

ENGINEERING PHYSICS

(20A56101T)

LECTURER NOTES

I – BTECH & I-SEM

Prepared by

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VEMU INSTITUTE OF TECHNOLOGY

(Approved by AICTE, New Delhi and Affiliated to JNTUA, Ananthapuramu)

Accredited by NAAC, NBA (EEE, ECE & CSE) & ISO 9001-2015 Certified Institution

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	R20 Regulations JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY ANANTAPUR (Established by Govt. of A.P., ACT No.30 of 2008) ANANTAPUR – 515 002 (A.P) INDIA
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Course Code	ENGINEERING	L	T	P	C
20A56101T	PHYSICS	3	0	0	3
Course Objectives					
<ul style="list-style-type: none"> To make a bridge between the physics in school and engineering courses To identify the importance of the optical phenomenon i.e. interference, diffraction and polarization related to its Engineering applications. To understand the mechanisms of emission of light, the use of lasers as light sources for low and high energy applications, study of propagation of light wave through optical fibres along with engineering applications To open new avenues of knowledge in dielectric and magnetic materials which find potential in the emerging micro device applications. 					
Course outcomes (CO) : After completion of the course, student can able to					
CO-1: Study the different realms of physics and their applications in both scientific and technological systems through physical optics.					
CO-2: Identify the wave properties of light and the interaction of energy with the matter & Assess the electromagnetic wave propagation and its power in different media					
CO-3: Understands the response of dielectric and magnetic materials to the applied electric and magnetic fields & Elucidates the importance of nano materials along with their engineering applications.					
CO-4: Explain the basic concepts of acoustics and ultrasonics. Apply the concept of NDT to material testing.					
CO-5: Study the important properties of crystals like the presence of long-range order, periodicity and structure determination using X-ray diffraction technique.					
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 and 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.					
Unit-III Engineering Materials					
Dielectric Materials- Introduction, Dielectric polarization, Dielectric polarizability, Susceptibility and Dielectric constant, Types of polarizations: Electronic, Ionic and Orientation polarization (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. Nanomaterials- Introduction – Surface area and quantum confinement – Physical properties: electrical and magnetic properties – Synthesis of nanomaterials: Top-down: Ball Milling – Bottom-up: Chemical Vapour Deposition – Applications of nanomaterials.					

Unit-IV Acoustics and Ultrasonics

Acoustics- Introduction, Requirements of acoustically good hall, Reverberation, Reverberation Time, Sabine’s formula (Derivation using growth and decay method), Absorption coefficient and its determination, Factors affecting acoustics of buildings and their remedies.

Ultrasonics- Introduction, Properties, Production by magnetostriction and piezoelectric methods, Detection, Acoustic grating, Non Destructive Testing, Pulse echo system through transmission and reflection modes, Applications.

Unit-V Crystallography and X-ray diffraction

Crystallography- Space lattice, Basis, unit cell and lattice parameters, Bravais Lattice, Crystal systems, Packing fraction, Coordination number, Packing fraction of SC, BCC & FCC, Miller indices, Separation between successive (hkl) planes.

X-Ray Diffraction- Bragg’s law, Bragg’s X-ray diffractometer, Crystal structure determination by Powder method.

Text books

- 1. Engineering Physics – Dr. M.N. Avadhanulu & Dr. P.G. Kshirsagar, S. Chand and Company
- 2. Engineering physics – D.K. Battacharya and Poonam Tandon, Oxford University press.

Reference books

- 1. Engineering Physics - Sanjay D. Jain, D. Sahasrambudhe and Girish, University Press
- 2. Engineering Physics – K. Thyagarajan, McGraw Hill Publishers
- 3. Engineering Physics – D K Pandey, S. Chaturvedi, Cengage Learning
- 4. Engineering Physics – M.R. Srinivasan, New Age Publications

UNIT -I: WAVE OPTICS

Introduction

Have you ever observed that the beautiful colors in soap bubbles, mica and film of oil floating on the surface of water when a sun light falls on them? Did you ever try to find out the reason? This is due to the phenomenon of interference in thin films by reflection of light. This was first explained by Thomas young on basis of Hugen’s wave concept and principle of superposition.

Principle of Superposition of Waves

When two or more light waves traveling through a medium superimpose one another then the resultant displacement at any point is equal to the algebraic sum of the individual displacements at that point. This is called principle of superposition.

$$i.e., \vec{y} = \vec{y}_1 \pm \vec{y}_2 \pm \vec{y}_3 \pm \dots \rightarrow (1.1)$$

where \vec{y} is the resultant displacement and $\vec{y}_1, \vec{y}_2, \vec{y}_3 \dots$ are the displacements of individual waves.

+ve sign is taken when displacements are in same direction.

-ve sign is taken when displacements are in opposite direction.

- (i) If two light waves are in same phase, the resultant displacement is the sum of displacements of two waves. This is called constructive interference.

i.e.,
$$\vec{y} = \vec{y}_1 + \vec{y}_2 \quad \rightarrow (1.2)$$

- (ii) If two light waves are out of phase, the resultant displacement is the difference of displacements of two waves. This is called destructive interference.

i.e.,
$$\vec{y} = \vec{y}_1 - \vec{y}_2 \quad \rightarrow (1.3)$$

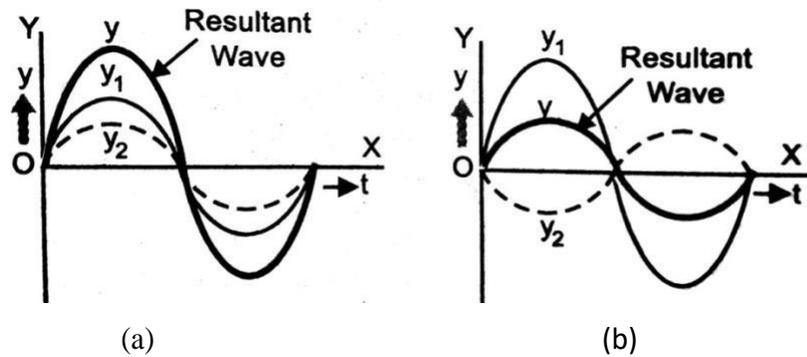


Fig. 1.1 Superposition of waves

Interference of light

When two or more light waves traveling through a medium superimpose one another then the resultant intensity at different points of the medium undergoes change from point to point.

The change in the intensity of light in a medium from point to point is called interference of light.

Thus, the phenomenon of modification or change in uniform redistribution of light energy or intensity or amplitude due to the superposition of two or more light waves is called interference.

Theory

According to Young's double slit experiment, the

amplitude of resultant waves is

$$A = \sqrt{a_1^2 + a_2^2 + 2a_1a_2\cos\phi} \quad \rightarrow (1.4)$$

The resultant intensity at point 'P' is given by the square of the amplitude

$$\text{i.e., } I = A^2 = a_1^2 + a_2^2 + 2a_1a_2\cos\phi \quad \rightarrow (1.5)$$

Case 1: Condition for constructive interference

- If the two waves are in phase with each other, then they undergo constructive interference producing maximum intensity of light called bright band or fringe.

The resultant intensity will be maximum when $\cos\phi = +1$

$$\text{i.e., } \phi = 0, 2\pi, 4\pi, 6\pi, \dots$$

From equation (1.1)

$$I_{\max} = a_1^2 + a_2^2 + 2a_1a_2 \quad \rightarrow (1.6)$$

$$\phi = n(2\pi) \text{ where } n = 0, 1, 2, 3, \dots$$

$$I_{\max} = (a_1 + a_2)^2 \quad \rightarrow (1.7)$$

Let $a_1 = a_2 = a$ (if two light waves are coherent)

$$I_{\max} = I_0 = (4a)^2 \quad \rightarrow (1.8)$$

Therefore, the intensity maximum when the phase difference is an integral multiple of 2π or path difference is an integral multiple of λ because phase difference of 2π corresponds to a path difference of λ .

$$\text{Path difference } \Delta = n\lambda \text{ or}$$

$$\text{Phase difference } \phi = 2n\pi$$

$$\rightarrow (1.9)$$

Case:2 Condition for destructive interference

If the two waves are out of phase, then they undergo destructive interference producing zero intensity of light called dark band or fringe.

The resultant intensity will be maximum when $\cos \phi = -1$

i.e., $\phi = \pi, 3\pi, 5\pi, \dots$

$\phi = (2n-1)\pi$ Where

$n = 1, 2, 3, \dots$

From equation (1.1)

$$I_{\min} = a_1^2 + a_2^2 - 2a_1a_2 \cos \phi \quad \rightarrow (1.10)$$

$I_{\min} = (a_1 - a_2)^2$	$\rightarrow (1.11)$
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Let $a_1 = a_2 = a$ (if two light waves are coherent)

$$I_{\min} = 0 \quad \rightarrow (1.12)$$

Therefore, the intensity minimum when the phase difference is an odd multiple of π or path difference is an odd multiple of $\lambda/2$ because phase difference of π corresponds to a path difference of $\lambda/2$.

Path difference $\Delta = (2n-1)\frac{\lambda}{2}$ Phase difference $\phi = (2n-1)\pi$	$\rightarrow (1.13)$
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Conditions for sustained interference

To observe a well defined interference pattern, the following conditions must be fulfilled.

a) Conditions for Sustained Interference

- i. To produce interference, we require two coherent light sources. i.e., the two sources must emit light of same frequency or wavelength, same amplitude and in the same phase or with a constant phase.
- ii. The two sources must be perfectly monochromatic, emitting light of a single wavelength or frequency.

b) Conditions for good visibility or observation

- i. The distance between the two sources ($2d$) must be small.

- ii. The distance between the two coherent sources and the screen (D) must be large.
- c) *Conditions for good contrast*

- i. The amplitudes of the two waves must be nearly the same or equal.
- ii. The two sources must be narrow and parallel.
- iii. The two sources must emit light in the same direction.
- iv. To view interference fringes, the background must be dark as shown in Fig 1.2.

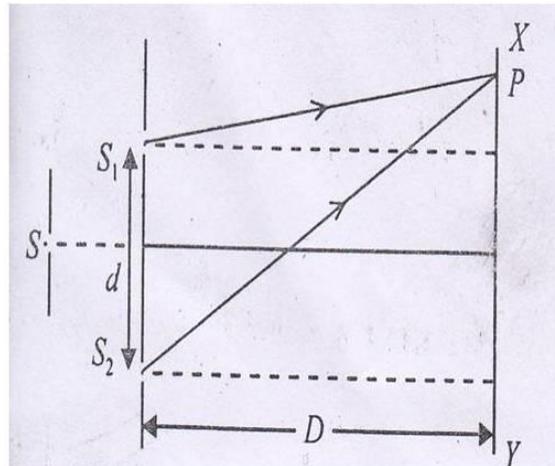


Fig. 1.2 Schematic representation of Interference due to two slits

Where 'S' is a source of monochromatic light, S_1 & S_2 are two pin holes and XY is background.

Interference in thin films

If a light incident on the thin film, a small part of light is reflected from the top surface and the remaining portion is transmitted into the film. Again, a small part of the transmitted component light is reflected back into the film by the bottom surface and emerges through the top surface. A small portion of the light thus is reflected partially several times in succession within the film. These reflected light waves superimpose with each other, producing interference and forming interference patterns.

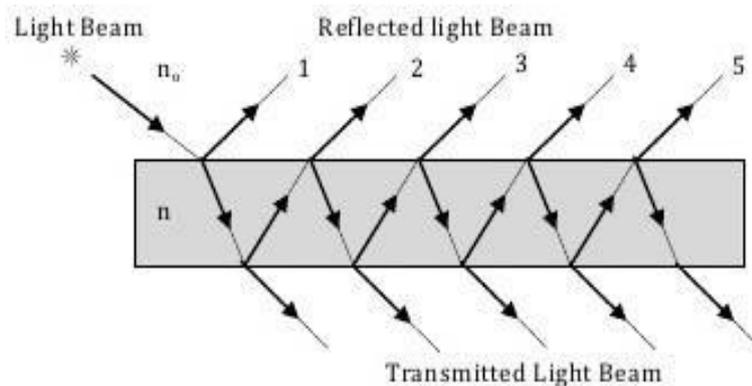
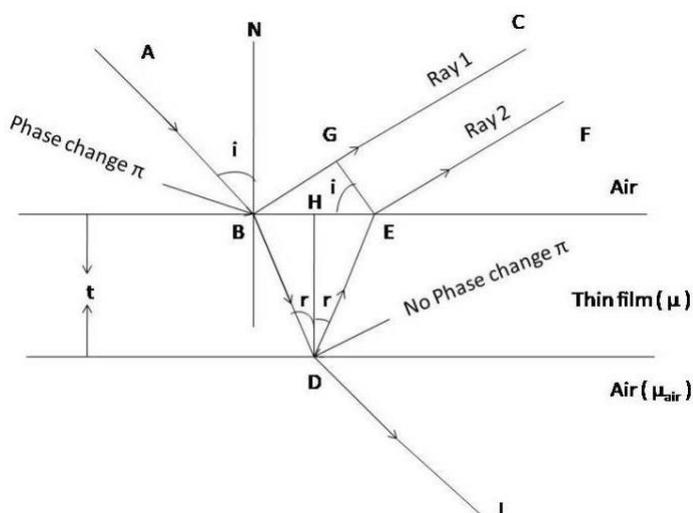


Fig. 1.3 Interference in thin films by reflection

Interference in thin films by reflection of light

When light is incident on plane parallel thin film, some portion of light gets reflected from the top surface and the remaining portion is transmitted into the film. Again, some portion of the transmitted light is reflected back into the film by the bottom surface and emerges through the top surface. These reflected light waves superimpose with each other, producing interference and forming interference patterns. This is the principle of interference in thin films by reflection of light.

- Let us consider a thin transparent film of uniform thickness t with refractive index μ and is surrounded by air on both sides. Let the refractive index of the air be μ_{air}



as shown in Fig 1.4.

Fig 1.4 Interference in thin films by reflection of light

- When a monochromatic light ray AB is incident on the top surface at an angle i , it is partly reflected along BC and partly refracted into the film along BD makes an angle ' r ' with the normal DH and meets the lower surface.
- At D, it is again partly reflected back into the film along DE and emerges along EF which is parallel to the ray BC. The major portion of light refracts into the outer medium along DJ.
- Since the two reflected light rays BC and EF are derived from the incident ray AB, so they act as coherent light rays. These two coherent light rays superimpose and produce interference patterns. Condition of interference depends on the optical path difference between the rays 1 and 2.
- To calculate let us draw normals from EG to BC and DH to BE and the rays GC and EF equal distances.

➤ The Optical path difference (OPD) between the rays (1) and (2) is

$$\begin{aligned} \Delta &= \mu \times \text{geometrical path BDE in film} - \mu_{\text{air}} \times \text{geometrical path BG in air} \\ &= \mu (BD + DE) - \mu_{\text{air}} (BG) \quad [\text{Since } \Delta = \mu L \text{ and } \mu_{\text{air}} = 1] \\ &= \mu (BD + DE) - BG \quad \rightarrow (1.14) \end{aligned}$$

Step 1: Calculation of geometrical path BDE in film

Let us calculate path BD + DE in film,

$$\text{From fig, } \Delta BDH, \cos r = \frac{DH}{BD}$$

$$BD = \frac{t}{\cos r} \quad \rightarrow (1.15)$$

Similarly,

$$\text{From } \Delta EDH, \cos r = \frac{DH}{DE} \quad \rightarrow (1.16)$$

$$DE = \frac{t}{\cos r}$$

$$\therefore BD + DE = \frac{t}{\cos r} + \frac{t}{\cos r}$$

$$= \frac{2t}{\cos r} \quad \rightarrow (1.17)$$

Step 2: Calculation of geometrical path BG in film

To calculate BG in air, first BE which is equal to (BH + HE) has to be obtained.

$$\text{From } \Delta BDH, \tan r = \frac{BH}{DH} = \frac{BH}{t}$$

$$BH = t \cdot \tan r \quad \rightarrow (1.18)$$

Similarly,

$$\text{From } \Delta EDH, \tan r = \frac{HE}{DH} = \frac{HE}{t}$$

$$HE = t \cdot \tan r \quad \rightarrow (1.19)$$

$$\therefore BE = BH + HE = t \cdot \tan r + t \cdot \tan r$$

$$= 2t \tan r \quad \rightarrow (1.20)$$

$$\text{From } \Delta BGE, \sin i = \frac{BG}{BE}$$

$$BG = BE \sin i$$

$$= 2t \tan r \sin i \quad \rightarrow (1.21)$$

$$\text{From Snell's law, } \mu = \frac{\sin i}{\sin r}$$

$$\sin i = \mu \sin r \quad \rightarrow (1.22)$$

From the equations (1.21) and (1.22) B

$$G = 2t \tan r \mu \sin r$$

$$= 2\mu t \tan r \sin r$$

$$= 2\mu t \frac{\sin r}{\cos r} \sin r$$

$$= 2\mu t \frac{\sin^2 r}{\cos r} \quad \rightarrow (1.23)$$

Substituting the equations (1.17) and (1.23) in equation (1.14); we have

$$\begin{aligned} \Delta &= \frac{2\mu t}{\cos r} - 2\mu t \frac{\sin^2 r}{\cos r} \\ &= \frac{2\mu t \cos r}{\cos r} (1 - \sin^2 r) \\ &= \frac{2\mu t \cos r}{\cos r} \cos^2 r \\ \Delta &= 2\mu t \cos r \end{aligned} \quad \rightarrow (1.24)$$

This is called Cosine law.

According to Stoke's principle, if a light wave traveling from a rarer medium to a denser medium undergoes a phase change of π or path change $\frac{\lambda}{2}$ (i.e., the wave loses half a wavelength)

when it gets reflected at the boundary of a rarer to denser medium.

$$\Delta = 2\mu t \cos r - \frac{\lambda}{2} \quad \rightarrow (1.25)$$

Case 1. Condition for constructive interference or bright band

Bright band occurs when the path difference $\Delta = n\lambda$

$\rightarrow (1.26)$

From the above equations (1.25) and (1.26); we have

$$2\mu t \cos r - \frac{\lambda}{2} = n\lambda$$

$$2\mu t \cos r = n\lambda + \frac{\lambda}{2}$$

$$2\mu t \cos r = (2n+1) \frac{\lambda}{2} \quad \rightarrow (1.27)$$

where $n = 0, 1, 2, 3, \dots$

This is the condition for constructive interference. The film appears bright under this condition.

Case 2. Condition for destructive interference or dark band

$$\Delta = (2n-1) \frac{\lambda}{2} \quad \rightarrow (1.28)$$

From the above equations (12) and (15); we have

$$2\mu t \cos r - \frac{\lambda}{2} = (2n-1) \frac{\lambda}{2}$$

$$2\mu t \cos r = (2n-1) \frac{\lambda}{2} + \frac{\lambda}{2}$$

$$2\mu t \cos r = n\lambda \quad \text{where } n = 0, 1, 2, 3$$

$\rightarrow (1.29)$ This is the condition for

destructive interference. The film appears dark under this condition.

Interference in Non-uniform thin films - Newton's Rings

Interference in non-uniform thin films by reflection of light was first experimentally observed by Newton.

Definition

When a Plano-convex lens of large radius of curvature is placed convex surface on a plane glass plate, an air film is formed between the lower surface of the Plano-convex lens and the upper surface of the glass plate. The thickness of the air film is zero at point of contact and gradually increases from the point of contact outwards. If a monochromatic light is allowed to fall normally on this air film, then interference pattern is formed in the form of alternate concentric bright and dark circular rings are formed in the air film due to superposition of reflected light, known as Newton's rings because these rings were discovered by Newton.

Principle

Newton's rings are formed due to interference between the light rays reflected from the top and bottom surfaces of air film between the glass plate and the Plano-convex lens.

Formation of Newton's rings

- The formation of Newton's rings can be explained with help of Fig 1.5.
- When a light ray (AB) is incident on the system, a part of the light is reflected by the curved surface of the lens (L) and a part is transmitted which is reflected back from the plane surface of the glass plate (P). Ray 1 undergoes no phase change but ray 2 undergoes a phase of π or path change $\frac{\lambda}{2}$ (i.e., the wave loses half of wavelength) when it gets reflected at the boundary of a rarer to denser medium.
- These reflected light rays superimpose with each other producing interference and forming interference patterns in the form of bright dark circular rings.

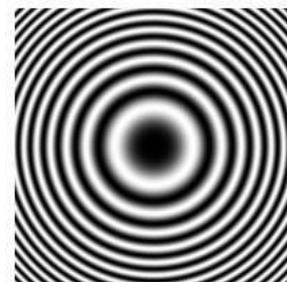
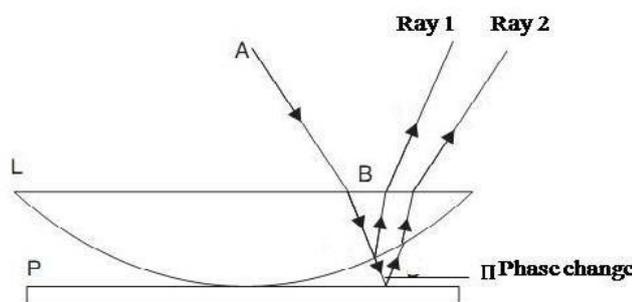


Fig. 1.5(a) Formation of Newton's rings

(b) Newton's rings

- We know that, the path difference between two reflected rays in uniform thin film (plane parallel)

allelthin film) is

$$\Delta = 2\mu t \cos r - \frac{\lambda}{2} \quad \rightarrow (1.30)$$

➤ Similarly for non-uniform thin film,

Let refractive index of air film $\mu = 1$ and $r = 0$ for normal incidence.

Thus the path difference $\Delta = 2t - \frac{\lambda}{2}$ → (1.31)

This is the path difference between two reflected rays in non-uniform thin film.

Case 1. Dark central spot

At the point of contact 'O' of the lens and glass plate, the thickness of air film is approximately zero.

i.e., $t \approx 0$

$$\begin{aligned} \therefore \text{The path difference } \Delta &= 2t - \frac{\lambda}{2} \\ &= 2(0) - \frac{\lambda}{2} \\ \Delta &= -\frac{\lambda}{2} \end{aligned} \quad \rightarrow (1.32)$$

Thus, at point of contact two waves are out of phase and interfere destructively.

Hence dark spot is formed at centre.

Case 2. Condition for bright band

Bright band occurs when the path difference $\Delta = n\lambda$

→ (1.33)

From equations (1.32) and (1.33), we have

$$\begin{aligned} 2t - \frac{\lambda}{2} &= n\lambda \\ 2t &= n\lambda + \frac{\lambda}{2} \\ 2t &= (2n+1)\frac{\lambda}{2} \end{aligned} \quad \rightarrow (1.34)$$

where $n = 0, 1, 2, 3, \dots$

This is the condition for maxima. The film appears bright under this condition.

Case 3. Condition for dark band

Dark band occurs when the path difference $\Delta = (2n-1)\frac{\lambda}{2}$ → (6)

From the above equations (1.32) and (1.35), we have

$$2t - \frac{\lambda}{2} = (2n-1)\frac{\lambda}{2}$$

$$2t = (2n-1) \frac{\lambda}{z} \frac{\lambda}{z}$$

$$2t = n\lambda$$

$$\rightarrow (1.35)$$

where $n = 0, 1, 2, 3, \dots$

This is the condition for minima. The film appears dark under this condition.

Experimental Arrangement

- The experimental arrangement for producing Newton rings is as shown in Fig 1.6
- Keep the convex surface of the Plano-convex lens over the plane glass plate and arrange glass plate G at an angle of 45° over the base set.
- Switch on the monochromatic light source 'S' (Sodium vapor lamp) and it is focused on the Double convex lens (L_1). This sends parallel beam of light. This beam of light falls on the glass plate B at 45° .
- The glass plate 'G' reflects a part of light toward the air film enclosed by the Plano-convex lens and the plane glass plate.
- A part of the light is reflected by the curved surface of the Plano-convex lens (P) and a part is transmitted which is reflected back from the plane surface of the plane glass plate (E).
- These reflected light rays superimpose with each other producing interference and forming interference patterns in the form of bright dark circular rings.
- These rings are seen with a microscope (M) focused on the air film.

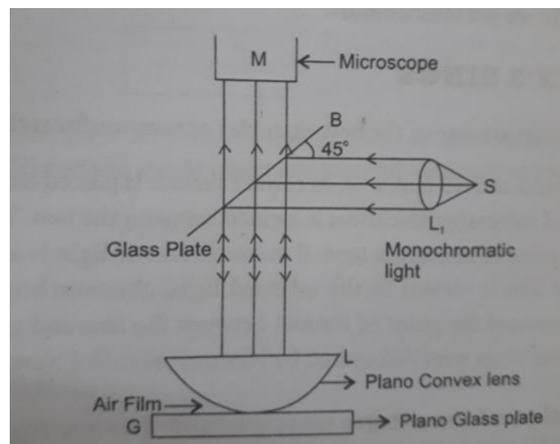


Fig. 1.6 The experimental arrangement of Newton rings

Theory of Newton's rings

To find the diameters (radii) of dark and bright rings, let 'L' be a Plano convex lens placed on a glass plate P. The convex surface of the lens is the part of spherical surface with center at C as shown in Fig.1.7.

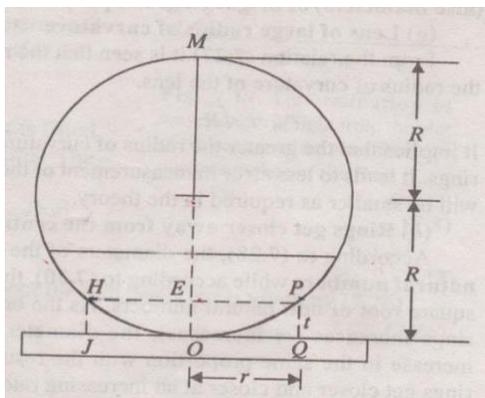


Fig.1.7 Theory of Newton's rings

Case 1. Diameters (Radii) of the dark rings

Let 'R' be the radius of curvature of the lens. Let a dark ring be located at the point Q is $PQ = t$. The radius of the ring at Q is $OQ = r$.

By the theorem of intersecting chords,

$$EP \times HE = OE \times EM \quad \rightarrow (1.36)$$

But $EP = OQ = HE = r$; $OE = PQ = t$ and $EM = OM - OE = 2R - t$

From equation (1.36)

$$r \times r = t \times (2R - t)$$

$$r^2 = 2Rt - t^2$$

As $2Rt \gg t^2$; t^2 can be neglected.

$$r^2 = 2Rt$$

Thus, the radius of the n th dark ring will be given by $r_n^2 = 2Rt$ $\rightarrow (1.37)$

We know that, the condition of the dark ring is $2t = n\lambda$ \rightarrow

(1.38) From the above equations (2) and (3)

$$r_n^2 = n\lambda R$$

$$r_n = \sqrt{n\lambda R} \quad \rightarrow (1.39)$$

This is the condition for radii of the dark rings.

The diameter of the dark ring is therefore given by $D_n = 2r_n$

$$D_n = 2\sqrt{n\lambda R} \quad \rightarrow (1.20)$$

∴ The radii (diameters) of the dark rings is directly proportional to (i) \sqrt{n} (natural number)

(ii) $\sqrt{\lambda}$

(iii) \sqrt{R}

Case 2. Diameters (Radii) of the bright rings

Let us now suppose that a bright ring be located at the point Q.

Therefore, the radius of the n^{th} bright ring will be given by $r^2 = 2Rt_n$ →(1.21)

We know that, the condition of the bright band is $2t = (2n+1) \frac{\lambda}{2}$ →(1.22)

From the above equations (1.21) and (1.22)

$$r^2 = (2n+1) \frac{\lambda}{2} R = (n + \frac{1}{2}) \lambda R$$

$$r_n = \sqrt{(n + \frac{1}{2}) \lambda R} \quad \rightarrow(1.23)$$

This is the condition for radii of the bright rings.

The diameter of the bright rings is therefore given by $D_n = 2r_n$

$$D_n = 2\sqrt{(n + \frac{1}{2}) \lambda R} \quad \rightarrow(1.24)$$

∴ The radii (diameters) of the bright rings is directly proportional to (i) $\sqrt{n + \frac{1}{2}}$

(ii) $\sqrt{\lambda}$

(iii) \sqrt{R}

Applications

The theory of Newton's rings can be used

- (i) To determine the wavelength of monochromatic light
- (ii) To determine the radius of curvature of Plano-convex lens and
- (iii) To determine the refractive index of a given liquid.

Determination of wavelength of monochromatic light source.

Let 'R' be the radius of curvature of a Plano-convex lens, λ be the wavelength of monochromatic light source.

Let D_m and D_n are the diameters of m^{th} and n^{th} dark rings respectively.

Then, $D_m^2 = 4m\lambda R,$

$$D_n^2 = 4n\lambda R,$$

$$\text{and } D_n^2 - D_m^2 = 4n\lambda R - 4m\lambda R$$

$$=4(n-m)\lambda R$$

$$\lambda = \frac{D_n^2 - D_m^2}{4(n-m)R}$$

A graph is drawn with the number of rings on the x-axis and the square of the diameter of the ring (D^2) on the y-axis. The graph is a straight line passing through the origin as shown in Fig. 1.8. From the graph the values of D_m^2 and D_n^2 corresponding to m^{th} and n^{th} rings are found. From the graph, the slope is calculated.

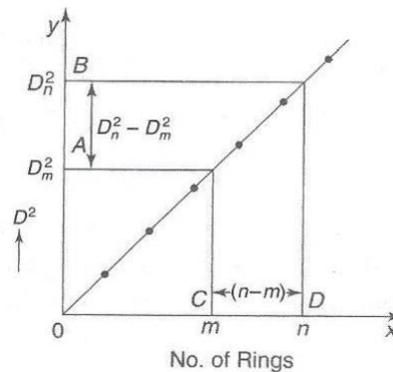


Fig. 1.8A graph between (D^2) and number of fringes

From graph, the slope

$$\frac{D_n^2 - D_m^2}{n - m} = \frac{AB}{CD} \quad \rightarrow (1.26)$$

The radius of curvature ' R ' of the Plano-convex lens is found by Boy's method or spherometer. Substituting the values of R and $D_n^2 - D_m^2$ in the above formula (1.26) λ can be calculated.

Determination of refractive index of a given liquid

To find the refractive index of a given liquid, the Plano convex lens and glass plate setup is placed in a small container 'C'. The transparent liquid of refractive index ' μ ' is introduced between the lens L and the glass Plate 'G' as shown as Fig 1.9. Then a film of liquid is formed between the lens and glass plate. The diameters of m^{th} and n^{th} dark rings are determined with the help of travelling microscope.

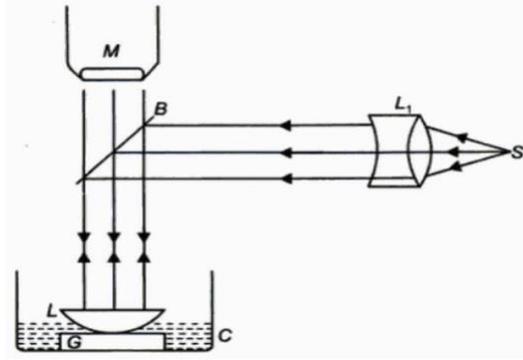


Fig. 1.9 Determination of refractive index of a given liquid

We know that,

The diameters of m^{th} and n^{th} dark rings in the air film are given by

$$D_m^2 = 4m\lambda R, D_n^2 = 4n\lambda R,$$

$$\text{and } D_n^2 - D_m^2 = 4n\lambda R - 4m\lambda R = 4(n-m)\lambda R \quad \rightarrow (1.27)$$

With liquid film, the diameters of m^{th} and n^{th} dark rings are determined;

$$D_m^{2I} = \frac{4m\lambda R}{\mu}$$

$$D_n^{2I} = \frac{4n\lambda R}{\mu}$$

$$\text{and } D_n^{2I} - D_m^{2I} = \frac{4n\lambda R}{\mu} - \frac{4m\lambda R}{\mu} = \frac{4\lambda R(n-m)}{\mu} \quad \rightarrow (1.28)$$

From the above equations (1.27) and (1.28), $D_n^{2I} - D_m^{2I} = \frac{n-m}{\mu} (D_n^2 - D_m^2)$

$$\mu = \frac{n-m}{D_n^{2I} - D_m^{2I}} \cdot (D_n^2 - D_m^2)$$

. Using the above formula μ can be calculated.

Engineering applications of Interference

The phenomenon of interference can be used in various engineering applications; some of the applications are given below.

- i. It is used in anti-reflecting coatings.
- ii. It is used to determine the thickness of a thin film coating.
- iii. It is used in testing of flatness of surfaces.
- iv. It is used in interference filters to transmit a very narrow range of wavelengths.

DIFFRACTION

Introduction

Diffraction is one of the natural phenomena. The effect of diffraction is usually seen in everyday

ylife. For example, their iridescent colors of peacock feathers, butterfly wings and some other insects, rainbow-like diffraction is produced by CD or DVD.

The English word diffraction was coined by the *diffRACTus* which means to spread out or to break out. This phenomenon was first discovered by Francesco Grimaldi.

When light waves encounter an obstacle they bend at the corners or edges of the obstacle and spreading into the geometrical shadow of an obstacle. This phenomenon is known as diffraction.

(or)

The phenomenon of redistribution of light intensity due to the superposition of secondary wavelets from the same wavefront is called diffraction.

The effect of diffraction depends on the size of the obstacle (d) and the wavelength (λ) of light wave as illustrated in Figure 1.10. Light waves are very small in wavelength, i.e., from 4×10^{-7} m to 7×10^{-7} m. If the size of opening or obstacle is near to this limit, only then we can observe the phenomenon of diffraction.

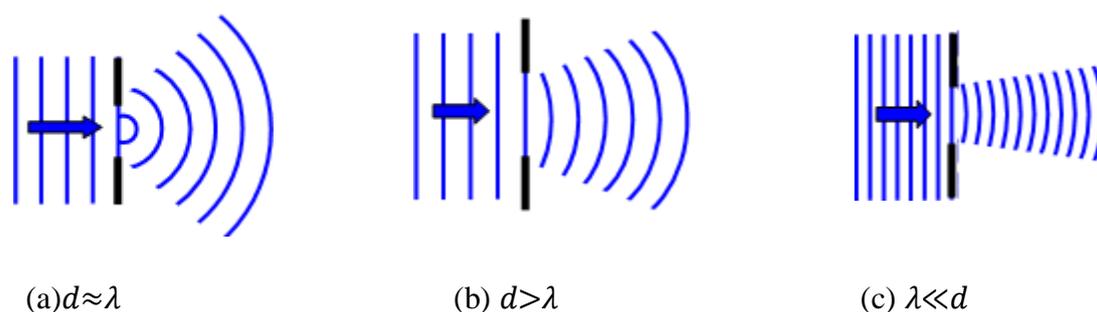


Figure 1.10 Illustration of diffraction phenomenon

From Fig. 1.12 it is observed that

- i. The effect of diffraction is more noticeable if the size of the obstacle is equal to the wavelength of light (i.e. $d \approx \lambda$).
- ii. The effect of diffraction is not noticeable if the size of the obstacle is greater than the wavelength of light (i.e. $d > \lambda$).
- iii. The effect of diffraction is less noticeable if the size of the obstacle is smaller than the wavelength of light (i.e. $\lambda \ll d$).

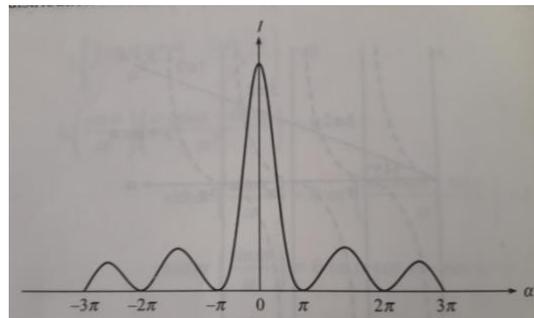
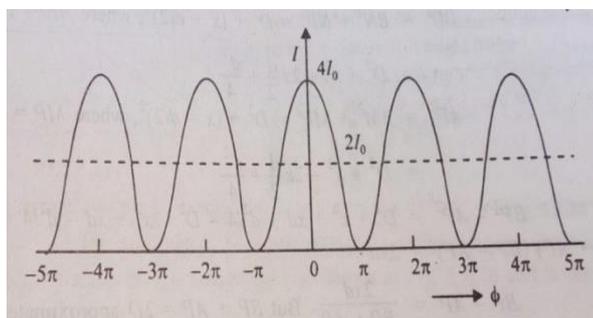
Conditions for diffraction

To observe diffraction

- i. Light must be monochromatic and
- ii. The wavelength of light must be comparable to the obstacle. ($\lambda \approx d$)

Differences between interference and diffraction

S.No	Interference	Diffraction
1	It is arises due to the superposition of waves from the two coherent sources.	It arises due to the superposition of secondary wavelets from the different parts of the same wavefront.
2	It is formed due to the uniform distribution of light intensity.	It is formed due to the non-uniform distribution of light intensity.
3	In interference pattern, all bright fringes are of the same intensity	In diffraction pattern, all bright fringes are not of the same intensity
4	The intensity of all dark fringes is zero.	The intensity of all dark fringes is not zero.
5	In interference pattern, the width of fringes is equal.	In diffraction pattern, the width of fringes is not equal.
6	The intensity distribution graph of interference is shown in Fig. 1.13.	The intensity distribution graph of diffraction is shown in Fig. 1.14.



Types of Diffraction

There are two types of diffraction.

- Fresnel diffraction and
- Fraunhofer diffraction.

(a) Fresnel diffraction

- In this class of diffraction, the source of light and the screen are finite from the diffraction slit (or) aperture.
- No double convex lenses (or) mirrors are used to observe diffraction effect.
- The diffraction pattern is the image of the slit.
- The centre of diffraction pattern is either bright (or) dark.

- The incident wavefront is spherical (or) cylindrical.
- It is very easy to observe experimentally and complex mathematically.

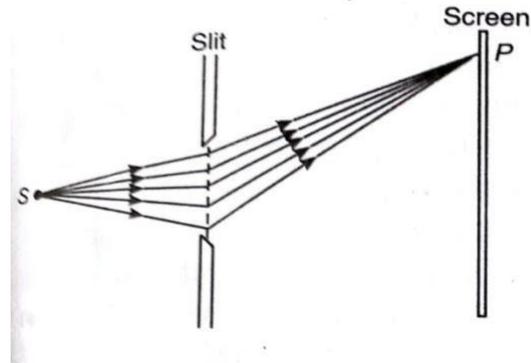


Fig.1.11 Fresnel diffraction

(b) Fraunhofer diffraction

- In this class of diffraction, the source of light and the screen are in infinite distance from the diffraction slit (or) aperture.
- Two double convex lenses (or) mirrors are used to observe diffraction effect.
- The incident wavefront is plane.
- The diffraction pattern is the image of source of itself.
- The centre of the diffraction pattern is bright.
- It is very simple and easy to observe both experimentally and mathematically.

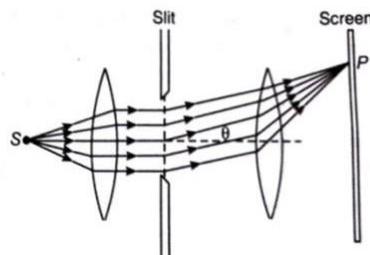


Fig.1.12 Fraunhofer diffraction

Fraunhofer diffraction due to single slit

The arrangement of Fraunhofer diffraction due to single slit is shown in Fig 1.13.

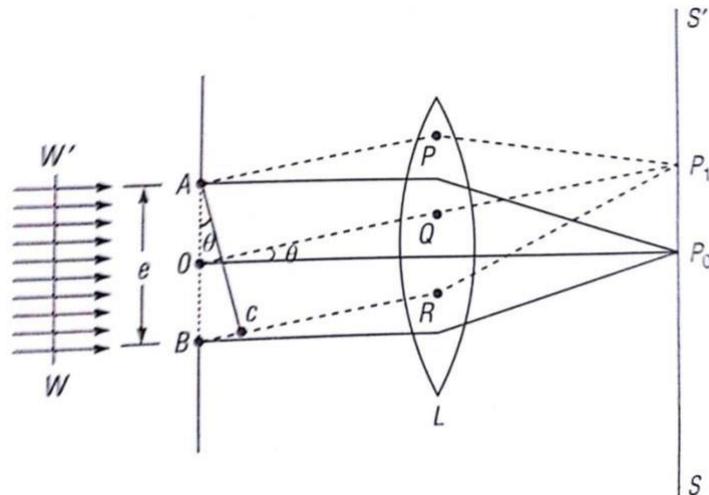


Fig 1.13 Fraunhofer diffraction due to single slit

- In Fig S is a point source of monochromatic light with wavelength λ and AB is the single slit of width "e"
- Let WW' be the plane wavefront and is incident on the single slit AB.
- According to Huygen's principle, each point on wavefront is a source of fresh disturbance called secondary wavelet that spread out to right angles in all directions. *Without diffraction ($\theta=0$)*
- Let us consider the wave front WW' travelling along OP_0 through the slit AB without diffraction and focus at P_0 by using lens L_2 . Since all these wavefronts have same phase and no path difference between them. Therefore, they undergo constructive interference and producing maximum intensity called central maximum or principal maximum.

With diffraction ($\theta \neq 0$)

- Let us consider the plane wave front WW' (secondary wavelets) travelling along OP_1 and diffract at an angle θ and focused at P_1 . The intensity at P_1 is either maximum or minimum depending upon the path difference between the two wavelets (A and B). To calculate path difference let us draw a normal AC to BR as shown in fig.

From fig, ΔABC ,

$$\sin \theta = \frac{BC}{AB}$$

$$BC = AB \sin \theta$$

\therefore The Path difference $BC = e \sin \theta$ $\rightarrow (1.29)$

And corresponding phase difference $= \frac{2\pi}{\lambda} BC$

$$= \frac{2\pi}{\lambda} e \sin \theta$$

×pathdifference

×*esin*θ

→(1.30)

Let us consider the width of slit AB is divided into parts and amplitude of each part is "a." Therefore, the phase difference between any two successive parts is

$$\frac{1}{n} \times \text{path difference} = \frac{1}{n} \times \text{path difference}$$

$$\frac{1}{n} \times \text{path difference} = \frac{1}{n} \times \left[\frac{2\pi}{\lambda} \times e \sin \theta \right] = d \quad \rightarrow (1.31)$$

By using the method of vector addition of amplitudes,

The resultant amplitude is given by $R = \frac{a \sin \frac{\alpha}{2}}{\sin \frac{\alpha}{2n}}$ $\rightarrow (1.32)$

Substituting equation (1.31) in equation (1.32)

$$R = \frac{a \sin \left(\frac{2\pi}{\lambda} \times e \sin \theta \right)}{\sin \left(\frac{1}{n} \left(\frac{2\pi}{\lambda} \times e \sin \theta \right) \right)}$$

$$= \frac{a \sin \left(\frac{\pi e \sin \theta}{\lambda} \right)}{\sin \left(\frac{\pi e \sin \theta}{n \lambda} \right)}$$

$$R = \frac{a \sin \alpha}{\sin \frac{\alpha}{n}}$$

where $\alpha = \frac{\pi e \sin \theta}{\lambda}$ $\rightarrow (1.33)$

Since $\sin \frac{\alpha}{n}$ is very small, $\sin \frac{\alpha}{n} \approx \frac{\alpha}{n}$

$$= \frac{a \sin \alpha}{\frac{\alpha}{n}}$$

$$= \frac{na \sin \alpha}{\alpha} \quad [\because na = A]$$

$$R = A \left(\frac{\sin \alpha}{\alpha} \right)$$

 $\rightarrow (1.34)$

This equation represents the resultant amplitude of the wavefronts at P_1 . And intensity $I=R^2$

$$I=A^2\left(\frac{\sin\alpha}{\alpha}\right)^2$$

→(1.35)

$$I = A^2 \left(\frac{\sin \alpha}{\alpha} \right)^2$$

Case 1. Principle maximum or Central maximum at P_0

The resultant amplitude (R) can be expressed in ascending power of α ,

$$R = \frac{A}{\alpha} \left[\alpha - \frac{\alpha^3}{3!} + \frac{\alpha^5}{5!} - \frac{\alpha^7}{7!} + \dots \right]$$

$$= \frac{A}{\alpha} \times \alpha \left[1 - \frac{\alpha^2}{3!} + \frac{\alpha^4}{5!} - \frac{\alpha^6}{7!} + \dots \right] \quad \rightarrow(1.36)$$

Intensity at P_0 will be maximum when the values of R is maximum.

For maximum value of R then negative terms must be vanish in equation (1.36)

i.e., $\alpha = 0$ [From the equation (1.33)]

$$\frac{\pi e \sin \theta}{\lambda} = 0$$

$$\pi e \sin \theta = 0$$

$$n \theta = 0$$

$$\theta = 0$$

Thus we can say that, the condition $\theta = 0$ means that the wave front passing through the slit AB without diffraction and focus at P_0 . Since all these wave front has same phase and no path difference between them. Therefore, they undergo constructive interference and producing maximum intensity called central maximum or principal maximum (i.e., $I_{\max} = R^2 = A^2 = I_0$).

Case 2 Minimum intensity positions

Intensity I will be minimum when $\sin \alpha = 0$.

i.e., $\alpha = \pm m \pi$

Where $m = 1, 2, 3, \dots$

$$\frac{\pi e \sin \theta}{\lambda} = \pm m \pi$$

$$e \sin \theta = \pm m \lambda$$

→(1.37)

This is the condition for minimum intensity. Thus, we obtain minimum intensity positions either side of the principle maximum.

Case.3 Maximum intensity positions (or) Secondary maximum

In addition to principle maximum, there exist weak secondary maximum between equally spaced minima. These secondary maximum intensity positions can be obtained by differentiating the expression of intensity with respect to “ α ” and equating to zero.

$$\begin{aligned}
 I &= A^2 \left(\frac{\sin \alpha}{\alpha} \right)^2 \\
 \frac{dI}{d\alpha} &= \frac{d}{d\alpha} \left[A^2 \left(\frac{\sin \alpha}{\alpha} \right)^2 \right] = 0 \\
 &= A^2 \cdot \frac{d}{d\alpha} \left(\frac{\sin \alpha}{\alpha} \right)^2 = 0 \qquad \left[\frac{d}{dx} \left(\frac{u}{v} \right) = \frac{v \frac{du}{dx} - u \frac{dv}{dx}}{v^2} \right] \\
 &= A^2 \cdot \frac{2 \sin \alpha}{\alpha} \cdot \frac{d}{d\alpha} \left(\frac{\sin \alpha}{\alpha} \right) = 0 \\
 &= A^2 \cdot \frac{2 \sin \alpha}{\alpha} \times \frac{\alpha \cos \alpha - \sin \alpha}{\alpha^2} = 0 \qquad \rightarrow (1.38)
 \end{aligned}$$

In the above equation (1.38) either $\sin \alpha = 0$ (or) $\alpha \cos \alpha - \sin \alpha = 0$

We know that, $\sin \alpha = 0$ gives the minimum intensity positions. Thus $\alpha \cos \alpha - \sin \alpha = 0$ gives the maximum intensity positions.

i. e, α

$$\begin{aligned}
 \alpha \cos \alpha - \sin \alpha &= 0 \\
 \alpha \cos \alpha &= \sin \alpha
 \end{aligned}$$

$\alpha = \tan \alpha$

→ (1.39)

The value of α satisfying the above equations are obtained graphically by plotting the curves $y = \alpha$ and $y = \tan \alpha$ on the same graph as shown in Fig 1.14.

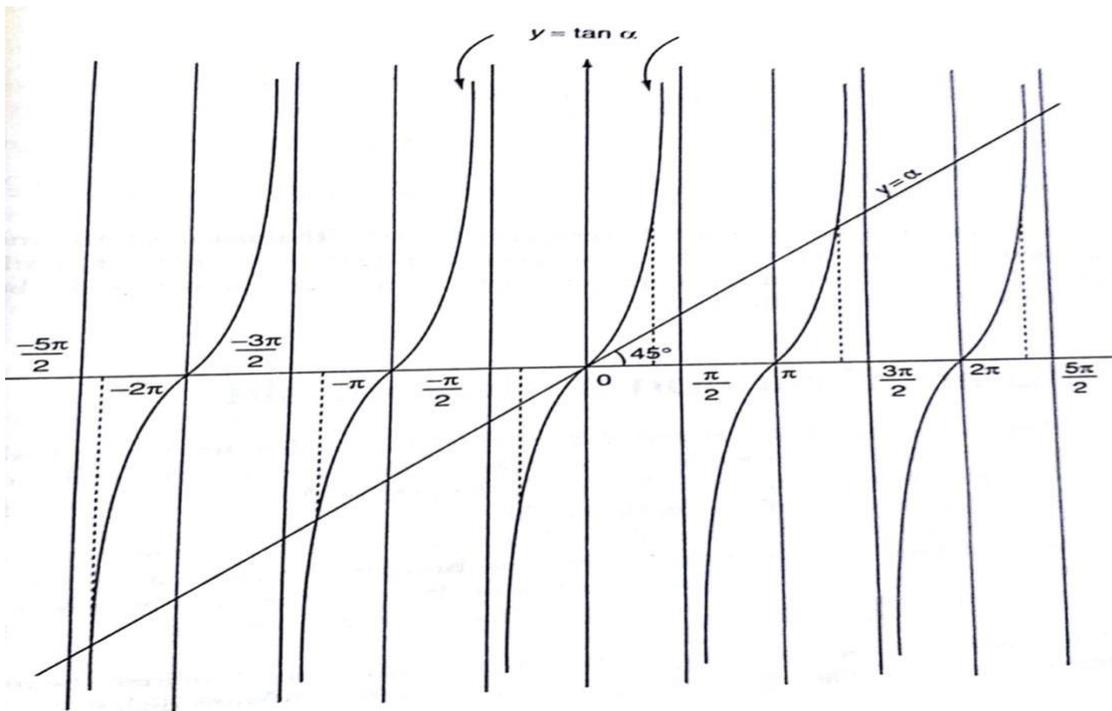


Fig1.14 The plot of $y = \alpha$ and $y = \tan \alpha$

The points of intersection of the two curves give the value of α which satisfy the above equation (1.3)

9). The points of intersections are $\alpha = 0, \pm \frac{3\pi}{2}, \pm \frac{5\pi}{2}, \pm \frac{7\pi}{2}, \dots, \frac{\pi}{2}, \frac{\pi}{2}, \frac{\pi}{2}$

The first value of α gives the principle maximum and remaining values of α give the secondary maxima.

The values are $\alpha = \pm \frac{3\pi}{2}, \pm \frac{5\pi}{2}, \pm \frac{7\pi}{2}, \dots$

$$\alpha = \pm (2m+1) \frac{\pi}{2} \quad \rightarrow (1.40)$$

where $m = 1, 2, 3, 4, \dots$

\therefore From the equations (5) & (12)

$$\frac{\pi e \sin \theta}{\lambda} = \pm (2m+1) \frac{\pi}{2}$$

$$e \sin \theta = \pm (2m+1) \frac{\lambda}{2}$$

→ (1.41)

This is the condition for maxima.

(i) For the principle maximum $\alpha = 0$

$$\therefore \text{The intensity } I = R^2 = A^2 = \left(\frac{\sin \alpha}{\alpha} \right)^2$$

$$(ii) \text{ For these secondary maxima } \alpha = \pm \frac{3\pi}{2}, \pm \frac{5\pi}{2}, \pm \frac{7\pi}{2}, \dots$$

$$\text{The intensity of first secondary maxima, } \alpha = \pm \frac{3\pi}{2}$$

$$\therefore \text{Intensity } (I_1) = A^2 \left(\frac{\sin\left(\frac{3\pi}{2}\right)}{\frac{3\pi}{2}} \right)^2$$

$$= \frac{4}{9} \pi^2 \cdot A^2$$

$$= \frac{A^2}{22}$$

$$I_1 = \frac{I_0}{22}$$

$$\frac{I_1}{I_0} = \frac{1}{22} = 4.5\%$$

\therefore The intensity of first secondary maximum is about $\frac{1}{22}$ of intensity of the principle maximum.

i.e., I_1 is 4.5% of I_0

$$\text{The intensity of second secondary maxima } \alpha = \pm \frac{5\pi}{2}$$

$$I_2 = A^2 \left(\frac{\sin\left(\frac{5\pi}{2}\right)}{\frac{5\pi}{2}} \right)^2$$

$$= A^2 \left(\frac{1}{25\pi^2} \right)$$

$$= \frac{A^2}{62} = \frac{I_0}{62}$$

$$\frac{I_2}{I_0} = \frac{1}{62} = 1.61\%$$

$$I_0 \quad 62$$

∴ The intensity of second secondary maxima is about $\frac{1}{62}$ of intensity of principle maxima.

i.e., I_2 is 1.61% of I_0

∴ In the same way the intensity of secondary maxima goes on decreasing very rapidly.

Intensity distribution graph

A graph is plotted between intensity of light (I) and α is shown in Fig 1.15.

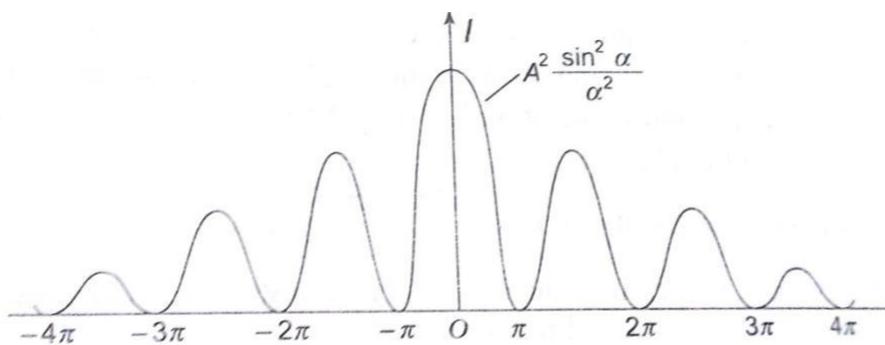


Fig 1.15 The intensity of diffraction pattern due to single slit

From the graph the following conclusions can be observed,

- At $\alpha=0$, the intensity is very high called principle maximum.
- At $\alpha = \pm \frac{3\pi}{2}, \pm \frac{5\pi}{2}, \pm \frac{7\pi}{2}, \dots$, the intensity is maximum called secondary maxima.
- At $\alpha = \pm \pi, \pm 2\pi, \pm 3\pi, \dots$, the intensity is minimum.
- The most of the light is concentrated in the principle maximum & the intensity of secondary maximum decreasing on either sides of principle maximum as shown in Fig 1.15.

Fraunhofer diffraction due to double slit

The arrangement of Fraunhofer diffraction due to double slit is shown in Fig 1.16.

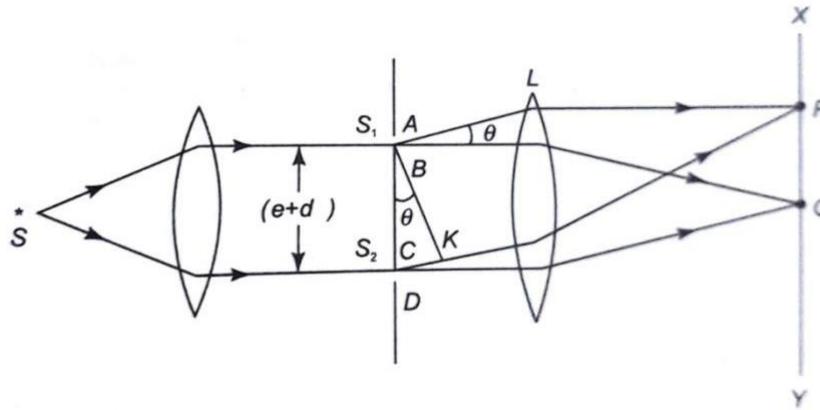


Fig1.16 Fraunhofer diffraction due to double slit

- In Figure 1.16, S is a point source of monochromatic light with wavelength λ and S_1 and S_2 are the two slits of same width e and separated by a distance d .
- Let WW' be the plane wavefront and is incident on the two slits S_1 and S_2 .
- According to Huygen's principle, each point on wavefront is a source of fresh disturbance called secondary wavelets that spread out in all directions.

Without diffraction ($\theta = 0$)

- Let us consider the plane wavefront ww' travelling along OP_0 through the slits S_1 and S_2 without diffraction ($\theta = 0^\circ$) and focused at P_0 by using lens L_2 . Since all these wavefronts have same phase and no path difference between them. So they undergo constructive interference and producing maximum intensity at P_0 called central maximum or principle maximum.

With diffraction ($\theta \neq 0$)

- Let us consider the plane wave front ww' (secondary wavelets) travelling along OP_1 through the slits S_1 and S_2 and diffract at an angle θ with respect to the normal and focused at P_1 . The intensity at P_1 is the combination of both interference and diffraction.
- *Interference:* It is due to the superposition of secondary diffracted wavelets from the two slits S_1 and S_2 .
- *Diffraction:* It is due to the single slit, the intensity at P_1 either maximum or minimum depending upon the path difference between secondary wavelets S_1 and S_2 .

From $\Delta S_1 S_2 K$,

$$\sin \theta = \frac{S_2 K}{S_1 S_2}$$

$$\therefore S_1 S_2 \sin \theta = S_2 K \quad \rightarrow (1.42)$$

\therefore The path difference $S_2 K = (e+d) \sin \theta$ and corresponding phase difference

$$\delta = \frac{2\pi}{\lambda}(e + d)\sin\theta \quad \rightarrow (1.43)$$

To find out resultant amplitude at P_1 we use vector addition method (as shown in figure) in which two sides of a triangle are represented by the amplitudes of S_1 and S_2 and third side gives the resultant amplitude.

According to vector addition method, From the figure,

$$\begin{aligned}
 (OH)^2 &= (OG)^2 + (GH)^2 + 2(OG)(GH)\cos\delta \\
 R^2 &= A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 + A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 + 2.A \left(\frac{\sin\alpha}{\alpha}\right).A \left(\frac{\sin\alpha}{\alpha}\right)\cos\delta \\
 &= 2A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 + 2A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 \cos\delta \\
 &= 2A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 [1 + \cos\delta] \\
 &= 2A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 2\cos\frac{\delta}{2} \\
 &= 4A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 \cos^2\frac{\delta}{2} \\
 &= 4A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 \cos^2\left(\frac{(e+d)\sin\theta}{2}\right) \\
 &= 4A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 \cos^2\frac{\pi(e+d)\sin\theta}{\lambda}
 \end{aligned}$$

$$\boxed{R^2 = 4A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 \cos^2\beta} \quad \rightarrow (1.44)$$

Where $\beta = \frac{\pi(e+d)\sin\theta}{\lambda}$ → (1.45)

The above equation (1.44) represents the resultant amplitude of the wave fronts S_1 and S_2 at P_1 . And intensity $I = R^2$

$$\boxed{I = R^2 = 4A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 \cos^2\beta} \quad \rightarrow (1.46)$$

From the above equation (1.46), we can say that the resultant intensity (I) at P_1 is the product of

two factors.

(i) $A^2 \left(\frac{\sin \alpha}{\alpha} \right)^2$ which represents the diffraction pattern due to a single slit.

(ii) $\cos^2 \beta$ which represents the interference pattern due to the superposition of secondary diffracted wavelets from two slits s_1 and s_2 .

Therefore, the resultant intensity is the combination of both diffraction and interference effects.

Diffraction effect

In the above equation (1.46), $A^2 \left(\frac{\sin \alpha}{\alpha} \right)^2$ gives the principle maximum at the centre of diffraction pattern with alternative minima and secondary maxima positions on the either side of it (Fig. 1.17).

Case (i) The principle maximum occurs at $\alpha = 0$

$$\text{i.e., } I = R^2 = A^2 = I_0$$

Case (ii) The minimum intensity positions occur at

$$\alpha = \pm m, \text{ where } m = 1, 2, 3, 4, \dots$$

$$\frac{\pi e \sin \theta}{\lambda} = \pm m \pi$$

$$e \sin \theta = \pm m \lambda$$

→ (1.47)

Case (iii) These secondary maxima positions occur at

$$\alpha = \pm (2m + 1) \frac{\pi}{2}, \text{ where } m = 1, 2, 3, 4, \dots$$

$$\frac{\pi e \sin \theta}{\lambda} = \pm (2m + 1) \frac{\pi}{2}$$

$$e \sin \theta = \pm (2m + 1) \frac{\lambda}{2}$$

→ (1.48)

Interference effect

In the above equation (1.46), $\cos^2 \beta$ gives the alternative maximum and minimum intensity positions with equal magnitude of intensity.

Case (i) The Minimum intensity positions will occur at

$$\cos^2 \beta = 0 \text{ When } \beta = \pm \frac{\pi}{2}, \pm \frac{3\pi}{2}, \pm \frac{5\pi}{2}, \pm \frac{7\pi}{2}, \dots$$

$$\therefore \beta = \pm (2m + 1) \frac{\pi}{2}$$

→ (1.49)

$$\text{where } m = 0, 1, 2, 3, 4, \dots$$

$$\text{But } \beta = \frac{\pi (e + d) \sin \theta}{\lambda}$$

→ (1.50)

From the equations (1.49) & (1.50)

$$\frac{\pi (e + d) \sin \theta}{\lambda} = \pm (2m + 1) \frac{\pi}{2}$$

$$(e+d) \sin\theta = \pm (2m+1) \lambda/2 \quad \rightarrow(1.51)$$

Case(ii) The maximum intensity positions will occur at

$$\cos^2\beta = 1 \text{ When } \beta = 0, \pm\pi, \pm2\pi, \pm3\pi, \pm4\pi, \dots, \pm m\pi$$

$$\therefore \beta = \pm m\pi \quad \rightarrow(1.52)$$

$$\text{But } \beta = \frac{\pi(e+d)\sin\theta}{\lambda} \quad \rightarrow(1.53)$$

From the equations (1.52) & (1.53)

$$\frac{\pi(e+d)\sin\theta}{\lambda} = \pm m\pi$$

$$(e+d)\sin\theta = \pm m\lambda$$

→(1.54)

Intensity distribution graph

Fig 1.21 shows the resultant intensity distribution due to the combination of both diffraction and interference effects. From the graph, it is observed that the resultant minima are not equal to zero; still they have some minimum intensity due to interference effect.

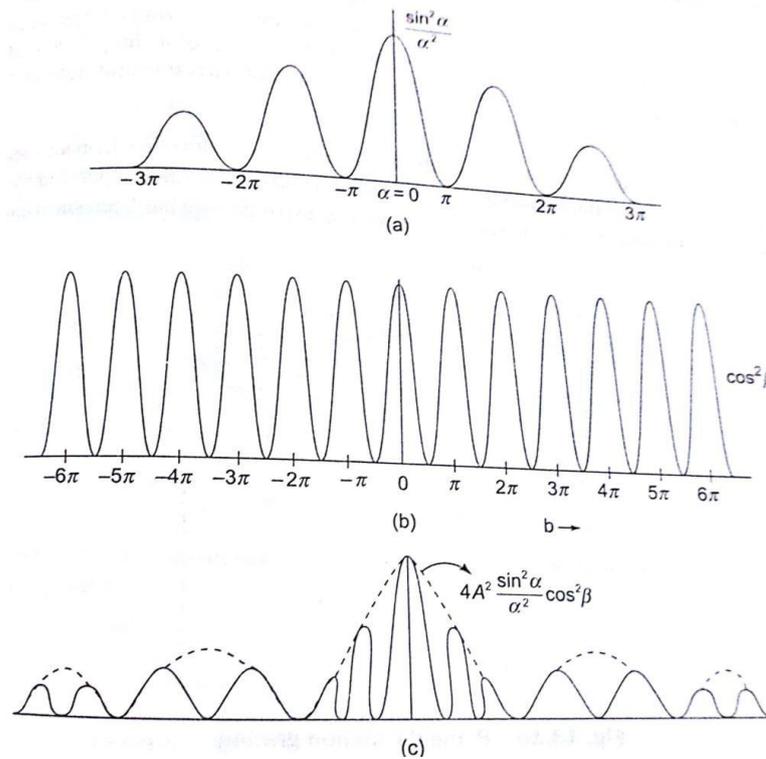


Fig.1.17 Intensity distribution due to diffraction double slit

Diffraction Grating

A diffraction grating is an optical device consisting of a large number of equidistant narrow parallel, rectangular slits of equal width and separated by opaque portions. This was first constructed by the German physicist Joseph von Fraunhofer in 1821.

Construction

- A diffraction grating is prepared by ruling a large number of equidistant narrow, parallel lines on an optically plane glass plate with a fine diamond point.
- The ruled lines are opaque to light called opaque portions while the space between any two successive ruled lines is transparent to light called transparent portions and act as slits.
- The distance between any two successive slits (or) ruled lines is called grating element as shown in Fig.1.18.

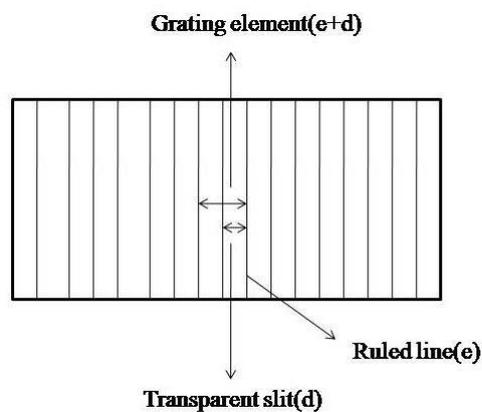


Fig.1.18. Construction of diffraction grating

- The commercial gratings are made up of a thin layer of colloidal solution (ex: Solution of cellulose acetate) is poured on the ruled surface and allowed to dry to form a thin film.
- The colloidal thin film is peeled carefully from the ruled surface. The film retains the impression of the ruling of the ruled surface.
- The ruled lines act as opaque portions whereas the space between them act

transparent portions which transmit incident light. The film is mounted between two glass plates called grating.

- When the light is incident on the grating surface then light is transmitted through transmission portions or slits and obstructed by the opaque portions or ruled lines. Such a grating is known as transmission grating.

Theory

Let 'e' be the width of each ruled line (or) opaque portion and 'd' be the width of transparent portion (or) slit then (e + d) represents the grating element. The relation between grating element and the angles of diffracted beams of light is known as grating equation. It is given by

$$(e+d)\sin\theta=n\lambda, \text{ Where } n=0, 1, 2, 3, \dots \rightarrow(1.55)$$

This expression is known as grating equation.

$$\sin\theta=\left(\frac{1}{e+d}\right)n\lambda$$

$$\sin\theta=Nn\lambda$$

Where $\frac{1}{e+d}=N$ is the number of grating elements or lines per unit width of the grating.

$$N(e+d) = 1 \text{ inch} = 2.54 \text{ cm}$$

$$e+d = \frac{2.54}{N} \text{ cm} \rightarrow(1.56)$$

Grating Spectrum

The diffraction pattern formed with a grating is known as grating spectrum.

The positions of principle maxima in grating are given by

$$(e+d)\sin\theta = n, \text{ Where } n = 0, 1, 2, 3, \dots$$

This expression is known as grating equation.

For a particular wavelength, the diffraction angle is different for different principal maxima of different orders.

The first order maximum is obtained for $n=1$, then $(e+d)\sin\theta_1 = \lambda$

The second order maximum is obtained for $n=2$, then $(e+d)\sin\theta_2 = 2\lambda$

The different orders

of principal maxima are obtained on both sides of zero order maxima as shown in Fig. 1.19.

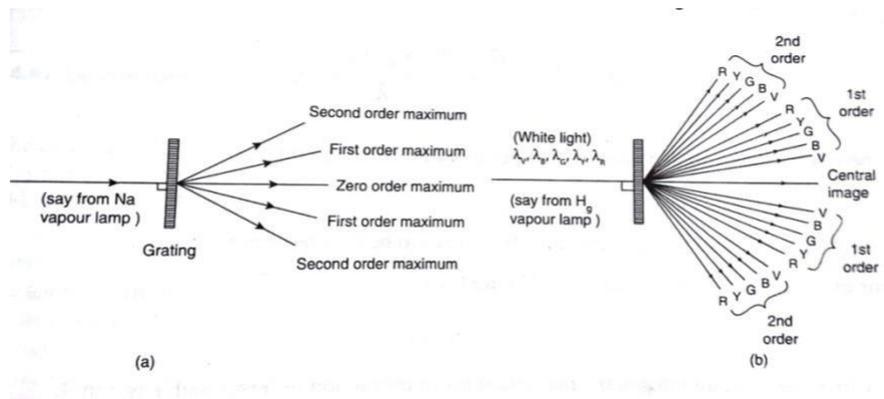


Fig. 1.19. Grating spectrum (a) for monochromatic source (b) for white light source

Determination of Wavelength (λ) of given source of light

The positions of principle maxima in grating are given by

$$(e+d)\sin\theta = n, \text{ Where } n = 0, 1, 2, 3, \dots$$

$$\sin\theta = \left(\frac{1}{e+d}\right)n\lambda$$

$$\sin\theta = Nn\lambda$$

$$\lambda = \frac{\sin\theta}{Nn}$$

→ (1.57)

Where $\frac{1}{e+d} = N$ is the number of grating elements or lines per unit width of the grating.

By knowing the values of angle of diffraction, order of the principal maxima and grating element, the wavelength can be determined.

Engineering applications of diffraction

The phenomenon of diffraction can be used in various engineering applications; some of the applications are given below.

1. It is used in x-ray diffraction studies of crystals.
2. It is also used in holography for reconstructing 3D images of objects using laser light.
3. Diffraction gratings are used in spectroscopes to separate a light source into its component wavelengths.
4. Diffraction grating can be chosen to specifically analyze a wavelength of light emitted by molecules in diseased cells in a biopsy sample.
5. Diffraction gratings are used in optical fiber technologies where fibers are designed to provide optimum performance at specific wavelengths.

POLARIZATION

Introduction

The phenomena of interference and diffraction tell us that light is a form of wave. But they do not tell us whether light is transverse or longitudinal wave in nature. The phenomenon of polarization confirms that light waves are transverse in nature.

In general, light waves are electromagnetic waves and contain vibrations of electric and magnetic field vectors (E & B) which are perpendicular to each other and also perpendicular to the direction of propagation of light waves. i.e., transverse waves. Therefore, light is a transverse wave motion. It has been found experimentally that the electric field vector (E) component of light is mainly responsible for polarization and other optical effects but not due to the magnetic field vector. Therefore, the electric field vector E is also called the light vector and vibration of light means vibrations of electric field vector of light.

The word polarization comes from the Greek word "*polos*" which means orientation. *Therefore the phenomenon of restricting or orienting the vibrations of the electric field vector in a particular direction is called polarization of light.*

Unpolarized light

If the light vector (electric field vector E) vibrates in all possible directions which are perpendicular to the direction of propagation then the light is said to be unpolarized light.

Let us consider an ordinary light ray passing perpendicular to the plane of the paper and into the paper. The electric field vectors are perpendicular to the ray propagating with equal amplitude in all possible directions as shown in Fig. 1.20. This is the nature of unpolarized light. A double-headed arrow shows the to and fro vibrations of the electric vector.

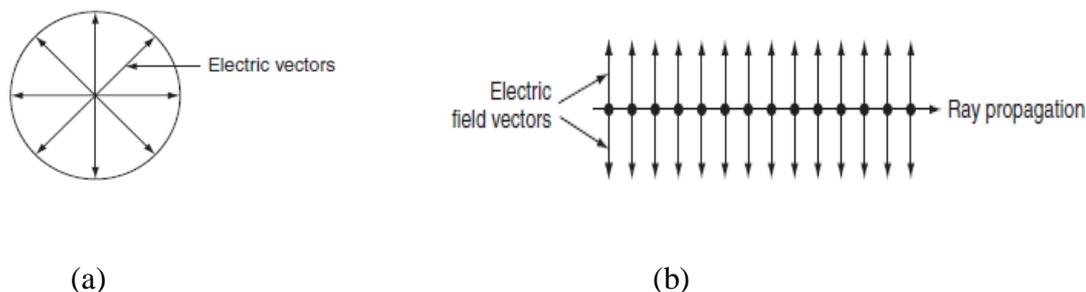


Fig 1.20. Representation of unpolarized light

Polarized light

The phenomenon of restricting the vibrations of the light vector or electric field vector

(E) in a particular direction is called polarization of light. The polarized light can be classified into three types. They are

- i. Linearly (or) Plane polarized light
- ii. Circularly polarized light and
- iii. Elliptically polarized light

Linearly (or) Plane polarized light

If the vibrations of light vector (electric field vector E) restricting along straight line only in a plane perpendicular to the direction of propagation of light, it is said to be plane polarized light.

The linearly polarized light is shown in 1.25. The arrowed lines represent in the plane of paper and the dots, the vibrations at right angles (perpendicular) to the paper. In Fig. 1.21 (a), the vibrations of electric field vectors lie in the plane of the paper and in Fig. 1.21 (b) the vibrations of electric field vectors are perpendicular to the plane of the paper.

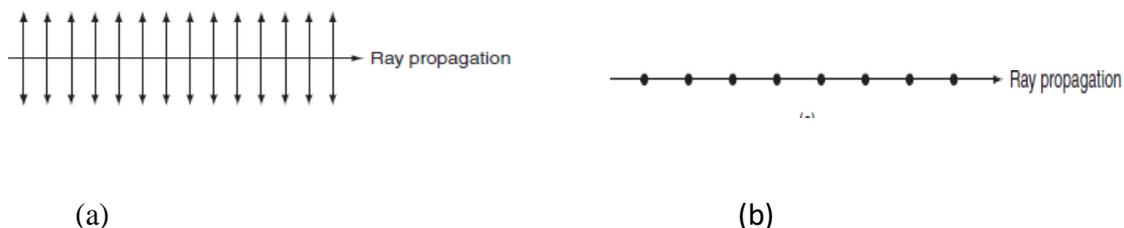


Fig1.21.Representationofplanepolarizedlight

Circularlypolarizedlight andellipticallypolarizedlight

When two plane polarized light waves are superimposed each other then under certain conditions the resultant light vector may rotate with a constant magnitude in a plane perpendicular to the direction of propagation of light.

If the magnitude of the resultant light vector remains constant while its orientation varies regularly, the tip of the vector traces a circle. Thus the light is said to be circularly polarized.

If however, both magnitude and orientation of light vector vary, the tip of the vector traces an ellipse. Thus the light is said to be elliptically polarized.

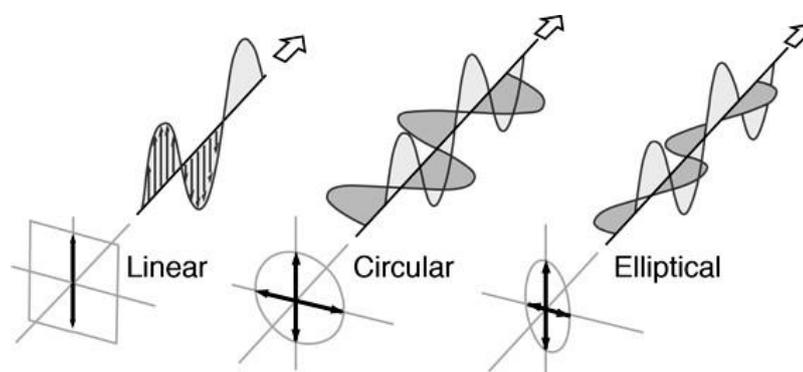


Fig 1.22. Representation of plane, circular and elliptically polarized light

Methods of producing polarized light

Polarized light can be produced by any one of the following.

- i. Polarization by reflection
- ii. Polarization by refraction
- iii. Polarization by double refraction
- iv. Polarization by scattering
- v. Polarization by selective absorption

In this section we only discuss polarization by double refraction.

Polarization by double refraction

When a light ray is passed through a glass plate, we get only one refracted ray. But when a light ray is passed through certain crystals like calcite or quartz, we get two refracted rays, one refracted light ray which obeys the laws of refraction is called ordinary or o -ray. The other ray does not obey the laws of refraction and is called extraordinary ray or e -ray. This phenomenon is called double refraction or birefringence. This was first discovered by Erasmus Bartholinus in 1669.

Explanation

When an ink dot is marked on a white paper and is seen through a calcite crystal, then two images (dots) are observed. If the crystal is rotated slowly with incident ray as vertical axis, then it is observed that one image remains fixed and the other image rotates with the rotation of the calcite crystal. The fixed image is called ordinary image and its refracted ray is called *o*-ray which has vibrations perpendicular to plane of the white paper. The other image is called extraordinary image and its refracted ray is called *e*-ray which has vibrations in the plane of the paper as shown in Fig .1.23.

Inside the crystal the *o*-ray travels with the same velocity in all direction.

But the *e*-ray has different velocities in different directions. If the incident ray strikes the crystal along a certain direction called the **optical axis** of the crystal, there will be no double refraction. Hence optical axis of the crystal is a direction along which both *o*-ray and *e*-ray travel in the same direction with the same velocity.

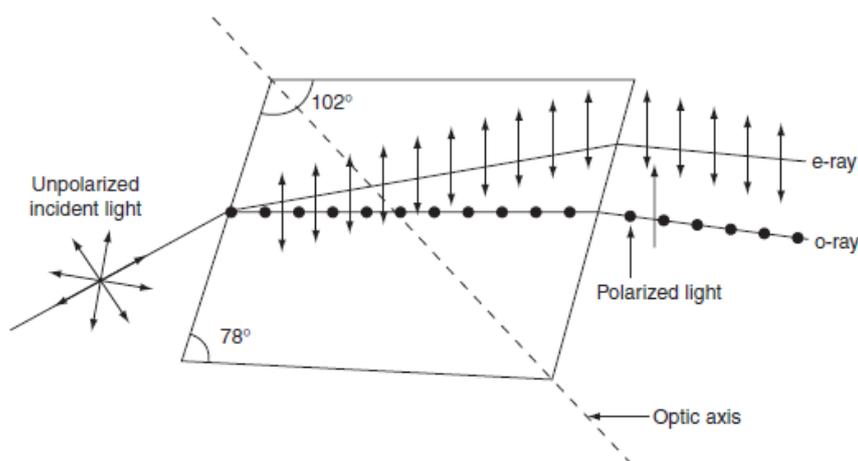


Fig.1.23.Double refraction in calcite crystal

Doubly refracting crystals

The crystals which exhibit double refraction are called doubly refracting crystals.

There are two types of doubly refracting crystals

- i. uni-axial crystals
- ii. biaxial crystals

Uni-axial crystals

If only one optical axis is present in the crystals, then they are called uni-axial crystals.

Examples: Calcite, quartz and tourmaline etc.

These crystals further divided into two crystals

- i. Uni-axial negative crystals
- ii. Uni-axial positive crystals

Uni-axial negative crystals

If the velocity of e -ray is more than that of o -ray in the crystals, then they are called negative crystals.

i.e., $v_e > v_o$ and $\mu_e < \mu_o$

Examples: Calcite, tourmaline, ruby and emerald etc

Uni-axial positive crystals

If the velocity of e -ray is less than that of o -ray in the crystals, then they are called positive crystals.

i.e., $v_e < v_o$ and $\mu_e > \mu_o$ **Examples:** Quartz and iron oxide.

Biaxial crystals

If two optic axes are present in the crystals, then they are called biaxial crystals.

Examples: Topaz and aragonite.

Note:

Optical axis

The direction in which the ray of transmitted light does not suffer double refraction inside the crystal is known as the optical axis. Along this axis both the velocities of o -ray and e -ray are the same and also refractive indices are same. *i.e.*, $v_e = v_o$ and $\mu_e = \mu_o$. So, there is no double refraction. Optical axis is a direction but not a line.

Wave Plates or Retardation Plates

Wave plates are the doubly refracting uniaxial (calcite) crystals whose refracting faces are cut parallel to the direction of the optic axis and are used to produce a phase difference between ordinary and extraordinary rays when they emerge from the doubly refracting crystals.

These are of mainly two types

- i. Quarter-wave plate
- ii. Half-wave plate

Quarter-waveplate

A quarter-wave plate is a thin double refracting crystal (calcite) having a thickness 't', cut and polished with its refracting faces parallel to the direction of optic axis such that it produces a path difference of $\lambda/4$ or phase difference of $\pi/2$ between the o-ray and e-ray when plane polarized light incident normally on the surface and passes through the plate.

Consider a calcite crystal of thickness 't'. When a plane polarized light is incident normally on the surface of calcite crystal, then the light will split up into o-ray and e-ray. These rays travel with different velocities in the crystal. As a result, when o-ray and e-ray emerging from the crystal, they have a phase or path difference between them due to variation in their velocities.

Let μ_o and μ_e are the refractive indices of o-ray and e-ray respectively. Let 't' be the thickness of the crystal. Hence the path difference between the two rays is

$$\begin{aligned} \Delta &= \text{Optical path for o-ray} - \text{Optical path for e-ray} \\ &= \mu_o t - \mu_e t \\ &= (\mu_o - \mu_e) t \end{aligned} \quad \rightarrow (1.57)$$

As the crystal is a quarter-wave plate, it introduces a path difference of $\lambda/4$ between o-ray and e-ray.

$$\Delta = \lambda/4 \quad \rightarrow (1.58)$$

From Eqs. (1.57) and (1.58), we get

$$\begin{aligned} (\mu_o - \mu_e) t &= \frac{\lambda}{4} \\ \text{Therefore } t &= \frac{\lambda}{4(\mu_o - \mu_e)} \end{aligned}$$

For positive crystal $\mu_e > \mu_o$, then $t = \frac{\lambda}{4(\mu_e - \mu_o)}$

For negative crystal $\mu_o > \mu_e$, then $t = \frac{\lambda}{4(\mu_o - \mu_e)}$

Applications

1. A quarter wave plate is used to produce circularly and elliptically polarized light.
2. Quarter wave plate converts plane-polarized light into elliptically or circularly polarized light.

light depending upon the angle that the incident light vector makes with the optic axis of the quarter waveplate.

Half-waveplate

A half-waveplate is a thin double refracting crystal (calcite) having a thickness 't', cut and polished with its refracting faces parallel to the direction of optic axis such that it produces a path difference of $\lambda/2$ or phase difference of π between the o-ray and e-ray when plane polarized light is incident normally on the surface and passes through the plate.

As the crystal is a half-waveplate, it introduces a path difference of $\lambda/2$ between o-ray and e-ray.

$$(\mu_e - \mu_o)t = \frac{\lambda}{2}$$

Therefore $t = \frac{\lambda}{2(\mu_e - \mu_o)}$

For positive crystal $\mu_e > \mu_o$, then $t = \frac{\lambda}{2(\mu_e - \mu_o)}$

For negative crystal $\mu_o > \mu_e$, then $t = \frac{\lambda}{2(\mu_o - \mu_e)}$

Applications

1. A half waveplate is used to produce plane polarized light.
2. It produces a phase difference of π between the ordinary and extraordinary ray.

Nicol's Prism

Nicol prism is an optical device used to produce and analyze plane polarized light. This was invented by William Nicol in the year 1828 and is known as Nicol prism. It is made from a double refracting calcite crystal.

Principle

It is based on the phenomenon of double refraction. When a light ray is passed through a calcite crystal, it splits up into two refracted rays such as ordinary (O-ray) and extraordinary ray (E-ray). Nicol prism transmits the extraordinary rays and eliminates ordinary rays with the help of the phenomenon of total internal reflection.

Construction

- It is constructed from the calcite crystal ABCD having length three times of its width.
- The end faces AB and CD are cut down such that the angles of principal section are 68° and 112° instead of 71° and 109° .

- The crystal is then cut diagonally into two parts. The surfaces of these parts are ground to make optically flat and then these are polished.

- These polished surfaces are connecting together with special cement known as Canada balsam which is a transparent liquid material.
- Canada balsam is optically (refractive index) more dense than e-ray and less dense for o-ray ($\mu_o = 1.6584, \mu_{ca} = 1.55$ and $\mu_e = 1.4864$).

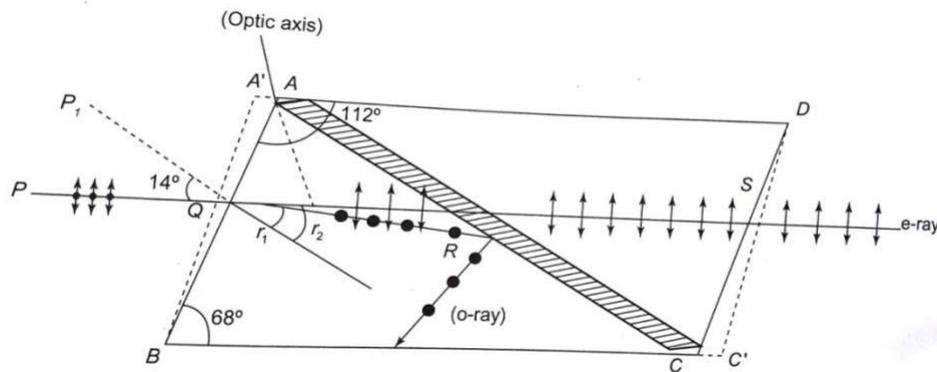


Fig.1.24. Nicol prism

Action or Working

- When a beam of unpolarized light PQ is incident on the face of AB, it splits into two refracted rays: o-ray (QR) and e-ray (QS) due to double refraction of calcite crystal.
- These two rays are plane polarized.
- From the refractive index values, we know that the Canada balsam acts as a rarer medium for the ordinary ray and acts as a denser medium for the extraordinary ray.
- When o-ray of light travels in the calcite crystal and enters the Canada balsam cement, it passes from denser to rarer medium. When the angle of incidence for ordinary ray on the Canada balsam is greater than the critical angle then the incident ordinary ray is totally internally reflected from the crystal and only e-ray is transmitted through the prism and emerges out of Nicol prism.
- In this way, plane polarized light is produced.

Nicol prism as polarizer and analyzer

- Nicol prism can be used as a polarizer and analyzer.
- In order to produce and analyze the plane polarized light, two Nicol prisms are arranged adjacently as shown in Fig.1.25.
- The first Nicol prism is used to produce plane polarized light and is called a polarizer. The second Nicol prism is used to test the emerging light and is called an analyzer.

- In the parallel positions, the extraordinary ray passes through both the prisms as shown in Fig. 1.29(a). In this case, the intensity of emergent extraordinary light is maximum.
- If the second prism is slowly rotated, then the intensity of the extraordinary ray decreases. When they are perpendicular to each other, no light comes out of the second prism because the e-ray that comes out from the first prism will enter into the second prism and act as an ordinary ray. So, this light is reflected in the second prism as shown in Fig. 1.29(b).

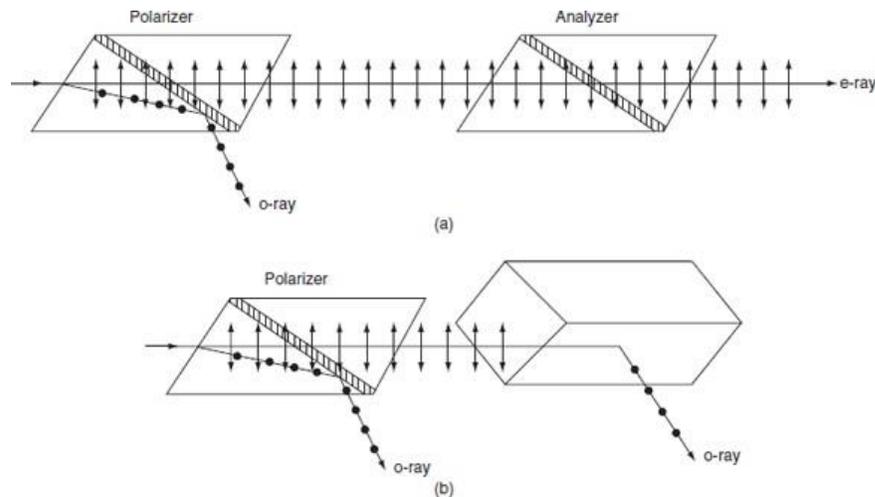


Fig. 1.26. Nicol prism as polarizer and analyzer

Engineering applications of Polarization

The phenomenon of Polarization can be used in various engineering applications; some of the applications are given below.

1. Polaroid glasses are used to reduce the amount of light that is approachable to eye.
2. Polarization is useful in receiving and transmitting wave signals.
3. Laser is an outcome of polarization of waves.
4. 3D movies (or stereoscopic movies) are possible because of polarization of light.
5. Photographic filters.
6. Photoelasticity—To study the objects with irregular boundaries and stress analysis.
7. LCD's.

UNIT-III-Dielectric and Magnetic properties of materials and Nanomaterials

Dielectric materials

Introduction

Dielectrics are insulating or non-conducting ceramic materials and are used in many applications such as capacitors, memories, sensors and actuators. Dielectrics are insulating materials that exhibit the property of electrical polarization, thereby they modify the dielectric function of the vacuum. A dielectric material is any material that supports charge without conducting it to a significant degree. In principle all insulators are dielectric, although the capacity to support charge varies greatly between different insulators. Although these materials do not conduct electrical current when an electric field is applied, they are not inert to the electric field. The field may cause a slight shift in the balance of charge within the material to form an electric dipole. Thus the material is called dielectric material.

Dielectric materials are used in many applications, from simple electrical insulation to sensors and circuit components.

Faraday was carried out the first numerical measurements on the properties of insulating materials when placed between the two parallel plates (capacitor), those materials, he called as dielectrics. He has found that the capacity of a condenser was dependent on the nature of the material separating the conducting surface. This discovery encouraged further empirical studies of insulating materials aiming at maximizing the amount of charge that can be stored by a capacitor. In search of suitable dielectric materials for specific applications, these materials have become increasingly concerned with the detailed physical mechanism governing the behavior of these materials.

The difference between dielectric material and insulator depends on its application. Insulating materials are used to resist flow of current through it, on the other hand dielectric materials are used to store electrical energy. In contrast to the insulation aspect, the dielectric phenomena have become more general

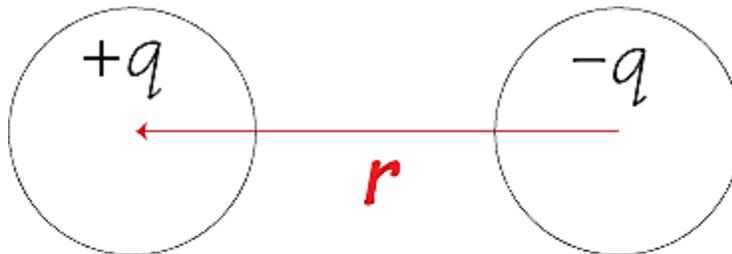
and fundamental, as it has the origin with the dielectric polarization.

Electric dipoles:

Upon application of a dc or static electric field, there is a long range migration of charges. However, there is a limited movement of charges leading to the formation of charge dipoles and the material, in this state, is considered as polarized. These dipoles are aligned in the direction of the applied field. The net effect is called Polarization of the material.

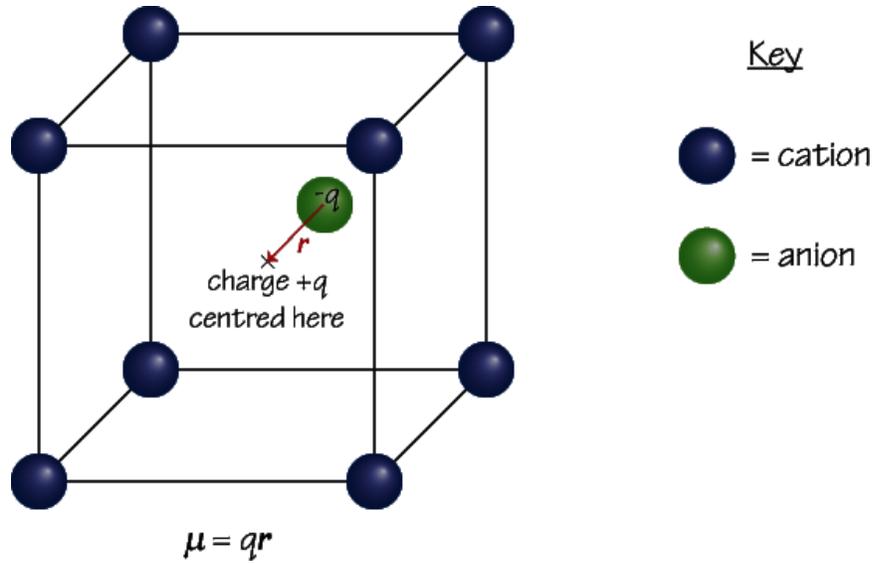
A dielectric supports charge by acquiring a polarisation in an electric field, whereby one surface develops a net positive charge while the opposite surface develops a net negative charge. This is made possible by the presence of electric dipoles – two opposite charges separated by a certain distance – on a microscopic scale.

1. If two discrete charged particles of opposite charges are separated by a certain distance, a dipole moment μ arises.



$$\mu = qr$$

2. If the centre of positive charge within a given region and the centre of negative charge within the same region are not in the same position, a dipole moment μ arises. For example, in the diagram below the centre of positive charge from the 8 cations shown is at X, while the centre of negative charge is located some distance away on the anion.



The second view of dipole moment is more useful, since it can be applied over a large area containing many charges in order to find the net dipole moment of the material.

The dipoles can be aligned as well as be induced by the applied field.

Note that in the equation for dipole moment, r is a vector (the sign convention is that r points from negative to positive charge) therefore the dipole moment μ is also a vector

Electric field intensity or electric field strength (E)

The force experienced by a unit test charge is known as electric field strength E

$$E = \frac{Q}{4\pi\epsilon r^2} \dots(1)$$

where ϵ is the permittivity or dielectric constant of the medium in which electric charge is placed.

For vacuum $\epsilon = \epsilon_0 = 8.854 \times 10^{-12} \text{Fm}^{-1}$

Electric flux density or electric displacement vector (D)

The electric flux density or electric displacement vector is the number of flux lines

crossing normal to a unit surface area. The electric flux density at a distance from the point charge Q is

$$D = \frac{Q}{4\pi r^2} \quad \dots(2)$$

then from (1) and (2) $D = \epsilon E \quad \dots (3)$

Dielectric constant (ϵ_r)

The dielectric constant of a material is defined as the ratio of the permittivity of the medium (ϵ) to the permittivity of free space (ϵ_0). It can also be defined as the ratio of the capacitance with dielectric (C_d) and with air (C_A) between the plates.

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} = \frac{C_d}{C_A} \quad \dots(4)$$

Capacitance: The property of a conductor or system of conductor that describes its ability to store electric charge.

$$C = q / V = A \epsilon / d \quad \text{where}$$

C is capacitance of capacitor

q is charge on the capacitor plate

V is potential difference between plates

A is area of capacitor plate

ϵ is permittivity of medium

d is distance between capacitor plates

Units: Farad .

Polarization

When an electric field is applied to a material with dielectrics, the positive charges are displaced opposite to the direction of the field and negative charges displaced in the direction of

the field. The displacement of these two charges create a local dipole, creation of dipole by applying electric field is called as polarization.



Polarization is defined as induced dipole moment per unit volume.

$$P = \frac{\sum \mu}{\text{Volume}} \quad \dots(5)$$

Polarisability

The polarization P is directly proportional to the electric field strength E

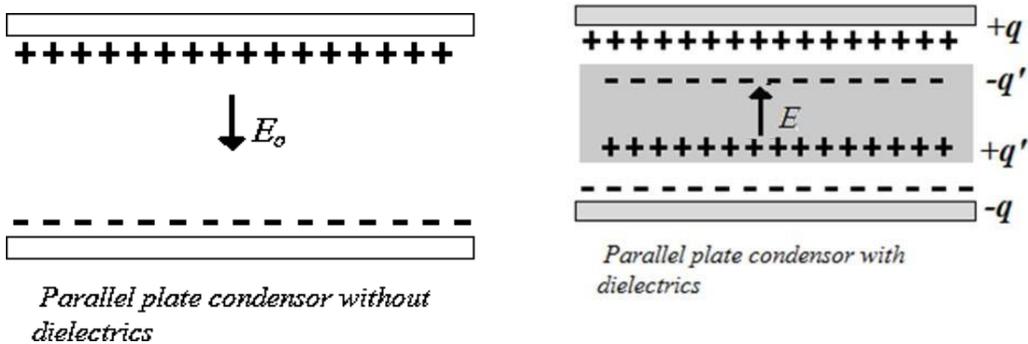
$$P \propto E$$

$$P = \alpha E \quad \dots(6)$$

Where α proportionality is constant called as polarisability. The polarisability is defined as polarization per unit applied electric field. If the material contains N number of dipoles per unit volume then

$$P = N\alpha E \quad \dots(7)$$

Relation between polarization and dielectric constant



Let us apply Gauss theorem for parallel plate condenser.

$$\int E \cdot dA = \frac{q}{\epsilon_0}$$

q

$$E_0 A = \frac{q}{\epsilon}$$

$$E_0 = \frac{q}{A \epsilon_0} = \frac{\sigma}{\epsilon_0} \quad \dots(1)$$

Where σ is the charge per unit area.

Let a dielectric slab placed between two plates. Due to polarization, charges appear on the two faces of the slab, and establish yet another field within the dielectric media. Let this field be E' . The direction of E' will be opposite to that of E_0 .

The resultant field E in the material can be written as,

$$E = E_0 - E' \dots\dots\dots (2)$$

If σ_p is the charge/unit area on the inserted dielectric slab surfaces, then by following equation (1), we write,

$$E' = \frac{q'}{A\epsilon_0} = \frac{\sigma_p}{\epsilon_0} \dots\dots\dots (3)$$

From (1), (2) and (3),

$$E = \frac{\sigma}{\epsilon_0} - \frac{\sigma_p}{\epsilon_0}$$

or

$$\epsilon_0 E = \sigma - \sigma_p \dots\dots\dots (4)$$

Since the magnitude of polarization $P =$ dipole moment/ Unit Volume

But dipole moment = induced charge X distance

Therefore

$$P = \text{induced charge/ Area} = \sigma_p$$

We know that electric displacement field or electric flux density D is given by charge /unit area

$$D = q/A = \sigma$$

Therefore Equation 4 becomes

$$\epsilon_0 E = D - P$$

$$P = D - E\epsilon_0 \quad \dots(5)$$

in free space where there is no dielectric $P=0$

$$D = E\epsilon_0$$

But in dielectric media the D changes. From electrostatics

$$D = \epsilon_0 \epsilon_r E$$

From (3)

$$P = E\epsilon_0 \epsilon_r - E\epsilon_0$$

$$P = E\epsilon_0 (\epsilon_r - 1)$$

.....(6)

$$(\epsilon_r - 1) = \frac{P}{E\epsilon_0} = \chi$$

Where χ is electric susceptibility of the dielectric medium. It doesn't have any units.

Since P and E are vectors eqn (6) can be written as

$$P = E\epsilon_0(\epsilon_r - 1) \dots(7)$$

This equation represents polarization vector.

Types of polarization

Dielectric polarization is the displacement of charge particles with the applied electric field. The displacement of electric charges results in formation of electric dipole moment in atoms, ions or molecules of the material. There are four different types of polarization, they are listed below.

1. Electric polarization,
2. Ionic polarization,
3. Orientation polarization
4. Space charge polarization

Electric polarization

The displacement of the positively charged nucleus and the negatively charged electrons of an atom in opposite directions, on application of an electric field, result in electronic polarization.

On applying a field, the electron cloud around the nucleus shifts towards the positive end of the field. As the nucleus and electron cloud are separated by a distance, dipole moment is created within each atom. The extent of this shift is proportional to the field strength.

Induced dipole moment

$$\mu_e \propto E$$

$$\mu_e = \alpha_e E$$

Where α_e is called electronic polarizability. The dipole moment per unit volume is called electronic polarization.

- It increases with increase of volume of the atom.
- This kind of polarization is mostly exhibited in monoatomic gases. (e.g. He, Ne, Ar, Kr, Xe etc..)
- It is independent of temperature.
- It occurs only at optical frequencies (10^{15} Hz)
- Vast fast process: $10^{-15} \sim 10^{-16}$ s.

Calculation of electronic polarizability:

Electronic polarization can be explained by classical model of an atom in gases. In gases the atoms are assumed that the interaction among the atoms is negligible. Here the nucleus of charge Ze is surrounded by an electron cloud of charge $-Ze$ distributed in the sphere of radius R .

$$\text{Charge density, } \rho = -Ze / (4/3)\pi R^3 \dots (1)$$

When an electric field E is applied, the nucleus and electrons experience Lorentz force of magnitude ZeE in opposite direction. Therefore the nucleus and electrons are pulled apart. As they are pulled apart a Coulomb force develops between them. At equilibrium these two forces are equal and nucleus and electron cloud are separated by a small distance x .

$$\text{Lorentz force} = -ZeE$$

Coulomb Force = $\frac{Ze \times Ze}{x^2} = \frac{Z^2 e^2}{x^2}$

x

...(3)

$$4\pi\epsilon_0 x^2 = \frac{Ze^2}{R^3} - 4\pi\epsilon_0 R^3 E$$

At equilibrium Lorentz force = Coulomb force (equation (2) equal to (3))

$$-ZeE = -\frac{Ze^2}{R^3} x$$

$$4\pi\epsilon_0 R^3$$

$$4\pi\epsilon R^3 E$$

$$x = \frac{Ze}{4\pi\epsilon R^3 E}$$

...(4)

$$Ze$$

The displacement of the electron cloud is proportional to applied electric field.

$$Ze4\pi\epsilon R^3 E$$

The electric dipole moment $\mu = Ze x = \frac{Ze^2}{4\pi\epsilon R^3 E}$

$$eZe$$

$$\mu_e = 4\pi\epsilon R_0^3 E$$

$$\mu_e \propto E$$

$$\alpha_e E$$

Where $\alpha_e = 4\pi\epsilon_0 R^3$ is called electronic polarizability.

$$P_e = N\mu_e = N\alpha_e E \quad \text{Where } N \text{ is the number of atoms/m}^3 \quad \dots(5)$$

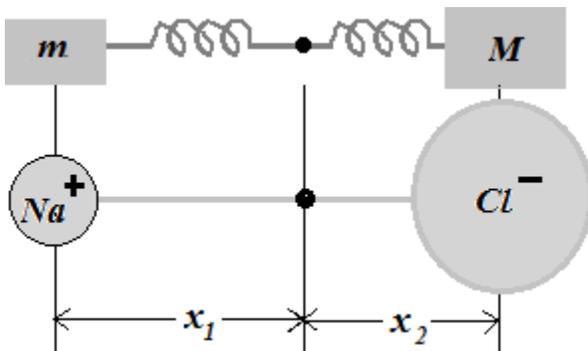
But polarization

$$P = E\epsilon_0 (\epsilon_r - 1) = N\alpha_e E$$

$$(\epsilon_r - 1) = \frac{N\alpha_e}{\epsilon_0} \quad \text{or } \alpha_e = \frac{(\epsilon_r - 1)\epsilon_0}{N}$$

Ionic Polarization

Ionic polarization occurs in ionic solids such as NaCl, KBr, and LiBr. When an electric field is applied to an ionic solid the positive and negative ions displace to their respective polarities creating an electric dipole this is called as ionic polarization.



In the absence of an electric field there is no displacement of ions. When an electric field is applied an induced dipole moment μ_i is produced.

Let x_1 and x_2 be the displacement of positive and negative ion respectively. Then the induced dipole moment.

$$\mu_j = e(x_1 + x_2) \quad \dots(6)$$

Let F be restoring force F

$$\propto x_1$$

$$\propto x_2$$

$$= \beta_1 x_1$$

$$= \beta_2 x_2$$

From mechanics the spring constant of mass attached to a spring is given by β

$= m\omega^2$ At equilibrium the Lorentz force = restoring force

$$eE = m\omega^2 x$$

Therefore

$$x = \frac{eEm}{2\omega^2}$$

Then $x_1 = \frac{eE}{m\omega^2}$

$$x_2 = \frac{eE}{M\omega^2}$$

$$\mu = \frac{e^2}{\omega^2} \left[\frac{1}{m} + \frac{1}{M} \right] E = \alpha_j E \quad \dots(7)$$

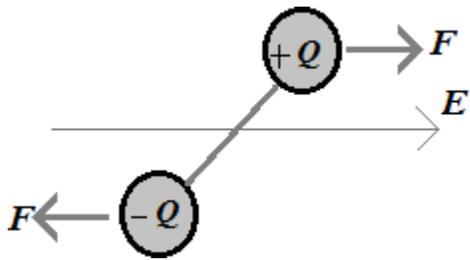
$$e^2 \left[\frac{1}{m} + \frac{1}{M} \right]$$

Where $\alpha_j = \frac{e^2}{\omega_0^2} \left[\frac{1}{m} + \frac{1}{M} \right]$ is called as ionic polarisability $\dots(8)$

Orientation Polarization

Orientation polarization occurs only in polar molecules (the molecules which have permanent dipole moment eg H₂O, Phenol, etc.). When an electric field is applied to a polar

molecule, the dipoles experience a torque and try to align parallel to the applied field.



Consider a polar molecule subjected to an electric field E . The alignment of electric dipole with the electric field is similar to the alignment of magnetic dipole with the applied magnetic field in paramagnetic material.

The expression for polarization can be obtained from the theory of paramagnetism.

The orientation polarization is given as

$$P = \frac{N \mu^2 E}{3KT} = \alpha E \quad \dots(9)$$

Where $\alpha = \frac{p_0}{3KT}$ is called as orientation polarisability ... (10)

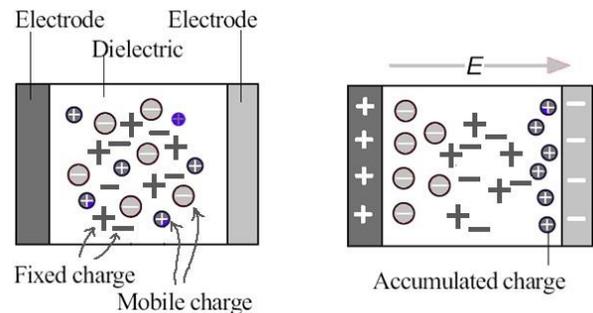
$$0 \quad 3KT$$

Space charge polarization

Space charge polarization occurs due to the accumulation of charges at the electrodes or at interfaces in a multiphase materials.

In the presence of an applied field, the mobile positive ions and negative ions migrate toward the negative electrode and positive electrode respectively to an appreciable distance giving rise to redistribution of charges, but they remain

in the dielectric material (electrode is blocking). The space charge polarization can be defined as the redistribution of charges due to the applied electric field and the charges accumulate on the surface of the electrodes. It occurs when the rate of charge accumulation is different from rate of charge removal. Space charge polarization is not significant in most of the dielectric materials.



Internal field in liquids and solids (one dimensional)

In gases state the atoms are separated by large distances and the interaction between the atoms can be neglected. When an external electric field E is applied, the intensity of the electric field experienced by an atom in gases state will be equal to the applied electric field E .

In solids and liquids, the atoms are close to each other leading to strong interaction between them. In solids and liquids the intensity of the electric field at a given point of the material is not equal to the applied electric field but equal to internal field which is the sum of applied electric field and field due to other dipoles present in the material.

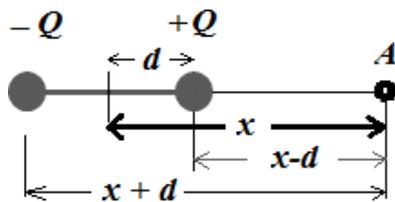
Internal field $E_i = E + E'$

...(1)

The internal field can be calculated by Epstein model in the case of one dimensional atomic array.

Electric field along the axis of an electric dipole

Consider an electric dipole of length $2d$ and charge Q , the field along the axis of the dipole at point A is the sum of the electric field due to $+Q$ and $-Q$.



The electric field due to $+Q$ at point A is

$$E^+ = \frac{Q}{4\pi\epsilon_0(x-d)^2}$$

The electric field due to $-Q$ at point A is

$$E^- = \frac{Q}{4\pi\epsilon_0(x+d)^2}$$

Electric field of dipole at A is $E = E^+ - E^- = \frac{Q}{4\pi\epsilon_0} \left[\frac{1}{(x-d)^2} - \frac{1}{(x+d)^2} \right]$

A

$$= \frac{2Q}{4\pi\epsilon_0} \left[\frac{2dx}{(x-d)^2(x+d)^2} \right]$$

oL J



since $x \gg d$ $(x-d)^2 \approx (x+d)^2 \approx x^2$ then

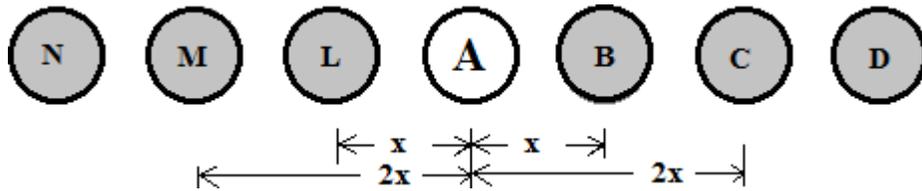
$$= \frac{2Q}{x} [2dx] = \frac{4dQ}{x}$$

since $2dQ = \mu_i$

$$E = \frac{2\mu_i}{4\pi\epsilon_0 x^3} \dots(2)$$

$$A \frac{2\mu_i}{4\pi\epsilon_0 x^3}$$

Consider an array of one dimensional atoms along x- axis. The all the atoms are similar, equally spaced and have induced electric dipole moment μ_i in an applied electric field E . The electric field experienced at the A is the sum of electric fields of other dipoles and applied electric field E .



The electric field at A due to the induced dipole B and L which are at a distance x is

$$E_B = E_L = \frac{2\mu_i}{4\pi\epsilon_0 x^3}$$

$$B \quad L \quad \frac{2\mu_i}{4\pi\epsilon_0 x^3}$$

The electric field at A due to the induced dipole C and M which are at a distance 2x is

$$E_C = E_M = \frac{2\mu_i}{4\pi\epsilon_0 (2x)^3}$$

Therefore the field due to other dipoles is

$$E' = E_B + E_L + E_C + E_M + E_D + E_N + \dots \quad \dots(3)$$

$$E' = \frac{2\mu_j}{i} + \frac{2\mu_j}{i_0} + \frac{2\mu_j}{i} + \frac{2\mu_j}{i} + \frac{2\mu_j}{i} + \dots$$

$$\frac{4\pi\epsilon_0 \mu_j x^3}{3} + \frac{4\pi\epsilon_0 \mu_j x^3}{3} + \frac{4\pi\epsilon(2x)^3}{3} + \frac{4\pi\epsilon(2x)^3}{3} + \frac{4\pi\epsilon(3x)^3}{3} + \frac{4\pi\epsilon(3x)^3}{3} + \dots$$

$$E' = \frac{4\mu_j}{i} + \frac{4\mu_j}{i_0} + \frac{4\mu_j}{i} + \dots$$

$$\frac{4\pi\epsilon_0 \mu_j x^3}{3} + \frac{4\pi\epsilon(2x)^3}{3} + \frac{4\pi\epsilon(3x)^3}{3} + \dots$$

$$E' = \mu_j \left[\frac{1}{1^3} + \frac{1}{2^3} + \frac{1}{3^3} + \frac{1}{4^3} + \frac{1}{5^3} + \dots \right] \quad \text{where } 1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots = 1.2$$

$$\frac{\pi\epsilon_0 \mu_j x^3}{3} \left[\frac{1}{2^3} + \frac{1}{4^3} + \frac{1}{5^3} + \dots \right] \quad \frac{\pi\epsilon_0 \mu_j x^3}{3} \left[\frac{1}{2^3} + \frac{1}{4^3} + \frac{1}{5^3} + \dots \right]$$

$$E' = 1.2 \mu_j$$

$$\frac{\pi\epsilon_0 \mu_j x^3}{3}$$

Therefore the internal field $E = E + \frac{1.2\mu_i}{\pi\epsilon_0 r^3}$... (4)

$$i \quad \frac{\mu_i}{\pi\epsilon_0 r^3}$$



The local field in a three dimensional solid is similar the above equation the number density N of atoms replaces $1/a^3$. Since $N\mu_i = P$ and $1.2/\pi$ is replaced by γ . Then the internal field is

$$E_i = E + \frac{1.2N\mu_i}{\pi\epsilon_0} = E + \frac{1.2P}{\pi\epsilon_0} = E + \gamma P$$

γ depends on the internal structure For a cubic symmetry crystal γ value is $1/3$

$$E_i = E + \frac{P}{3\epsilon_0} \quad \dots(5)$$

The field given by the above equation is called Lorentz field.

Clausius - Mosotti equation

Let us consider elemental solid dielectric which exhibits only electronic polarization. If α_e is the electronic polarisability per atom, it is related to the bulk polarization P through the relation

$$P = N\alpha_e E_i \quad \dots(6)$$

$$\alpha_e = \frac{P}{NE_i} \quad \dots(7)$$

Where N is the number of atoms per unit volume and E_i is the local field using the relation (5)

$$\alpha_e = \frac{P}{E_i}$$

$$\overline{P} \quad \dots$$

$$\left(\begin{array}{c} 8 \\ \end{array} \right)$$

$$N \left[\frac{E + \frac{P}{3}}{\epsilon_0} \right]$$

By using the relation between the polarization and permittivity we have

$$P = E \epsilon_0 (\epsilon_r - 1) \quad \dots(9)$$

$$E = \frac{P}{\epsilon_0 (\epsilon_r - 1)} \quad \dots(10)$$

Substitute the value of E from (10) in (8)

$$\alpha_e = \frac{P}{N \left[\frac{P}{\epsilon_0 (\epsilon_r - 1)} + \frac{P}{3} \right]}$$

$$N \alpha_e = \frac{1}{\frac{1}{\epsilon_0 (\epsilon_r - 1)} + \frac{1}{3}} = \frac{3 \epsilon_0 (\epsilon_r - 1)}{\epsilon_r + 2}$$

$$\epsilon_0 \left[\frac{3}{\epsilon_r + 2} \right]$$

$$|(\varepsilon - 1)| \quad | |3(\varepsilon - 1)| |$$



$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{N \alpha_e}{3 \epsilon_0} \quad \dots(11)$$

The above equation is known as Clausius-Mosotti equation which is valid for nonpolar solids

Dielectric loss:

Dielectric loss is the dissipation of energy through the movement of charges in an alternating electromagnetic field as polarisation switches direction.

An efficient dielectric supports a varying charge with minimal dissipation of energy in the form of heat is called dielectric loss. There are two main forms of loss that may dissipate energy within a dielectric. In conduction loss, a flow of charge through the material causes energy dissipation.

Dielectric loss is especially high around the relaxation or resonance frequencies of the polarisation mechanisms as the polarisation lags behind the applied field, causing an interaction between the field and the dielectric's polarisation that results in heating. This is illustrated by the diagram below (recall that the dielectric constant drops as each polarisation mechanism becomes unable to keep up with the switching electric field.)

Dielectric loss quantifies a dielectric material's inherent dissipation of electromagnetic energy into, e.g., heat.

It can be represented in terms loss tangent $\tan \delta$ and is defined:

$$\tan \delta_e = \frac{\epsilon''}{\epsilon'}$$

Dielectric Breakdown : The dielectric breakdown is the sudden change in state of a dielectric material subjected to a very high electric field , under the influence of which , the electrons are lifted into the conduction band causing a surge of current , and the ability of the material to resist the current flow suffers a breakdown .

Or

When a dielectric material loses its resistivity and permits very large current to flow through it, then the phenomenon is called dielectric breakdown

Or

At high electric fields, a material that is normally an electrical insulator may begin to conduct electricity – i.e. it ceases to act as a dielectric. This phenomenon is known as dielectric breakdown.

Frequency dependence of polarizability:

On application of an electric field, polarization process occurs as a function of time. The polarization $P(t)$ as a function of time t is given by

$$P(t) = P[1 - \exp(-t/t_r)]$$

Where P – max. Polarization attained on prolonged application of static field. t_r - relaxation time for particular polarization process

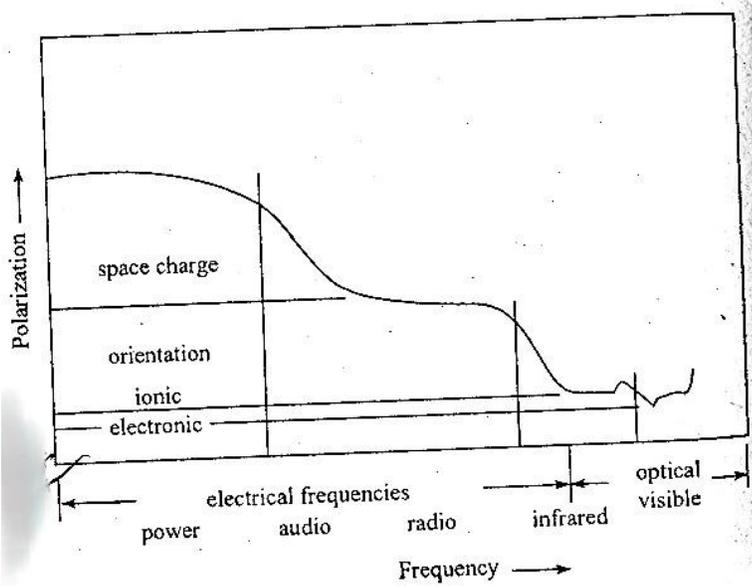
The relaxation time t_r is a measure of the time scale of polarization process. It is the time taken for a polarization process to reach 0.63 of the max. value.

Electronic polarization is extremely rapid. Even when the frequency of the applied voltage is very high in the optical range ($\approx 10^{15}$ Hz), electronic polarization occurs during every cycle of the applied voltage.

Ionic polarization is due to displacement of ions over a small distance due to the applied field. Since ions are heavier than electron cloud, the time taken for displacement is larger. The frequency with which ions are displaced is of the same order as the lattice vibration frequency ($\approx 10^{13}$ Hz). Hence, at optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than 10^{13} Hz, the ions respond.

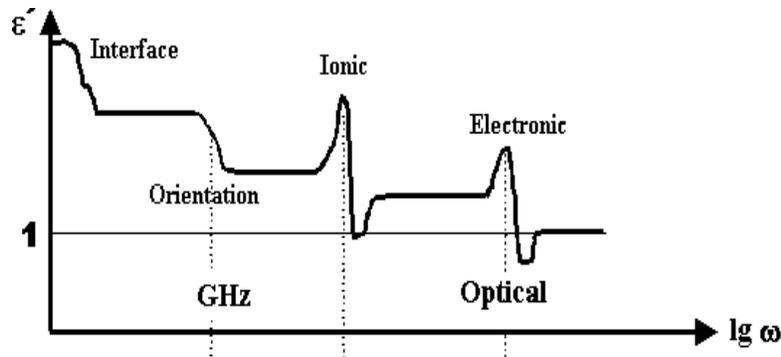
Orientation polarization is even slower than ionic polarization. The relaxation time for orientation polarization in a liquid is less than that in a solid. Orientation polarization occurs, when the frequency of applied voltage is in audio range (10^3 Hz).

Space charge polarization is the slowest process, as it involves the diffusion of ions over several interatomic distances. The relaxation time for this process is related to frequency of ions under the influence of applied field. Space charge polarization occurs at power frequencies (50-60 Hz).



Frequency Dependence of dielectric constant

When a dielectric material is subjected to an alternating field, the polarization component required to follow the field in order to contribute to the total polarization of the dielectrics. The relative permittivity which is a measure of the polarization also depends on the frequency. The dependence of ϵ_r on frequency of the electric field is shown in the figure.



At very low frequency, the dipoles will get sufficient time to orient themselves completely with the field and all types of polarization exist. Since the dielectric is characterized by polarisability α ($\alpha = \alpha_e + \alpha_i + \alpha_o$) at low frequency i.e at radiofrequency region the dielectric constant will be due to all polarisability.

The orientation polarization, which is effective at low frequencies, is damped out for higher frequencies. In the microwave region the dipoles fail to follow the field and the polarisability reduces to ($\alpha = \alpha_e + \alpha_i$), as a result ϵ_r decreases to some amount.

In the IR region the ionic polarization fails to follow the field so the contribution of ionic polarization dies away. In this region only electronic polarization contributes to the total polarization. Therefore ($\alpha = \alpha_e$) the ϵ_r still decreases and only electronic polarization exist.

We know that

$$P = N\alpha_e E = \epsilon_0 (\epsilon_r - 1)E$$

Then the relative permittivity is

$$\epsilon_r = 1 + \frac{N\alpha_e}{\epsilon_0}$$

$$\dots(1) \quad \frac{\quad}{0}$$

In the ultraviolet region even the electron cloud could not follow the field and electronic polarizability becomes almost zero and the permittivity becomes one.

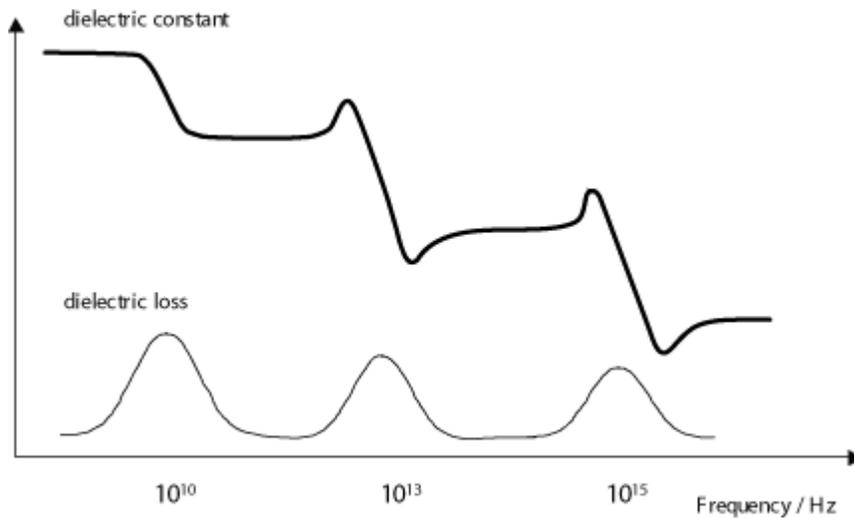
$$[\epsilon_r]_{X-ray} = 1$$

For example at low frequency the dielectric constant of water at room temperature is about 80, but it fall to about 1.8 in the optical region.



Frequency Dependence of dielectric loss:

Dielectric loss tends to be higher in materials with higher dielectric constants. This is the downside of using these materials in practical applications. Dielectric loss is utilised to heat food in a microwave oven: the frequency of the microwaves used is close to the relaxation frequency of the orientational polarisation mechanism in water, meaning that any water present absorbs a lot of energy that is then dissipated as heat. The exact frequency used is slightly away from the frequency at which maximum dielectric loss occurs in water to ensure that the microwaves are not all absorbed by the first layer of water they encounter, therefore allowing more even heating of the food.



Ferroelectrics

Below certain temperature it is found that some materials spontaneously acquire an electric dipole moment. These materials are called as ferroelectric materials or ferroelectrics. The temperature at which ferroelectric property of the material disappears is called as ferroelectric Curie temperature.

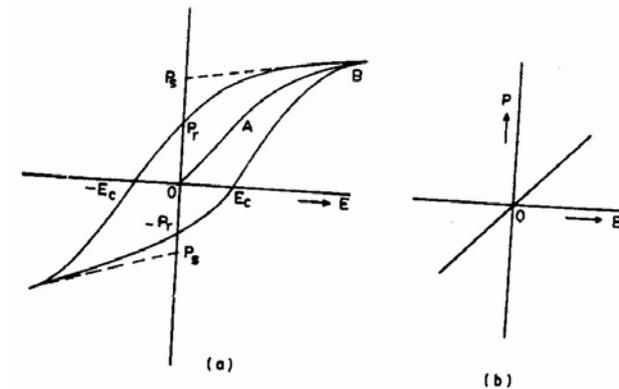
Ferroelectric materials are anisotropic crystals which exhibit a hysteresis curve P versus E which can be explained by domain hypothesis.

Ferro electricity: Ferro electric materials are an important group not only because of intrinsic Ferro electric property, but because many possess useful piezo electric, birefringent and electro optical properties.

The intrinsic Ferro electric property is the possibility of



reversal or change of orientation of the polarization direction by an electric field. This leads to hysteresis in the polarization P , electric field E relation, similar to magnetic hysteresis. Above a critical temperature, the Curie point T_c , the spontaneous polarization is destroyed by thermal disorder. The permittivity shows a characteristic peak at T_c .



Piezo – Electric Materials and Their Applications: Single crystal of quartz is used for filter, resonator and delay line applications. Natural quartz is now being replaced by synthetic material.

Rochelle salt is used as transducer in gramophone pickups, ear phones, hearing aids, microphones etc. the commercial ceramic materials are based on bariumtitanate, lead zirconate and lead titanate. They are used for high voltage generation (gas lighters), accelerometers, transducers etc. Piezo electric semiconductors such as GaS, ZnO & CdS are used as amplifiers of ultrasonicwaves.

Applications of DielectricMaterials:

Almost any type of electrical equipment employs dielectric materials in some form or another. Wires and cables that carry electrical current, for example, are always coated or wrapped with some type of insulating (dielectric) material. Sophisticated electronic equipment such as rectifiers, semiconductors, transducers, and amplifiers contain or are fabricated from dielectric materials. The insulating material sandwiched between two conducting plates in a capacitor is also made of some dielectric substance.

Liquid dielectrics are also employed as electrical insulators. For example, transformer oil is a natural or synthetic substance (mineral oil, silicone oil, or organic esters, for example) that has the ability to insulate the coils of a transformer both electrically and thermally.



1. Capacitors

Commercially manufactured capacitors typically use a solid dielectric material with high permittivity as the intervening medium between the stored positive and negative charges. This material is often referred to in technical contexts as the *capacitor dielectric*.

The most obvious advantage to using such a dielectric material is that it prevents the conducting plates, on which the charges are stored, from coming into direct electrical contact. More significantly, however, a high permittivity allows a greater stored charge at a given voltage. This can be seen by treating the case of a linear dielectric with permittivity ϵ and thickness d between

$$\sigma_\epsilon = \epsilon \frac{V}{d}$$

two conducting plates with uniform charge density σ_ϵ . In this case the charge density is given by

and the capacitance per unit area by

$$c = \frac{\sigma_\epsilon}{V} = \frac{\epsilon}{d}$$

From this, it can easily be seen that a larger ϵ leads to greater charge stored and thus greater capacitance.

Dielectric materials used for capacitors are also chosen such that they are resistant to ionization. This allows the capacitor to operate at higher voltages before the insulating dielectric ionizes and begins to allow undesirable current.

2. Dielectric resonator

A *dielectric resonator oscillator* (DRO) is an electronic component that exhibits resonance of the polarization response for a narrow range of frequencies, generally in the microwave band. It consists of a "puck" of ceramic that has a large dielectric constant and a low dissipation factor. Such resonators are often used to provide a frequency reference in an oscillator circuit. An unshielded dielectric resonator can be used as a Dielectric Resonator Antenna (DRA).

3. Insulators-

Required Qualities of Good Insulating Materials: The required qualities can be classified as under electrical, mechanical, thermal and chemical applications.

- i) Electrical:
 1. electrically the insulating material should have high electrical resistivity and high dielectric strength to withstand high voltage.
 2. The dielectric losses must be minimum.
 3. Liquid and gaseous insulators are used as coolants. For example transformer oil, Hydrogen and helium are
- ii) Mechanical:
 1. insulating materials should have certain mechanical properties depending on the use to which they are put.
 2. When used for electric machine insulation, the insulator should have sufficient mechanical strength to withstand vibration.
- iii) Thermal: Good heat conducting property is also desirable in such cases. The insulators should have small thermal expansion and it should be non-ignitable.
- iv) Chemical:
 1. chemically, the insulators should be resistant to oils, liquids, gas fumes, acids and alkalis.
 2. The insulators should be water proof since water lowers the insulation resistance and the dielectric strength.

Other Applications:

Solid dielectrics are perhaps the most commonly used dielectrics in electrical engineering, as very good insulators. Some examples include porcelain, glass, and most plastics.

Air, nitrogen and sulfur hexafluoride are the three most commonly used gaseous dielectrics.

Industrial coatings such as parylene provide a dielectric barrier between the substrate and its environment.

Mineral oil is used extensively inside electrical transformers as a fluid dielectric and to assist in cooling. Dielectric fluids with higher dielectric constants, such as electrical grade castor oil, are often used in high voltage capacitors to help prevent corona discharge and increase capacitance.

Because dielectrics resist the flow of electricity, the surface of a dielectric may retain stranded excess electrical charges. This may occur accidentally when the dielectric is rubbed (the triboelectric effect). This can be useful, as in a Van de Graaff generator or electrophorus, or it can be potentially destructive as in the case of electrostatic discharge.

Piezoelectric materials are another class of very useful dielectrics which are used for transducers and sensors.

Ferroelectric materials often have very high dielectric constants, making them quite useful for capacitors.



Sample Questions:

Dielectric Materials:

1. Explain the phenomenon of electric polarization in dielectric materials?.
2. Describe in brief
 - (a) electronic polarization
 - (b) ionic polarization
 - (c) Orientation polarization
 - (d) Space charge polarisation with diagrams. Also find the total polarizability.
3. Differentiate between polar and nonpolar dielectrics.
4. Derive an expression for internal field in solids and liquids. Or Derive an expression for internal field by Lorentz method?
5. Derive Clausius-Mossotti equation.
6. What are ferroelectric materials? Describe in detail the Ferroelectric hysteresis.
7. Applications of Dielectric materials.
8. Derive the relation between dielectric polarization and dielectric constant?
9. What is its dielectric constant? Explain its importance in dielectric materials?
10. Which of the following properties are typical for dielectrics?
11. Write a note on
 - (a) Ferroelectricity
 - (b) Dielectric constant
 - (c) internal field in solids
12. Discuss the frequency dependence of various polarization processes in dielectric materials.
13. What is dielectric loss? And also explain *Dielectric Breakdown*.
14. Describe the frequency dependence of dielectric constant.
15. Explain the applications of dielectric materials as insulators.

Magnetic Materials:

1. Define magnetization and show that $B = \mu_0(H + M)$
-

2. Explain the classification of magnetic materials in detail?
 3. Give important features of ferromagnetic materials. Explain the hysteresis curve on the basis of domains.
 4. What is hysteresis loss? Explain.
 5. Distinguish between soft and hard magnets.
 6. What is ferromagnetic Curie temperature? Discuss the behaviour of a ferromagnetic material below the Curie temperature.
 7. What are ferrites? Explain the magnetic properties of ferrites and mention their industrial applications.
 8. Write the importance of hard magnetic materials in engineering applications?
 9. What are the applications of soft and hard magnetic materials?
-

Important formulae:



Problems



2.



3. The dielectric constant of Sulphur is 3.4. Assuming a cubic lattice for its structure, calculate the electronic polarizability for Sulphur.

Given: Sulphur density= 2.07 gm/cc, and atomic weight =32.07 Given

data:



4. Find the polarization produced in a dielectric medium of relative permittivity 15 in presence of an electric field of 500 V/m.

Given data:

Relative permittivity, $\epsilon_r = 15$.

Strength of electric field, $E = 500 \text{ V/m}$.

find :

Polarization, $P = ?$

We have,

$$\begin{aligned} P &= \epsilon_0 (\epsilon_r - 1) E, \\ &= 8.854 \times 10^{-12} (15 - 1) 500, \\ &= 6.198 \times 10^{-8} \text{ cm}^{-2}. \end{aligned}$$

Polarization produced in the medium is $6.198 \times 10^{-8} \text{ cm}^{-2}$.

1. In a magnetic material, the field strength is 10^6 Am^{-1} . The magnetic susceptibility of the material is 0.5×10^{-5} . Calculate the intensity of magnetization and the flux density of the material.

$$\chi = \frac{M}{H}$$

H

$$M = \chi H = 0.5 \times 10^{-5} \times 10^6 = 5$$

$$B = \frac{\phi}{A} = \mu_0 (M + H)$$

A

$$= 4\pi \times 10^{-7} (5 + 10^6)$$

$$= 1.257 \text{ Wbm}^{-2}$$

2. If a magnetic field of 1800 Am^{-1} produces a magnetic field $3 \times 10^{-5} \text{ Wb}$ in an iron bar of cross sectional area 0.2 cm^2 , Calculate permeability.
-

$$B = \frac{\phi}{A} = 1.5 \text{ Wbm}^{-2}$$

$$B = \mu_0 \mu_r H$$

A

$$\mu_r = \frac{B}{H \mu_0} = \frac{1.5}{4\pi \times 10^{-7} \times 1800} = 663.14$$

3. Calculate the saturation magnetization for Ni ferrite. The lattice parameter of a cubic unit cell of Ni ferrite is 0.835nm and the magnetic moment per unit cell is 18.4 μ_B .

$$(\mu_B = 9.27 \times 10^{-24})$$

$$M = \frac{\text{Magnetic moment}}{\text{volume}} = \frac{18.4 \times 9.27 \times 10^{-24}}{(0.835 \times 10^{-9})^3} = 2.929 \times 10^5$$

Introduction:

Magnetism

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

Magnetic Poles:

When a bar magnet is dipped in a heap of iron filings and taken out, it is seen that maximum amount of iron filings are seen to cling to the magnet at the two ends of the magnet. Practically no iron filings cling in the middle. The regions of the magnet at which maximum amount of iron filings cling are called poles of the magnet. *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” ($2l$).

Magnetic Dipole:

- Magnetic dipoles are found to exist in magnetic materials, analogous to electric dipoles.
 - 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 $2l$ (**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.
-

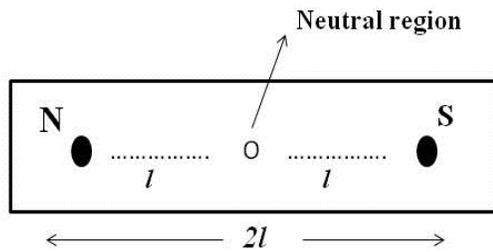


Fig : Magnetic dipole

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 (2l).

$$\vec{\mu}_m = m (2l)$$

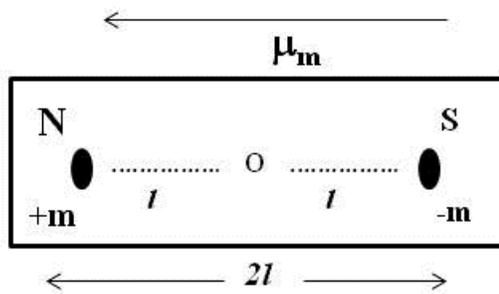


Fig : Magnetic dipole moment

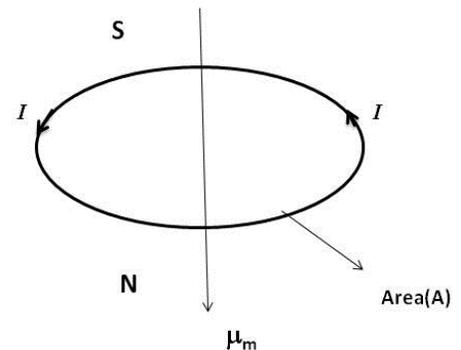


Fig : Current carrying conductor loop

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

The S.I. Unit of magnetic dipole moment: Ampere – meter² (A-m²).

(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

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

$$\mu_m \propto I.A$$

$$\mu_m = K IA$$

$$\mu_m = IA$$

Where K is a proportionality whose value is one

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.

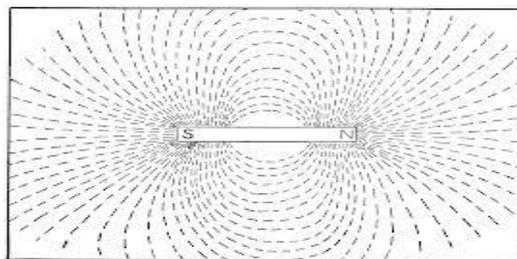


Fig: Magnetic field.

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).

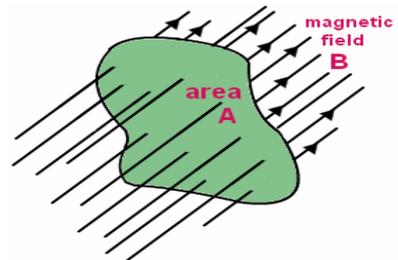
One Weber is equal to 1×10^8 magnetic fieldlines.

Magnetic Flux Density:

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

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

$$B = \frac{\Phi}{A} \text{ Tesla}$$



Magnetization:

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

The process of converting a non-magnetic material into a magnetic material is known as “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.

$$M \propto H$$

$$M = \chi_m H$$

$\text{Magnetic Susceptibility } (\chi_m) = \frac{M}{H}$
--

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):

- It is the natural property of material.
- 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.

$$B \propto H$$

$$B = \mu H$$

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

Where “ μ ” is the permeability of a medium.

For vacuum,

$B = \mu_0 H$

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

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

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

$\mu_r = 1$ for vacuum. 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**.

$$B = \mu_0 H + \mu_0 M$$

$$B = \mu_0 (H + M)$$

$$\mu H = \mu_0 (H + M) \quad (B = \mu H \text{ and } \mu = \mu_0 \mu_r)$$

$$\mu_0 \mu_r H = \mu_0 \left(1 + \frac{M}{H}\right)$$

$$\mu_r = (1 + \chi_m)$$

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 ((μ_{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.

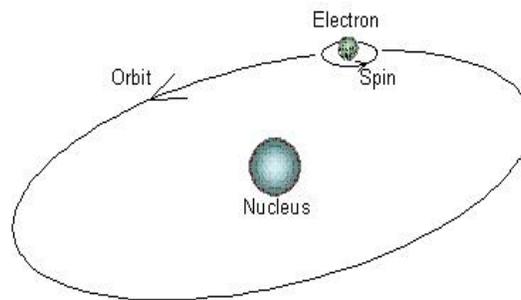


Fig: Motion of electron

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}) .

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

Proof:

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

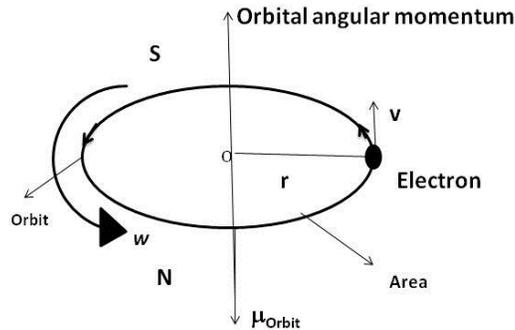


Fig : Orbital motion of electron

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

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

Where 'w' is the angular frequency of the electron

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

$$v = r w$$

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

Substituting the equation (3) in (2),

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

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

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

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.

$$\text{The Area of the orbit is } A = \pi r^2 \quad \rightarrow (6)$$

Then the corresponding magnetic dipole moment is given by

$$\mu_{\text{Orbit}} = IA$$

$$\begin{aligned} &= \frac{-ve}{2\pi r} \times \pi r^2 \\ &= \frac{-evr}{2} \quad \rightarrow (7) \end{aligned}$$

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

$$\begin{aligned} \mu_{\text{Orbit}} &= \frac{-evr}{2} \times \frac{m}{m} \\ &= \frac{-e(mvr)}{2m} \\ &= \frac{-e(L)}{2m} \quad \rightarrow \quad (\text{But } L = mvr) \quad \rightarrow \end{aligned}$$

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

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

→

An electron has an intrinsic orbital angular momentum (L) itself cannot be measured. However, its component along any axis can be measured.

Let us assume that the component of orbital angular momentum (\mathbf{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_l is called orbital magnetic quantum number = $0, \pm 1, \pm 2, \pm 3 \dots$

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 $\mu_{\text{Orbit}, z}$ can have only the two values is given by

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

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

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

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

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

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

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

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

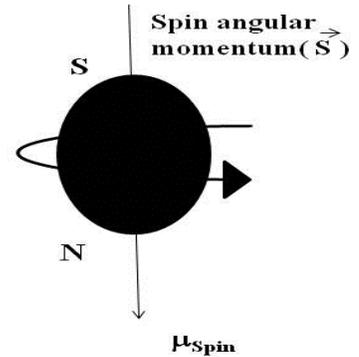


Fig: Spin motion of electron

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

$g_l=1$ 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

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

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 $\mu_{\text{Spin}, z}$ can have only the two values is given by

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

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

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

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

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

Nuclear spin magnetic dipole moment (μ_{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

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

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 absence 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

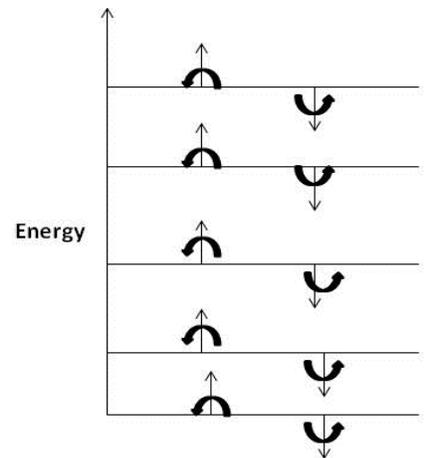
Examples:

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.



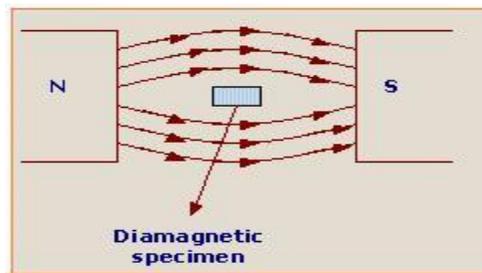
Effect of external magnetic field:

- 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
-

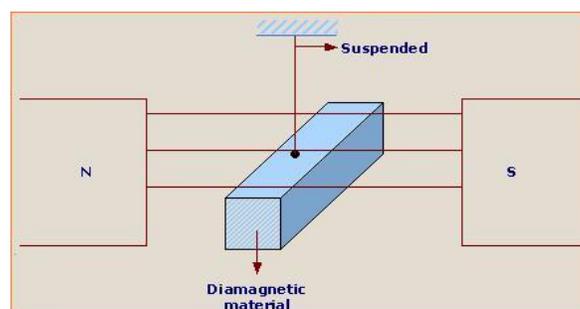
magnetic field which opposes the applied magnetic field. Hence, the induced magnetic moments of atoms/molecule/ions are opposite to the applied magnetic field.

Properties:

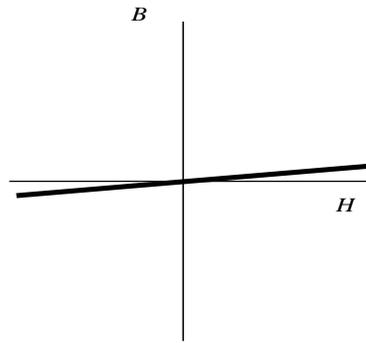
- They don't possess permanent magnetic dipole moment.
- When a diamagnetic material is placed in a magnetic field, it is feebly magnetized in a direction opposite to that of the applied magnetic field.
- When a diamagnetic material is placed in a magnetic field, the magnetic lines force prefers to pass 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.
- When a rod of diamagnetic material is suspended freely in a uniform magnetic field, the rod comes to rest with its axis perpendicular to the direction of the applied field.



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



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.
-

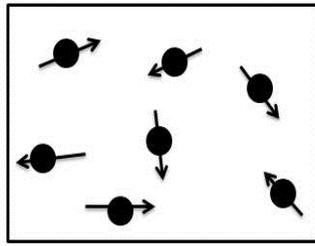


Fig: In the absence of external magnetic field (H=0)

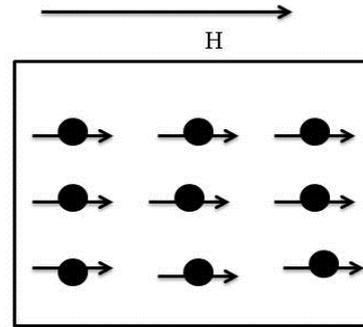
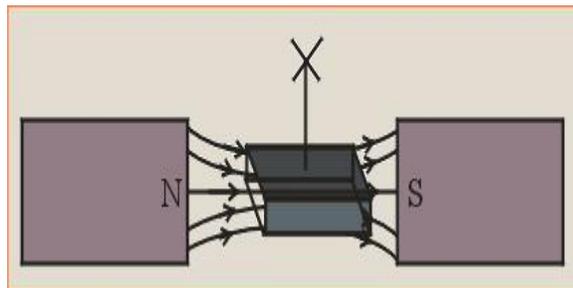


Fig: In the presence of external magnetic field

Properties:

- They possess permanent magnetic dipole moment.
- When a paramagnetic material is placed in a magnetic field, it is feebly or weakly 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.

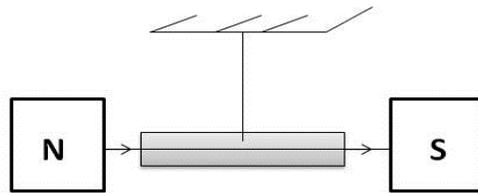
$$\chi_m = \frac{C}{T - \theta_C} \text{ (Curie-Weiss law)}$$

Where C \rightarrow Curie constant

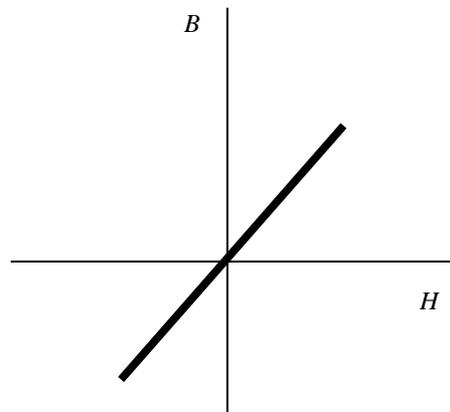
T \rightarrow Absolute temperature and

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} m³.

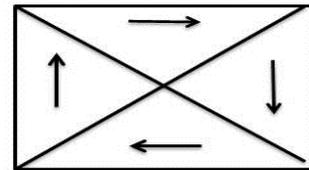


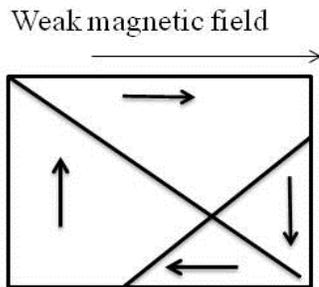
Fig: Without field

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.
- 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.



**Fig: Displacement of domain walls
With weak magnetic field**

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.

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.

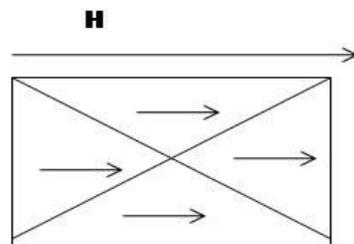
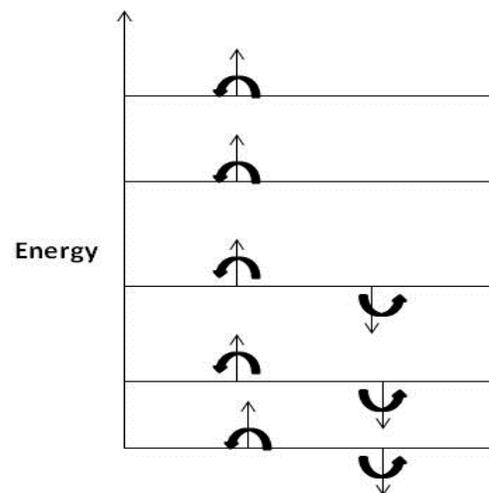
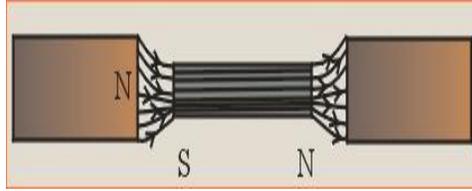


Fig: Rotation of domain walls in strong magnetic field

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 crowd into the Ferro magnetic material.





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

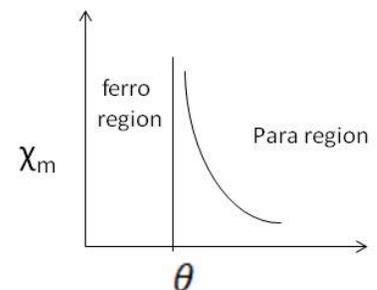
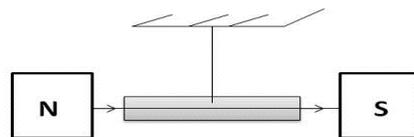
$$\chi_m = \frac{C}{T - \theta_c} \text{ (Curie-Weiss law)}$$

Where $C \rightarrow$ Curie constant

$T \rightarrow$ Absolute temperature and

θ_c Curie temperature \rightarrow

- 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:

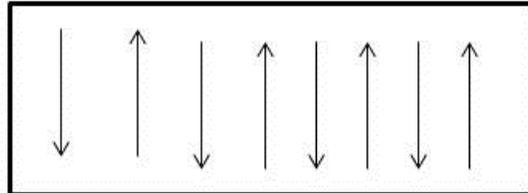
Depending upon the spin orientation of the electrons, ferromagnetic materials are classified into two types, they are 1. Antiferromagnetic materials 2. Ferri magnetic materials

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 (MnO₄),
- Manganese sulphide (MnS),
- Chromium Oxide (Cr₂O₃),
- Ferrous Chloride (FeCl₂) etc



dipole

Properties:

- In this materials spin magnetic 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.

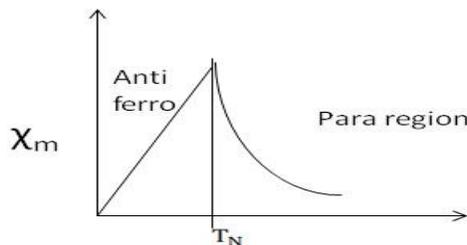
$$\chi_m = \frac{C}{T \pm \theta_C}$$

Where C → Curie constant

T → Absolute temperature and

θ_C Curie temperature →

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



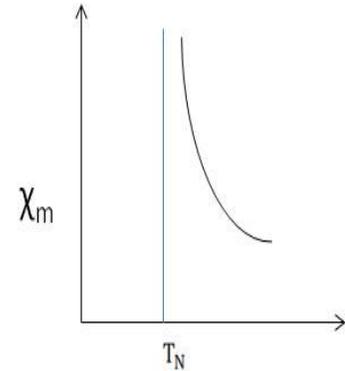
Ferrimagnetic materials:

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

Examples:

Ferrites-general formula: $Me^{+2} Fe_2O_4$

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.

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

Where C → Curie constant

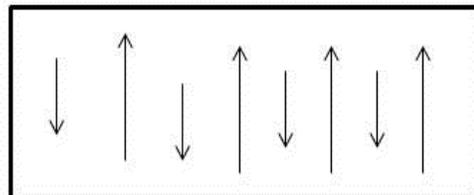
T → Absolute temperature and

θ_c Curie temperature →

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.



Hysteresis 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.
- Consider an iron-cored toroid carrying current I . If N is the total number of turns and ℓ the length of toroid, then magnetizing force is $H = NI/\ell$. The value of H can be changed by varying current in the coil.

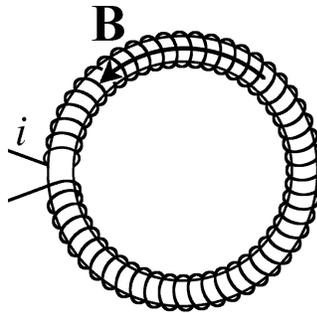


Fig: Toroid

- To start with, the toroid is unmagnetised and its situation is represented by point
 - in fig. As H is increased (by increasing current I), B increases along oa and reaches its saturation value B_{max} at a . At this stage, all the domains are aligned.
 - If now H is gradually reduced by decreasing the current in the toroid, 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*.
 - In order to reduce flux density in the material to zero, it is necessary to apply H in the reverse direction. This can be done by reversing the current I the toroid. When H is
-

gradually increased in the reverse direction, the 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).

- 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.
- vi. Based on the area of the hysteresis loop, the magnetic materials are classified into soft and hard magnetic materials.

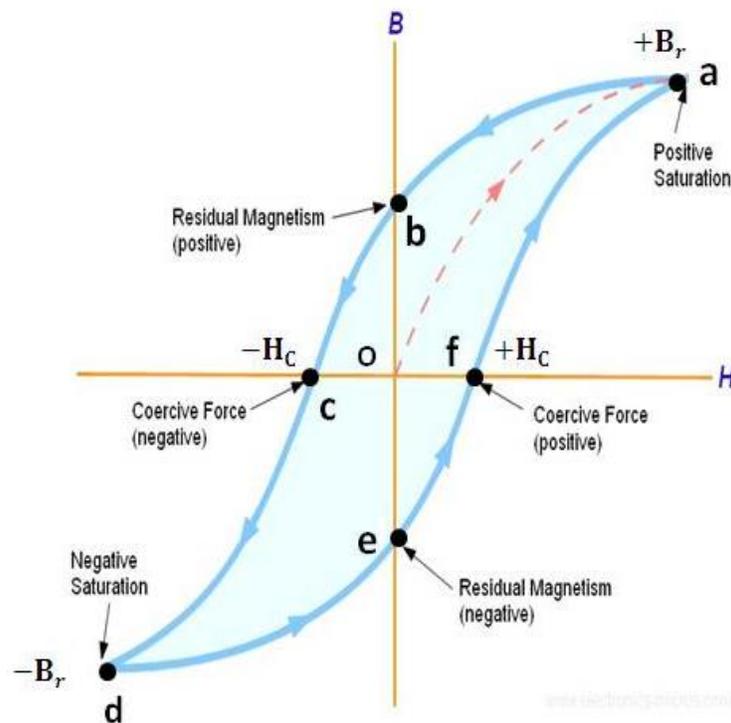


Fig: B-H Curve

Soft magnetic materials:-

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

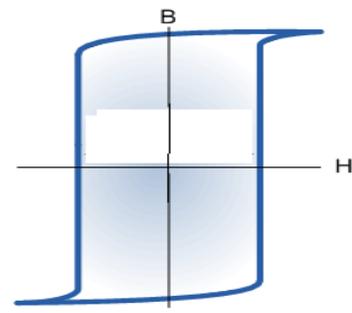
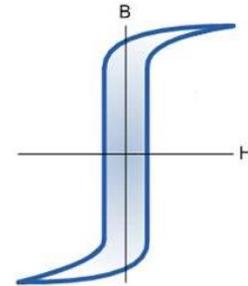
Properties:

- 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, Ferrites 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.
 -

Hard magnetic materials	Soft magnetic materials
Difficult to magnetize and demagnetize	Easy to magnetize and demagnetize
large hysteresis loop area	small hysteresis loop area
Have large hysteresis loss	Have very low hysteresis loss
The domain wall movement is difficult and it is irreversible in nature	Domain wall movement is relatively easier. Even for small change in the magnetizing field ,magnetization changes by large amount
The coercivity and retentivity are large	The coercivity and retentivity are small
Magnetostatic energy is large	Magnetostatic energy is small.



Small values of permeability and susceptibility	Large values of permeability and susceptibility
Used to make permanent magnets Examples- <i>Iron-nickel-aluminium alloys (alnicol)</i> <i>Copper nickel iron (cunife)</i>	Used to make electromagnet Examples- <i>Fe-Si , Ferrous nickel alloys</i> <i>,Ferrites,Garnets</i>

NANOMATERIALS

Introduction:-

- Nano technology deals with the design, manufacturing and application of devices (or) materials which lie in the sizes of 1 to 100 nm. This was first discovered by Feynman in 1959
- Nano means 10^{-9} (one-billionth)
- A nanometer $1\text{nm} = 10^{-9}\text{m}$ (one-billionth of meter)
- Nano materials are found in both biological systems and man-made structures.
- Nature has been using nano materials for millions of years.

Nano materials:-

All materials are composed of grains, which in turn comprise many atoms. The visibility of these grains depends on their size. The materials possessing grains of size ranging from 1 to 100 nm, are known as “**Nanomaterials**”.

Examples: zno, cu-Fe alloys, Ni, Pd, Pt etc.

Classification of Nanomaterials:

➤ **One-dimensional Nanomaterial:**

In these Nanomaterial, grains will be layered in the form of multi-layers such as thin films or surface coatings.

➤ **Two dimensional Nanomaterials:**

This consists of ultrafine grains layered over layers or buried layers, which include nano wires and nano tubes.

➤ **Three dimensional Nanomaterials:**

This consists of nano meter sized grains.

Examples: precipitates, colloids and quantum dots.

Why the properties of nano materials are different? (Or)

Basic principles of Nanomaterials:-

Two principle factors cause the properties of nano materials to differ significantly from other materials (i) increased in surface area to volume ratio, and (ii) quantum confinement. These factors can change or enhance the properties such as reactivity, strength and electrical characteristics.

INCREASE IN SURFACE AREA TO VOLUME RATIO :-

➤ Nanomaterials have a relatively larger surface area when compared to the larger form of the material of same volume. Let us consider a sphere of radius 'r'.

$$\text{Its surface area} = 4\pi r^2$$

$$\text{Its volume} = \left(\frac{4}{3}\right)\pi r^3$$

$$\text{Surface area to its volume ratio} = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{1}{r} = \frac{3}{r}$$

- Thus, when the radius of the sphere decreases, its surface area to volume ratio increases.
- Let us consider another example. For a one cubic volume shown in fig .4
- The surface area is 6m^2 .
- When it is divided into eight pieces its surface area becomes 12m^2 .
- When the same volume is divided into 27 pieces its surface area becomes 18m^2 .
- Thus we find that when the given volume is divided into two smaller pieces, the surface area increases.
- Hence as particle size decreases a greater proportion of atoms are found at the surface compared to those in-sides.
- For example, a particle of size 30 nm has 5% of atoms its surface, at 10nm 20% of its atoms, and at 3nm has 50% of its atoms.

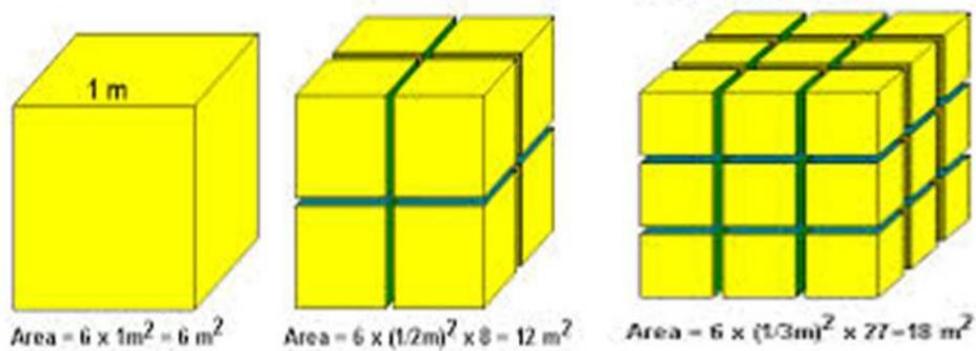


Fig: When the given object divided into smaller particles, the surface area increases.

QUANTUM CONFINEMENT: -

- The properties of materials can be studied based on their energy levels.
-

➤ When atoms are isolated, their energy levels are discrete. When very large number of atoms closely packed to and form bands.

➤ Nanomaterial is a result, the energy size is reduced to electrons changes. **confinement”**.

➤ This affects the properties of nano **Fabrication of** Nano materials can ways, namely

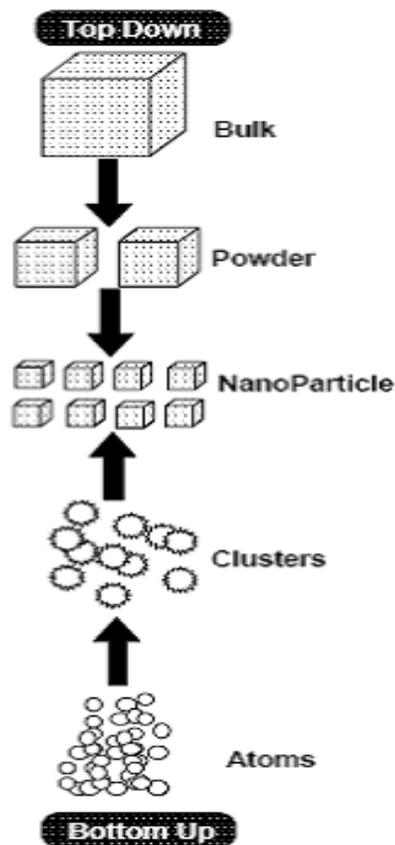
i. Top-down

In which, the bulk nano sizes.

ii. Bottom - up

In which, the nano materials are build up from the bottom: atom by atom, molecule by molecule or cluster by cluster..

The schematic representation of the synthesis and building of nano structured materials are shown in fig (1) and fig (2) respectively.



form a solid, the energy levels split

intermediate to the above cases. As levels change, when the material nano scale, energy levels of This effect is called “Quantum

optical, electrical and magnetic materials.

Nanomaterials:-

be generally fabricated in two broad

Approach:

solid materials are broken in to

approach

Figure: Schematic representation of the building up of Nanostructure.

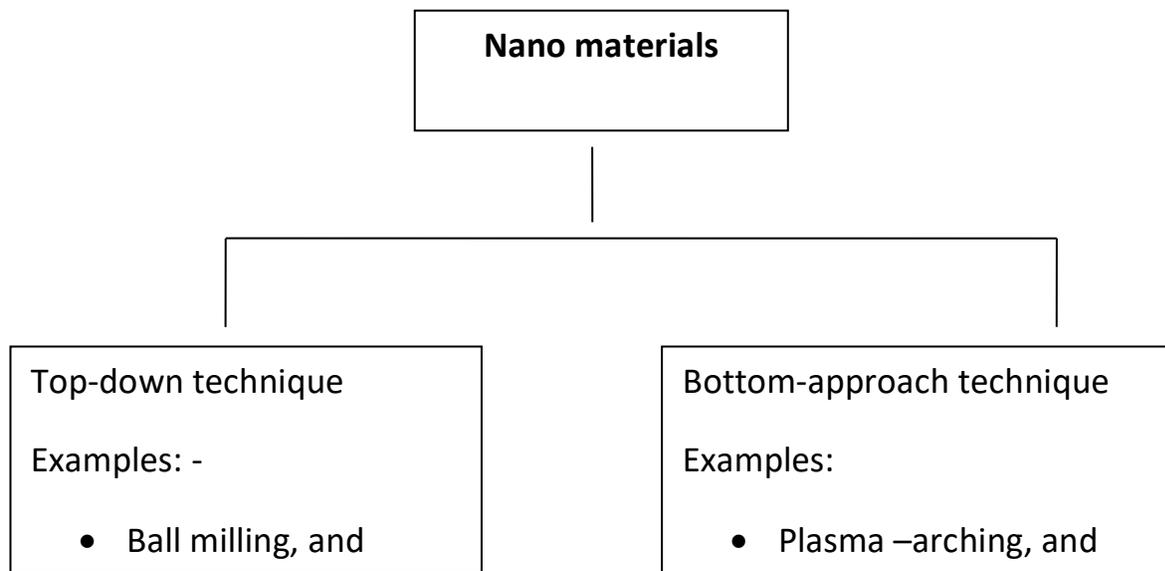


Fig:-Synthesis of nano materials.

Ball milling (or) Mechanical crushing:-

- The ball milling method is a typical example of top-down method of fabrication of nano materials.
- A **ball mill** is a type of grinder used to grind materials into extremely fine powder in order of nm.
- In this method, small balls of the material are allowed to rotate around the inside of a drum and then fall on a solid with gravity force.
- The balls are broken in to nano crystallites. This is also known as mechanical crushing.
- This method is used to prepare a wide range of elemental powders. For example iron nano particles of sizes 13 to 30nm can be formed.
- This method is used for produce metal oxide nano crystals (cerium oxide CeO_2 and Zinc oxide ZnO_2 .



Fig: Ball milling method

Sol-gel process:

- The sol-gel process is a bottom-up approach technique.
 - A sol is a solution with particles suspended in it.
 - When particles in the sol form long polymers (chains) that span the entire sol, a gel is formed.
 - In this process, the starting material is processed to form a dispersible oxide and a colloidal
-

suspension (sol) of the particles of the metal compound is prepared first and then converted into a gel.

- The gel so formed is network in continuous liquid phase.
- Removal of the liquid from the sol yields the gel, and the sol/gel transition controls the particle and shape.
- Calcination of the gel produces the oxide.
- The sol/gel formation occurs in four stages
 - Hydrolysis
 - Condensation
 - Growth of particles and
 - Agglomeration of particles.
- Production of SiO_2 is an example of this process.
- The sol-gel process may be summarized in fig.

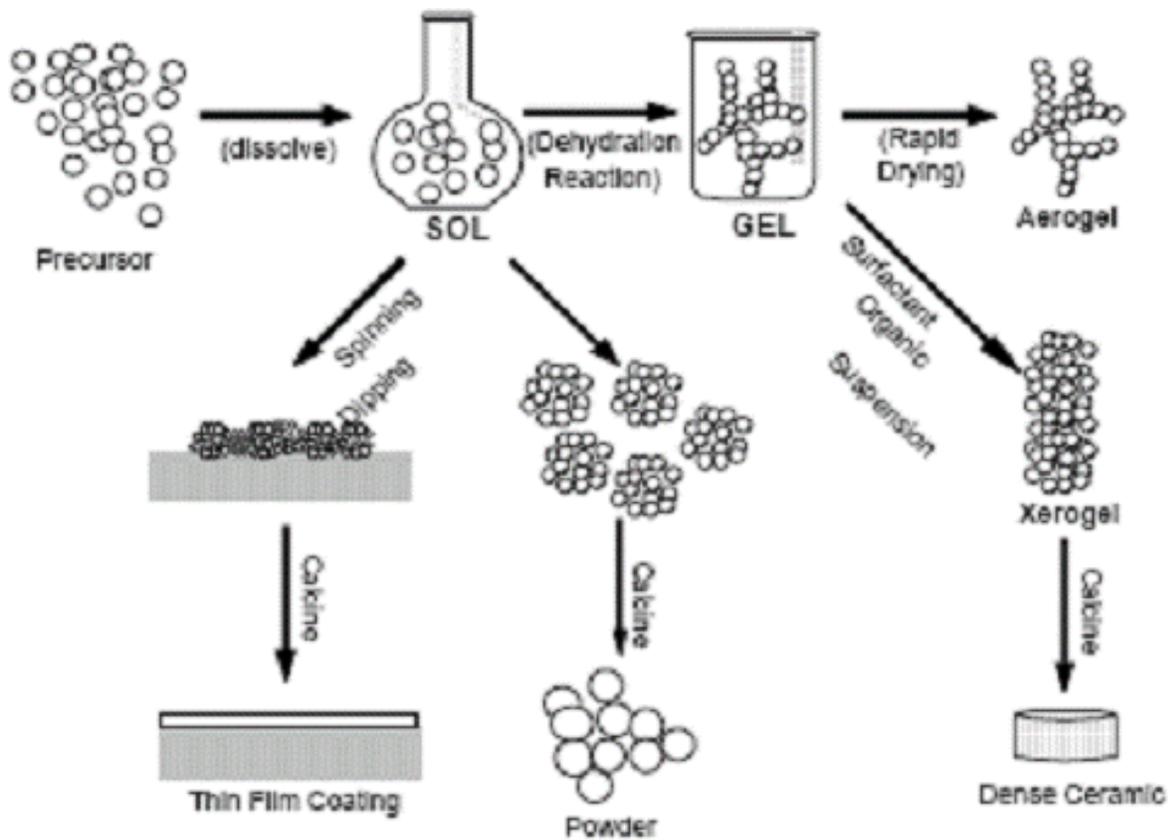


Fig: Schematic representation of sol-gel process of synthesis of nanomaterials

Chemical vapour deposition:-

- This method is used to prepare nano powder.
- In this method nano particles are deposited from the gas phase. Material is heated to form a gas and then allowed to deposit on a solid surface, usually under vacuum condition. The deposition may be either physical (or) chemical.
- In deposition by chemical reaction new product is formed. Nano powder of oxides and carbides of metals can be formed if vapours of carbon (or) oxygen are present with the metal.
- This method can also be used to grow surfaces, i.e. suppose if an object has to be created with nano powders, then the object has to be introduced inside the chemical vapour deposition area so that the nano powders can be deposited all over the object.

Examples: - Nano powders of oxides and carbides and Pure metal nano powders.

Properties of Nano particles: -

As the size of the nano particle is very less, these materials exhibit peculiar physical, electronic, magnetic, mechanical and chemical properties.

Physical properties :-

- Since the size of the particle is very less, the particles are very close to each other and hence the inter particle spacing is very less in nano materials.
- Because of its very less size, these nano materials cannot be further divided into smaller particles and it does not have any dislocation in it. Thus we can say that they have high strength, hardness and toughness.
- The melting point of nano materials will be very less.

Electronic properties: -

- The energy bands in these materials will be very narrow.
- The electrical conductivity and energy band width of some materials change when they pass from bulk phase to nano particle phase.
- For example, bulk silicon is an insulator; it becomes a conductor in nano phase.
- Nano material semiconductors such as Ge and Si do not show semi conducting property.

Magnetic properties: -

The nano materials show variation in their magnetic property, when they change from bulk state to nano phase state. Some of the examples are listed in table (1).

Material	Bulk state	Nano-phase state
Iron, Ni, Cobalt	ferro-magnetic	super Para-magnetic
Lithium, Potassium	para-magnetic	ferro magnetic
Rhodium	anti-ferromagnetic	para-magnetic

Mechanical properties :-

- Mechanical properties such as hardness, toughness, elastic modulus varies from material to material.
- They exhibit super plastic behaviour.

Chemical properties:-

- The nano structures in chemistry are clusters and these are formed in a condensed phase having size in the range from 1 to 100nm.
 - The chemical reactivity of a cluster depends on the cluster size.
 - This is useful in the preparation of catalytic agents. Some chemically inert bulk materials become good chemical catalyst in the nano phase, for example: Platinum and gold.
 - In chemical reactions, the rate of increase in mass transport increases as the particle size decreases.
-

Applications of Nano-technology:-

(i) Mechanical Engineering :-

- Since they are stronger, lighter etc; they are used to make hard metals.
- Nano-MEMS (Micro-Electro Mechanical Systems) are used in ICS, optical switches, pressure sensors, mass sensors etc

(ii) Electrical Electronics and Communication Engineering:-

- Orderly assembled nano materials are used as quantum electronic devices and photonic crystals.
- Some of the nano materials are used as sensing elements. Especially the molecular nano materials are used to design the robots, assemblers etc.
- They are used in energy storage devices such as hydrogen storage devices, magnetic refrigeration and in ionic batteries.
- Dispersed nano materials are used in magnetic recording devices, rocket propellant, solar cells, fuel cells etc.
- Recently nano robots were designed which are used to remove the damaged cancer cells and also to modify the neuron network in human body.

(iii) Computer Science Engineering and IT:-

- Nano materials are used to make CD's and Semiconductor laser.
- These materials are used to store the information in smaller chips.
- They are used in mobiles, lap-tops etc.
- Further they are used in chemical/ optical computer.
- Nano-dimensional photonic crystals and quantum electronic devices plays a vital role in the recently developed computers.

(iv) Bio-Medical and Chemical Engineering:-

- Consolidated state nano particles are used as catalyst, electrodes in solar and fuel cells.
 - Bio-sensitive nano particles are used in the production of DNA-chips, bio- sensors etc.
 - Nano-structured ceramic materials are used in synthetic bones.
-

- Few nano materials are also used in adsorbents, self-cleaning glass, fuel additives, drugs, Ferro fluids, paints etc.
- Nano-metallic colloids are used as film precursor.

Unit IV : Lasers & Fiber optics

Introduction:

Laser:

- 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 electromagnetic radiation**.
- The term "laser" originated as an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

Characteristics of Lasers:

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

- Monochromatic
- Directional
- Intensity
- Coherent

1. Monochromaticity:

- Mono means single and chromo means color. i.e., Monochromatic means that it consists of single color or wavelength or frequency.
- The light emitted from a laser is highly monochromatic, i.e., it consists of one color/wavelength/frequency. But ordinary white light is a combination of many colors (or wavelengths) of light.

2. Directionality:

- Directional means that the beam is well collimated (very parallel) and travels over long distances with very little spread.
 - The light emitted from a laser is highly directional, i.e., laser light is emitted as a relatively narrow beam in a specific direction with very little spread
 - An ordinary source of light (bulb) emits light waves in all the directions and is highly divergent.
-

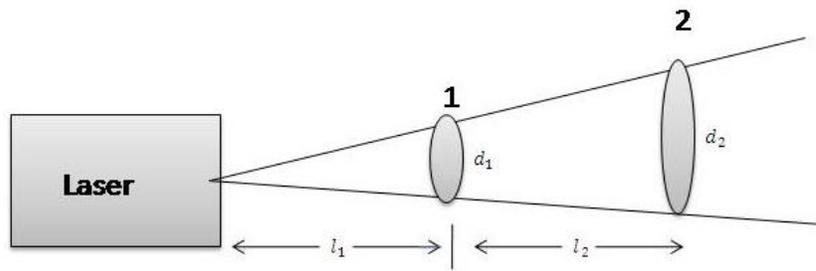


Fig:

Measurement of beam divergence.

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

The angular spread of ordinary light is 1 meter/meter or 1 radian.

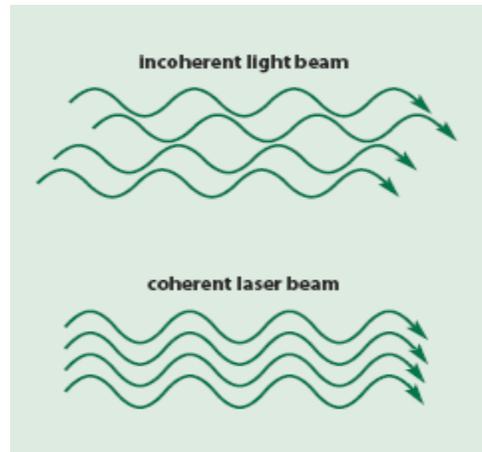
The angular spread of laser light is 1 mm/meter or 10^{-3} radians.

3. Intensity:

- 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 is high. Hence its brightness is more.
-

4. Coherence:

- The light from a laser is said to be coherent, which means that the wavelengths of the laser light are in phase in space and time.
- Ordinary light can be a mixture of many wavelengths.



Interaction of radiation with matter:

Introduction:

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

- Absorption of radiation
- Spontaneous emission of radiation
- Stimulated emission of radiation

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(1). This process is called absorption of radiation.

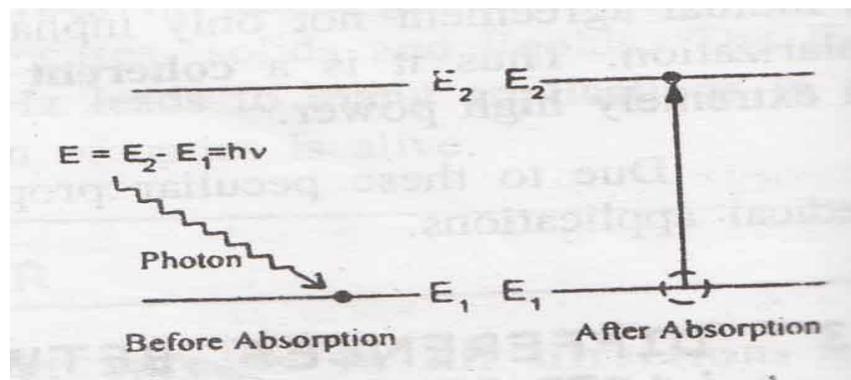
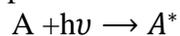


Fig: Absorption of radiation

The process may be expressed as



Where A=Atom in the ground state

A^* = Excited atom

$h\nu$ = Incident photon

- 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_ν .

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

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

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

$$\therefore \boxed{R_{12} = B_{12} \rho_\nu N_1} \rightarrow (1)$$

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

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 (2).

This process is known as Spontaneous emission of radiation.

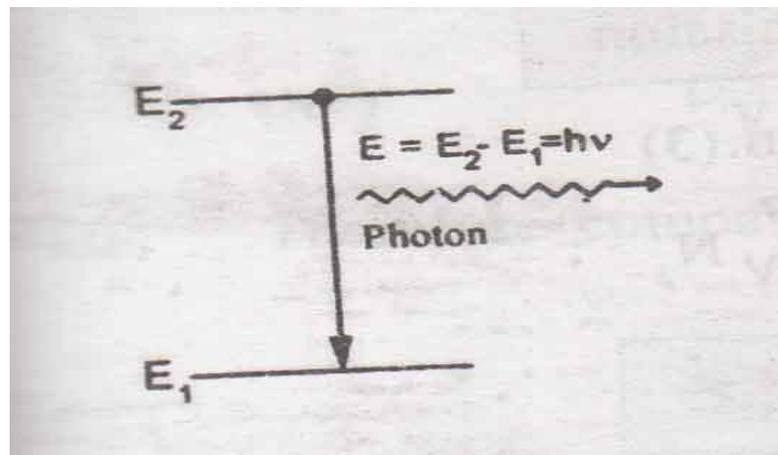
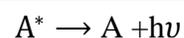


Fig: Spontaneous emission of radiation.

The process may expressed as



Where A = Atom in the ground state
 A^* = Excited atom
 $h\nu$ = Incident photon.

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

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

$$\therefore \boxed{R_{21(SP)} = A_{21}N_2} \rightarrow (2)$$

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

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.

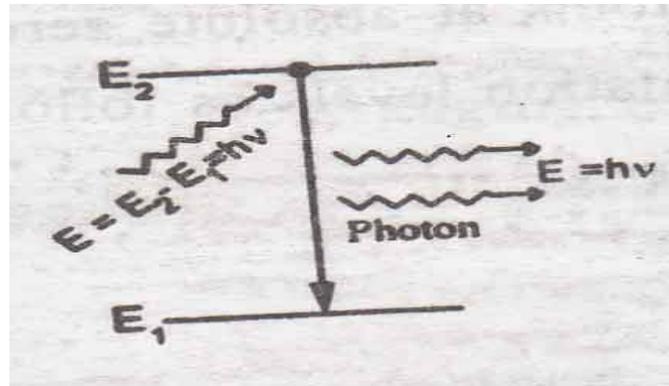
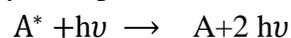


Fig: Stimulated emission of radiation.

The process may be expressed as



The number of stimulated emission depends on the number of atoms in the energy level (E_2), N_2 and the incident radiation density ρ_ν .

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

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

$$\propto \rho_\nu$$

$$R_{21(S)} \propto N_2 \rho_\nu$$

$$\therefore \boxed{R_{21(S)} = B_{21} \rho_\nu N_2} \rightarrow (3)$$

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

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 inducement or stimulus 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 $R_{21(S)} = B_{21} \rho_\nu N_2$
9. Example: Light from sodium vapor lamp and mercury vapor lamp	9. Example: Light from Ruby laser, He-Ne laser and GaAs laser etc.

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

$$N = N_0 \exp \frac{-E}{K_B T}$$

Where, N_0 is the population of lower energy level and K_B is Boltzmann's constant ($1.3807 \times 10^{-23} \text{ J K}^{-1}$)

Einstein's coefficient's 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 .

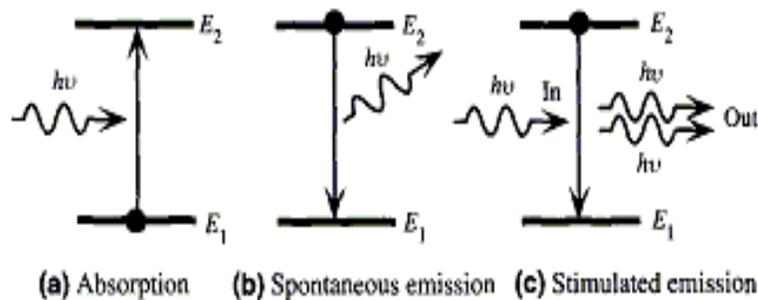


Fig: Three different processes during the interaction of light with matter.

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

1) Absorption :-

$$\text{The rate of absorption } (R_{12}) = B_{12} \rho_\nu N_1 \rightarrow (1)$$

2) Spontaneous emission :-

The rate of spontaneous emission is given by

$$R_{21(SP)} = A_{21}N_2 \quad \rightarrow (2)$$

3) Stimulated Emission:-

The rate of stimulate emission is given by

$$R_{21(S)} = B_{21} \rho_\nu N_2 \quad \rightarrow (3)$$

Under thermal equilibrium,

The rate of absorption = The rate of emission

$$\text{i.e.,} \quad \text{Eq(1)} \quad = \text{Eq(2)} + \text{Eq(3)}$$

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

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

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

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

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

$$\rho_\nu = \frac{A_{21}}{B_{12} \left(\frac{N_1}{N_2}\right) - B_{21}} \quad \rightarrow (4)$$

$$= \frac{A_{21}}{B_{12} \left[\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}}\right]} \quad \rightarrow (5)$$

We know that; Boltzmann distribution law

$$N_1 = N_0 \exp \frac{-E_1}{K_{BT}} \quad \rightarrow (6)$$

$$\text{Similarly} \quad N_2 = N_0 \exp \frac{-E_2}{K_{BT}} \quad \rightarrow (7)$$

$$\text{And} \quad \frac{N_1}{N_2} = \exp \frac{-E_1}{K_{BT}} \cdot \exp \frac{E_2}{K_{BT}}$$

$$\text{i.e.,} \quad \frac{N_1}{N_2} = \exp \frac{(E_2 - E_1)}{K_{BT}}$$

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

$$\frac{N_1}{N_2} = \exp \frac{h\nu}{K_{BT}} \quad \rightarrow (8)$$

Substituting Eq (8) in Eq (5) we have

$$\rho_\nu = \frac{A_{21}}{B_{21} \left[\exp \frac{h\nu}{k_{BT}} - \frac{B_{21}}{B_{12}} \right]} \rightarrow (9)$$

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

$$\rho_\nu = \frac{8\pi h\nu^3}{C^3} \left[\frac{1}{\exp \frac{h\nu}{k_{BT}} - 1} \right] \rightarrow (10)$$

Therefore comparing equations (9) and (10), we can write

$$\boxed{\frac{B_{21}}{B_{12}} = 1 \text{ or } B_{21}=B_{12}=1 \text{ and}} \rightarrow (11)$$

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{C^3}} \rightarrow (12)$$

These results were obtained by Einstein in 1917, and that is why the coefficients A_{21} , B_{21} and B_{12} are called Einstein's coefficients.

From eq. (11), we conclude that the coefficient of absorption B_{12} is equal to the coefficient of stimulated emission B_{21} .

From eq. (11), we conclude that the coefficient of spontaneous versus stimulated emission is proportional to the third power of frequency of the radiation.

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

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, known as population inversion, is required.

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.

Fig: $N_1 > N_2$

Fig: $N_2 > N_1$

Explanation:

- To explain Population Inversion, let us Consider a three 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.

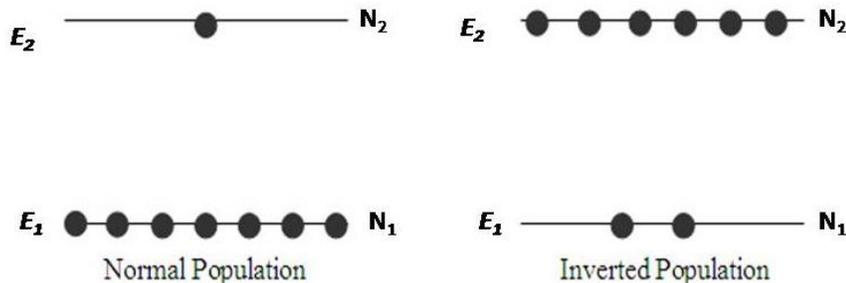
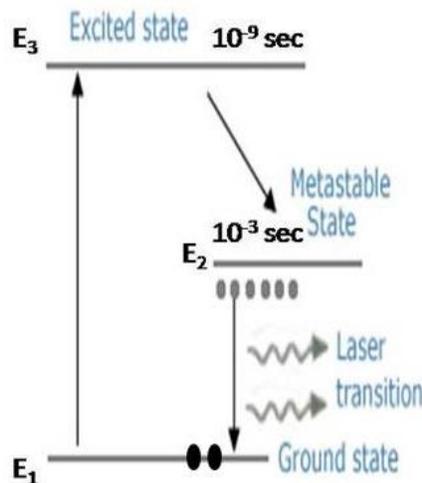


Fig: (a) Boltzmann's distribution

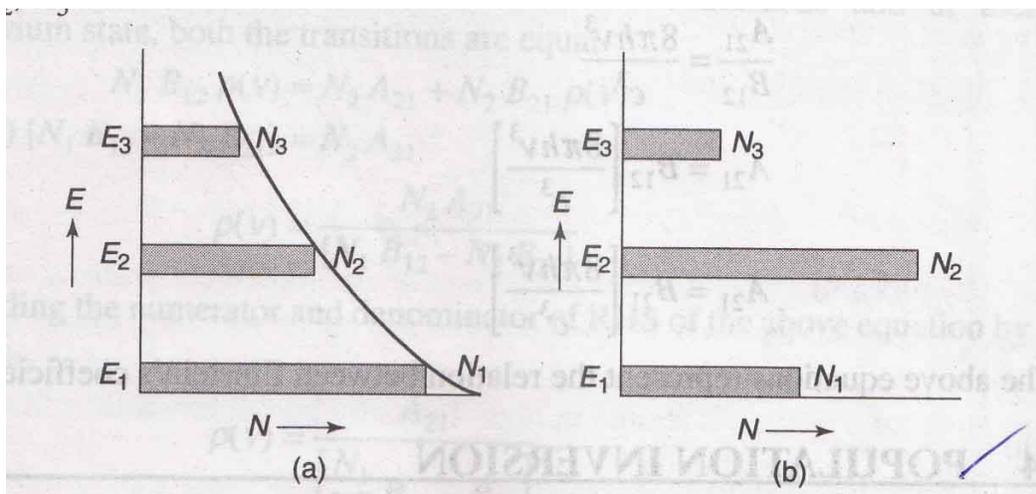
Fig: (b) Population inversion between E_1 and E_2

- Let the atoms in the system be excited from E_1 state to E_3 state by supplying energy equal to $E_3 - E_1 = h\nu$ 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 can stay time(10^{-3} sec)
- As energy are exciting
- A state the State is state situation



state, the atoms for a very long 10^{-3} s). atoms in E_1 state continuously to E_3 , so the population in E_1 state goes decreasing. will reach at which population in E_2 greater than E_1 (i.e. $N_2 > N_1$). This is known as population inversion.



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 method
- (ii) Electrical discharge(Direct electron excitation) pumping method
- (iii) Inelastic atom-atom collision pumping method
- (iv) Direct conversion pumping method
- (v) Chemical reactions pumping method.

(i). Optical pumping method:

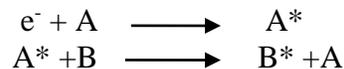
- The process of supplying suitable form of optical energy to a system to achieve population inversion is called optical pumping.
- In this method, light source is used to supply suitable form of optical energy to excite the atoms to higher energy level to achieve population inversion.
- This type of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

(ii). 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 CO₂ Laser).

(iii). Inelastic atom-atom collision pumping method

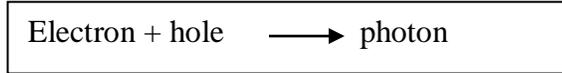
- In this method a combination of two types of gases are used say A and B, both having same or nearly coinciding excited states A* and B* .
- In the first step ,during electric discharge , A gets excited to A* (meta stable state) due to collision with electrons .The excited atom now collide with the 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.

(iv).Direct conversion pumping method

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



- This method is used in semiconductor lasers.

(v).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.



Block diagram of a laser system:

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

- (i) Source of energy
- (ii) Active medium and
- (iii) Optical resonator as shown in fig.

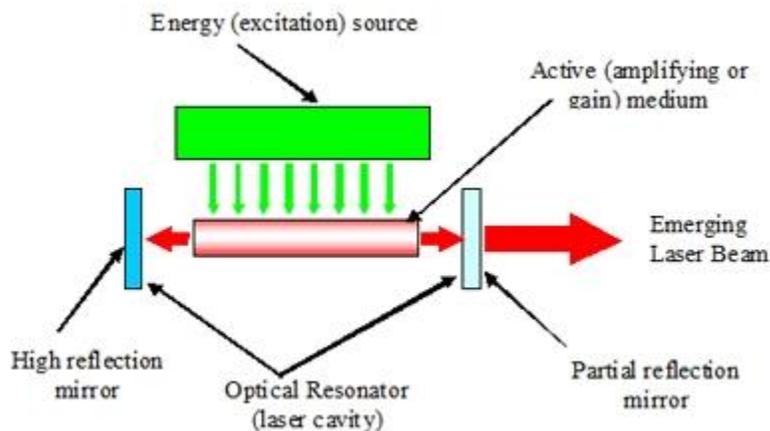


Fig: Components of LASER system.

(i) 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.
-

(ii) **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 excited 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.

(iii) **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 as shown in fig.

Types of lasers :

Nd-YAG [Neodymium-Yttrium Aluminum Garnet] laser:-

Characteristics of laser:-

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

Active medium : Yttrium Aluminum Garnet [$\text{Y}_3\text{Al}_5\text{O}_{12}$]

Active centre : Nd_3^+ ions

Pumping method : Optical pumping

Pumping source : Xenon flash lamp

Optical resonator : two ends of the rod polished with silver

Nature output : pulsed

Power output : 2×10^4 watts

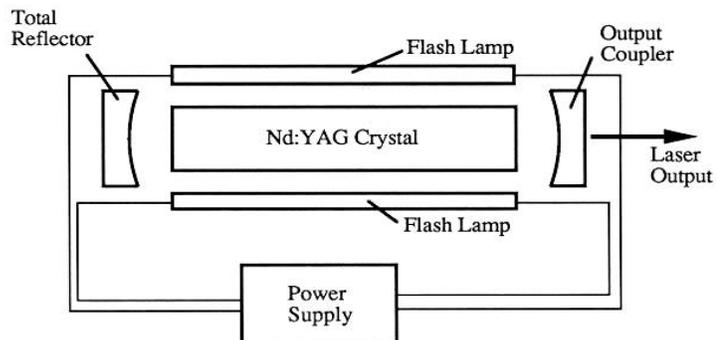
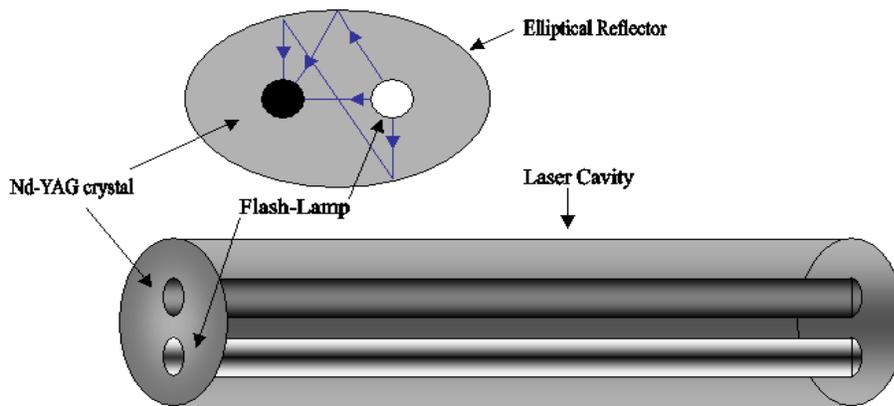
Wave length : 1.064 μm .

Principle:-

The neodymium ions are raised to excited states optical pumping using xenon flash lamp. 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 wavelength $1.064 \mu\text{m}$ emitted.

Construction

- A Nd-YAG laser consists of a cylindrical Nd-YAG rod [$\text{Y}_3\text{Al}_5\text{O}_{12}$].
- 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 as shown in fig.



Fig; Construction of Nd-YAG laser.

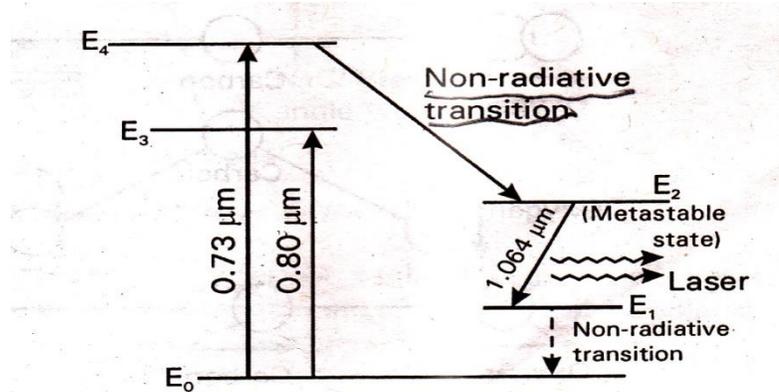


Fig: Energy level diagram of Nd-YAG laser.

Working:-

- The xenon flash lamp is switched on.
- A few thousand joules of light energy are 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 $0.73 \mu\text{m}$ and go to E_4 excited state and by absorbing wavelength $0.80 \mu\text{m}$ 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^{-9} 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 translated from Meta stable state to ground state.
- Hence, pulsed form of laser beam of wavelength $1.064 \mu\text{m}$ is emitted during transition from E_2 to E_1 .

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.

Applications of laser: - 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 tumours 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.

3) 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.

Fiber optics

Introduction

Fibre optics deals with the light propagation through thin glass fibres. Fibre optics plays an important role in the field of communication to transmit voice, television and digital data signals from one place to another. The transmission of light along the thin cylindrical glass fibre by total internal reflection was first demonstrated by John Tyndall in 1870 and the application of this phenomenon in the field of communication is tried only from 1927. Today the applications of fibre optics are also extended to medical field in the form of endoscopes and to instrumentation engineering in the form of optical sensors.

Generally, communication is transferred through carrier waves in any communication system. When the frequencies of the carrier waves are high then the

information carrying capacity also enhances. As the propagation of light takes place in the form of high frequency waves, these light waves can be used to carry information, i.e., as carrier waves. For the proper guiding of information carrying light waves, we need a proper guiding medium or material. That material is the optical fibre.

1. Optical fibre

Optical fibre is a guiding medium or material which guides the information carrying light waves. To guide the light waves, optical fibre should be transparent. To minimize the transmission losses through the optical fibre it is made thin.

Thus Optical fibre is a thin transparent guiding medium or material which guides the information carrying light waves

2. The Basic principle of optical fibre (Or) Working principle of optical fibre (or) Total internal reflection

The transmission of light in an optical fibre is based on the phenomenon of total internal reflection. Optical fibre consists of inner most layer known as core, a denser medium and next layer is known as cladding a rarer medium.

Total internal reflection:-

Definition: When the light ray travels from denser medium to rarer medium the refracted ray bends away from the normal. When the angle of incidence is greater than the critical angle, the refracted ray again reflects into the same medium. This phenomenon is called total internal reflection.

Let us consider n_1 and n_2 are refractive indices of core and cladding mediums. Let, a light ray

from core medium to cladding medium, then the refracted ray bends away from the normal with i is the angle of incidence and r is the angle of refraction.

In this we get three cases

Case I:

When $i < \theta_c$, the light ray refracts into cladding medium. [Figure 1]

Core medium

Case II:-

When $i \in \theta_c$, the light ray travels along the interface of core and cladding, θ_c is known as critical angle. [Figure 2]



Core medium

When the angle of incidence is increased angle of reflection also increases and for a particular angle of incidence ($i = \theta_c$) the refracted ray travels along the interface of two mediums. This angle of incidence is known as **critical angle** (θ_c).

$$n_1 \sin \theta_c = n_2 \sin 90$$
$$n_1 \sin \theta_c = n_2 \Rightarrow \sin \theta_c = \frac{n_2}{n_1}$$

$$\sin^{-1}\left(\frac{n_2}{n_1}\right)$$

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

Case III:-

When $i > \theta_c$, then the light ray will be reflected back into the core medium and undergoes total internal reflection. [Figure 3]

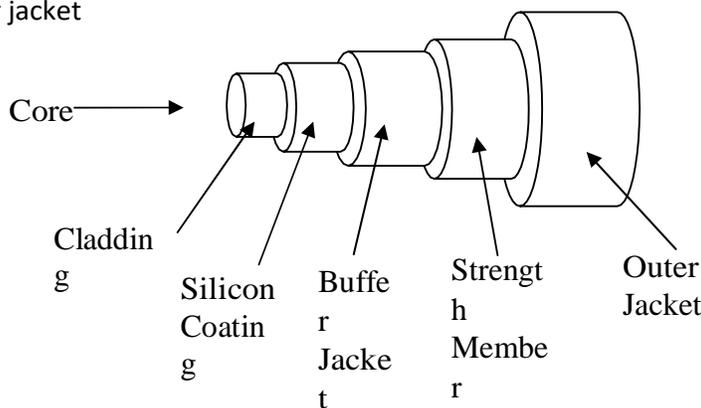
Core medium

When the angle of incidence is greater than the critical angle ($i > \theta_c$), the refracted ray again reflects into the same medium. This phenomenon is called total internal reflection

3. Construction of optical fibre

The optical fibre mainly consists the following six parts as shown in figure

1. Core
2. Cladding
3. Silicon coating
4. Buffer jacket
5. Strength member
6. Outer jacket



Core:

A typical glass fibre consists of a central core material. Generally core diameter is ranges from 5 to 600 μN . The core is surrounded by cladding. The core medium refractive is always greater than the cladding refractive index. **Cladding**

Cladding

Cladding refractive index is lesser than the cores refractive index. The overall diameter of cladding is 125 μN to 750 μN .

Silicon Coating

Silicon coating is provided between buffer jacket and cladding. It improves the quality of transmission of light.

Buffer Jacket

Silicon coating is surrounded by buffer jacket. Buffer jacket is made of plastic and protects the fibre cable from moisture.

Strength Member

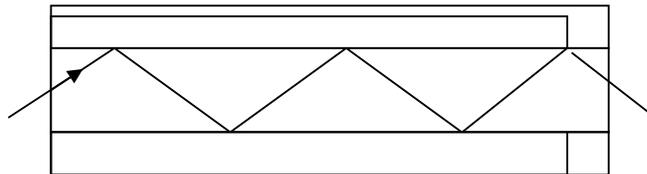
Silicon coating is surrounded by strength member. It provides strength to the fibre cable.

Outer Jacket

Finally the fibre cable is covered by polyurethane outer jacket. Because of this arrangement fibre cable will not be damaged during pulling, bending, stretching and rolling through the fibre cable is made up of glasses.

4. Dimensions of optical fibre

Optical fibres are made in lengths of 1km. optical fibres can be connected with suitable connectors. Generally its outer diameter ranges from 0.1 to 0.15 mm. Naturally the diameter of core and cladding ranges from 5 to 600 μN and 125 to 750 μN respectively. Due the outer jacket 100 μN may add to diameter of the total optical fibre. The optical signal passes through the core medium of the optical fibre. The propagation of optical signal in the optical fibre in the form of multiple total internal reflection is shown in figure.



5. Classification of fibres

Based on the refractive index of core medium, optical fibres are classified into two categories.

- i. Step index fibre
- ii. Graded index fibre

Based on the number of modes of transmission, optical fibres are classified into two categories

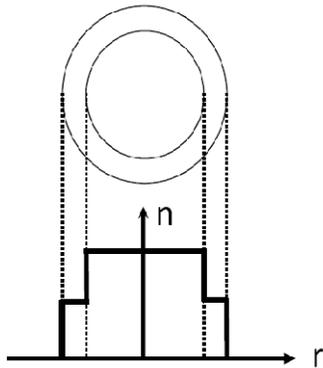
- i. Single mode fibre
- ii. Multi mode fibre

Based on the material used, optical fibres are may broadly classified into four categories

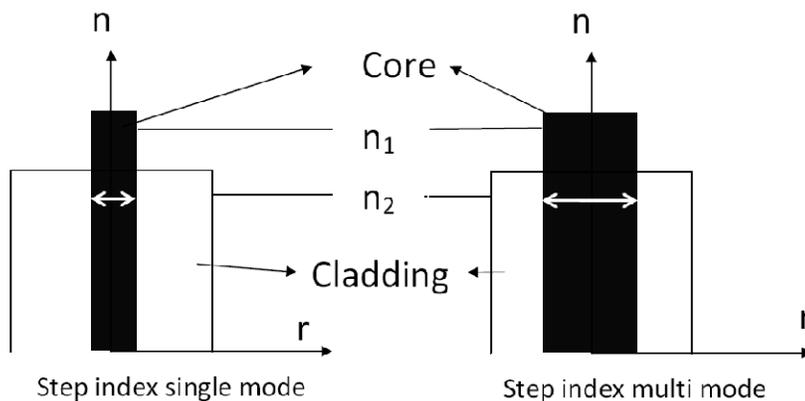
- i. All glass fibre
 - ii. All plastic fibre
 - iii. Glass core with plastic cladding fibre
 - iv. Polymer clad silica fibre.
-

6. Step index fibre- refractive index profile

In step index fibre the refractive index of the core medium is uniform and undergoes an abrupt change at the interface of core and cladding as shown in figure.



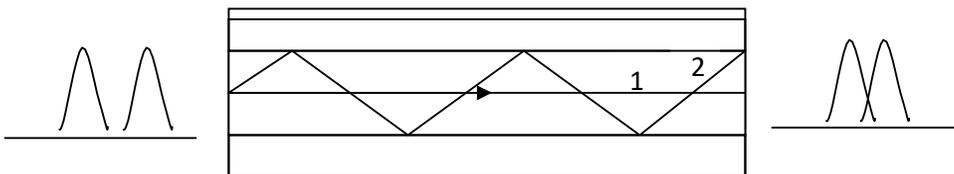
The diameter of core is about 50 to 200 micrometers in case of multi mode and 10 micrometers in single mode fibre.



Attenuation is more for step index multi mode fibres but less in step index single mode fibres. Numerical aperture is more for step index multi mode fibres but it is less in step index single mode fibres. This fibre is called reflective type fibre.

Transmission of signal in step index fibre

Generally, the optical signal is transmitted through the fibre in the digital form i.e., in the form of 1's and 0's. The propagation of signals through the multi mode fibre is shown in figure. The transmitted optical signal will cross the fibre axis during every reflection at the core cladding boundary. The shape of propagation of the optical signal is in zigzag manner. Generally the signal through the fibre is in digital form i.e. in the form of pulses representing 0s and 1s.



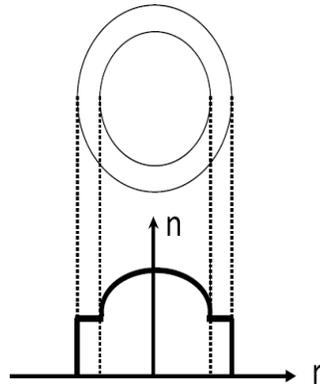
From figure the ray 1 follows shortest path (i.e. travels along the axis of fibre) and the ray 2 follows longer path than ray 1. Hence the two rays reach the received end at different times. Therefore, the pulsed signal received at other end gets broadened. This is called intermodal dispersion. This

difficulty is overcome in graded index fibres.



7. Graded index fibre - refractive index profile:-

In graded index fibres, the refractive index of the core medium is varying in the parabolic manner such that the maximum refractive index is present at the center of the core.

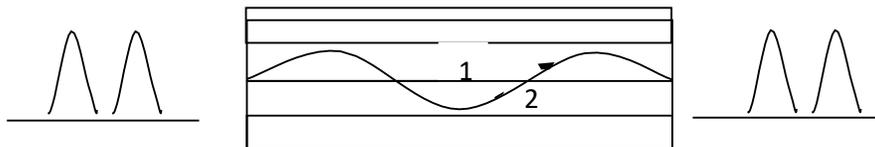


The diameter of the core is about 50 micro meters. Attenuation is very less in graded index fibres Numerical aperture is less in graded index fibres This fibre is called reflective type fibre.

Transmission of signal in graded index fibre:-

The shape of propagation of the optical is in helical or spiral manner.

The transmitted optical signal will never cross the fibre axis during every reflection at the core cladding boundary.



To discuss intermodal dispersion, we consider two rays as shown in figure, the ray 1 is traveling along the axis of the core and the other ray 2 traveling away from the axis undergoes refraction and bent. Since, ray 2 is traveling in the lesser refractive index medium, so ray 2 moves slightly faster than ray 1. Hence the two rays reach the other end simultaneously. Thus the problem of intermodal dispersion can be overcome by using graded index fibre.

8. Single mode optical fibre:-

- In single mode optical fibres only one mode of propagation is possible.
- These fibres have small core diameter and the difference between the refractive indices of core and cladding is very small.
- In single mode fibres there is no dispersion, so these are more suitable for communication.
- The single mode optical fibres are costly, because the fabrication is difficult.
- The process of launching of light into single mode fibres is very difficult.
- Fabrication is very difficult and the fibre is costly.
- The condition for single mode operation is

$$V = \frac{2\pi}{\lambda} a NA$$

□

Where a is the radius of the core of the fibre, n_1 the refractive of the core, NA is the numerical

aperture and λ is the wave length of light traveling through the fibre



9. Multi mode optical fibre:-

- In multi mode optical fibres many number of modes of propagation are possible.
- These fibres have large core diameter and the difference between the refractive indices of core and cladding is also large compared to the single mode fibres.
- Due to multi mode transmission, the dispersion is large, so these fibres are not used for communication purposes.
- The multi mode optical fibres are cheap than single mode fibres, because the fabrication is difficult.
- The process of launching of light into single mode fibres is very easy.
- Fabrication is very easy and the fibre is cheaper.
- The condition for multi mode propagation is

$$N = 4.9 \left| \frac{(d \cdot NA)^2}{\pi} \right|$$

Where d the radius of the core of the fibre and NA is the numerical aperture.

10. Glass fibre

If the optical fibres are made by fusing mixtures of metal oxides and silica glasses, then it is known as glass fibre. The most common material used in glass fibre is silica (oxide glasses). It has a refractive index of

1.458 at 850 nm. To vary the refractive indices of core and cladding either fluorine or various of oxides such as B_2O_3 , GeO_2 or P_2O_5 are added to silica.

Example of glass fibre compositions are

$GeO_2 - SiO_2$ core SiO_2 cladding.

$P_2O_5 - SiO_2$ core SiO_2 cladding.

SiO_2 core, $P_2O_5 - SiO_2$ cladding

11. Plastic fibre

If the optical fibres are made by plastic, then it is known as Plastic fibre. The plastic fibres are low cost and can be handled without special care due to their toughness and good durability.

Example of glass fibre compositions are

a polystyrene core ($n=1.60$) and methylmethacrylate cladding (1.49).

a poly methylmethacrylate core (1.49) and cladding made of its co-polymer ($n=1.40$)

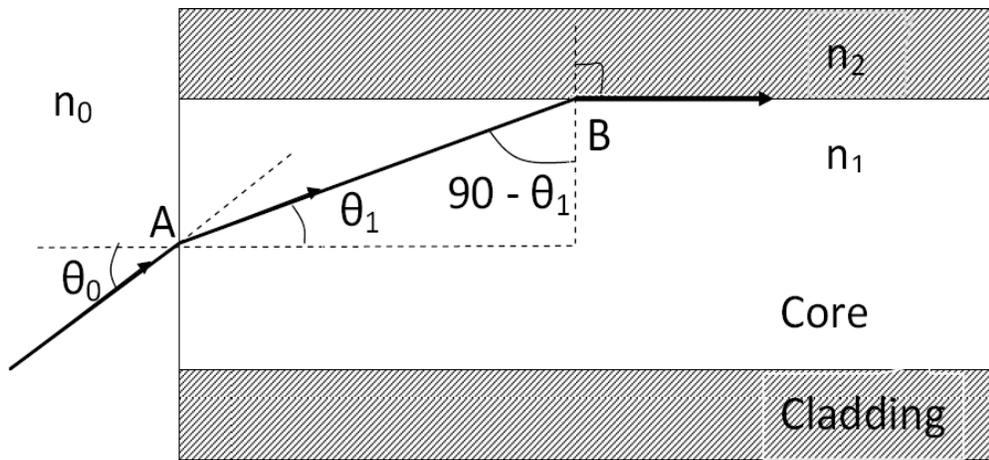
12. Acceptance angle

Definition:-

Acceptance angle is defined as the maximum angle of incidence at the interface of air medium and core medium for which the light ray enters into the core and travels along the interface of core and cladding.

Let n_0 , n_1 and n_2 be the refractive indices of air, core and cladding media. Let a light ray OA is incident

on the interface of air medium and core medium with an angle of incidence θ_0 then the light ray refracts into the core medium with an angle of refraction θ_1 , and the refracted ray AB is again incidenting on the interface of core and cladding with an angle of incident $(90^\circ - \theta_1)$. If $(90^\circ - \theta_1)$ is equal to the critical angle of core and cladding media then the ray travels along the interface of core and cladding along the path BC. If the angle of incident at the interface of air and core $\theta_1 < \theta_c$, then $(90^\circ - \theta_1)$ will be greater than the critical angle. Therefore, the total internal reflection takes place.



According to Snell's law at point A

$$n_0 \sin \theta_0 = n_1 \sin \theta_1$$

$$\sin \theta_1 = \frac{n_0}{n_1} \sin \theta_0$$

According to Snell's law at point B

$$n_1 \sin(90 - \theta_1) = n_2 \sin \theta_c$$

$$n_1 \cos \theta_1 = n_2$$

$$\cos \theta_1 = \frac{n_2}{n_1}$$

$$\sin \theta_1 = \sqrt{1 - \cos^2 \theta_1}$$

$$\sin \theta_1 = \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

$$\sin \theta_0 = \frac{n_1}{n_0} \sin \theta_1 = \frac{n_1}{n_0} \frac{\sqrt{n_1^2 - n_2^2}}{n_1} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

$$\sin \theta_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

$$\sin \theta_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

$$\theta_0 = \sin^{-1} \left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0} \right)$$

13. Acceptance cone

Definition:-

A cone obtained by rotating a ray at the end face of an optical fibre, around the fibre axis with acceptance angle is known as acceptance cone.

14. Numerical aperture

Definition: -

Numerical aperture is defined as the light gathering capacity of an optical fibre and it is directly proportional to the acceptance angle.

Numerically it is equal to the sin of the acceptance angle.

$$NA = \sin(\text{acceptance angle})$$

$$NA = \sin^{-1} \left(\sqrt{\frac{n_1^2 - n_2^2}{n_1^2}} \right)$$

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

If the refractive index of the air medium is equal to unity then

$$NA = \sqrt{(n_1^2 - 1)}$$

Fractional change in refractive index

$$\frac{(n_1 - n_2)}{n_1}$$

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

$$n_1 \Delta = (n_1 - n_2)$$

$$NA = \sqrt{(n_1 - n_2)(n_1 + n_2)}$$

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

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

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

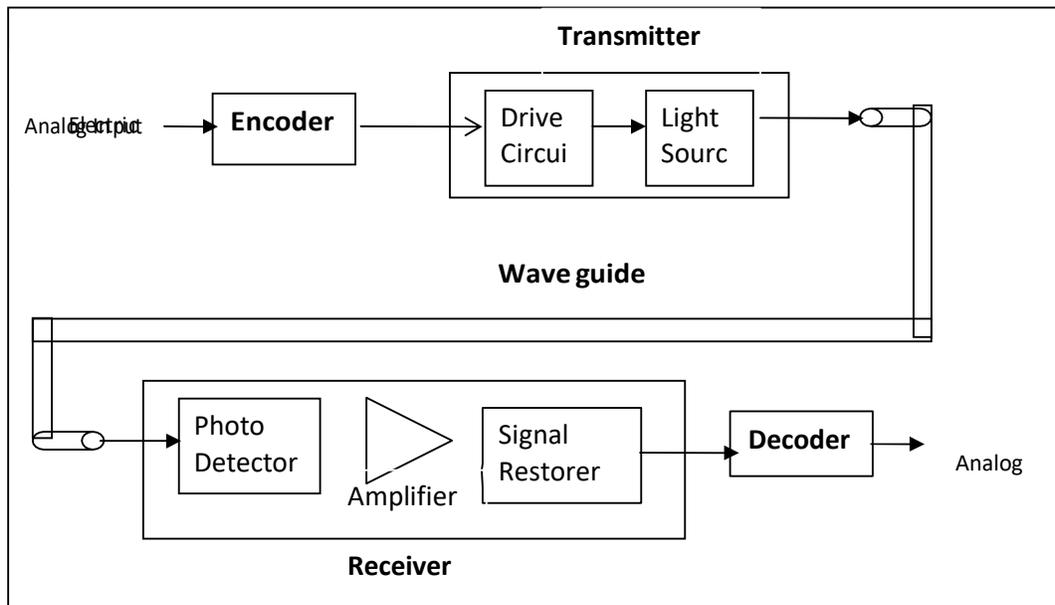
$$n_1 \Delta = (n_1 - n_2)$$

$$Q_1 \approx Q_2; \quad n_1 + n_2 = 2n_1$$

The above equation gives a relationship between numerical aperture and fractional change in relative refractive index.

15. Optical fibre communication system

An efficient optical fibre communication system requires high information carrying capacity, fast operating speed over long distances with a minimum number of repeaters. An optical fibre communication system mainly consists of the following parts as shown in figure.



1. Encoder

Encoder is an electronic system that converts the analog information like voice, figures, objects etc., into binary data.

2. Transmitter

It contains two parts, they are drive circuit and light source. Drive circuit supplies the electric signals to the light source from the encoder in the required form. The light source converts the electrical signals into optical form.

With the help of specially made connector optical signals will be injected into wave guide from the transmitter.

3. Wave guide.

It is an optical fibre which carries information in the form of optical signals over distances with the help of repeaters. With the help of specially made connector optical signals will be received by the receiver from the wave guide.

4. Receiver.

It consists of three parts; they are photo detector, amplifier and signal restorer. The photo detector converts the optical signal into the equivalent electric signals and supply to them to amplifier. The amplifier amplifies the electric signals as they become weak during the long journey through the wave guide over longer distance. The signal restorer deeps the

electric signals in a sequential form and supplies to the decoder in the suitable way.

5. Decoder

It converts electric signals into the analog information.

16. Advantages of fibre optic communication

The optical fibre communication has more advantages than convectional communication.

1. Enormous bandwidth
2. low transmission loss
3. electric isolation
4. signal security
5. small size and less weight
6. low cost
7. immunity cross talk

1. Enormous bandwidth

The information carrying capacity of a transmission system is directly proportional to the frequency of the transmitted signals. In the coaxial cable (or convectional communication system) transmission the bandwidth range is up to around 500MHz. only. Where as in optical fibre communication, the bandwidth range is large as 10^5 GHZ.

2. Low transmission loss:-

The transmission loss is very low in optical fibres (i.e. 0.2Km^{-1}) than compare with the convectional communication system. Hence for long distance communication fibres are preferred.

3. Electric isolation

Since fibre optic materials are insulators, they do not exhibit earth and interface problems. Hence communicate through fibre even in electrically danger environment.

4. Signal security

The transmitted signal through the fibre does not radiate, unlike the copper cables, a transmitted signal cannot be drawn from fibre with out tampering it. Thus the optical fibre communication provides 100% signal security.

5. Small size and less weight

The size of the fibre ranges from $10\mu m$ to $50\mu m$, which is very small. The space occupied by the fibre cable is negligibly small compared to convectional electrical cables. Optical fibres are light in weight.

6. Low cost

Since optical fibres made up of silica which is available in abundance, optical fibres are less expensive.

7. Immunity cross talk

Since the optical fibres are dielectric wave guides, they are free from any

electromagnetic interference and radio frequency interference. Since optical interference among different fibres is not possible, cross talk is negligible even many fibres are cabled together.

17. Differences between step index fibres and graded index fibres:-

Step index fibre	Graded index fibre
1. In step index fibres the refractive index of the core medium is uniform through and undergoes an abrupt change at the interface of core and cladding.	1. In graded index fibres, the refractive index of the core medium is varying in the parabolic manner such that the maximum refractive index is present at the center of the core.
2. The diameter of core is about 50 to 200 micrometers in case of multi mode and 10 micrometers in single mode fibre	2. The diameter of the core is about 50 micrometers.
3. The transmitted optical signal will cross the fibre axis during every reflection at the core cladding boundary.	3. The transmitted optical signal will never cross the fibre axis at any time.
4. The shape of propagation of the optical signal is in zigzag manner.	4. The shape of propagation of the optical signal appears in the helical or spiral manner
5. Attenuation is more for multi mode step index fibres but Attenuation is less in single mode step index fibres	5. Attenuation is very less in graded index fibres
6. Numerical aperture is more for multi mode step index fibres but it is less in single mode step index fibres	6. Numerical aperture is less in graded index fibres

18. Differences between single mode and multi mode fibres:-

Single mode fibre	Multi mode fibre
1. In single mode optical fibres only one mode of propagation is possible	1. In multi mode optical fibres many number of modes of propagation are possible.
2. These fibres have small core diameter and the difference between the refractive indices of core and cladding is very small.	2. These fibres have large core diameter and the difference between the refractive indices of core and cladding is also large compared to the single mode fibres.
3. —In single mode fibres there is no dispersion, so these are more suitable for communication.	3. Due to multi mode transmission, the dispersion is large, so these fibres are not used for communication purposes.
4. The process of launching of light into single mode fibres is very difficult	4. The process of launching of light into single mode fibres is very easy.

<p>5. The condition for single mode operation is</p> $V = \frac{2\pi}{\lambda} a NA$ $V = \frac{2\pi}{\lambda} a n_1 \sqrt{2\Delta}$ <p>Multi mode optical fibre</p>	<p>5. The condition for multi mode propagation is</p> $N = 4.9 \left(\frac{d \cdot NA}{\pi} \right)^2$ <p>Where d the radius of the core of the fibre and NA is the numerical aperture.</p>
<p>6. Fabrication is very difficult and the fibre is costly.</p>	<p>6. Fabrication is very easy and the fibre is cheaper.</p>

Unit-IV : Acoustics & Ultrasonics

ACOUSTICS

Acoustics deals with the production, propagation and detection of sound waves

Classification of sound:

- (i) *Infrasonic < 20 Hz (Inaudible)*
- (ii) *Audible 20 to 20,000 Hz (Music and Noise)*
- (iii) *Ultrasonic > 20,000 Hz (Inaudible)*

Characteristics of Musical sound:

(i) Pitch or frequency

Frequency: number of vibrations of sound producing object/second

Pitch :- a degree of sensation depends on frequency

High frequency – shrill sound- voice of ladies, children,

mosquito Low frequency - grave sound- sound by lion

(ii) Quality or Timbre

- ability to distinguish b/w any two or more musical sound having same pitch and frequency
- smallest frequency is called **fundamental** and frequencies accompanying fundamental are called **overtones**.

(iii) Intensity or Loudness

Intensity :amount of sound energy flowing per sec per unit area

$$I = Q / A \text{ watt/m}^2$$

Loudness :degree of sensation varies from one observer from other

WEBER-FECHNER LAW

- loudness is directly proportional to the logarithm of intensity

$$L \propto \log \frac{I}{I_0} = K \log \frac{I}{I_0}$$

where K is a constant.

DECIBEL

L

- The intensity level (L) of sound is expressed in bel.
- Comparatively bel is a large unit, so for convenience, one tenth of bel is called a decibel (db)

$$1 \text{ bel} = 10 \text{ decibel} = 10 \text{ Db}$$

- Intensity level $L = 10 \log_{10}(I_1/I_2)$
 - Other units of loudness are Phon and Sone.
-

ACOUSTICS OF BUILDINGS

- deals with design and construction of hall
- halls or rooms are acoustically poor due to
 - distribution of intensity is not uniform
 - different frequency of sound interfere at some point reduces the quality
- to get good acoustical building, factors to be considered
 - Reverberation time
 - Focusing and interference
 - Echoes and Echelon effect
 - Resonance and
 - Extraneous noise

Reverberation : persistence or prolongation of sound in a hall even after the sound source is stopped

Reverberation Time : time taken by the sound wave to fall below the

minimum audibility level *i.e.*, to fall to one millionth of its initial intensity, after the source is stopped

$$I = 10^{-6} I_0 \quad \text{or} \quad I / I_0 = 10^{-6}$$

Sabine's Formula for Reverberation Time

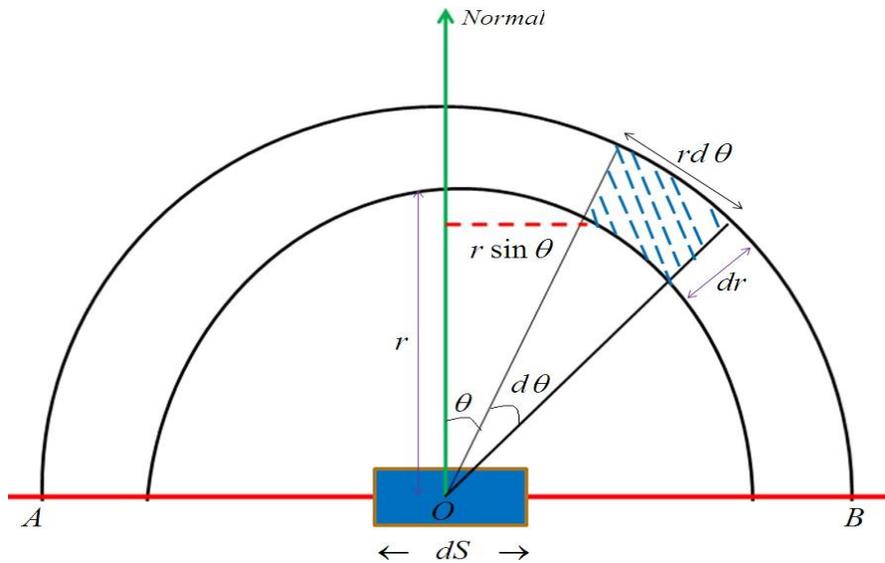
- **Professor Wallace C. Sabine (1868–1919)**
- derived from reverberation theory which explains the nature of growth and decay of sound energy.

Assumptions :

- The sound energy is uniformly distributed throughout the hall
- The absorption of sound by the air is neglected
- The source emits the sound energy constantly.

Steps involved:

1. calculate the rate of incident energy on the walls and the rate of absorption by the walls in terms of average energy density E
 2. calculate the final steady value of E in terms of average energy density
 3. calculate the final steady value of E in terms of rate of emission of power P of the source.
 4. obtain an expression for the rate of growth and decay of sound energy in a room.
 5. obtain the reverberation time.
-



- Consider a small element 'ds' on a plane wall AB
- Sound energy received by 'ds' is E
- Draw two concentric circles of radii 'r' and 'r+dr' from centre point 'O'
- Consider a small shaded portion lying between circles having θ and $\theta+d\theta$ from normal
- If radial length = dr Arc length = $r d\theta$

$$\text{Area of shaded portion} = r d\theta dr \quad \dots(1)$$

- If the whole figure is rotated about the normal through an angle $d\phi$, then area of shaded portion travel a distance of dx

$$dx = r \sin\theta d\phi \quad \dots (2)$$

Volume traced by a shaded portion $dV = \text{area} \times \text{distance}$

$$\begin{aligned} &= r d\theta dr r \sin\theta d\phi \\ &= r^2 \sin\theta d\theta dr d\phi \quad \dots(3) \end{aligned}$$

Sound energy present in this volume = $E \times dV$

$$= E r^2 \sin\theta d\theta dr d\phi$$

This sound energy travels in all the direction through this element.

$$\text{Sound energy present in this volume } dV / \text{unit solid angle} = \frac{E r^2 \sin\theta d\theta dr d\phi}{4\pi}$$

Solid angle subtended by the area dS at this element of vol. dV is $\frac{dS \cos\theta}{r^2}$

Sound energy travelling towards dS from dV is

$$= \frac{E r^2 \sin\theta d\theta dr d\phi}{4\pi} \cdot \frac{dS \cos\theta}{r^2}$$



$$= \frac{E \sin\theta \cos\theta d\theta dr dS d\phi}{4\pi} \quad \dots (4)$$

To find the total energy by dS in one sec, Integrate the eqn. (4) for whole volume lying within a distance of C of dS,

$$\begin{aligned} \phi &= 0 \text{ to } 2\pi \\ \theta &= 0 \text{ to } \pi/2 \\ r &= 0 \text{ to } C \end{aligned}$$

Energy received/sec =

$$\begin{aligned} \text{w.r.t. } \phi &= \frac{E \sin\theta \cos\theta d\theta dr dS \int_0^{2\pi} d\phi}{4\pi} \\ &= \frac{E \sin\theta \cos\theta d\theta dr dS \cdot 2\pi}{4\pi} \\ &= \frac{E \sin\theta \cos\theta d\theta dr dS}{2} \\ \text{w.r.t } \theta &= \frac{E dr dS \int_0^{\pi/2} \sin\theta \cos\theta d\theta}{2} \\ \text{X and } \div \text{ by } 2 &= \frac{E dr dS \int_0^{\pi/2} 2\sin\theta \cos\theta d\theta}{4} \\ &= \frac{E dr dS \int_0^{\pi/2} \sin 2\theta d\theta}{4} \\ &= \frac{E dr dS}{4} \\ \text{w.r.t. } r &= \frac{E dS \int_0^C dr}{4} \\ &= \frac{EC dS}{4} \quad \dots (5) \end{aligned}$$

Let 'a' be the absorption coefficient of wall.

Then,

$$\begin{aligned} \text{Sound energy absorbed by dS in one sec} &= \frac{1}{4} EC a dS \\ \text{Total energy absorbed at anytime} &= \frac{1}{4} EC \Sigma a = \frac{1}{4} ECA \quad \dots (6) \end{aligned}$$

If 'P' is the rate of emission of sound energy, then,

$$P = \frac{1}{4} E_{max} CA \quad \text{or} \quad E_{max} = \frac{P}{CA} \quad \dots (7)$$

Rate of Growth and Decay

Total rate of energy increase in medium:

Energy density = E Total

volume of the Hall = V Total

sound energy = EV

Rate of growth of sound energy: $\frac{d(EV)}{dt} = V \frac{dE}{dt}$



W.K.T,

Rate of emission of sound energy = Rate of growth of sound energy + Rate of absorption of sound energy

$$P = \frac{dE}{dt} + \frac{4P}{4V}E$$

$$\frac{P}{V} = \frac{dE}{dt} + \frac{CA}{4V}E$$

Let $\frac{CA}{4V} = \alpha$ or $\frac{CA}{4\alpha} = V$

$$\frac{dE}{dt} + \alpha E = \frac{4P}{4V}\alpha$$

Multiplying both sides by $e^{\alpha t}$,

$$\frac{d}{dt}(Ee^{\alpha t}) + \alpha Ee^{\alpha t} = \frac{4P}{4V}\alpha e^{\alpha t}$$

$$\frac{d}{dt}(Ee^{\alpha t}) = \frac{4P}{4V}\alpha e^{\alpha t}$$

Integrating the above eqn. we get,

$$Ee^{\alpha t} = \frac{4P}{4V}\alpha e^{\alpha t} + K \quad \dots (8)$$

Growth of Energy

During Growth, $t = 0, E = 0$

From eqn. (8),

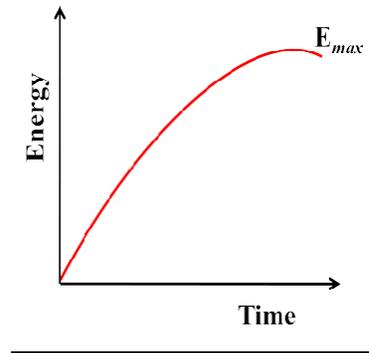
$$K = -\frac{4P}{4V}\alpha$$

Then,

$$Ee^{\alpha t} = \frac{4P}{4V}\alpha e^{\alpha t} - \frac{4P}{4V}\alpha$$

$$Ee^{\alpha t} = \frac{4P}{4V}\alpha (e^{\alpha t} - 1)$$

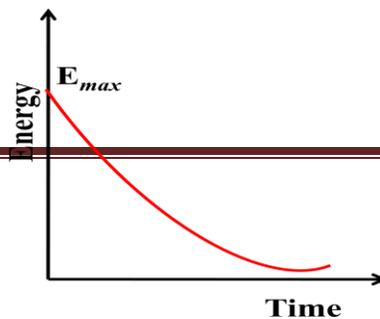
$$E = E_{max} (1 - e^{-\alpha t})$$



E increases until $E = E_{max}$ and $t = \infty$

Decay of Energy

If sound energy is cut off,



rate of emission $P = 0$

$$t = 0$$

$$E = E_{max}$$

From eqn.(8), $K = E_{max}$

then,

$$Ee^{at} = \frac{4P}{CA} e^{at} + E_{max}$$

Since $P = 0$

$$\overline{CA}$$

$$Ee^{at} = E_{max}$$



$E = E_{max}e^{-\alpha t}$, even though source is cutoff, energy decreases exponentially

Reverberation time

By definition, $E = E_{max} / 10^6$

from decay of energy, $E = E_{max} e^{-\alpha t}$

$$E_{max} / 10^6 = E_{max} e^{-\alpha t}$$

$$10^{-6} = e^{-\alpha t}$$

Take log on both sides, $\log_e 10^{-6} = -\alpha t$

$$-6 \times 2.3026 \log_{10} 10 = -\alpha t$$

$$\alpha t = 6 \times 2.3026$$

$$\alpha = \frac{CA}{4V} \quad t = T, \text{ then,}$$

$$\frac{CA T}{4V} = 6 \times 2.3026$$

$$T = \frac{4V \times 6 \times 2.3026}{CA}$$

$$= \frac{0.167 V}{A}$$

ABSORPTION COEFFICIENT

- Reciprocal of its area which absorbs the same amount of sound energy absorbed by unit area of open window
- Absorption coefficient = $\frac{\text{Sound energy absorbed by the surface}}{\text{Total sound energy incident on it}}$

- measured in OWU or Sabine.

Determination of Absorption Coefficient:

- without sound absorbing material

$$= 0.167V$$

$$\frac{\Sigma}{a} \overline{s}$$

- with sound absorbing material

$$T_2 = \frac{0.167V}{\Sigma a s + a_m s_m}$$

- from $T_2 - T_1$,
-

$$\alpha = \frac{0.167}{s_m} \cdot \frac{T_1 - T_2}{T_1 T_2}$$

Materials and their Absorption coefficient

Brick wall	0.02	Carpet	0.24
Wooden floor	0.057	Cushion	0.45
Chair	0.25	Rubber floor	0.05
Glass	0.02	Human	0.4



FACTORS AFFECTING GOOD ACOUSTICAL BUILDING AND THEIR REMEDIES

FACTOR S	DEFINITION	REMEDIES
Reverberation Time	<ul style="list-style-type: none"> - Time taken by the sound wave to fall below the minimum audibility level after the source is stopped - <i>Reverberation Time is too high</i>: overlapping of successive sound - <i>Reverberation Time is too low</i> : produced sound will disappear - for the good audibility , reverberation time should be kept at an optimum value. 	<ul style="list-style-type: none"> by installing sound <ul style="list-style-type: none"> ▪ providing wall ▪ arranging furniture ▪ completely covering with carpets ▪ heavy curtains ▪ decorating with sound absorbing boards, pictures
Loudness	<ul style="list-style-type: none"> - degree of sensation produced in the ear. - uniform distribution of loudness must be maintained - due to high absorption or low reflecting surfaces near the sound source 	<p><i>If loudness is low:</i></p> <ul style="list-style-type: none"> ▪ speakers maintain proper distances ▪ lowering the height of reflecting surfaces <p><i>If loudness is high:</i></p> <ul style="list-style-type: none"> ▪ sound absorbing materials in places
Echo	<p>If the time interval between the direct sound and the reflected sound is less than 1/15 of a second, the reflected sound reaches the audience later than the direct sound.</p>	<ul style="list-style-type: none"> ▪ properly covering the high ceiling with sound absorbing material
Echelon Effect	<ul style="list-style-type: none"> - new sound produced by <i>repetitive echoes</i> - regular reflecting surface like stair case may create this effect. 	<ul style="list-style-type: none"> ▪ Cover such regular reflecting surfaces properly.
Focusing	<ul style="list-style-type: none"> - Reflected sound by the ceiling and wall is focused at a particular area of the hall. - Plane surface : reflect and distribute the sound evenly. 	<ul style="list-style-type: none"> ▪ cover the curved surfaces with sound absorbing material ▪ use large radius of curvature
	<p>Curved surface : focuses the sound in the front portion only.</p>	<p>should be two curved surfaces in a building.</p>

Interference Effect	- Caused by interference of direct and reflected wave constructive interference : max. sound intensity occurs destructive interference : min. sound intensity occurs	<ul style="list-style-type: none"> ▪ By the usage of absorber it can be
Resonance	If window panels or any other wooden sections are not covered properly, the original sound may vibrate with the natural frequency of them.	<ul style="list-style-type: none"> ▪ Vibrating materials are non-vibrating materials. ▪ Panels must be eliminated through Air-Conditioning
Noise	<p>- Unwanted sound produced externally/internally gives an irritating experience</p> <p>Air-Borne Noise outside noise which reaches the audience through window, door and ventilator</p>	<ul style="list-style-type: none"> ▪ The hall should be populated area, factories and railways ▪ by air conditioning system it can be
	<p>Structure-Borne Noise - noise reaches the audience through the structural defect of the building - due to the movement of furniture, footsteps and the operation of heavy machinery like generators.</p>	<ul style="list-style-type: none"> ▪ Use double wall mounts, carpet
	<p>Inside Noise noise produced inside the hall like crying kids, the sound generated by type writers, fan, A/C, Refrigerators, etc.,</p>	<ul style="list-style-type: none"> ▪ equipments must ▪ equipment should absorb mounting ▪ Floor, wall and
		with suitable sound materials.

ULTRASONICS

Production of ultrasonics by magnetostriction and piezoelectric methods - acoustic grating -Non Destructive Testing - pulse echo system through transmission and reflection modes - A,B and C - scan displays, Medical applications – Sonogram

INTRODUCTION

-
- The word *ultrasonic* combines the Latin roots *ultra*, meaning 'beyond' and *sonic*, or *sound*.
 - The sound waves having frequencies above the audible range i.e. above 20000 Hz are called *ultrasonic waves*.
 - Generally these waves are called as *high frequency waves*.
 - The broad sectors of society that regularly apply ultrasonic technology are the medical community, industry and the military.

PROPERTIES

- They have high energy content.
- Just like ordinary sound waves, ultrasonic waves get reflected, refracted and absorbed.
- They can be transmitted over large distances with no appreciable loss of energy.
- If an arrangement is made to form stationary waves of ultrasonics in a liquid, it serves as a diffraction grating. It is called an *acoustic grating*.
- They produce intense heating effect when passed through a substance.

PRODUCTION OF ULTRASONIC WAVE

Ultrasonic waves are produced by the following methods.

- (1) Magnetostriction generator or oscillator
- (2) Piezo-electric generator or oscillator



(1) MAGNETO-STRICTION GENERATOR

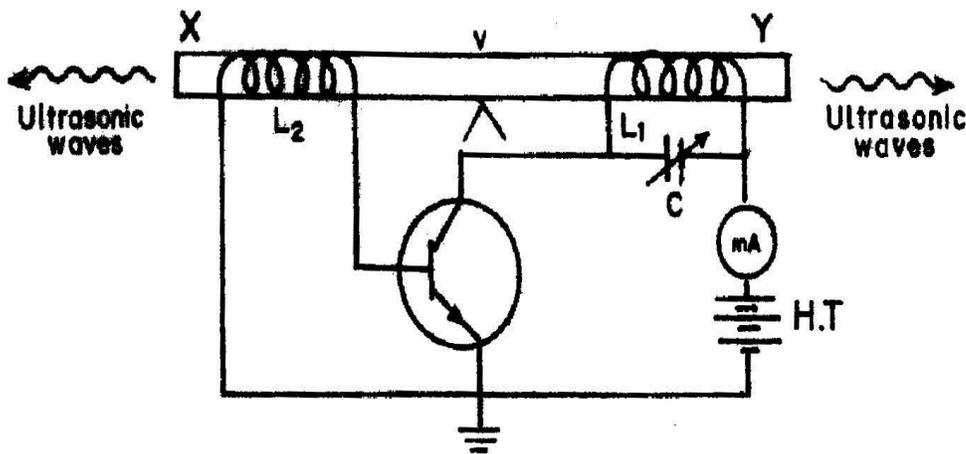
Principle:

Magnetostriction effect: When a ferromagnetic rod like iron or nickel is placed in a magnetic field parallel to its length, the rod experiences a small change in its length. This is called magnetostriction effect.

The change in length (increase or decrease) produced in the rod depends upon the strength of the magnetic field, the nature of the materials and is independent of the direction of the magnetic field applied.

Construction

- The experimental arrangement is shown in Figure.



- XY is a rod of ferromagnetic materials like iron or nickel. The rod is clamped in the middle.
- The alternating magnetic field is generated by electronic oscillator.
- The coil L_1 wound on the right hand portion of the rod along with a variable capacitor C.
- This forms the *resonant circuit* of the collector tuned oscillator. The frequency of oscillator is controlled by the variable capacitor.
- The coil L_2 wound on the left hand portion of the rod is connected to the base circuit. The coil L_2 acts as *feed-back loop*.

Working

- When High Tension (H.T.) battery is switched on, the collector circuit oscillates with a frequency,

$$2\pi\sqrt{L_1C}$$

$$f = \square^1$$



-
- This alternating current flowing through the coil L_1 produces an alternating magnetic field along the length of the rod. The result is that the rod starts vibrating due to magnetostrictive effect.
 - The frequency of vibration of the rod is given by

$$f = \frac{1}{2l} \sqrt{\frac{Y}{\rho}}$$

where l = length of the rod

Y = Young's modulus of the rod material and

ρ = density of rod material

- The capacitor C is adjusted so that the frequency of the oscillatory circuit is equal to natural frequency of the rod and thus resonance takes place.
- Now the rod vibrates longitudinally with maximum amplitude and generates ultrasonic waves of high frequency from its ends.

Advantages

- The design of this oscillator is very simple and its production cost is low
- At low ultrasonic frequencies, the large power output can be produced without the risk of damage of the oscillatory circuit.

Disadvantages

- It has low upper frequency limit and cannot generate ultrasonic frequency above 3000 kHz (ie. 3MHz).
- The frequency of oscillations depends on temperature.
- There will be losses of energy due to hysteresis and eddy current.

(2) PIEZO ELECTRIC GENERATOR

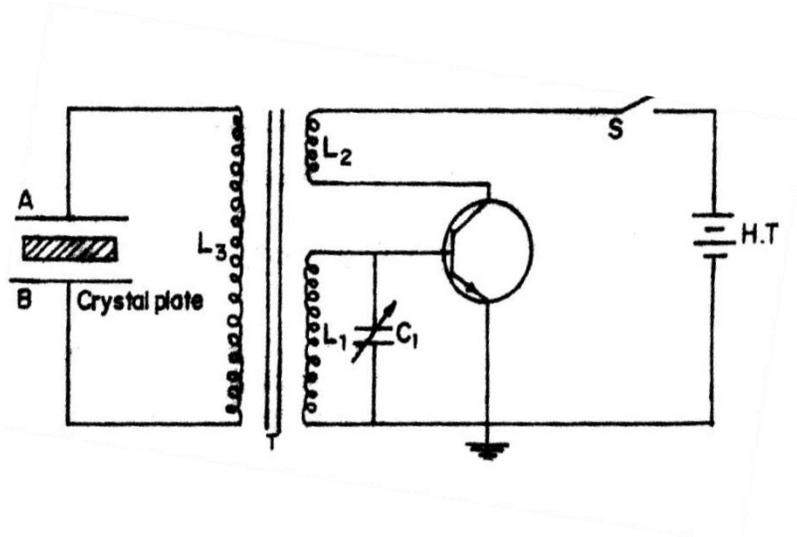
Principle: Inverse piezo electric effect

- If mechanical pressure is applied to one pair of opposite faces of certain crystals like quartz, equal and opposite electrical charges appear across its other faces. This effect is called as piezo-electric effect.
 - The converse of piezo electric effect is also true.
-

- If an electric field is applied to one pair of faces, the corresponding changes in the dimensions of the other pair of faces of the crystal are produced. This effect is known as inverse piezo electric effect.

Construction

The circuit diagram is shown in Figure



- The quartz crystal is placed between two metal plates A and B.
- The plates are connected to the primary (L_3) of a transformer which is inductively coupled to the electronic oscillator.
- The electronic oscillator circuit is a base tuned oscillator circuit.
- The coils L_1 and L_2 of oscillator circuit are taken from the secondary of a transformer T.
- The collector coil L_2 is inductively coupled to base coil L_1 .
- The coil L_1 and variable capacitor C_1 form the *tank circuit* of the oscillator.

Working

- When H.T. battery is switched on, the oscillator produces high frequency alternating voltages with a frequency.

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

- Due to the transformer action, an oscillatory e.m.f. is induced in the coil L_3 . This high frequency alternating voltages are fed on the plates A and B.
- Inverse Piezo-electric effect takes place and the crystal contracts and expands alternatively. The crystal is set into mechanical vibrations.
- The frequency of the vibration is given by

$$f = \frac{P}{2l} \sqrt{\frac{Y}{E}}$$

where $P = 1, 2, 3, 4 \dots$ etc. for fundamental, first overtone, second overtone etc.,
 Y = Young's modulus of the crystal and
 ρ = density of the crystal.

- The variable condenser C_1 is adjusted such that the frequency of the applied AC voltage is equal to the natural frequency of the quartz crystal, and thus resonance takes place.
- The vibrating crystal produces longitudinal ultrasonic waves of large amplitude.

Advantages

- Ultrasonic frequencies as high as 5×10^8 Hz or 500 MHz can be obtained with this arrangement.
- The output of this oscillator is very high.
- It is not affected by temperature and humidity.

Disadvantages

- The cost of piezo electric quartz is very high
- The cutting and shaping of quartz crystal are very complex.

ACOUSTIC GRATING

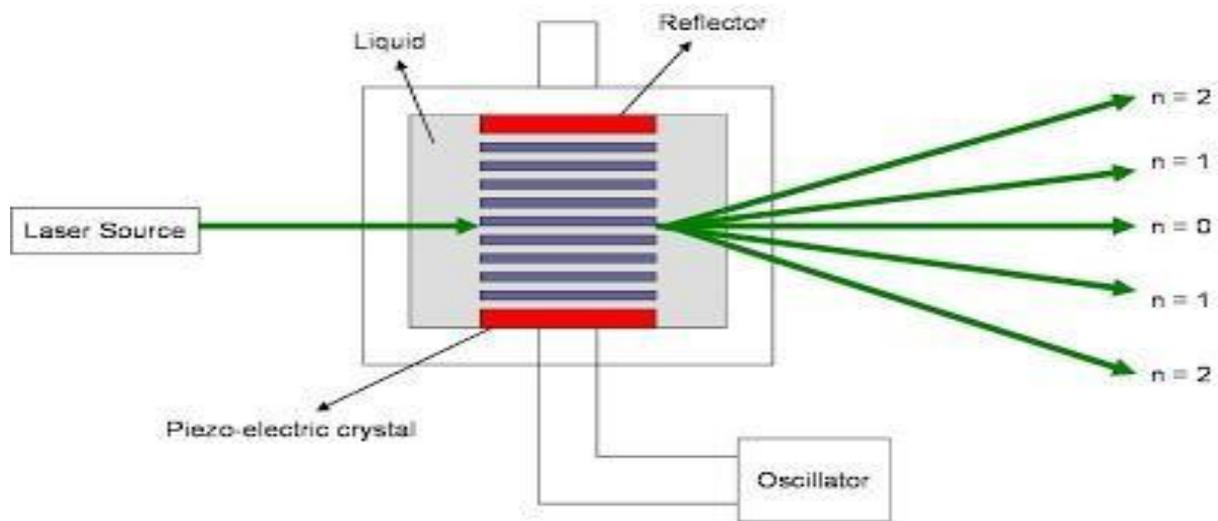
Principle:

- When ultrasonic waves are passed through a liquid, the density of the liquid varies layer by layer due to the variation in pressure and hence the liquid will act as a diffraction grating, so called acoustic grating.
- Under this condition, when a monochromatic source of light is passed through the acoustic grating, the light gets diffracted. Then, by using the condition for diffraction, the velocity of ultrasonic waves can be determined.

Construction & Working:

- The liquid is taken in a glass cell. The Piezo-electric crystal is fixed at one side of the wall inside the cell and ultrasonic waves are generated.
 - The waves travelling from the crystal get reflected by the reflector placed at the opposite wall. The reflected waves get superimposed with the incident waves producing longitudinal standing wave pattern called acoustic grating.
 - If light from a laser source such as He-Ne or diode laser is allowed to pass through the liquid in
-

a direction perpendicular to the grating, diffraction takes place and one can observe the higher order diffraction patterns on the screen.



- The angle between the direct ray and the diffracted rays of different orders (θ_n) can be calculated easily.
- According to the theory of diffraction,

$$d \sin \theta_n = n \lambda \text{ ----- (1)}$$

where $n = 0, 1, 2, 3, \dots$ is the order of diffraction,

λ is the wavelength of light used and

d is the distance between two adjacent nodal or anti-nodal planes.

- Knowing n , θ_n and λ , the value of d can be calculated from eqn. (1). If λ_a is the wavelength of the ultrasonic waves through the medium, then

$$d = \lambda_a / 2 \text{ (or) } \lambda_a = 2d \text{ ----- (2)}$$

- If the resonant frequency of the Piezo-electric oscillator is N , then the velocity of ultrasonic wave is given by

$$v = N \lambda_a = 2Nd \text{ (3)}$$

- This method is useful in measuring the velocity of ultrasonic waves through liquids and gases at various temperatures. From these measurements, many parameters of the liquid such as free volume, compressibility, etc., can be calculated.

NON DESTRUCTIVE TESTING

What is NDT?

- Nondestructive testing is a method of finding defects in an object without harming the object.

Most Common NDT Methods

- Visual Inspection Method
- Liquid Penetrant Method
- Magnetic Particle Inspection
- Ultrasonic Flaw Detection
- Eddy Current Testing
- X-Ray Diffraction Method

How is ultrasound used in NDT?

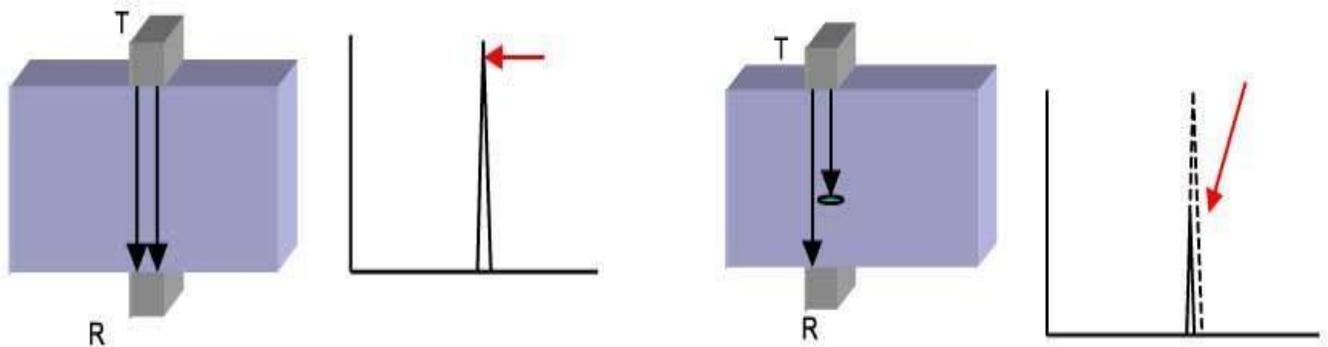
- Sound with high frequencies, or ultrasound, is one method used in NDT.
- Ultrasonic waves are used to detect the presence of flaws or defects in the form of cracks, blowholes, porosity etc., in the internal structure of a material.
- Basically, ultrasonic waves are emitted from a transducer into an object and the returning waves are analyzed. If an impurity or a crack is present, the sound will bounce off of them and be seen in the returned signal.
- There are two methods of receiving the ultrasound waveform:
 - (i) attenuation (or through-transmission) and
 - (ii) reflection (or pulse-echo) mode

THROUGH TRANSMISSION METHOD

- Through transmission was used in the early days of ultrasonic testing and is still used in plate and bar production.
 - In attenuation (or through-transmission) mode, a transmitter sends ultrasound through one surface, and a separate receiver detects the amount that has reached it on another surface after traveling through the medium. Imperfections or other conditions in the space between
-

the transmitter and receiver reduce the amount of sound transmitted, thus revealing their presence.

- Two transducers located on opposing sides of the test specimen are used. One transducer acts as a transmitter, the other as a receiver.
- A probe on one side of a component transmits (T) an ultrasonic pulse to a receptor (R) probe on the other side. The absence of a pulse coming to the receiver indicates a defect.
- Discontinuities in the sound path will result in a partial or total loss of sound being transmitted and be indicated by a decrease in the received signal amplitude.
- Using the couplant increases the efficiency of the process by reducing the losses in the ultrasonic wave energy due to separation between the surfaces.



Advantages

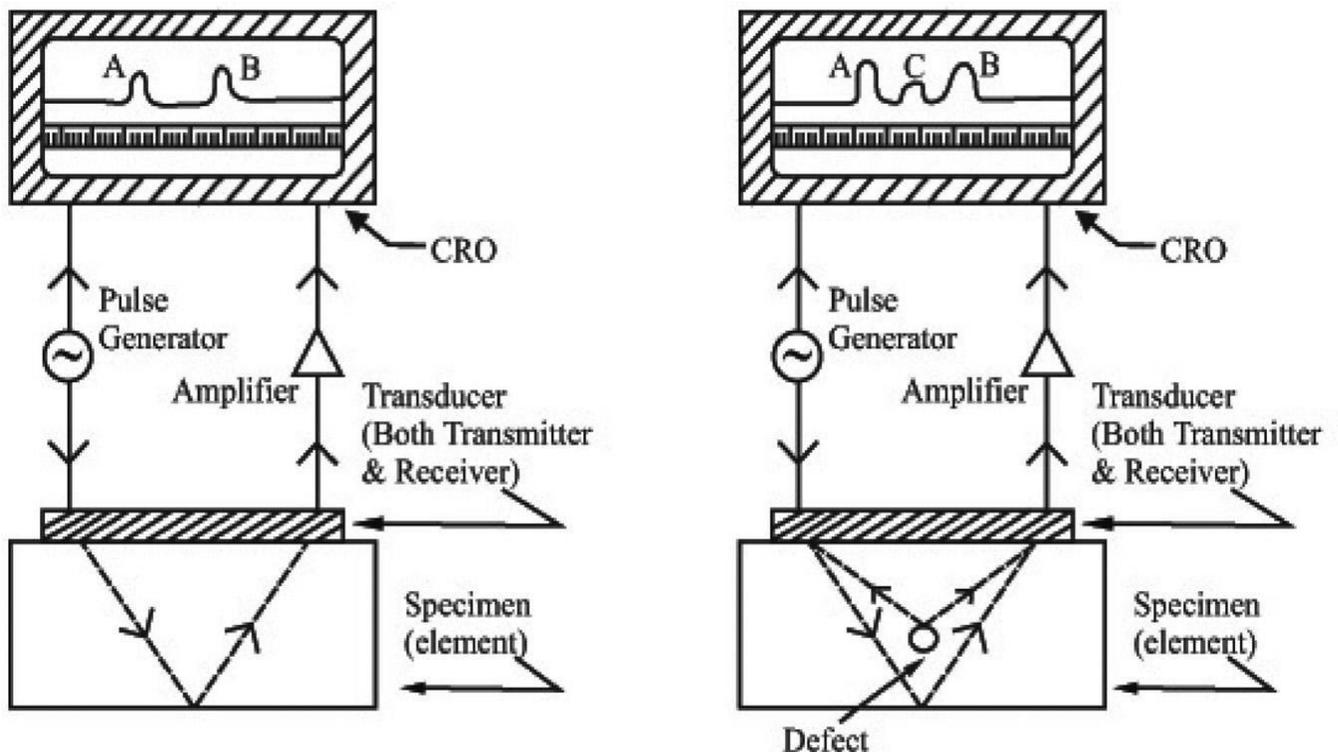
1. Less attenuation of sound energy
2. No probing
3. No dead zone on the screen
4. The orientation of a defect does not matter in the way that it does on the pulse echo display.

Disadvantages

1. The defect cannot be located
2. The component surfaces must be parallel
3. Vertical defects do not show
4. Through transmission is useful in detecting discontinuities that are not good reflectors, and when signal strength is weak. It does not provide depth information
5. There must be access to both sides of the component.

PULSE-ECHO SYSTEM THROUGH REFLECTION MODE

- In reflection (or pulse-echo) mode, the transducer performs both the sending and the receiving of the pulsed waves as the "sound" is reflected back to the device. Reflected ultrasound comes from an interface, such as the back wall of the object or from an imperfection within the object. The diagnostic machine displays these results in the form of a signal with an amplitude representing the intensity of the reflection and the distance, representing the arrival time of the reflection.
- A typical pulse-echo UT inspection system consists of several functional units, such as ultrasonic frequency generator and a cathode ray oscilloscope (CRO), transmitting transducer(A), receiving transducer(B) and an amplifier.
- The transducer is typically separated from the test object by a couplant (such as oil) or by water
- Driven by the high frequency generator G, the transducer A generates high frequency ultrasonic energy.
- An ultrasound transducer connected to a diagnostic machine is passed over the object being inspected. The sound energy is introduced and propagates through the materials in the form of waves.



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- When there is a discontinuity (*such as a crack*) in the wave path, part of the energy will be reflected back from the flawsurface.
 - The reflected wave signal is transformed into an electrical signal by the transducer B and is displayed on a screen.
 - Knowing the velocity of the waves, travel time can be directly related to the distance that the signal traveled. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.

Advantages

1. High penetrating power, which allows the detection of flaws deep in the part.
2. High sensitivity, permitting the detection of extremely small flaws.
3. Only one surface needs to be accessible.
4. Greater accuracy than other nondestructive methods in determining the depth of internal flaws and the thickness of parts with parallel surfaces.
5. Some capability of estimating the size, orientation, shape and nature of defects.
6. Non hazardous to operations or to nearby personnel and has no effect on equipment and materials in the vicinity.
7. Capable of portable or highly automated operation.

Disadvantages

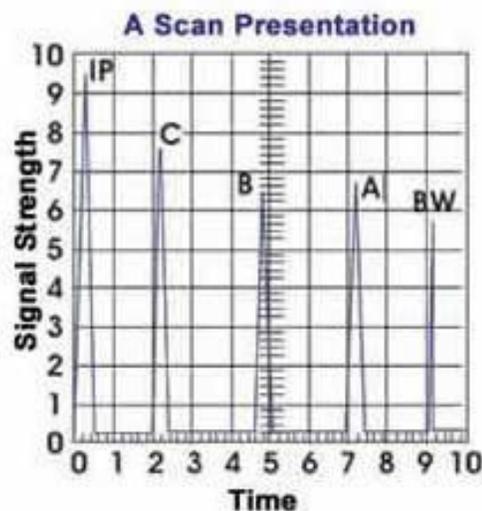
1. Manual operation requires careful attention by experienced technicians.
 2. Extensive technical knowledge is required for the development of inspection procedures.
 3. Parts that are rough, irregular in shape, very small or thin, or not homogeneous are difficult to inspect.
 4. Surface must be prepared by cleaning and removing loose scale, paint, etc., although paint that is properly bonded to a surface need not be removed.
 5. Couplants are needed to provide effective transfer of ultrasonic wave energy between transducers and parts being inspected unless a non-contact technique is used. Non-contact techniques include Laser and Electro Magnetic Acoustic Transducers (EMAT).
 6. Inspected items must be water resistant, when using water based couplants that do not contain rust inhibitors.
-

MODE OF DISPLAYS

- Ultrasonic data can be collected and displayed in a number of different formats. The three most common formats are known in the NDT world as
 - A-scan
 - B-scan
 - C-scan presentations.
- Each presentation mode provides a different way of looking at and evaluating the region of material being inspected. Modern computerized ultrasonic scanning systems can display data in all three presentation forms simultaneously.

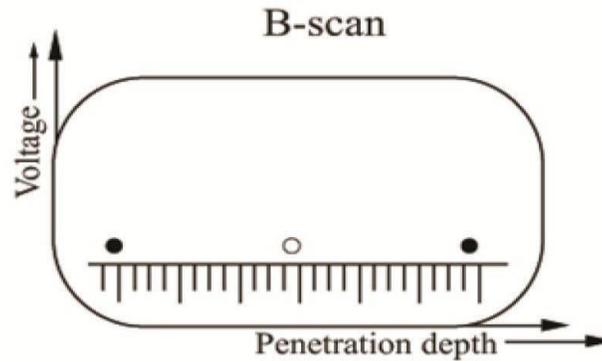
CAN

- The A-scan presentation displays the amount of received ultrasonic energy (amplitude mode) as a function of time.
- The relative amount of received energy is plotted along the vertical axis and the elapsed time (which may be related to the traveled distance within the material) is displayed along the horizontal axis.
- Reflector depth can be determined by the position of the signal on the horizontal time axis.
- It gives 1-D information



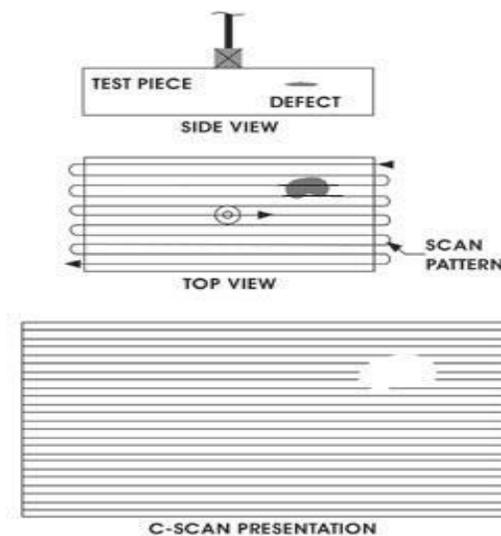
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- It gives 2-dimensional image
- The transducer can be removed.
- The reflected Echoes are displayed as dots
- The brightness and size of the dot depends on the intensity and strength of the reflected echo respectively.



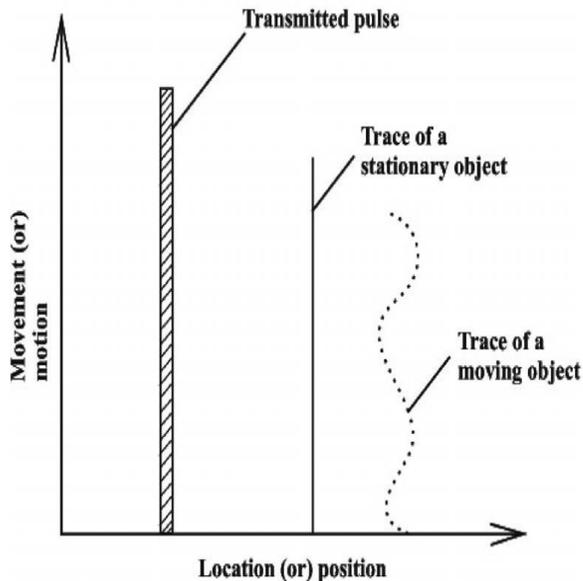
CAN

- It gives two-dimensional information that provides the
- It provides the location and size of defect
- It was scanned over the test piece.
- The relative signal amplitude is displayed as a shade of gray or a color for each of the positions
- The C-scan presentation provides an image of the features that reflect and scatter the sound within and on the surfaces of the test piece.



T.M. SCAN (time-motion mode display).

- It provides three-dimensional image of the specimen.
- It gives information about the moving object
- The transducer is held stationary as in A-scan and echoes appear as dots as in the B-scan.



- It can be used for analyzing moving body parts commonly in cardiac and fetal cardiac imaging

SONOGRAM

A sonogram is a medical procedure that uses ultrasound waves to create a picture of something that is happening within a person's body. This is a very common procedure in pregnancy, and is what produces the black-and-white fetal pictures.

How it Works

Sonogram machines emit sound waves, often known as ultrasound waves, that bounce off of organs, bones, and muscles. The machines are able to calculate the distance between waves in order to generate a very accurate picture, which is displayed on a specialized computer screen.

Ultrasound is primarily used to:

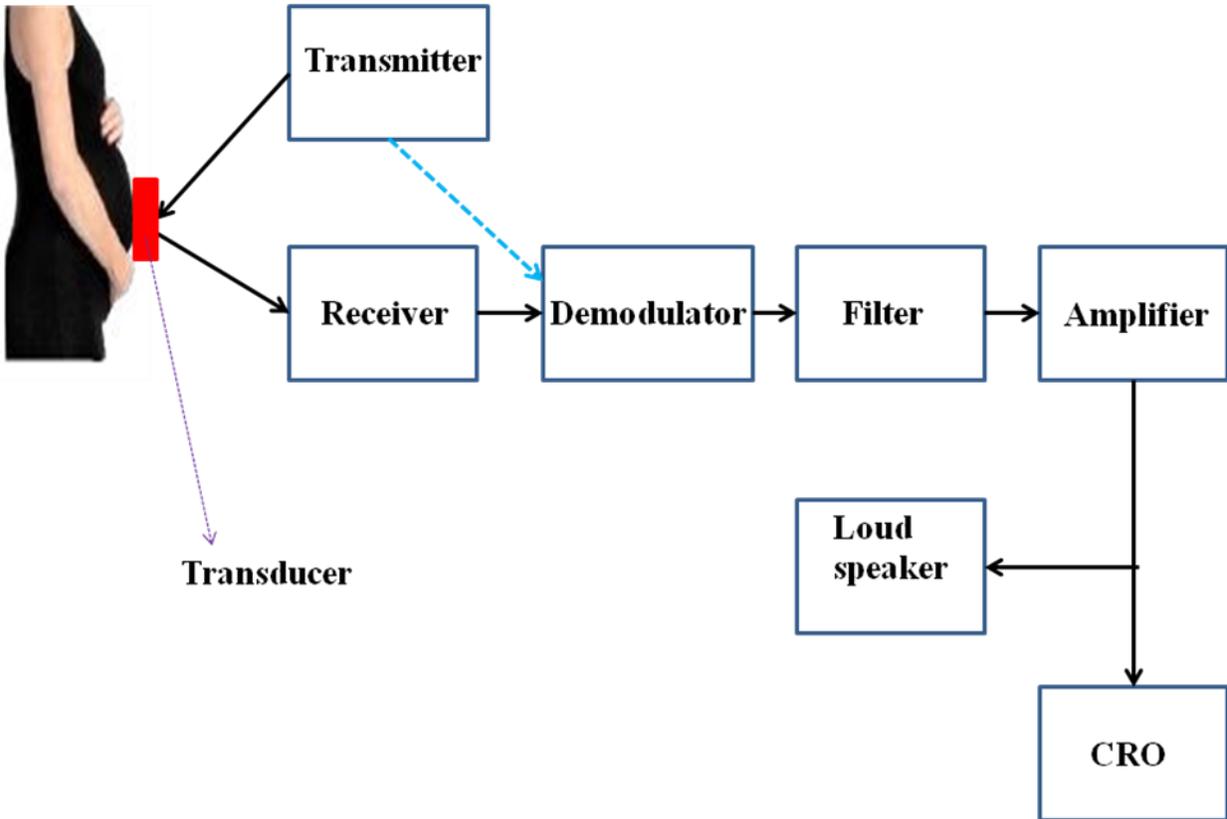
- Date the pregnancy
 - Determine location of fetus, intrauterine vs ectopic
 - Check the location of the placenta in relation to the cervix
 - Check for the number of fetuses (multiple pregnancy)
 - Assess fetal growth (for evidence of intrauterine growth restriction (IUGR))
-

-
- **Check for fetal movement and heartbeat.**
 - Determine the sex of the baby



Fetal movement and heartbeat

Principle : Doppler Effect



- When echo falls on the transducer, it generates the electrical pulses and it sent to the ultrasonic scanner.
- There they are processed and transformed into a digital image.
- The time taken for the echo to travel back to the probe is measured and used to find the depth of the tissue interface causing the echo.
- If the difference between acoustic impedances is greater and the echo is also larger.
- If the pulse falls on the gases or solids the density difference is very high. Most of the acoustic energy is reflected and it becomes impossible to see deeper.

Image formation

- Time taken to receive the echo is observed.
 - Time enables a sharp image and it represents the depth.
 - The strength of the echo in the form of pulse represents the movement of objects.
-

Other Medical Applications of Ultrasonics

Ultrasonics waves are noninvasive medical tool.

- cancer treatment and neurosurgery.
- to clean teeth and also for dental cutting.
- used for cataract treatment.
- A fetus in the womb can be viewed in a sonogram.
- Focused ultrasound may be used to break up kidney stones.
- Low-intensity ultrasound has the ability to stimulate bone-growth.
- Ultrasonics guides the blind person who uses ultrasonic guiding stick as a guiding tool

UNIT-V CRYSTAL STRUCTURES AND X-RAY DIFFRACTION

INTRODUCTION:

Solid:

- All that is (The whole) limited by form, semblance (shape), size, sound, color is called solid.
- It is one of the states of matter.
- It consists of a large number of closely packed atoms or molecules. The physical structure of a solid and its properties related to the arrangement of atoms or molecules within it.

Every solid element has its own internal structure.

It may be crystal or amorphous in the nature.

Crystallography is the way to study the crystal structures as they are.

Crystallography:

The word "crystallography" derives from the Greek words *krystallon* = clear ice, with its meaning extending to all solids with some degree of transparency, and *grapho* = write.

The study of the geometrical form and other physical properties of crystalline solids by using X-Ray, electron beams and neutron beams etc. is termed as the science of crystallography.

It is the

- a) Experimental science of determining the arrangement of atoms in solids.
- b) The study of crystals.

Note:

X-ray are most widely used to study the crystal structure because, the wavelength of X-rays (10^{-12} to 10^{-10} m) is almost equal to that of the interatomic distance and hence diffraction can easily occur, when they are passed through the crystal.

Classification of solids:

Every solid element has its own internal structure. The internal structure of solid depends on the internal arrangement of atoms or molecules or ions.

Solid are classified in two categories based on the internal arrangement of atoms or molecules.

1. Crystalline solid or crystals

2. Amorphous solids or no-crystalline solids

1. Crystalline solids or crystals:

Solids that have a definite shape and size are called crystalline solids. The word crystal comes from Greek word *krystallone* which means “clear ice”

Properties of crystalline solids:

- In Crystal solids, the atoms or molecules are arranged in a regular and periodically in three-dimensional manner.
 - If the crystal breaks, the broken pieces also have regular shape.
 - They have characteristic geometrical shape.
-

- Some crystalline solids are anisotropic i.e. the magnitude of physical properties (such as refractive index, electrical conductivity, thermal conductivity, etc.) are different along different directions of the crystals.

- Melting point of crystalline solids is extremely sharp. Because, when the temperature increases, bonds break at the same time.

- They are most stable.

- Examples: **i.Metallic crystals:** Gold, Silver, Aluminum, etc.

ii.Non-metallic crystals: Diamond, Silicon, Germanium, and Sodium chloride etc.

- Again crystalline solids are classified into two types; they are single crystalline solids and polycrystalline solids.

- **Single crystals or mono crystals:**

- Single crystal which contains only one crystal.

- There are no grain boundaries in these crystals.

- Single crystal may consist of same atoms or different types of atoms and yet all the atoms or molecules are arranged in a regular and periodically in three-dimensional manner.

- Single crystals naturally form as they are and yet they produce artificially from their vapor or liquid state.

- Most of the single crystals have different refractive index, electrical conductivity as well as mechanical strength different in all directions. This is also known as the anisotropic behavior of the crystals.

Examples of Single crystals:

Quartz, salt, diamond, Graphite and snowflakes, pearls, gem stones (such as **Sapphire, Ruby, Fluorite and emeralds** et)...

- **Poly crystals:**

- Poly crystals which composed of many microscopic or tiny crystals are called grains.

- Fig (b) shows the diagram of poly crystalline material. Notice that this type of material thereexists some mismatch within the region where two grains meet. This area is called grain boundary.
- Due to the mismatch math of grains, defects are formed in the crystals.
- Examples of polycrystalline solids include the common metals, and ceramics, sulfur, etc.

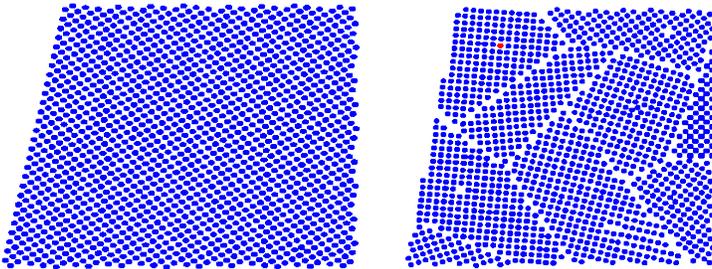
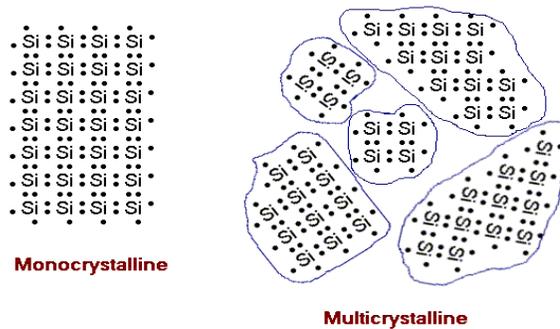


Fig (a) Model of a perfect single crystal Fig (b) Model of a poly-crystal with many defects

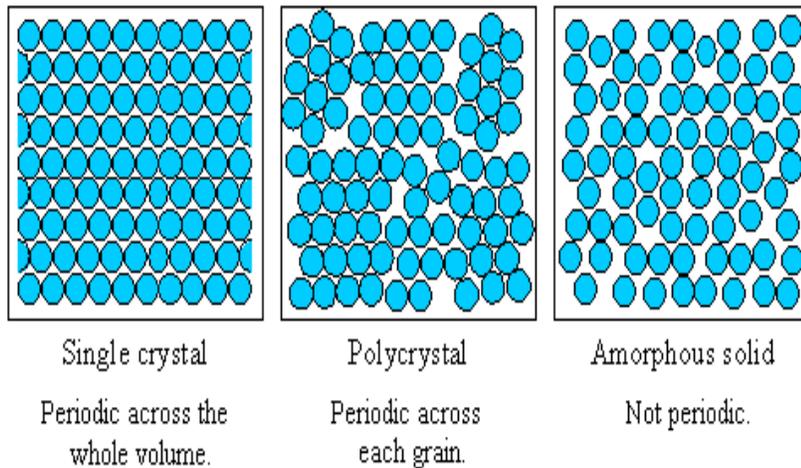
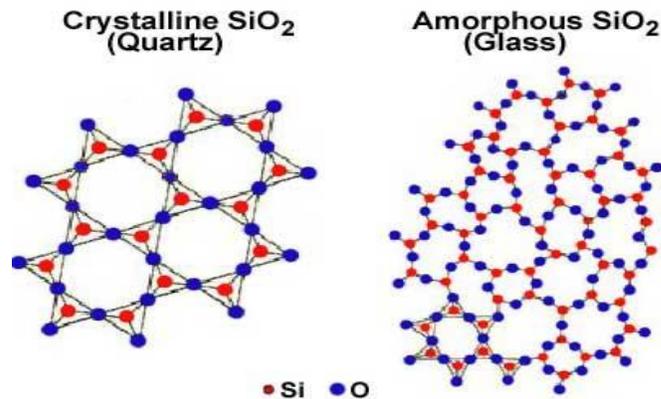
Example:



Amorphous solids or Non-crystalline solids:

The word **amorphous** comes from the Greek *a* means without, and *morphé*, means shape, form)

- In amorphous solids, the atoms or molecules are arranged in an irregular manner.
 - If an amorphous solid breaks, the broken pieces are irregular in shape.
 - They do not have sharp melting points.
 - They are less stable.
 - Example Glasses, plastics, Rubbers etc.
-



Language of crystals or crystal geometry:

Crystal geometry is useful to understand the crystal structures. If we want to understand the crystal structures, some basics are needed. Crystal geometry gives us those basics.

1. Crystal lattice (or) space lattice

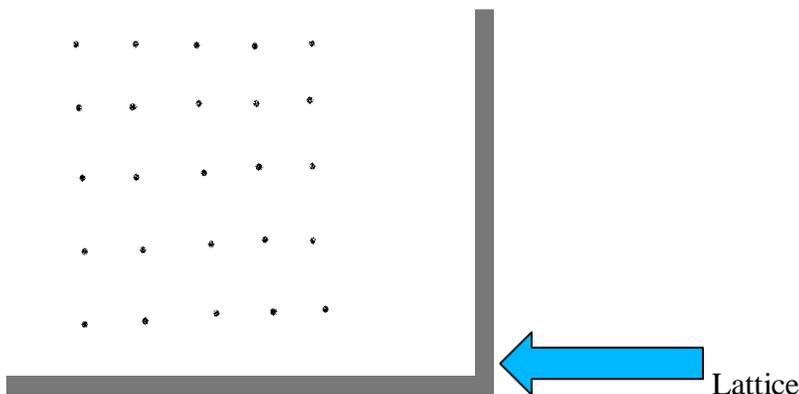
A crystal structure can be studied in terms of an idealized (imaginary) geometrical concept is called a space lattice and is introduced by Auguste Bravais in 1848.



Auguste Bravais
(1811-1863)

According to this concept,

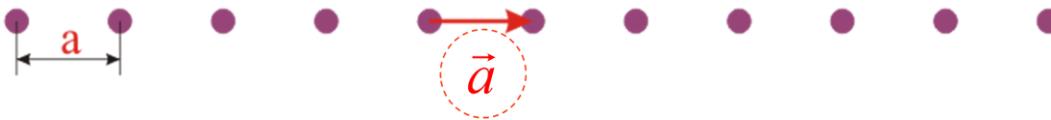
- Each atom in the structure can be replaced by a point in space. These points are known as lattice points.
- A Three dimensional collection of points in space are called space lattice or A Geometrical representation of the crystal structure in terms of lattice points is called “space lattice (or) crystal lattice”
- Lattice points are an array points in space.
- Lattice points are arranged in regular and periodically in three-dimensional order in space or array of points in space. In which every lattice point has the same environment with respect to all other points.
- Lattice points are geometrical points.
- Lattice points denote the position of atoms (or) molecules or ions in the crystal (fig.1)
- It is an imaginary concept.



1D-lattice:

It is defined as an infinite array of points in one-dimensional space in which every lattice point has the same environment with respect to all other points.

- In 1D there is only one kind of lattice
- This lattice can be described by a single lattice parameter (a)
- The unit cell for this lattice is a line segment of length a



2D- Lattice:

It is defined as an infinite array of points in two-dimensional space in which every lattice point has the same environment with respect to all other points.

A two dimensional space lattice is shown in fig. Consider an origin “O” a in XY-plane .two translational vectors a and b are taken along X-axis and Y-axis respectively. The resultant vector $op = T$

$$T = n_1a + n_2b \text{ ----- (1)}$$

Where n_1 and n_2 are the integers and a and b are the fundamental translation vectors along x and y directions.

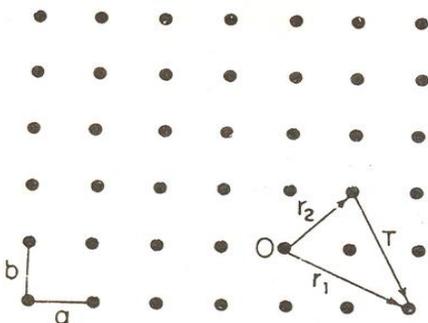


Figure 2: Two-dimensional array of points

(NOTE: Consider a lattice point at 'O' AS origin. And join the origin to successive lattice points along x and y directions. Let the position vectors of these lattice points be a and b. when a is repeated regularly, then it gives the position of lattice points along the x direction, i.e., 2a, 3a, 4a...similarly, if b is repeated regularly, then it gives the position of lattice points along the y direction, i.e., 2b, 3b, 4b, ... since, a and b when repeated regularly give the array of lattice points in space, they are known as fundamental translational vectors or basic vectors or primitive vectors)

3D- Lattice:

It is defined as an infinite array of points in three-dimensional space in which every lattice point has the same environment with respect to all other points.

In this case, the resultant position vector can be expressed as

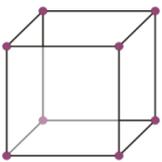
$$T = n_1a + n_2b + n_3c \text{ ----- (2)}$$

Where n_1 , n_2 and n_3 are the integers and a, b and c are the fundamental translation vectors along x, y, and z directions.

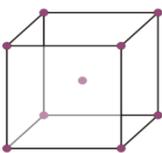
The possible types of Bravais lattices are four and following names and symbols represent them,

Primitive lattice-P, Body centered lattice-I, Face centered lattice-F, and Base centered lattice-C.

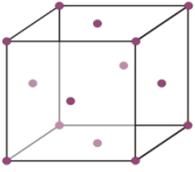
➤ In the simple primitive lattice (P), the lattice points are situated only at the corners of the unit cell.



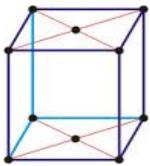
➤ In the body-centered lattice (I - from the German "Innenzentriert" means inner centered), the lattice points are situated at the corners and also at the intersection of the diagonals (centre) of the unit cell.



- In the face- centered lattice (F- from the German "Flächenzentriert" means face centered), the lattice points are lie at the corners and also at the centers of all the six faces of the unit cell.

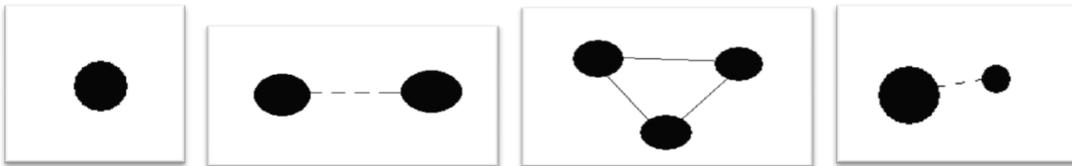


- In the base- centered lattice (C), the lattice points are lie at the corners as well as at the centers of the unit cell, which are opposite to each other.



2. Basis (or) motif:

- ❖ A Group of atoms or molecules or ions is called 'Basis'
- ❖ Basis may consist of single atom or a group of atoms.



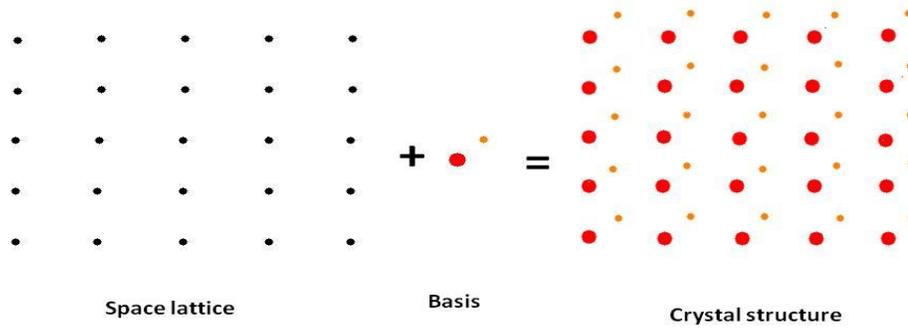
(a) single atom (b) Di atomic molecule (c) Tri atomic molecule (d) Ion

3. Crystal structure:

- Crystal structure is a combination of lattice and basis.
 - A crystal structure is formed by adding basis (atoms) to every lattice point of the space lattice.
- The number of atoms in the basis may be one or more than one.
- Thus the crystal structure is real and the crystal lattice is imaginary

Mathematically

$$\text{Crystal structure} = \text{space lattice} + \text{basis.}$$



3. Unitcell:

- Crystal structure can be defined in terms of unit cell.
- The unit cell is the smallest block or geometric figure of crystal, from which the entire crystal is built up by repetition in three dimensional manners.
- It represents the actual structure of crystal.
- The three dimensional representation of unit cell is as shown in figure.

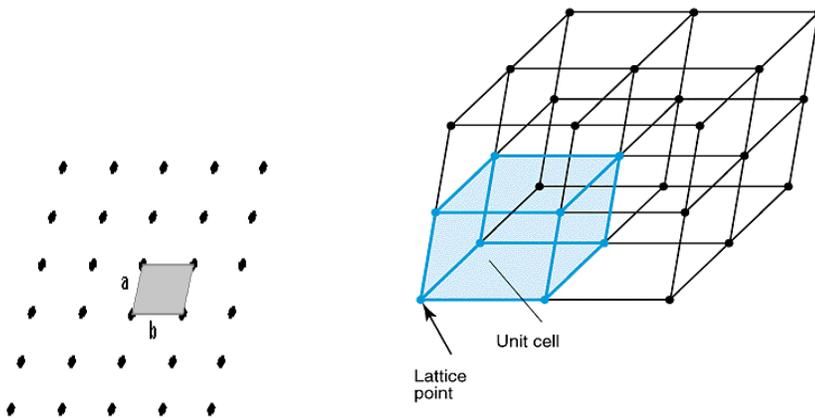


Fig. Unit cell in 2D -space lattice

Fig. Unit cell in 3D -space lattice

Types of unit cells:

There are two distinct types of unit cells: **primitive** and **non-primitive**.

1. Primitive cell:

- A primitive cell is the simplest type of unit cell which contains only one lattice point per unit cell (contains lattice points at its corner only).
- Primitive unit cells contain only one lattice point, which is made up from the lattice points at each of the corners. Ex: Simple cubic (SC)

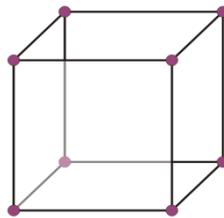
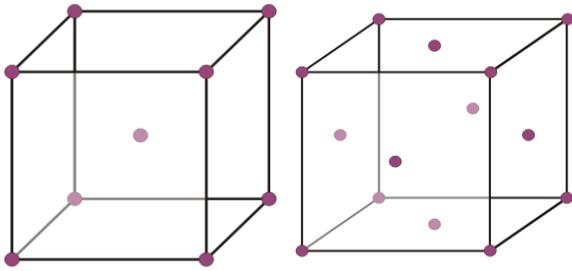


Fig: Simple Cube

2. Non-primitive cell:

- If there are more than one lattice points in a unit cell, it is called a Non-primitive cell.
 - Non-primitive unit cells contain additional lattice points, either on a face of the unit cell or within the unit cell, and so have more than one lattice point per unit cell. Ex: BCC and FCC contain more than one lattice point per unit cell.
-



(a) BCC

(b) FCC

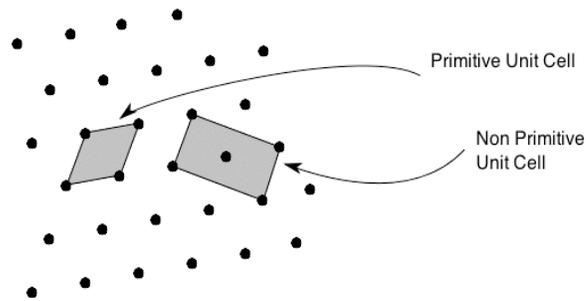


Fig: primitive and non- primitive unit cell in 2D-Spce lattice.

Lattice parameters of unit cell:

Definition:

To represent a lattice unit cell, we require the six parameters i.e., Axial lengths (a,b,c) and interfacial angles (α,β,γ) these quantities are known as “Lattice Parameters”.

i.e., Lattice parameters are

1. Axial lengths (a,b,c)
2. Interfacial angles (α, β, γ)

Explanation:

Consider a cubic unit cell with crystallographic axes X, Y, Z as shown in figure.

Let OA=a, OB=b, and OC=c be the intercepts made by the unit cell along the crystallographic axes. These quantities a, b and c are called translational vectors (or) axial lengths or primitives.

The angles between the three crystallographic axes are known as interfacial angles.

The angle between a and b is alpha (α) and b and c, is beta (β), and that between a and c is gamma (γ).

These three angles (α , β , γ) are called **interfacial angles**.

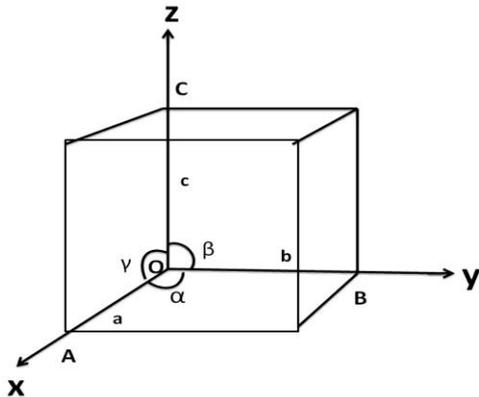


Fig: Cubic unit cell

Note :

The size (edge length) of a unit cell depends on the size of the atoms or ions and their arrangement. Because a unit cell is representative of the entire structure, the ratio of ions in the unit cell is the same as the ratio in the overall structure.

The crystal systems and Bravais lattices:

Crystals are classified in to 7 crystal systems on the basis of lattice parameters viz:

- (i) Axial lengths a,b,c and
- (ii) Interfacial (axial) angles α,β,γ .

The 7 basic crystal systems are

1. Cubic
 2. Tetragonal
 3. Orthorhombic
 4. Monoclinic
 5. Triclinic
 6. Rhombohedral OR Trigonal
-

7. Hexagonal

Bravais Lattices:

Bravais in 1880 showed that there are 14 possible types of space lattices in the 7 crystal systems as shown in table.

According to Bravais, there are only 14 possible ways of arranging points in space lattice from the 7 crystal systems such that, all the lattice points have exactly the same surrounding. These 14 space lattices are called the Bravais lattices.

Crystal System	axial lengths	interfacial angles	Number of Bravais Lattices	Bravais Lattice
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90^\circ$	3	Simple Cubic, FCC, BCC
Trigonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	2	Trigonal
Rhombohedral	$a = b = c$	$\alpha = \beta = \gamma \neq 90^\circ$	1	Rhombohedral
Monoclinic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ \neq \alpha$	2	Monoclinic, Base Centred Monoclinic
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	4	Orthorhombic, Base Centred Orthorhombic, FCC, BCC
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	2	Tetragonal
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90^\circ, \gamma = 120^\circ$	1	Hexagonal

The 7 crystal systems and Bravais lattices are discussed briefly one by one as follows

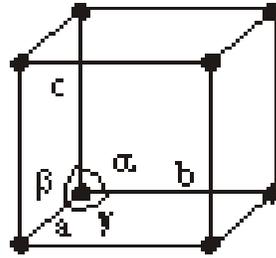
1. Cubic crystal system:

In cubic crystal system, the three crystal axes perpendicular to each other and axial lengths are the same along the entire three axes as shown in fig.

Lattice parameters:

All three sides equal, $a=b=c$

All three right angles, $\alpha = \beta = \gamma = 90^\circ$



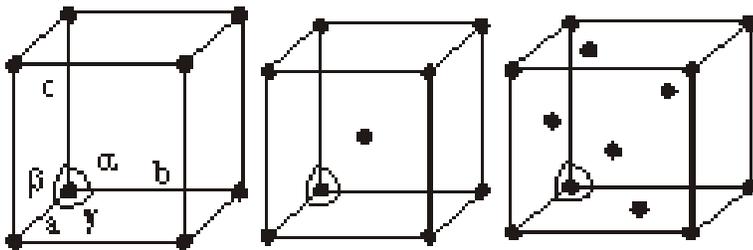
Simple or Primitive

Fig: cubic system

Examples: Pb, Hg, Ag, Po, Au, Cu, ZnS, diamond, KCl, CsCl, NaCl, Cu₂O, CaF₂ and alums etc.

Possible Bravais lattices:

- Primitive
- Body centered
- Face centered.



Simple or Primitive

Body centred

Face centred

Fig: Possible Bravais lattices of cubic system

2. Tetragonal System:

In tetragonal system, the three crystal axes are perpendicular to each other. Two of the three axis lengths are the same, but the third length is different, as shown in fig.

Lattice parameters:

- Two sides equal , $a=b \neq c$
- All three right angles; $\alpha= \beta= \gamma=90^0$

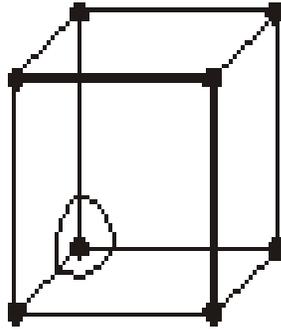


Fig: Tetragonal

Examples:

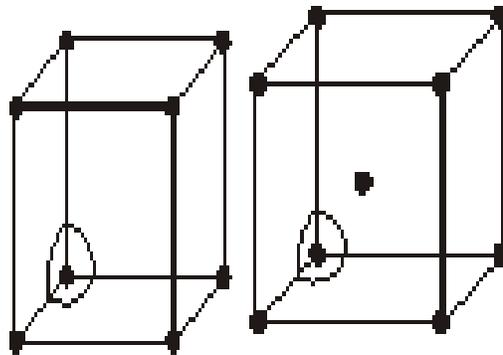
NiSO4

SnO2 and

Indium

Possible Bravais lattices:

- Primitive
- Body centered



Simple

Body centred

Fig: Possible Bravais lattices of tetragonal system

3. Orthorhombic Crystal System:

In orthorhombic crystal system, the crystal axes are perpendicular to each other and all the three axial lengths are of unequal lengths (different), as shown in fig.

Lattice parameters:

- All the sides different $a \neq b \neq c$
- All three right angles; $\alpha = \beta = \gamma = 90^\circ$

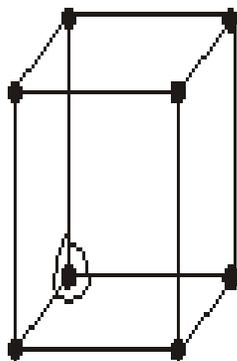


Fig: Orthorhombic

Examples: KNO_3 , BaSO_4 and MgSO_4 etc

Possible Bravais lattices:

- Primitive
 - Body centered
 - Base centered
 - Face centered.
-

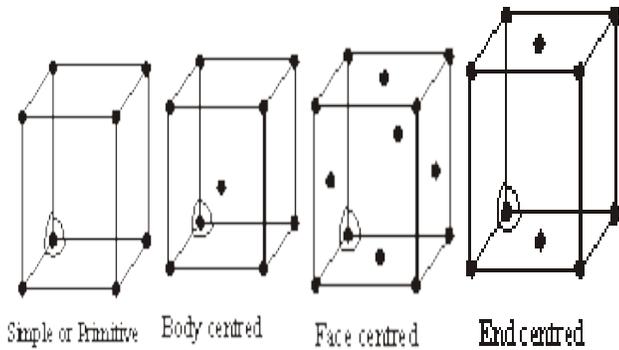


Fig: Possible Bravais lattices of orthorhombic system

4. Monoclinic Crystal system:

In monoclinic crystal system, two of the crystal axes perpendicular to each other, but the third obliquely inclined. The three axial lengths are different along the axes as shown in Fig.

Lattice Parameters:

- All the sides different $a \neq b \neq c$
- Two right angles, third arbitrary $\alpha = \beta = 90^\circ, \gamma \neq 90^\circ$

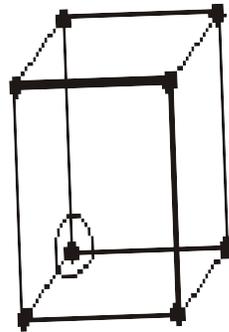


Fig: Monoclinic system

Examples: $\text{Na}_2\text{SO}_4, \text{FeSO}_4, \text{NO}_2\text{SO}_3$ etc

Possible Bravais lattices:

- Primitive
- Base centered

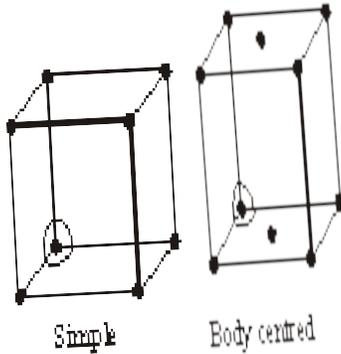


Fig: Possible Bravais lattice of monoclinic system

5. Triclinic crystal system:

In triclinic crystal system, all the three crystal axes are not perpendicular to each other. The axial lengths are also not equal (different) along the three axis, as shown in fig.

Lattice parameters:

- All three sides different $a \neq b \neq c$
- All three angles different $\alpha \neq \beta \neq \gamma \neq 90^\circ$

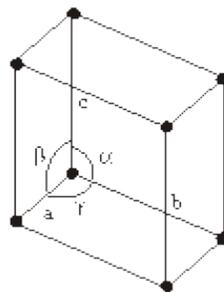


Fig: Triclinic system

Examples: CuSO_4 and $\text{K}_2\text{Cr}_2\text{O}_7$

Possible Bravais lattices:

- Primitive

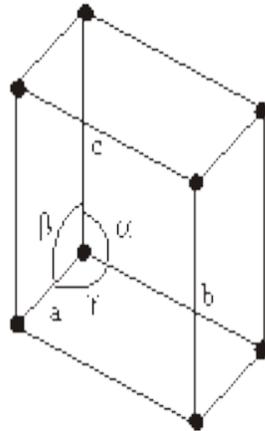


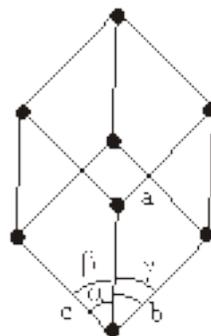
Fig: Possible Bravais lattice of triclinic system

6. Trigonal (rhombohedral) crystal system:

In trigonal crystal system, the three axes are inclined to each other at an angle other 90° . The three axial lengths are equal along three axes as shown in fig.

Lattice parameters:

- All the sides equal $a=b=c$
- All three angles equal, of arbitrary value $\alpha=\beta\neq 90^\circ$



Rhombohedral

Fig: Trigonal system

Examples: CaSO_4 , Bi, Sb, calcite etc.

Possible Bravais lattice:

- Primitive

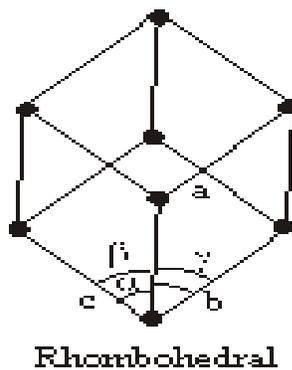


Fig: possible Bravais lattice of rhombohedral system

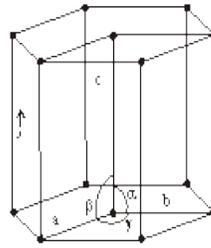
7. Hexagonal system:

In hexagonal crystal system, two of the crystal axes are 90° apart, while the third is perpendicular to both of them.

The axial lengths are the same along three axes that are 90° apart, but the axial length along the third axis is different as shown in figure.

Lattice parameters:

- Two sides equal, third arbitrary $a=b \neq c$
- Two right angles, third angles 120° , $\alpha=\beta=90^\circ$; $\gamma=120^\circ$



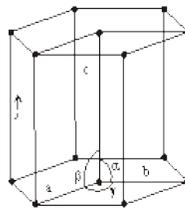
Hexagonal

Fig: Hexagonal system

Examples: Tourmaline, Quartz, AgI and SiO_2

Possible Bravais lattices:

- Primitive.



Hexagonal

Fig: possible Bravais lattice of hexagonal system

Structures of cubic system:

There are three types of structures possible in this system depending on the position of the latticepoint (atoms) in the unit cell fig.

- (1) Simple cubic (sc) (or) primitive



-
- (2) Body centered cubic (BCC) and
 - (3) Face centered cubic (FCC)

1. Simple cubic (SC) crystal structure:

- In this structure; there are only 8 atoms one at each corner of the cube.
- The corner atoms touch each other along the edges as shown in fig.
- Each and every corner atom is shared by 8 adjacent unit cells.

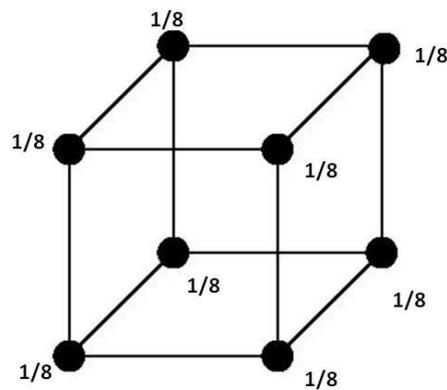
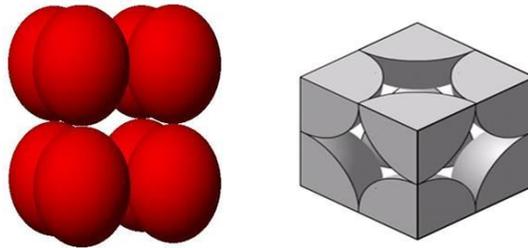


Fig: Simple cubic structure

(B) Body-centered cubic structure (BCC):

- In this case, we have two types of atoms fig,(i) corner atoms and (ii) Body centered atoms i.e., there are 8 corner atoms, one at each corner of the unit cell and one body centered atom at the centre of the unit cell as shown in fig.
-

- In this structure, the corner atoms do not touch each other. But each corner atom touches the body centered atom along the body diagonal as shown in fig.
- Each and every corner atom is shared by 8 adjacent unit cells and the body centered atom is shared by that particular unit cell alone and is not shared by any other unit cell.

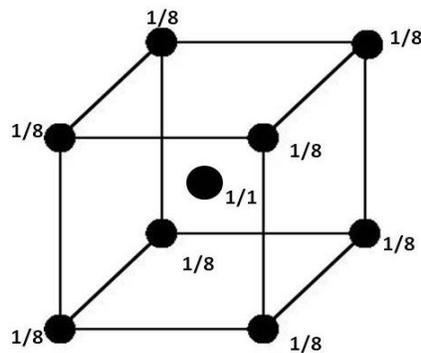
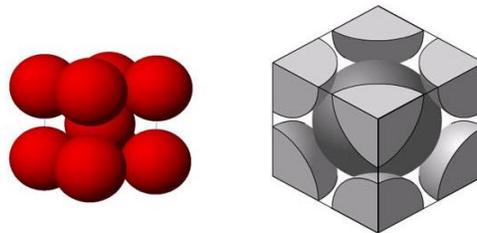


Fig: Body centered cubic structure

(C) Face-centered cubic structure (FCC):

- In this case, we have two types of atoms viz (i) Corner atoms and (ii) Face centered atoms, i.e. there are 8 corner atoms, one at each corner of the unit cell and six atoms at the centers of six faces of unit cell as shown in Fig.
- In this structure, the corner atoms do not touch each other. But each corner atom touches the face centered atoms along the diagonal of the face of the cube as shown in fig.
- Each and every corner atom is shared by adjacent unit cells, and each face centered atom is shared by only two unit cell, which lie on either side of the atom.

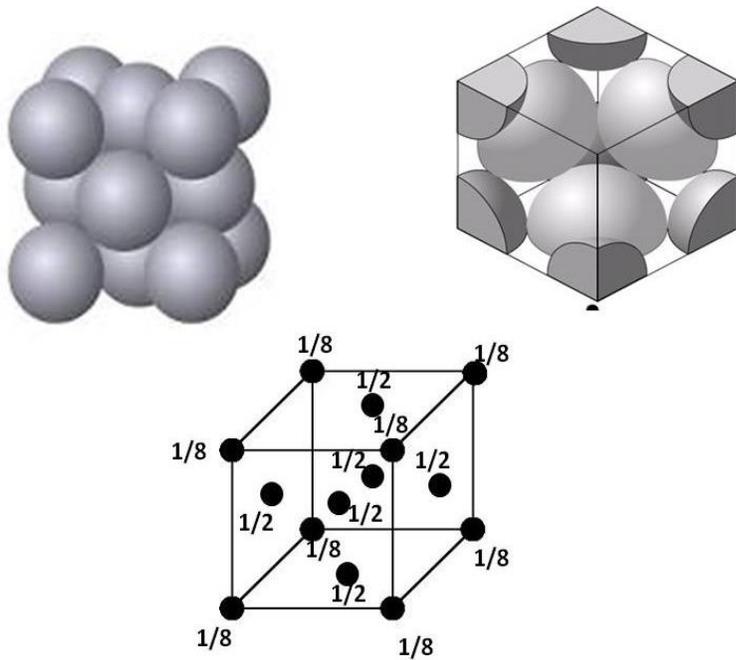


Fig :Face-centered cubic structure (FCC)

Parameters determining the crystal structure of materials:

Let us discuss some of the important parameters which are used to describe the crystal structure.

1. Number of atoms per unit cell (or) Effective number:

The total number of atoms present in (or) shared by a unit cell is known as the number of atoms per unit cell.

2. Co-ordination number:

It is the number of nearest neighboring atoms to a particular atom.

3. Atomic radius:

Atomic radius is defined as half of the distance between any two nearest neighbors which have direct contact with each other, in a crystal of a pure element. It is usually expressed in terms of the cube edge 'a'.

4. Atomic packing factor (packing density):

Atomic packing factor is defined as the ratio between the volume occupied by the total number of atoms per unit cell (v) to the total volume of the unit cell (V).

$$\text{i.e. APF} = \frac{\text{Volume occupied by the total no. of atoms per unit cell}}{\text{Total volume of the unit cell}} = V/V$$

$$= \frac{\text{No. of atoms per unit cell} \times \text{volume of one atom}}{\text{Total volume of the unit cell}}$$

5. Void space or interstitial space:

The void space in the unit cell is the vacant space left unutilized in the unit cell. It is equal to $(1 - \text{APF})$. It is often expressed as percentage.

$$\text{Void space} = (1 - \text{APF}) \times 100.$$

6. Density of solid:

The density of a crystalline solid is defined as the ratio of the mass of the unit cell and the volume of a unit cell.

$$\text{Density (P)} = \frac{\text{Mass of unit cell}}{\text{volume of unit cell}}$$

Let us discuss all the above parameters one by one for a simple cubic structure.

Number of atoms per unit cell:

Definition:

The total number of atoms present in (or) shared by a unit cell is known as number of atoms per unit cell.

Note: This number depends on the number of corner atoms, body centered atom, face centered atom, which varies from structure to structure.

Let us evaluate the number of atoms per unit cell for the three systems.

(a) Simple cubic structure:

Figure (1) shows the unit cell of simple cubic structure. In this case, there are only 8 atoms, one at each corner of the cube (or) the unit cell.

But in actual crystal, each and every corner atom is shared by 8 adjacent unit cells. In other words, we can say that each corner atom contributes only $1/8^{\text{th}}$ of its part to a single unit cell.

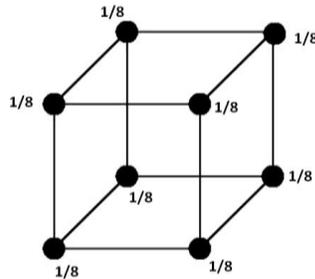


Fig: Simple cubic structure

i.e., total number of atoms per unit cell = $\frac{1}{8} \times$ total number of corner atoms
 $= \frac{1}{8} \times 8 = 1$

Therefore, the number of atoms per unit cell in S.C is one. Thus, *simple cubic is a primitive unit cell.*

(b) Body centered cubic structure:

In this case, we have two types of atoms namely

- (i) Corner atoms (ii) Body centered atom

i.e., there are 8 corner atoms, one at each other corner of the unit cell and one body centered atom at the centre of the unit cell as shown in fig.

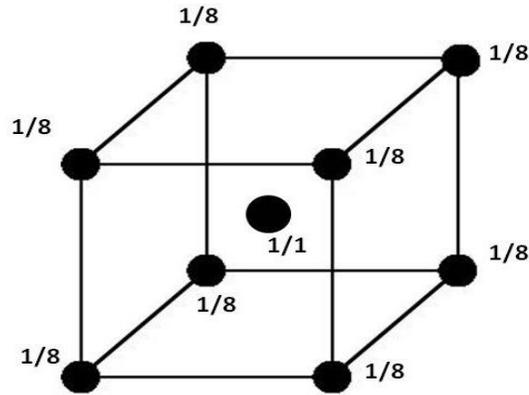


Fig: Body centered cubic structure

(i) Number of corner atoms per unit cell

Each and every corner atom is shared by 8 adjacent unit cells.

The total number of corner atoms per unit cell = $\frac{1}{8} \times 8 = 1$

(ii) Number of body centered atoms per unit cell

The body centered atom is shared by that particular unit cell alone and is not shared by any other unit cell.

The number of body centered atoms per unit cell = $1/1 \times 1 = 1$

Total no. of atoms = Total no. of corner atoms per unit cell in Bcc + Total no. of body centered atoms per unit cell.

$$= 1 + 1 = 2$$

Therefore, the number of atoms per unit cell in BCC is two. Thus, *BCC is a non-primitive unit cell.*

(C) Face-centered cubic structure:

In this case, we have two types of atoms namely

- (i) Corner atoms
- (ii) Face centered atoms.

i.e. there are 8 corner atoms, one at each corner of the unit cell and six atoms at the centers of six faces of unit cell as shown in fig.

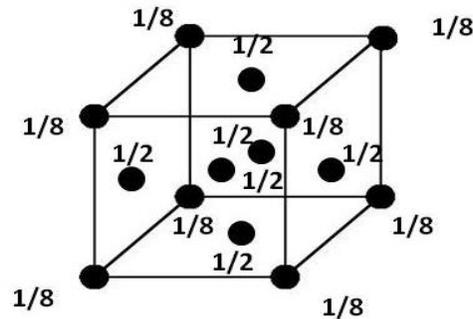


Fig :Face-centered cubic structure (FCC)

(i) Number of corner atoms per unit cell:

Each and every atom is shared by 8 adjacent unit cells. The total number of corner atoms per unit cell = $\frac{1}{8} \times 8 = 1$.

(ii) Number of face centered atoms per unit cell

Each face centered atom is shared by only two unit cells, which lie either side of the atom (similarly we have six face centered atoms in an unit cells)

The total number of centered atoms per unit cell
 $= \frac{1}{2} \times 6 = 3$

The total no. of atoms per unit cell in FCC = Total no. of corner atoms per unit cell + total no. of facecentered atoms per unit cell
 $= 1 + 3 = 4$

Therefore, the number of atoms per unit cell in FCC is four. Thus, **FCC is a non-primitive unit cell.**

Coordination Number:

Definition:

Coordination Number is the number of nearest neighboring atoms to a particular atom which are direct contact with each other.

The Coordination Number for the three types of cubic crystal structure can be calculated as follows.

(a) Simple Cubic Structure:

In this case, there are only 8 atoms, one at each corner of the cube (or) unit cell. For a particular atom say 'C' atom, there are 4 nearest neighboring atoms, i.e. atoms 1,2,3 and 4 on its own plane and there are 2 more nearest atoms i.e., atom-5 directly above the plane and atom-6 directly below the plane as shown in figure.

Therefore,

The total Number of neighboring atoms to particular atom (C) = $4+1+1=6$

Hence, the coordination for SC = 6

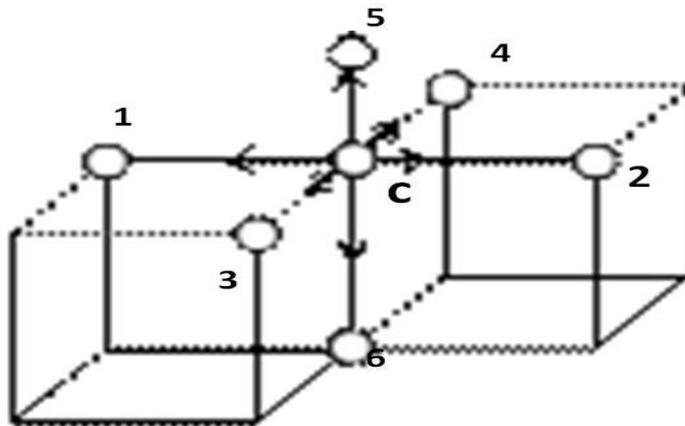


Fig: Co- ordination number in Simple cubic structure

(b) Body centered cubic Structure:

In this case, we have two types of atoms namely 1. Corner atoms 2. Bodycentered atoms i.e., there are 8 corner atoms, one at each corner of the unit cell and one body centered atom at the center of the unit cell as shown in figure.

The corner atoms do not touch each other. But each corner atom touches the body centered along the body diagonal. Thus for particular atom 'C' at the body centre obviously, there are 8 nearest neighbor (corner atoms).

Hence, the coordination for BCC =8

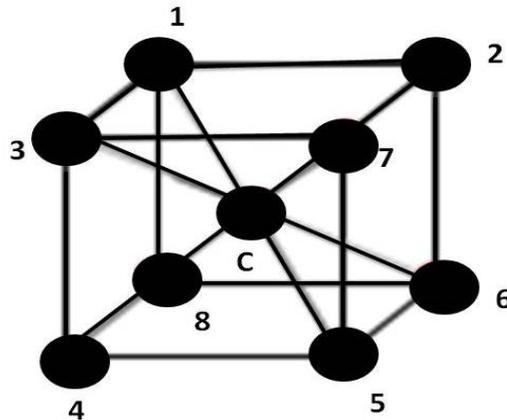


Fig: Co- ordination number in Base centered cubic structure.

(C). FaceCentered Cubic Structure (FCC):

In this case, we have 2 types of atoms namely, 1. Corner atoms and 2. Face centered atoms. There are 8 corner atoms, one at each corner of the unit cell and six atoms at the centers of six faces of unit cells as shown in figure.

Let us consider 2 unit cells one above the other if the reference atom 'C' taken as the face centered atom then it is surrounded by 4 corner atoms on the plane, and 4-face centered atoms above the plane and 4-face centered atoms below the plane as shown figure.

Therefore the coordination number for FCC = 4+4+4=12

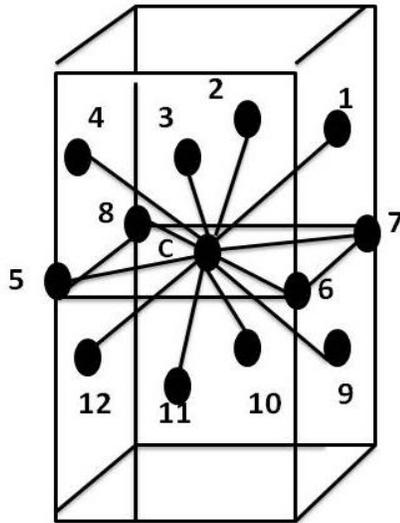


Fig: Co- ordination number in Face centered cubic structure.

Atomic Radius:

Definition:

Atomic radius is defined as half of the distance between any two nearest neighbor atoms which have direct contact with each other. It can be expressed in terms of cube edge **a** and vice versa. All the atoms are assumed to be spherical in shape.

For the three cubic structures it can be calculated as follows.

(a) Simple Cubic Structure:

In simple cubic (SC) structure the corner atoms touch other along the edges as shown in fig. Let us consider one offace of the simple cubic structure as shown in fig (2).

Hence the nearest neighbor distance is $2r=a$

$$\therefore \text{Atomic radius } r = \frac{a}{2}$$

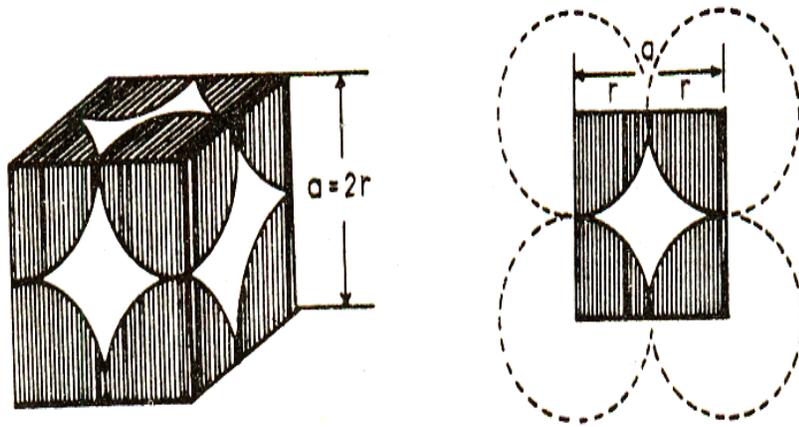


Fig: simple cubic structure

(b) Body centered cubic structure (BCC):

In BCC structure, the corner atoms do not touch each other. But each corner atom touches the body centered atom along the body diagonal as shown in fig. Therefore the two corner atoms (**A and D**) situated at the opposite ends can be joined by drawing a diagonal as shown in fig. Thus, the diagonal of the cube **AD** is $4r$.

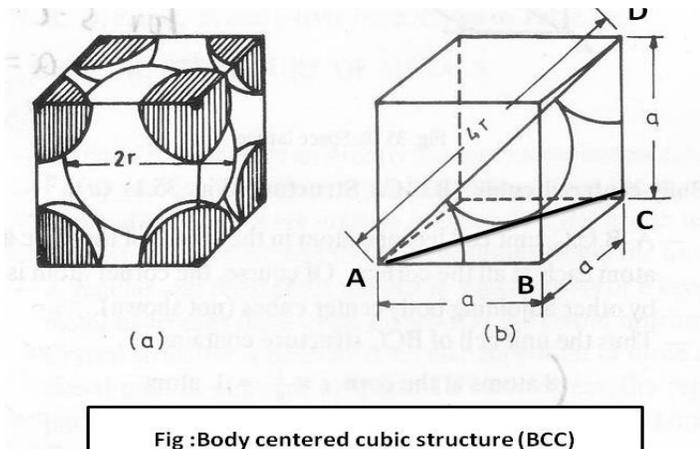


Fig :Body centered cubic structure (BCC)

But, from the geometry of the fig; we can write

$$(AD)^2 = (AC)^2 + (CD)^2$$

$$= (AB)^2 + (BC)^2 + (CD)^2$$

[From fig ; $AC^2 = AB^2 + BC^2$ and $AB = BC = CD = a$]

$$= a^2 + a^2 + a^2$$

$$= 3a^2$$

(Or) $AD = a\sqrt{3}$; But $AD = 4r$

$$4r = a\sqrt{3}$$

$$r = \frac{a\sqrt{3}}{4}$$

\therefore **Atomic radius $r =$**

$$\frac{a\sqrt{3}}{4}$$

(C) Face-centered cubic structure (FCC):

In FCC structure the corner atoms do not touch each other. But each corner atom touches the face centered atoms along the diagonal of the face of the cube as shown in fig. Therefore, the two corner atoms (**A and C**) situated at the opposite ends of the same face can be joined by drawing a diagonal as shown in fig. Thus, the diagonal of the cube **$AC = 4r$** .

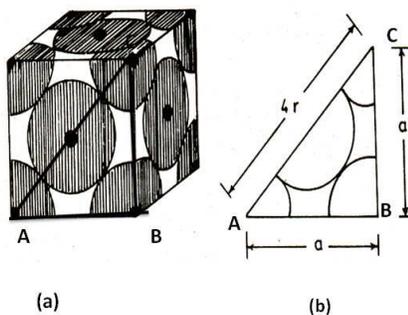


Fig :Face centered cubic structure (FCC)

From the geometry of the figure, we can write

$$(AC)^2 = (AB)^2 + (BC)^2$$

$$= a^2 + a^2$$

$$AC^2 = 2a^2$$

$$AC = a\sqrt{2} ; \text{ But } AC = 4r$$

$$4r = a\sqrt{2}$$

$$r = \frac{a\sqrt{2}}{4}$$

$$\therefore \text{ Atomic radius } r = \frac{a\sqrt{2}}{4}$$

4. Atomic packing factor (APF) or packing density:

Definition:

Atomic packing factor is defined as the ratio of the volume occupied by the total number of atoms per unit cell to the total volume occupied by the unit cell.

$$\text{i.e., APF} = \frac{\text{Volume occupied by the total no. of atoms per unit cell}}{\text{Total volume of the unit cell}} = \frac{V}{V}$$

$$= \frac{\text{No. of atoms per unit cell} \times \text{volume of one atom}}{\text{Total volume of the unit cell}}$$

The packing factor (or) packing density of the three cubic systems can be calculated as follows.

(a) Simple cubic structure (SC):

In simple cubic,

The number of atoms per unit cell = 1

Volume of 1 atom (spherical) = $\frac{4}{3} \pi r^3$

\therefore Volume occupied by the total no. of atoms per unit cell (v)

= No. of atoms per unit cell x volume of one atom

$$= 1 \times \frac{4}{3} \pi r^3$$

We know the radius of atom in simple cubic $r = \frac{a}{2}$

$$= 1 \times 1 \times \frac{4}{3} \pi \left(\frac{a}{2}\right)^3$$

Volume of the unit cell (V) = length x breadth x height

We know that for a cubic system, length=breadth=height=a

$$\therefore V = a \times a \times a$$

$$= a^3$$

$$\therefore \text{A.P.F} = \frac{v}{V} = \frac{1 \times \frac{4}{3} \pi \left(\frac{a}{2}\right)^3}{a^3}$$

$$= \frac{\pi}{6}$$

$$= 0.052$$

$$\therefore \text{APF} = \frac{\pi}{6} = 0.052$$

And Void space = (1-APF) x 100

$$= (1-0.052) \times 100$$

$$= 48\%$$

Therefore, we can say that 52% volume of the unit cell of sc is occupied by atoms and remaining 48% volume is vacant. Thus, the packing density 52%

Since the packing density is very low, SC has loosely packed structure.

(b) Body-centered cubic Structure:

In body-centered cubic structure,

The number of atoms per unit cell=2

$$\text{Volume of one atom (spherical)} = \frac{4}{3} \pi r^3$$

∴ Volume occupied by the total no. of atoms per unit cell (v) =

No. of atoms per unit cell x Volume of one atom

$$= 2 \times \frac{4}{3} \pi r^3$$

$$= 2 \times \frac{4}{3} \pi \left[\frac{a\sqrt{3}}{4} \right]^3$$

$$= \frac{8\pi}{3} \left[\frac{a^3 \times 3\sqrt{3}}{4 \times 4 \times 4} \right]$$

$$v = \pi a^3 \frac{\sqrt{3}}{8}$$

Volume of the unit cell for a cubic system (V) = a^3

$$\therefore \text{APF} = \frac{v}{V} = \frac{\pi a^3 \sqrt{3}}{8 a^3}$$

$$= 0.68$$

$$= \frac{\pi\sqrt{3}}{8}$$

$$\therefore \text{APF} = \frac{\pi\sqrt{3}}{8} = 0.68$$

And Void space = $(1 - \text{APF}) \times 100$

$$= (1 - 0.68) \times 100$$

$$= 32\%$$

Therefore, we can say that 68% volume of the unit cell of BCC is occupied by atoms and remaining 32% volume is vacant. Thus, the packing density is 68%. Since the packing density is very low, SC has a loosely packed structure.

(C) Face-centered cubic structure:

In face centered cubic structure,

The number of atoms per unit cell = 4

$$\text{Volume of one atom (spherical)} = \frac{4}{3} \pi r^3$$

\therefore Volume occupied by the total no. of atoms per unit cell (V) = No. of atoms per unit cell \times volume of one atom

$$= 4 \times \frac{4}{3} \pi r^3$$

We know that the radius of atom in FCC is $r = \frac{a\sqrt{2}}{4}$

$$\therefore V = 4 \times \frac{4}{3} \pi \left(\frac{a\sqrt{2}}{4}\right)^3$$

$$= \frac{4 \times 4 \pi}{3} (a^3 2\sqrt{2} / 4 \times 4 \times 4)$$

$$= \pi a^3 \sqrt{2} / 6$$

Volume of the unit cell for a cubic system (V) = a^3

$$\therefore \text{APF} = \frac{V}{V} = \frac{\pi a^3 \sqrt{2}}{a^3}$$

$$= \pi \frac{\sqrt{2}}{6}$$

$$= 0.74$$

$$\therefore \text{APF} = \frac{\pi \sqrt{2}}{6} = 0.74$$

And Void space = $(1 - \text{APF}) \times 100$

$$= (1 - 0.74) \times 100$$

$$= 26\%$$

Therefore, we can say that 74% volume of the unit cell of FCC is occupied by atoms and remaining 26% volume is vacant. Thus, the packing density 74%. Since the packing density is very high, FCC has closely packed structure.

Density of a crystalline solid:

The density of a crystalline solid is defined as the ratio of mass of the unit cell and the volume of a unit cell.

$$\text{Density (P)} = \frac{\text{Mass of unit cell}}{\text{Volume of unit cell}}$$

Let us consider a cubic unit cell of the following parameters.

- The lattice constant of the cell = a
- The number of atoms per unit cell = n
- The atomic weight of crystalline substance = M
- The density of unit cell = ρ
- The Avogadro's number = N
- The volume of unit cell = a^3

$$\text{Mass of each atom in unit cell} = \frac{M}{N}$$

If there are 'n' no. of atoms in a unit cell, then the mass of the cubic unit cell = $\frac{nM}{N}$

$$\rho = \frac{\frac{nM}{N}}{a^3} = \frac{nM}{Na^3}$$

$$\therefore \rho = \frac{nM}{Na^3}$$

$$\text{And } a^3 = \frac{nM}{N\rho}$$

$$\boxed{a = \left(\frac{nM}{N\rho}\right)^{1/3}}$$

The above expression represents the expression for lattice constant.

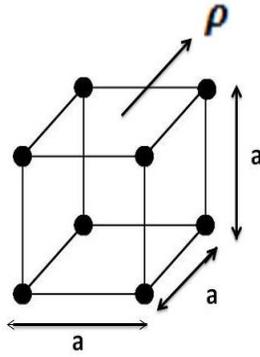


Fig:Cubic unit cell

The density for the three types of cubic crystal structure can be calculated as follows,

(a) **Simple Cubic structure (SC):**

For SC; $n=1$

$$\therefore \rho = \frac{M}{Na^3}$$

(b) **Body-centered cube (BCC)**

For BCC $n=2$

$$\therefore \rho = \frac{2M}{Na^3}$$

(C) **Face centered cubic Structure (FCC)**

For FCC; $n=4$

$$\therefore \rho = \frac{4M}{Na^3}$$
