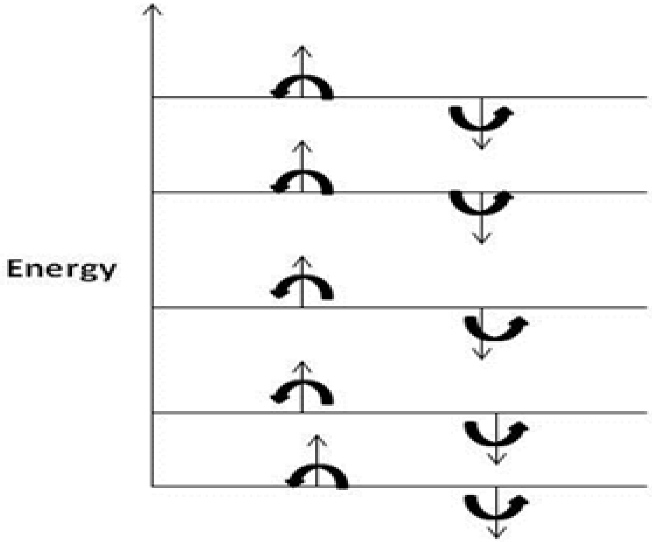
Those materials which when placed in a magnetic field are weakly or feebly magnetized in a direction opposite that of the applied magnetic field are called diamagnetic materials

Examples:

Bismuth, Copper, Zinc, Gold, Water, etc

Cause of diamagnetism:

In the Diamagnetic materials, there exist paired electrons, so the spins in two opposite directions are equal and hence magnetic dipole moments cancel with each other. i.e., the resultant magnetic dipole moment is equal to zero. Therefore, most of these materials do not have magnetism in the absence of magnetic field.



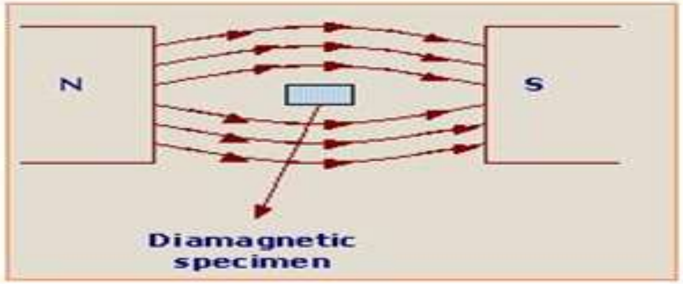
Effect of external magnetic field:

a) In the absence of external magnetic field, the atoms/molecule/ions of the diamagnetic substance have no net magnetic dipole moment. Hence, the material does not exhibit diamagnetism

b) When a diamagnetic material is placed in an external magnetic field, currents are induced in the current loops of atom/molecule/ion according to Faraday's law of electromagnetic induction. According to Lenz's law, these currents give rise to a magnetic field which opposes the applied magnetic field. Hence, the induced magnetic moments of atoms/molecule/ions are opposite to the applied magnetic field.

Properties:

- They don't possess permanent magnetic dipole moment.
- When a diamagnetic material is placed in a magnetic field, it is feebly magnetized in a direction opposite to that of the applied magnetic field.
- When a diamagnetic material is placed in a magnetic field, the magnetic lines force prefers to pass through the surroundings air rather than through the diamagnetic magnetic material.



- The magnetic flux density inside is small than that in the free space. Hence the relative permeability $\mu_r < 1$.
- The magnetic susceptibility (χ_m) is negative and small.
- The magnetic susceptibility (χ_m) is independent of temperature.

Para magnetic materials:

Those materials which when placed in a magnetic field are weakly or feebly magnetized in the direction of the applied magnetic field are called Para magnetic materials.

Examples:

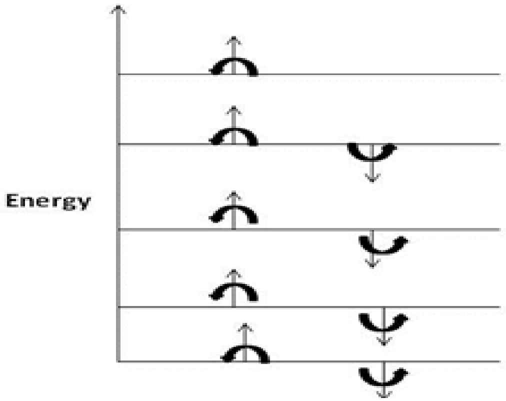
Aluminum, platinum, copper sulphate ($CuSo_4$), manganese, chromium etc.

Cause of paramagnetism:

In the case of paramagnetic materials, the spins in two opposite directions will not be equal. There exist some unpaired electrons which gives rise to spin magnetic dipole moment.

Hence the resultant magnetic dipole moment will not be equal to zero.

i.e., they possess permanent magnetic dipole moment.



Effect of external magnetic field:

c) In the absence of external magnetic field, the dipoles of the paramagnetic material are randomly oriented and, therefore, the net magnetic dipole moment of the material is zero. Hence, the material does not exhibit paramagnetism.

d) When a paramagnetic material is placed in an external magnetic field, the magnetic dipoles are partially aligned in the direction of the applied magnetic field. Therefore, the material is weakly or feebly magnetized in the direction of the applied magnetic field.

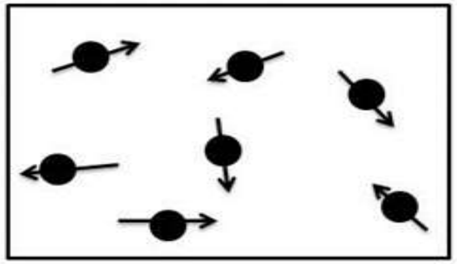


Fig: In the absence of external magnetic field (H=O)

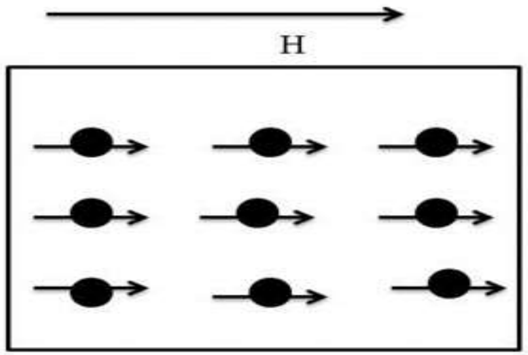
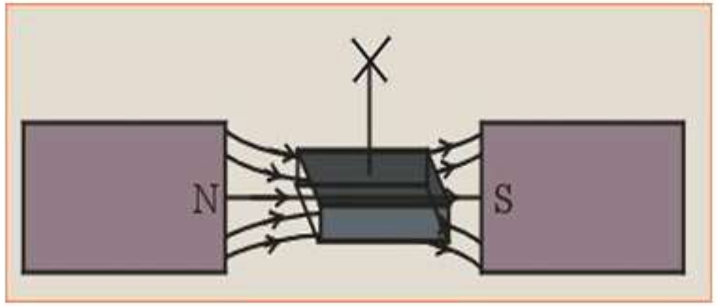


Fig: In the presence of external magnetic field

Properties:

- They possess permanent magnetic dipole moment.
- When a paramagnetic material is placed in a magnetic field, it is feebly or weekly magnetized in the direction of applied magnetic field.
- When a paramagnetic material is placed in a magnetic field, the magnetic lines force prefers to pass through the paramagnetic magnetic material rather than air.



- The magnetic flux density inside is greater than that in the free space. Hence the relative permeability $\mu_r > 1$.
- The magnetic susceptibility (χ_m) is positive and small.

- The magnetic susceptibility (χ_m) is inversely proportional to the temperature.

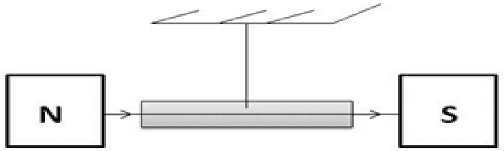
$$\chi_m = \frac{C}{T-\theta_C} \text{ (Curie-Weiss law)}$$

Where C ⟶ Curie constant

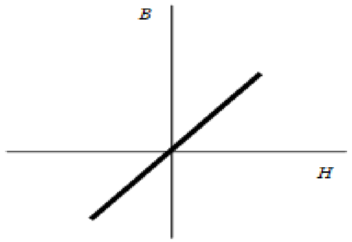
T ⟶ Absolute temperature and

θ_C ⟶ Curie temperature

- When the temperature is less than the Curie temperature, paramagnetic materials becomes diamagnetic material.
- When a rod of paramagnetic material is suspended freely in a uniform magnetic field, the rod comes to rest with its axis parallel to the applied field.



- The B-H curve of Para magnetic material as shown in fig.



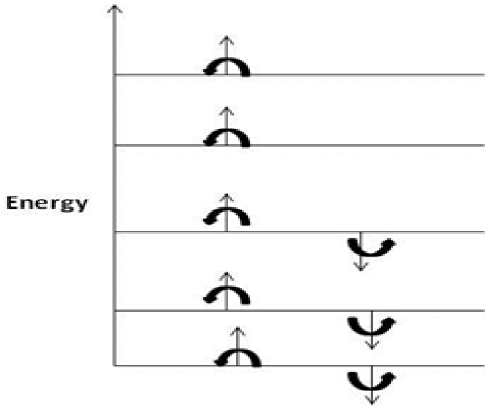
Ferro magnetic materials:

Those materials which when placed in a magnetic field are strongly magnetized in the direction of the applied magnetic field are called Ferro magnetic materials.

Examples:

Iron, Steel, Nickel, Cobalt, etc

Cause of Ferro magnetism:



- In a Ferro magnetic material, the number of unpaired electrons is more and most of the magnetic dipole moments align parallel to each other even in the absence of magnetic field. Hence they possess permanent magnetic dipole moment even in the absence of magnetic field.
- In Ferro magnetic materials, atoms grouped into regions called *domains,* instead of acting independently like paramagnetic materials.
  The region of space over which the magnetic dipole moments are aligned is called domain. A typical domain contains 10^{17} to 10^{21} atoms and occupies a volume of 10^{-12} to 10^{-8} m^3.

Effect of external magnetic field:

a) In the absence of external magnetic field, the domains of a ferromagnetic material are randomly oriented. In other words, within the domain, all magnetic dipole moments are aligned, but the direction of alignment varies from domain to domain. The result is that there is no net magnetic dipole moment. Therefore, a Ferro magnetic material does not exhibit magnetism in the normal state.

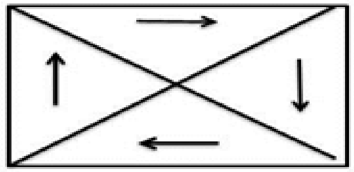


Fig: Without field

b) When a Ferro magnetic material is placed in an external magnetic field, a net magnetic dipole moment develops. This can occur in two ways:

i) By the movement of domain walls

ii) By the rotation of domain walls.

i) **By the movement of domain walls:**

- The movement of domain walls takes place in weak magnetic fields.
- Due to weak magnetic field applied to the material the magnetic dipole moments increases and hence the boundary of domains displaced, so that the volume of the domains changes as shown in fig.

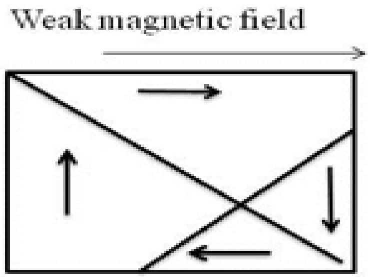


Fig: Displacement of domain walls With weak magnetic field

ii) By the rotation of domain walls

- The rotation of domain wall takes place in strong magnetic fields.
- Due to strong magnetic field applied to the material the magnetic dipole moments increases enormously and hence the domains rotate, so that the magnetic dipole moments are aligned in the direction of applied magnetic field as shown in fig.

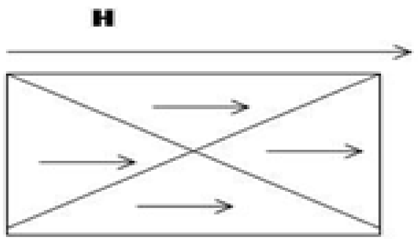
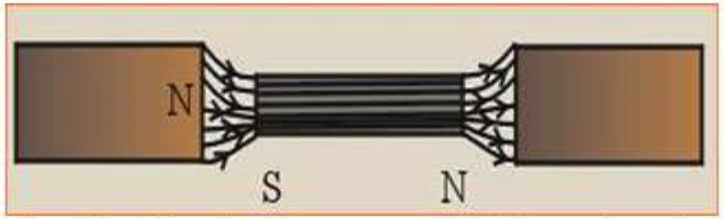


Fig : Rotation of domain walls in strong magnetic field

Properties:

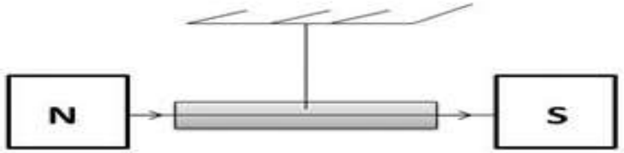
- They possess permanent magnetic dipole moment.
- When a Ferro magnetic material is placed in a magnetic field, it is strongly magnetized in the direction of applied magnetic field.
- When a Ferro magnetic material is placed in a magnetic field, the magnetic lines force tend to crowed into the Ferro magnetic material.



- The magnetic flux density inside is very greater than that in the free space. Hence the relative permeability $\mu_r >> 1$.
- The magnetic susceptibility (χ_m) is positive and very high.
- The magnetic susceptibility (χ_m) is inversely proportional to the temperature.

$$\chi_m = \frac{C}{T-\theta_C} \text{(Curie-Weiss law)}$$

- When the temperature is greater than the Curie temperature, ferromagnetic materials becomes Para magnetic material.
- When a rod of Ferro magnetic material is suspended freely in a uniform magnetic field, it quickly aligns itself in the direction of the applied magnetic field.



Classification of Ferro magnetic materials:

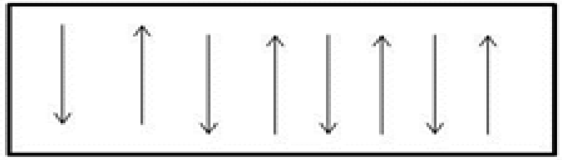
Depending upon the spin orientation of the electrons, ferromagnetic materials are classified into two types, they are 1.Antiferromagnetic materials

2. Ferri magnetic materials

Antiferromagnetic materials:

The materials which consist of anti-parallel spin magnetic dipole moment with same magnitudes are known as anti-ferromagnetic materials.

Examples:



Ferrous oxide (FeO),

Manganese oxide (MnO_4),

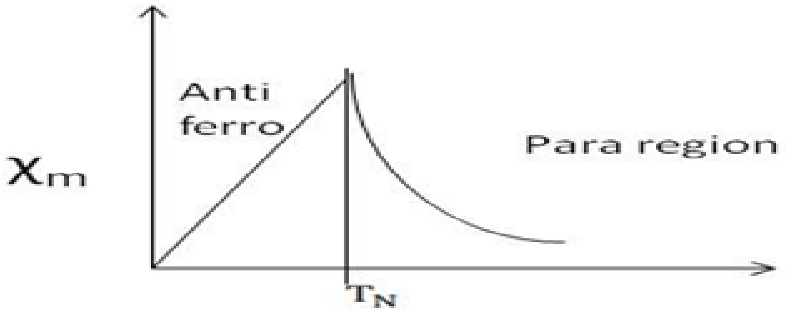
Manganese sulphideMnS),

Chromium Oxide (Cr_2O_3),

Ferrous Chloride ($FeCl_2$) etc

Properties:

- In this materials spin magnetic dipole moments are aligned in anti parallel manner.
- The magnetic susceptibility is very small and positive
- The magnetic susceptibility is inversely proportional to temperature. The variation of susceptibility with temperature is shown in fig.

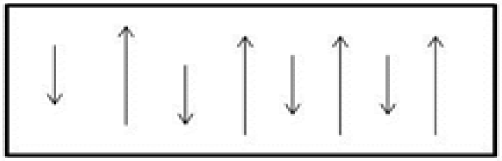


$$\chi_m = \frac{C}{T \pm \theta_C}$$

χ_m is increases gradually with temperature and attains a maximum value at Neel temperature(T_N) and then decreases with increase in temperature.

Ferrimagnetic materials:

The materials which consist of anti parallel magnetic dipole moments of different magnitudes are known as ferri magnetic materials.



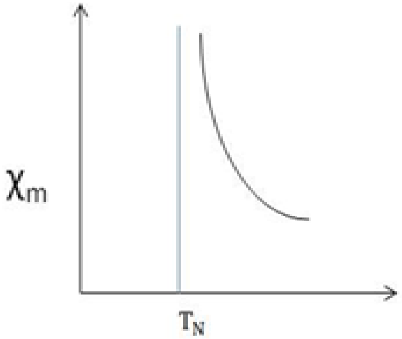
Examples:

Ferrites-general formula: $Me^{+2}\ Fe^{2}O_4$

Where Me^{+2} =divalent metal ions(Zn,Cu,Ni).

Properties:

- In this materials spin magnetic dipole moments of different magnitudes are aligned in anti parallel manner.
- The magnetic susceptibility is very high and positive
- The magnetic susceptibility is inversely proportional to temperature. The variation of susceptibility with temperature is shown in fig.



$$\chi_m = \frac{C}{T \pm \theta_C}$$

HYSTERISIS:-

When a Ferro magnetic substance (e.g. iron) is subjected to a cycle of magnetization, it is found that flux density B in the material lags behind the applied magnetizing force H. This phenomenon is known as hysteresis.

The term hysteresis is derived from the Greek word hysterein meaning to lag behind.

Hysterisis loop:

- If a piece of ferromagnetic material is subjected to one cycle of magnetization, the resultant B-H curve is a closed loop "a b c d e f a" is Called hysteresis loop.

i. In fig, O represents unmagnetised position of ferromagnetic material.

ii. As H is increased, B increases along oa and reaches its saturation value B_{max} at 'a' .At this stage, all the domains are aligned.

iii. If now H is gradually reduced, then it is found that curve follows the path ab instead of ao .At point b, H=0 but flux density in the material has a finite value $+B_r$ (=ob) called *residual flux density*. It is also called **remanence** or **retentivity**. Note that *B* lags behind H. This effect is called *hysteresis*.

iv. In order to reduce flux density in the material to zero, it is necessary to apply *H* in the reverse direction.When *H* is gradually increased in the reverse direction, he curve follows the path bc. At point c, B=0 and H= $-H_C$ .The value of *H* needed to wipe out residual magnetism is called coercive force (H_C).

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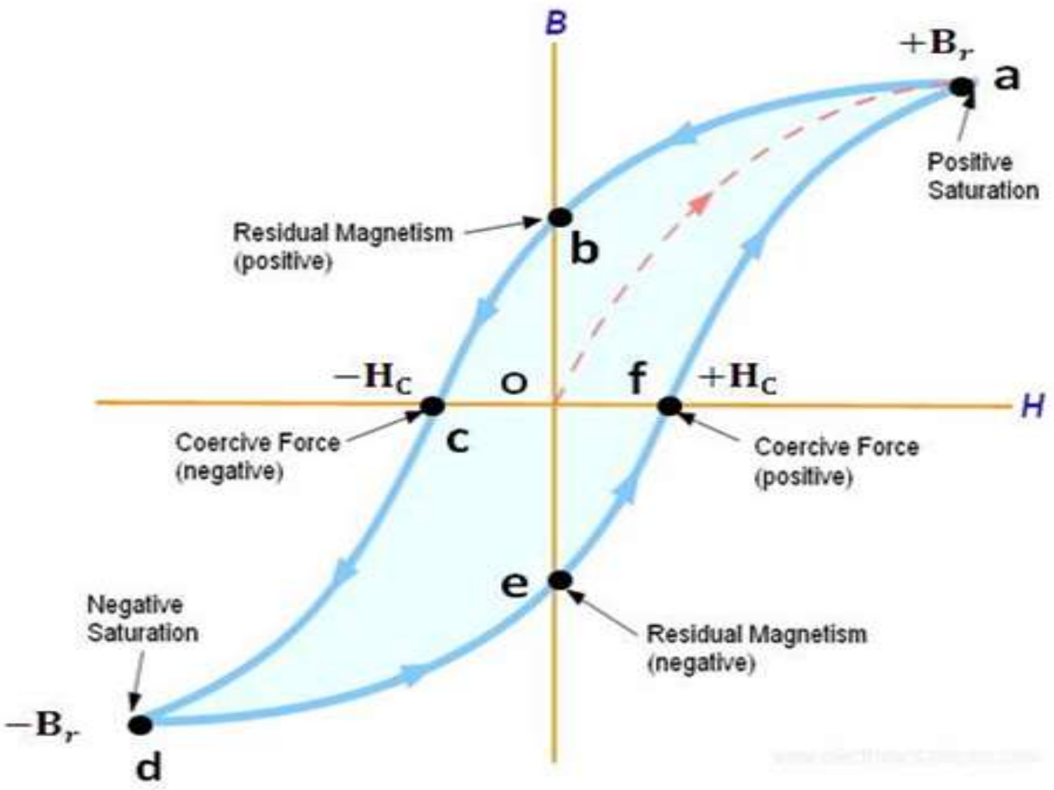
v. Now H is further increased in the reverse direction until point d is reached where the sample is saturated in the reverse direction ($-B_{max}$).If H is now reduced to zero point e is reached and the sample again retains magnetic flux density ($-B_r$).The remaining part of the loop is obtained by increasing current to produce H in the original direction. The curve "*a b c d e f a*" is called hysteresis loop. Thus hysteresis loop results because the domains do not become completely unaligned when H is made zero. The area enclosed by the hysteresis loop represents loss in energy. This energy appears in the material as heat.



B
+B_r
a
Positive Saturation
Residual Magnetism (positive)
b
−H_C
o
f
+H_C
H
c
Coercive Force (negative)
Coercive Force (positive)
e
Negative Saturation
Residual Magnetism (negative)
−B_r
d

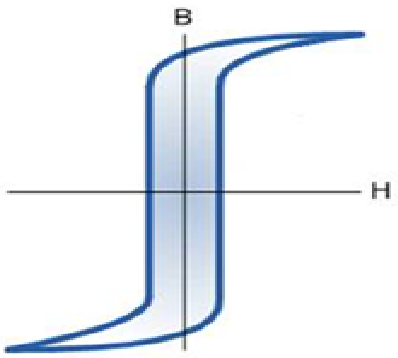
Fig: B-H Curve

Soft magnetic materials:-

The materials which can be easily magnetized and demagnetized are called Soft magnetic materials.

Properties:

- They can be easily magnetized and demagnetized and hence they show high values of susceptibility and permeability.
- Movement of domain wall is easy and hence even for small applied field large magnetization occurs.
- The nature of hysteresis loop is very narrow
- The hysteresis loop area is very small hence the hysteresis loss is also small as shown in fig.
- The coercivity and retentivity values are small
- These materials are free from irregularities or impurities or imperfections



- **Examples:**

  Fe- Si alloys, Ni-Fe alloys, Fe-Co alloys, Ferrities and Garnets etc

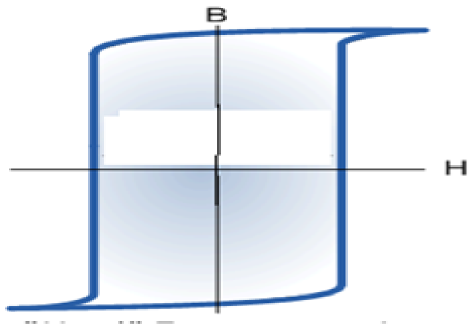
- **Applications:**
  - They are used in switching devices, electromagnets,
  - They are used in matrix storage of computers.
  - They are used in motors, relays and sensors
  - They are used to make the temporary magnets.

Hard magnetic materials:-

The materials which can't be easily magnetized and demagnetized are called hard magnetic materials.

Properties:

- They can't be easily magnetized and demagnetized and hence they show low values of susceptibility and permeability.
- Movement of domain wall is not easy due to presence of impurities and hence large magnetic field is required for magnetization



- The nature of hysteresis loop is very broad.
- The hysteresis loop area is large hence the hysteresis loss is also large as shown in fig.
- The coercivity and retentivity values are high
- These materials are have irregularities or impurities or imperfections
- **Examples:**

  Carbon steel, tungsten steel, chromium steel,

  Cu-Ni-Fe alloys

  Cu-Ni-Co alloys

  Al-Ni-Co alloys

- **Applications:**
  - They are used in magnetic detectors ,
  - They are used in microphones.
  - They are used in magnetic separators.
  - They are used to make the permanent magnets.

Superconductivity

Introduction :

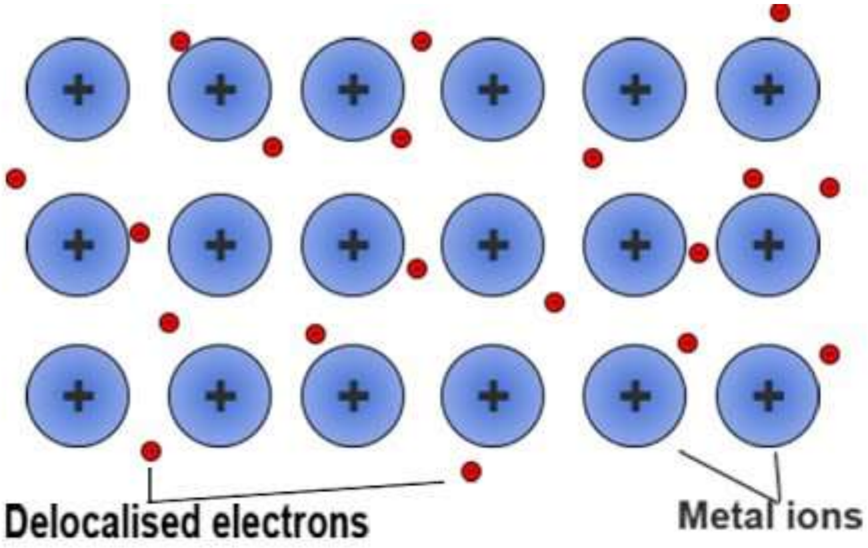
The origin of electrical resistance

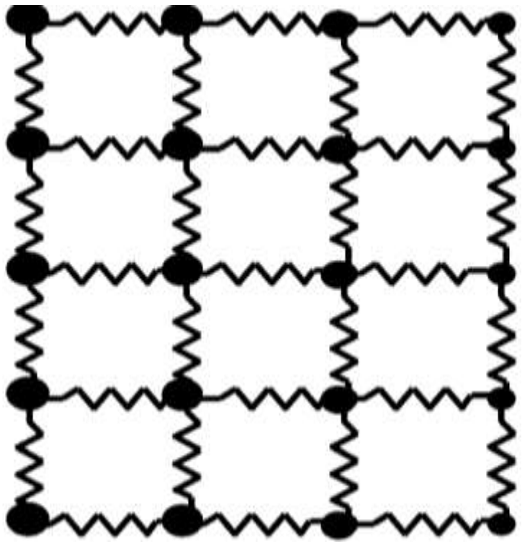
We know that, the opposition offered by substances to flow of charge carriers through them is called electrical resistance.

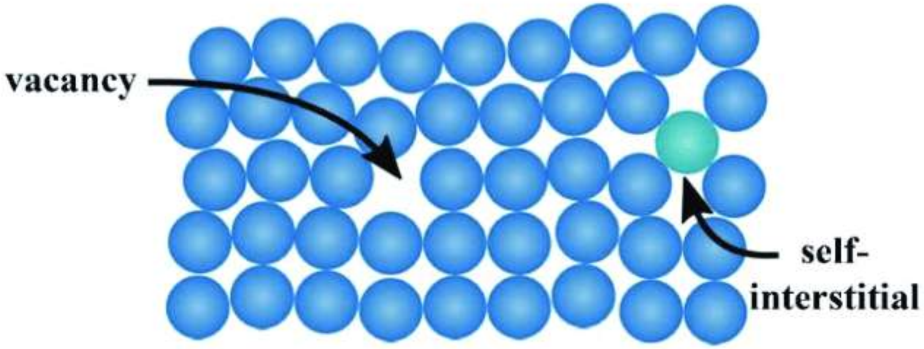
This opposition arises due to the collision (scattering) of electrons with positive ions. The cause for scattering of electrons is the non periodicity of the lattice. This non periodicity in the lattice arises due to mainly three reasons.

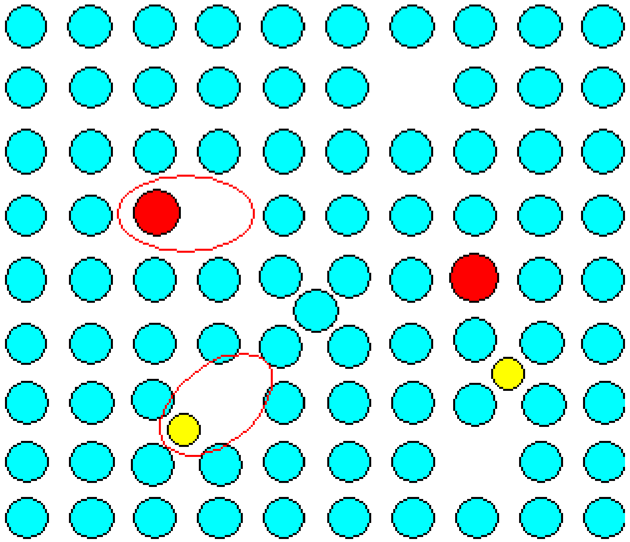
They are

i) Lattice vibrations
ii) Imperfections (Crystal defects) and
iii) Impurities present in the materials etc.


Delocalised electrons
Metal ions




vacancy
self-
interstitial



Discovery of Superconductivity

➢Before the discovery of super conductivity, it was thought the electrical resistance of material becomes zero only at absolute zero temperature.

➢ But it is found that, in some materials the electrical resistance becomes zero, when they cooled to very low temperatures.

➢For example, the electrical resistance of pure mercury suddenly drops to zero, when it is cooled below 4.2 Kelvin and becomes a superconductor. This was first observed by the Dutch physicist, Heike Kammerlingh Onnes on April 8, 1911. He named the phenomenon as superconductivity.

➢Further, the theory of super conductivity was developed in 1957 by three American physicists-John Bardeen, Leon Cooper, and John Schrieffer, through their Theories of Superconductivity, known as the **BCS Theory**.

➢***Therefore; Super conductivity is the phenomenon in which the electrical resistance of certain materials (like metals, compounds, alloys and ceramics etc) becomes zero at very low temperatures. The material that exhibit superconductivity and which are in super conducting state are called super conductors.***

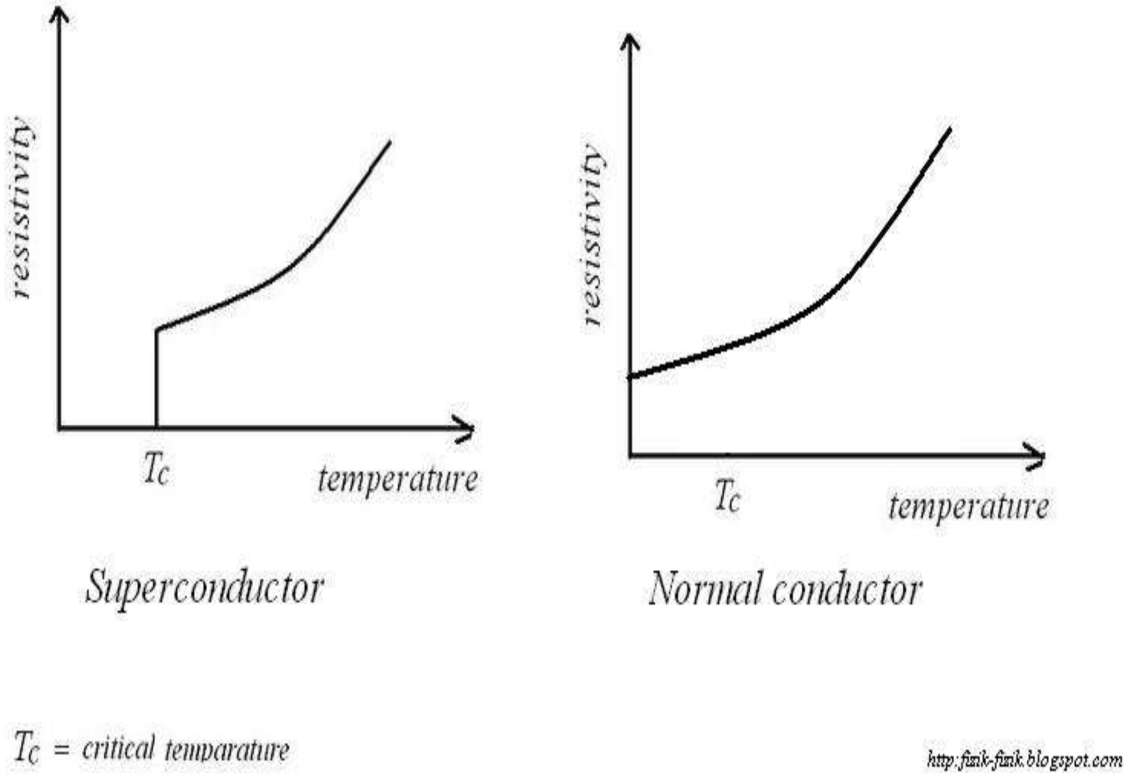


Fig: The variation of electrical resistance with temperature.

Super conductors:

Those materials which lose their resistance to flow of electric current throgh them, when they cooled below certain low temperatures are known as superconductor.

Examples:

Material	Type
Tungsten	Metal
Zinc	Metal
Aluminum	Metal
Tin	Metal
Mercury	Metal
Lead	Metal
NbTi	Inter metallic compound
Nb_3Sn	Inter metallic compound
Nb_3Ge	Inter metallic compound
$YBa_2Cu_3O_7$	Ceramic
TlBaCaCuO	Ceramic

Effect of temperature-Critical temperature:

The temperature at which a normal conductor loses its resistivity and becomes a super conductor is known as transition temperature or critical temperature (T_C) as show in fig.

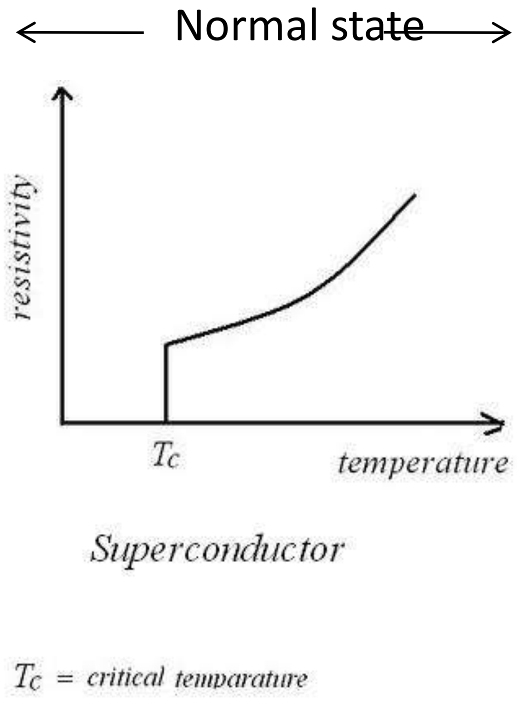


Fig: The variation of electrical resistance with temperature

The value of this critical temperature varies from material to material

Material	**Type**	T_c(K)
Tungsten	Metal	0.01
Zinc	metal	0.88
Aluminum	metal	1.19
Tin	metal	3.72
Mercury	metal	4.15
Lead	metal	7.2
NbTi	Inter metallic compound	9.5
Nb_3Sn	Inter metallic compound	21
Nb_3Ge	Inter metallic compound	23.2
$YBa_2Cu_3O_7$	ceramic	90
TlBaCaCuO	ceramic	125

Effect of magnetic field - Critical magnetic field:

Kammerlingh Onnes observed in 1913 that superconductivity vanishes if a suffiently strong magnetic field is increased.

When a magnetic field is applied to a super conductor, then particular value of applied field and below its critical temperature, it loses super conductivity and becomes a normal conductor. This minimum magnetic field required to destroy the super conducting state is called the critical magnetic field H_C.

The critical magnetic field of a superconductor is a function of temperature.

The variation of Hc with temperature is given by

$$\mathbf{H_C = H_0} \left[1- \left(\frac{T}{T_C}\right)^2\right]$$

Where

H_C = critical magnetic field,
H_0= critical magnetic field at T=ok, and
T_C= critical temperature.

Figure shows the variation of critical magnetic field H_C as a function of temperature.

The material is said to be in the superconducting state within the curve and is non super conducting (i.e., normal state) in the region the outside the curve.

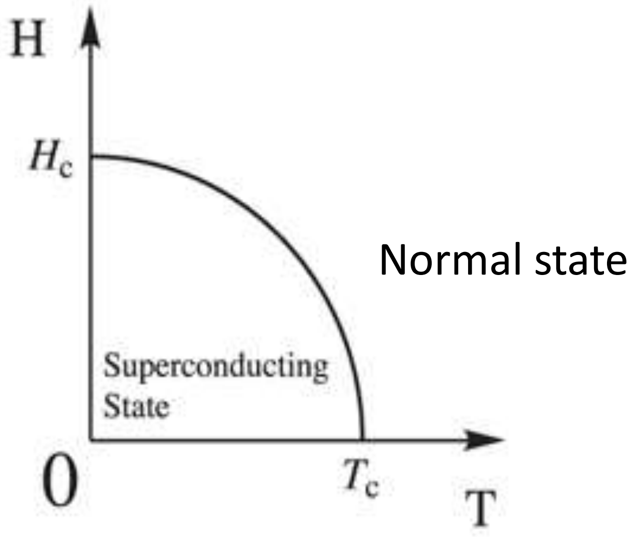


Figure: Effects of temperature and magnetic field on the superconducting state

General Properties of Superconductors

1. Super conductivity is a low – temperature phenomenon.
2. Temperature at which the material undergoes a transition from normal state to super conducting state is known as Critical Temperature or Transition Temperature T_c
3. Different materials will have different Critical Temperature.
4. The current once set up in a super conductor persists for a long time due to zero resistivity.
5. Super conductors do not allow magnetic field (magnetic lines) through them and behave as a diamagnetic. This property of expulsion of magnetic field is known as Meissner Effect.
6. The magnetic field at which the super conductor losses its super conductivity and becomes a normal conductor is known as Critical magnetic field H_C.

7. The induced current in a super conductor induces a magnetic field in it. If the magnetic field is equal to the critical magnetic field then it converts into a normal conductor. The current in it is known as Critical current (I_C). If the ‘r’ is the radius of the super conductor then $I_C = 2\pi r H_C$

   The current density at which it occurs is known as critical current density and is given by $J_c = I_c / A$, where A is the area of cross section of the super conductor.

8. Super conductivity occurs in metallic elements in which the number of valence electrons lies between 2 and 8.

9. Super conducting materials are not good conductors at room temperature.