Annamacharya Institute of Technology and Sciences, Tirupati
(Autonomous)

Engineering Physics Material

Subject Code: 20ABS9903
(AK20 Regulation)
(Common to CE and ME)

Course Outcomes:

1. Explain physics applied to solve engineering problems
2. Apply the principles of acoustics in designing of buildings
3. Explains the applications of ultrasonic in various engineering fields
4. Apply electromagnetic wave propagation in different Optical Fibers and the concepts of lasers in various applications.
5. Explains the concepts of dielectric and magnetic materials and Identify the sensors for various engineering applications

Unit-I

Mechanics

Introduction:

The dot product of two vectors is the product of magnitude of two vectors and cosine of angle between them.

$$\bar{A} \cdot \bar{B} = |\bar{A}|\,|\bar{B}|\cos\theta$$

Examples:

A.) Work done is the dot product of force and displacemen

$$W = F.S \quad \text{or } W = \int F.ds$$

B.) Potential difference between two points in an electric field

$$V = E.dl \text{ or } V = \int E.dl$$

Vector product or cross product:

- Cross product of two vectors is defined as a vector having magnitude equal to the product of magnitudes of two vectors and the sine of angle between them and its direction is perpendicular to the plane containing two vectors.
- Direction is taken by right hand convention.

Properties:

- Vector product is not commutative, i.e., $\overline{A} \times \overline{B} \neq \overline{B} \times \overline{A}$
- 2. It follows distributive law, i.e., $\overline{A} \times (\overline{B} + \overline{C}) = \overline{A} \times \overline{B} + \overline{A} \times \overline{C}$
- 3. Vector product of a vector by itself is equal to null vector.

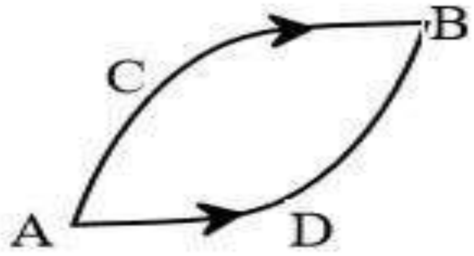
$$\overline{A} \times \overline{A} = 0$$

- 4. Vector product of perpendicular vectors is equal to product of magnitudes of two vectors in perpendicular direction to plane of vectors.
- $i \times i = j \times j = k \times k = 0$ and
- $j \times k = - k \times j = i$ and
- $k \times i = - i \times k = j$

Conservative forces:

- If the work done by a force in displacing from one point to another point is independent of the path followed then the force is said to be conservative force.

- Consider a particle moving from A to B by a force F as shown in the figure. Work done by the force,



Non conservative force:

Definition of non-conservative force:

If the work done by a force in displacing a particle from one point to another is dependent of the path followed the particle, then the force is said to be non-conservative

Example: friction, air resistance etc

Gradient of a scalar: Gradient of a scalar at a point is a vector with magnitude equal to the maximum rate of increase of scalar and whose direction is normal to level surface at that point

Grad φ.

- If the work done by a force in displacing a particle from one point to another is independent of path followed by the particle, then in a conservative force field
- Where is the (conservative) force acting on a particle.
- Applying stoke 's theorem for a conservative force field we get
- The work done by the conservative force given by

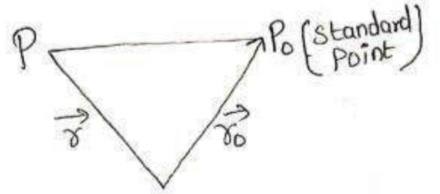


Figure 3

Angular momentum:

- Let us consider a partial of mass ‘m’ at ‘ p ‘ (figur4) position vector with respect to origin ‘ o ‘ be ‘r’
- Let its leaner momentum be P=Mv .The angular momentum ‘L’of the particle with respect to a fixed point O is defined as the vector product of the position vector and the linear momentum.
- The angular momentum also called moment of momentum ,is a vector quantity and its scalar magnitude is given by, L=rp

Where is the angle between r and p.

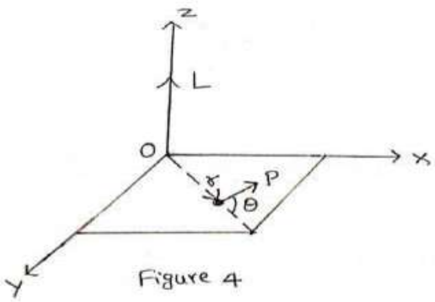


Figure 4

Torque:

- Let a force F be acting on particle P having position vector ‘r’ with respect to the origin of an inertial reference frame as shown in figure 5.
- The torque acting on the particle is defined as the vector product of force and position vector . That is ,
- and its scalar magnitude is given by

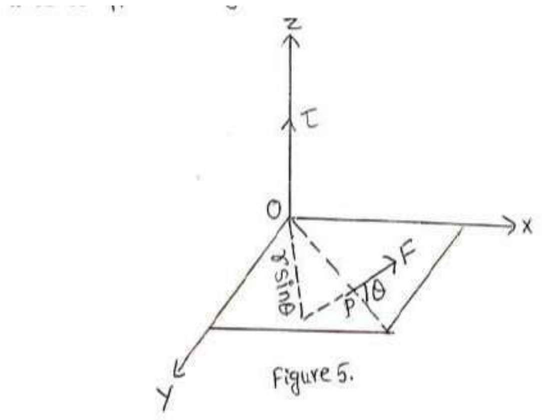


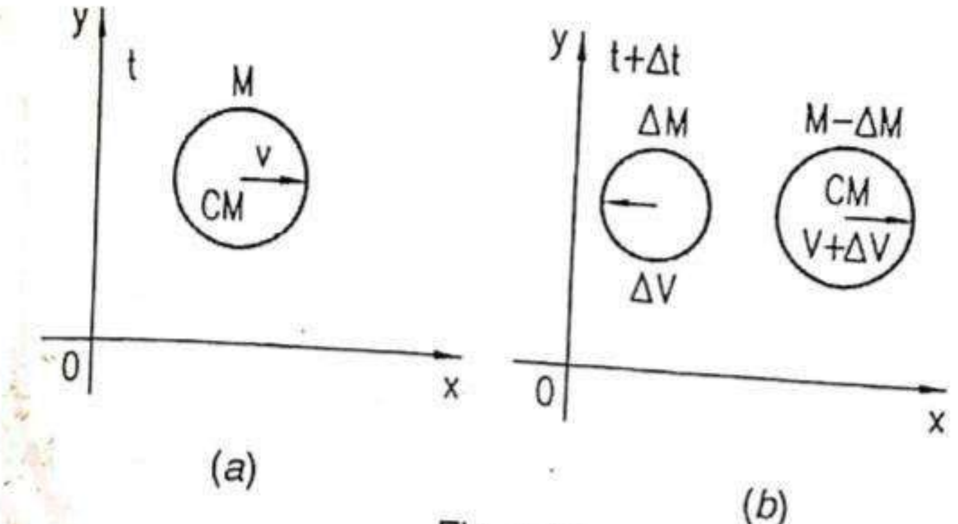
Figure 5.

- **Conservation of momentum (Linear momentum)**

- Linear momentum of bodyis defined as the product of its mass and velocity quantity so momentum is a vector quantity and denoted by P. Thus if a particle of mass ‘m’ is moveing with velocity ‘v’ its momentum P is given by ,
- P=mv _____________(1)
- Let be particle be displaced from position to A position B position under the influence of a conservation force .The amount of work done on the particle by the definition of kinetic energy and potential energy are varies
- But E=KE+PE

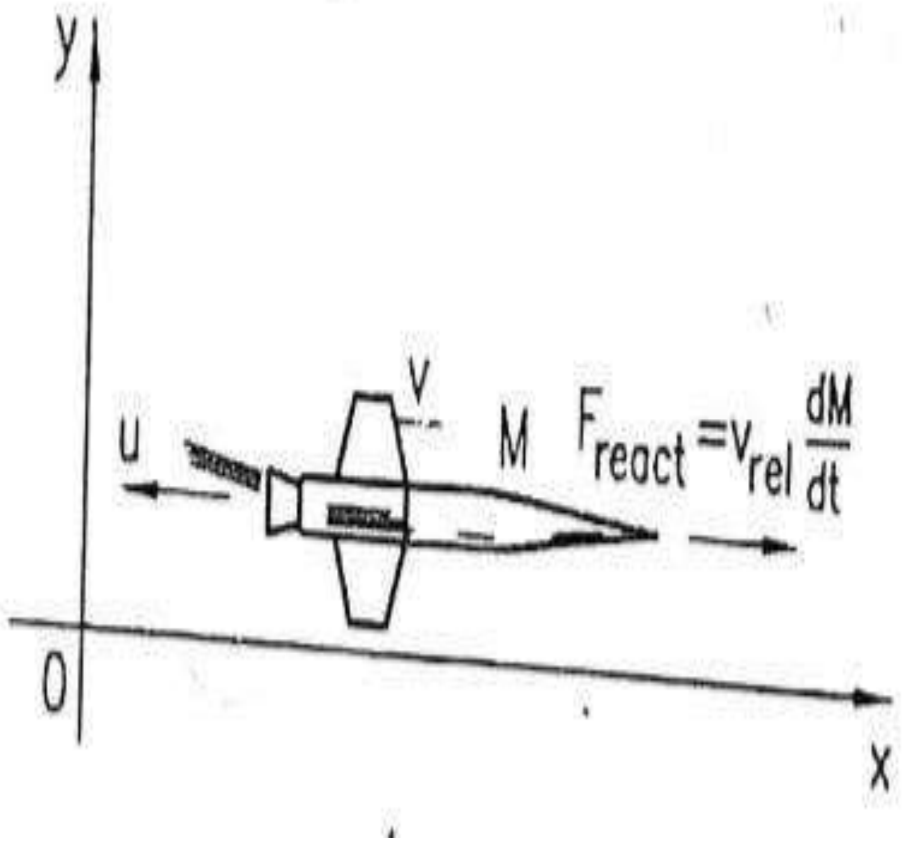
Motion of variable mass system: Motion of a rocket:

As rocker in which the gases are continuously exhausted from a jet and thus while moving mass of rocket continuously decreases consider a system of total mass ‘M’ moving with a velocity ‘V’ in a particular reference frame ,under an external force F ext .after a time interval of the system has changed to as shown figure 4.16(b) i.e a mass is ejected and this ejected mass moves with a velocity ‘u’ in direction opposite to the remaining.



(a) (b)

Fig. 4.16



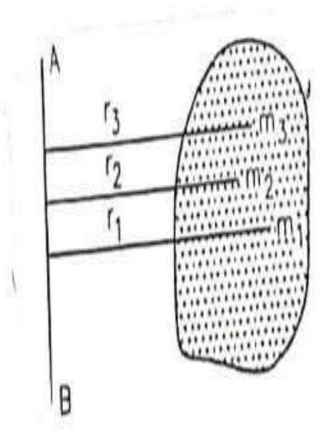
- Consider a body of mass “M” composed of a large number of small particles of masses m_1, m_2,m_3 ---------- at distances r_1, r_2, r_3 ----------etc. from the axis AB about which the body is rotating (fig 5.5). the moment of inertia of particle of mass m_1 will be m_1r^2 and that of m_2 will be m_2r^2 -----hence the moment of inertia of the body ‘I’ about the axis AB is equal to sum of the moment of inertia of all the particles about the axis AB. i e

$I = m_1r_1^2 + m_2r_2^2 + \text{---------} + m_nr_n^2$

or

$I = MK^2$

Where M is the mass of the body and K is the radius gravitation of the body about axis AB.



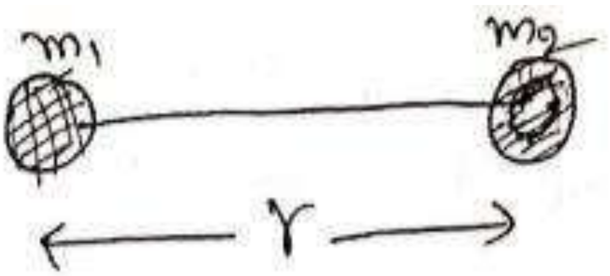
Radius of gyration (k):

Definition of radius of gyration: The effective distance of the all particles of a body it axis of rotation is called of gyration. (OR)

The radius of gyration is defined as the perpendicular distance from the axis of rotation and the point where the whole mass of the body were to be concentrated

Gravitational force:

- Newton discovered the law of universal gravitation and this law states that every particle of matter in this universe attracts every other particle and this force of attraction is directly proportional to the product of their masses and inversely proportional to the square of the distance between them



Kepler’s laws and proof of Kepler’s laws of planetary motion:

Kepler’s laws of planetary motion:

To understand the solar system, kepler found important regularities in the motion of planets and stated the following three laws concerning the motion of planets around the sun.

First law:

“All the planets move in an elliptical having the sun as one focus”. This law is also called law of orbits.

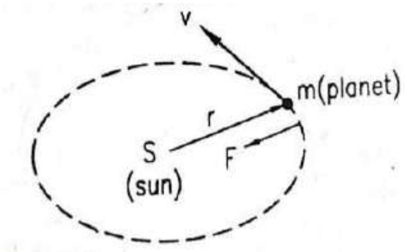
Second law :

“A line joing any planet to the sun sweeps out equal areas in equal times” This law is also called law of area.

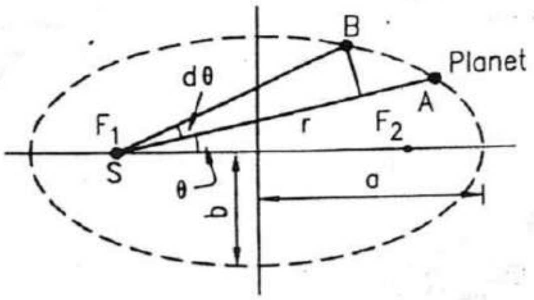
Third law:

The square of time period of any planet about the sun is proportional to sun the cube of the planet’s mean distance from the sun. This law is also called law of periods.

Proof of kepler’s first law planetary motion :



Consider the motion of a planet of mass ‘m’ around the sun as shown in figure 6.17. let s be the center of the sun and A that of the planet in its orbit. Let r be the radius of the vector of the planet with respect to the sun at force F_1(figure).



Unit II : Acoustics and Ultrasonics

Introduction to acoustics

- Acoustics is a branch of science of sound and deals with origin, propagation and auditory sensation of sound.
- The study of sound plays a very important role in various branches of engineering and has developed to such a level that it has become an independent engineering branch known as 'Acoustic Engineering' or Sound engineering'.
- The design of buildings, auditoriums, music halls, building halls, recording rooms etc are called 'Architectural acoustics'.
- Architectural acoustics deals with the behaviour of sound waves in closed spaces and their design to give the sound effects.

Musical sound has following 3 characteristics

- Pitch or Frequency
- Quality or Timbre
- Intensity or Loudness

The reflection of sound in an enclosed space leads to two important factors

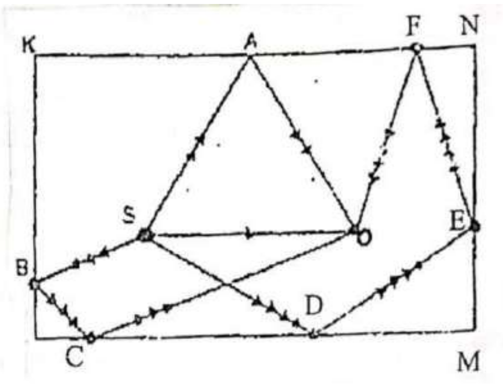
(1) Echo

(2) Reverberation

(1) Echo :

Echo is defined as 'a repeated sound that is caused by the reflection of sound waves from a surface'.

Reverberation : Reverberation is defined as ' the persistence of the sound in a closed room as a result of multiple reflections of sound even after the source of sound is switched off '.



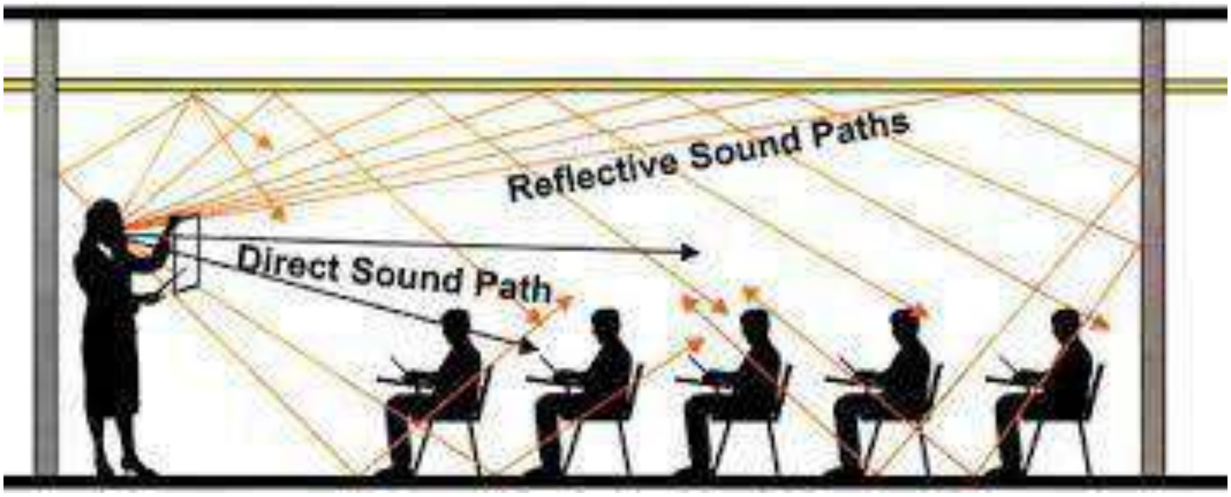
KLMN – Enclosed surface
S – Source of sound
O – Observer or listener
A,B,C,D,E,----different points in a closed surface

Reverberation Time

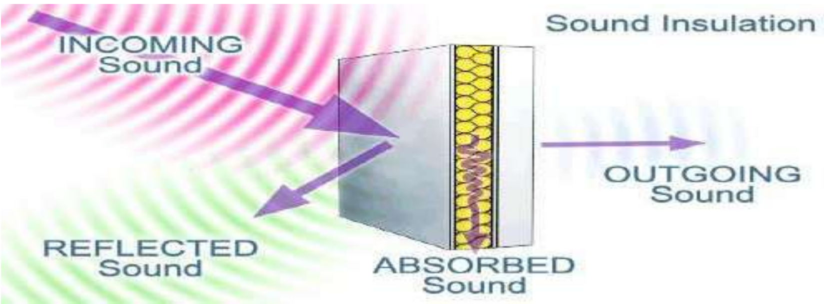
Reverberation time is defined as ‘the time taken by the sound in a room to fall from its average intensity to inadudiability level’.

(OR)

The time that the sound waves takes to fall in intensity to its one millionth of its original intensity after the source is stopped in a closed enclosure is called ‘reverberation time’.



2.1.2.2.Sound absorption:



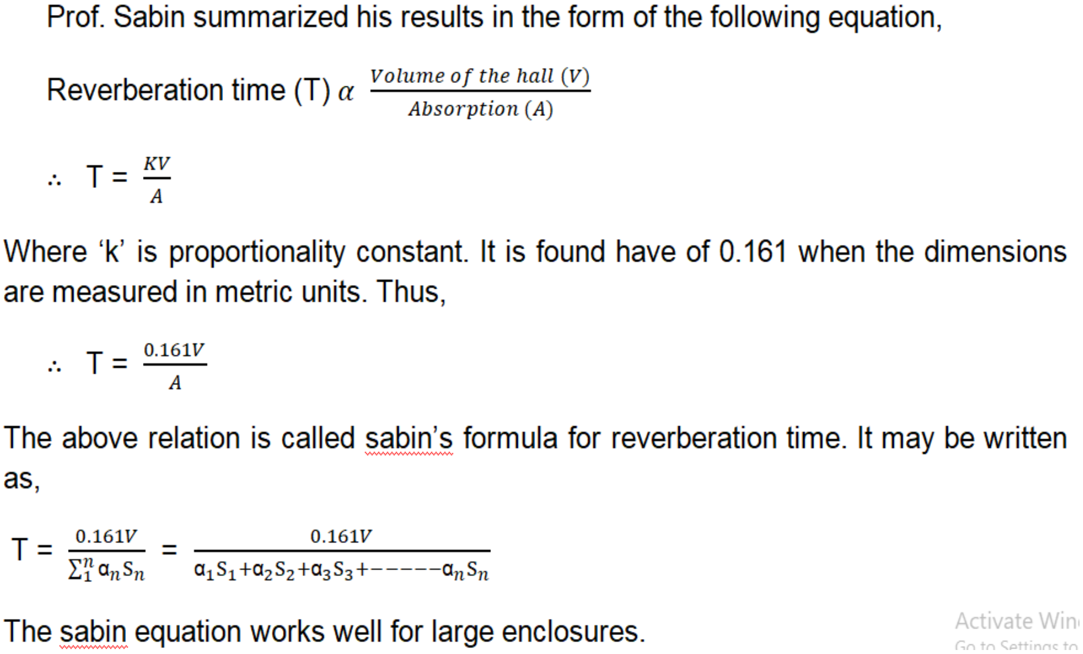
The property of a surface by which the sound energy is converted into other form of energy is called ‘sound absorption’.

2.1.2.2.1. Absorption coefficient:

The effectiveness of a surface in absorbing sound energy is expressed with the help of absorption coefficient.

The unit of absorption is an open window unit (O.W.U) which is termed as ‘sabin’.

2.1.3. Sabin’s formula for reverberation time:



Prof. Sabin summarized his results in the form of the following equation,

$$\text{Reverberation time (T)} \ \alpha \ \frac{Volume\ of\ the\ hall\ (V)}{Absorption\ (A)}$$

$$\therefore \quad T = \frac{KV}{A}$$

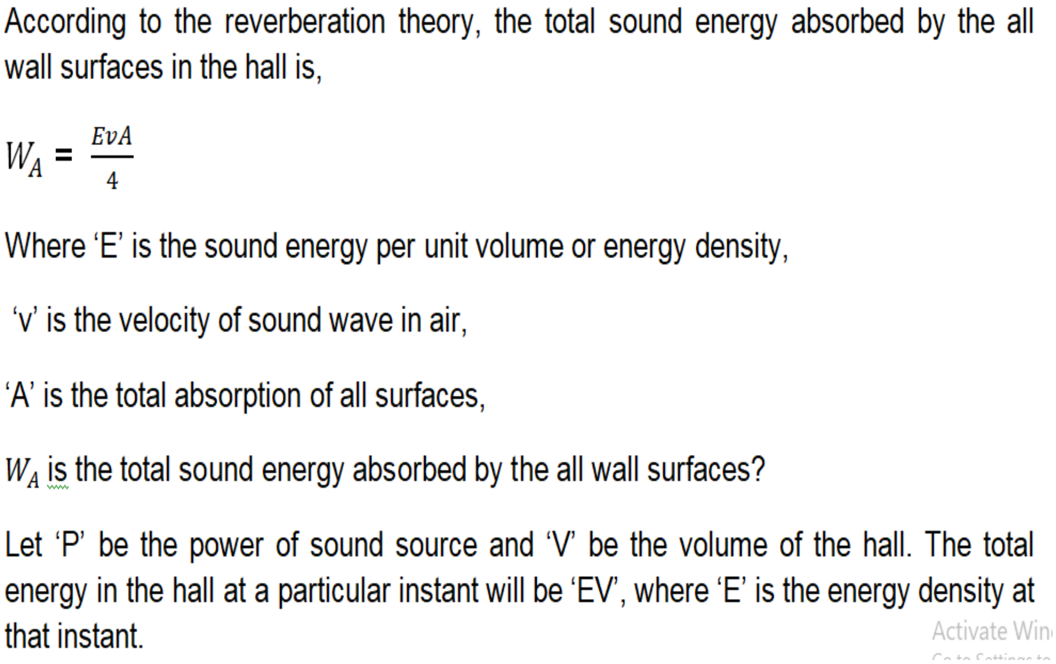
Where ‘k’ is proportionality constant. It is found have of 0.161 when the dimensions are measured in metric units. Thus,

$$\therefore \quad T = \frac{0.161V}{A}$$

The above relation is called sabin’s formula for reverberation time. It may be written as,

$$T = \frac{0.161V}{\sum_1^n \alpha_n S_n} = \frac{0.161V}{\alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + - - - - - \alpha_n S_n}$$

The sabin equation works well for large enclosures.



According to the reverberation theory, the total sound energy absorbed by the all wall surfaces in the hall is,

$$W_A = \frac{EvA}{4}$$

Where ‘E’ is the sound energy per unit volume or energy density,

‘v’ is the velocity of sound wave in air,

‘A’ is the total absorption of all surfaces,

W_A is the total sound energy absorbed by the all wall surfaces?

Let ‘P’ be the power of sound source and ‘V’ be the volume of the hall. The total energy in the hall at a particular instant will be ‘EV’, where ‘E’ is the energy density at that instant.

Rate of growth of sound energy in the hall = $\frac{d\,(EV)}{dt}$ = V $\frac{dE}{dt}$

At any instant,

Rate of growth of energy in the hall = Rate of supply of energy from the source-rate of absorption of all surfaces in the hall.

$$V\frac{dE}{dt} = P - \frac{EvA}{4}$$

$$\frac{dE}{dt} + \frac{vA}{4V}E = \frac{P}{V}$$

Putting $\frac{vA}{4V}$ = α, the above equation can be written as,

Multiplying with $e^{\alpha t}$ on both sides of the above equation, we get

$$\left(\frac{dE}{dt} + \alpha E\right) e^{\alpha t} = \frac{4P}{vA}\alpha e^{\alpha t}$$

$$\frac{d}{dt}\,[Ee^{\alpha t}] = \frac{4P}{vA}\alpha e^{\alpha t}$$

Integrating on both sides we get,

$$\int \frac{d}{dt}\,[\mathrm{E}e^{\alpha t}]\,\mathrm{dt} = \int \frac{4P}{vA}\alpha e^{\alpha t}\,\mathrm{dt}$$

$$\mathrm{E}e^{\alpha t} = \frac{4P}{vA}e^{\alpha t} + k \qquad \text{---------------- (1)}$$

Where 'k' is called integration constant. The value of 'k' may found using the boundary conditions.

Growth of the energy density

If time't' is measured from the instant the sound source emits sound, the initial condition becomes E=0 at t=0.

Using these initial conditions into equation (1), we obtain the value of 'k'.

$$K = -\frac{4P}{vA} \quad (\because E = 0 \; at \; t = 0 \; in \; eq \; (1))$$

Using the value of 'k' into equation (1) we get

$$Ee^{\alpha t} = \frac{4P}{vA}e^{\alpha t} - \frac{4P}{vA}$$

$$Ee^{\alpha t} = \frac{4P}{vA}e^{\alpha t}\,[1-e^{-\alpha t}]$$

$$E = \frac{4P}{vA}\,[1-e^{-\alpha t}]$$

$$E = E_m\,[1-e^{-\alpha t}]] \quad \text{-------------} \; (2)$$

$$\text{Where } E_m = \frac{4P}{vA} \quad \text{-------------} \; (3)$$

Decay of the sound energy in the hall

Let us assume that after certain time that the energy attained the steady state value, the source of the sound is switched off. Then 'P' becomes zero and let that instant be taken as t=0. Then the initial condition would be P=0 at t=0 and $E=E_m$. Using the conditions into eq (1) we get

$$K = Ee^{\alpha t} \quad \text{-------------} \; (4)$$

$$|K| = \frac{4P}{vA} = E_m$$

We can write eq (4) as

$$E = E_m\, e^{-\alpha t} \quad \text{---------} \; (5)$$

Above equation indicates that the sound energy decays exponentially after the source of sound is switched off.

Figure 11.5 shows the growth and decay of sound energy in the hall.

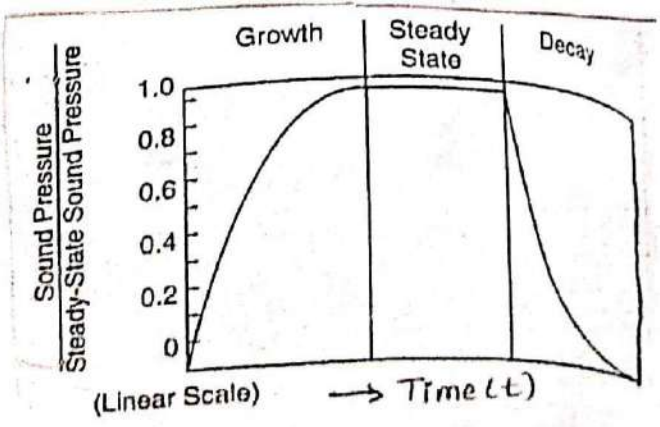


Figure 11.5

Deduction of Sabin's formula:

The reverberation time 'T' is defined as the time taken for the sound energy density to fall from its steady state value to its one-millionth value. It means that,

$\frac{E}{E_m} = 10^{-6}$, at t=T then

$e^{-\alpha t} = 10^{-6}$

Taking log on both sides we have,

$\alpha t = 6\log_e 10 = 6 \times 2.3026$

$$T = \frac{4x6x2.3026xV}{vA}$$

Taking v = 344 m/s we have

$$T = \frac{4x6x2.3026xV}{344xA} = \frac{0.161V}{A}$$

$$\therefore T = \frac{0.161V}{A}$$

The above equation is identical to the empirical formula that sabin proposed for reverberation time.

2.1.5. Determination of absorption coefficient:

If T_1 be the reverberation time of the empty room, then

$$T_1 = \frac{0.161V}{\sum_1^n \alpha_n S_n} = \frac{0.161V}{A}$$

Where $A=\sum_1^n \alpha_n S_n$ is the absorption due to the walls, flooring, ceiling of the empty hall.

Then a certain amount of absorbing material of area 'S' and absorption coefficient $\alpha^I$is added in the room and again the reverberation time is measured. Let it be T_2.

$$T_2 = \frac{0.161V}{A+\alpha^I S}$$, Then

$$\frac{1}{T_2} - \frac{1}{T_1} = \frac{\alpha^I S}{0.161\ V}$$

$$\alpha^I = \frac{0.161\ V}{S} \left[\frac{1}{T_2} - \frac{1}{T_1}\right]$$

Knowing the quantities on the RHS of the above equation, the absorption coefficient α^I of the material under test can be calculated.

6.Factors affecting the acoustics of buildings and their remedies:

There are several factors that affect the quality of a hall. These are

- Reverberation time
- Loudness
- Focussing
- Echoes
- Echelon effect
- Resonance
- Noise

ULTRASONICS

2. ULTRASONICS

1. INTRODUCTION TO ULTRASONICS

- The science and technology which deals with production, properties and applications of ultrasonic waves is called ultrasonics.
- 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 20000Hz (20 kHz) 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 etc.

1. PRODUCTION OF ULTRASONIC WAVES

Ultrasonic waves are produced by the following methods.

(1) Magnetostriction Method (Magneto-striction generator or oscillator)
(2) Piezo-electric Method (Piezo-electric generator or oscillator)

(1) MAGNETO-STRICTION METHOD (MAGNETO-STRICTION GENERATOR)

Principle:

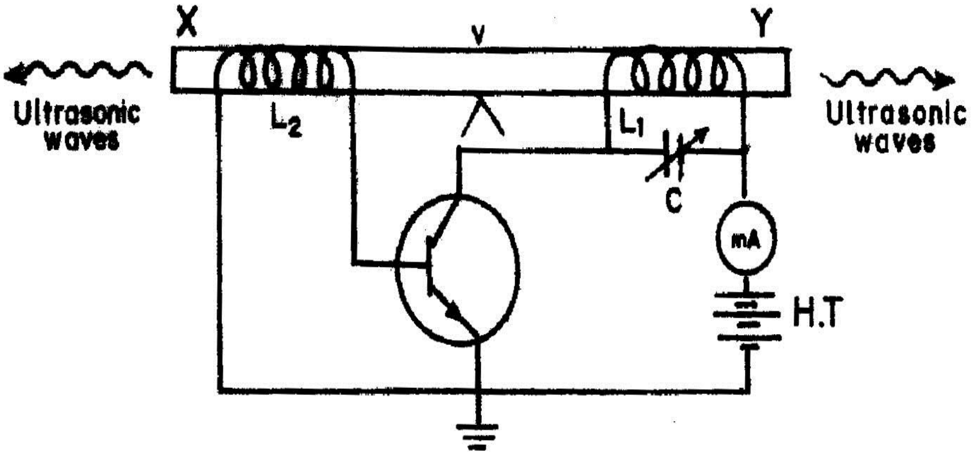
Magnetostriction effect: When a ferromagnetic rod like iron or nickel is placed in a magnetic field parallel to its length, the rod experiences a small change in its length. This is called magnetostriction effect.

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, $f = \frac{1}{2\pi\sqrt{L_1 C}}$

- 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.

Advanatages

- 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.

Disadvanatges

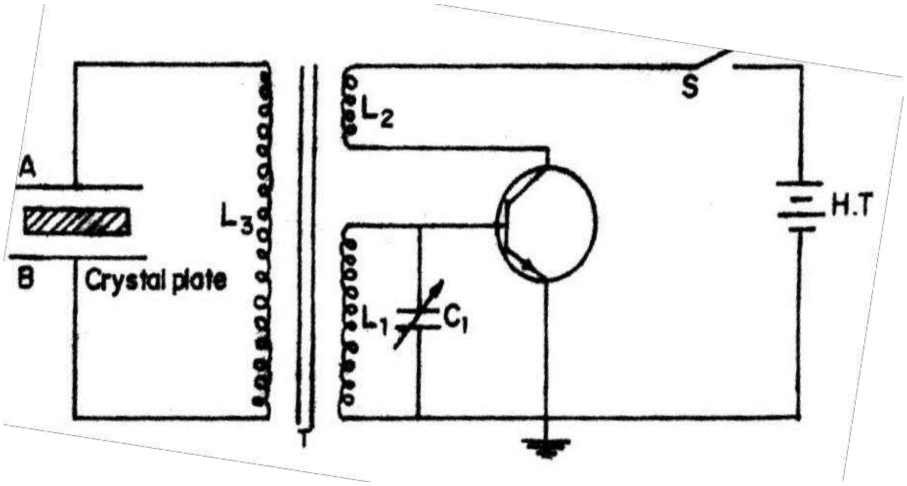
- It has low upper frequency limit and cannot generate ultrasonic frequency above 3000 kHz (ie. 3MHz).
- The frequency of oscillations depends on temperature.
- There will be losses of energy due to hysteresis and eddy current.

(2) PIEZO-ELECTRIC METHOD (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 electronics 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,

$$f = \frac{P}{2l}\sqrt{\frac{Y}{\rho}}$$

where P = 1,2,3,4 … etc. for fundamental, first over tone, second over tone 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 x 108Hz 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.

3. PROPERTIES OF UTRASONICS

1. They have high energy content.
2. Just like ordinary sound waves, ultrasonic waves get reflected, refracted and absorbed.
3. They can be transmitted over large distances with no appreciable loss of energy.
4. 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.*
5. They produce intense heating effect when passed through a substance.

6. The wavelength of the waves is very small and the waves exhibit negligible diffraction effects.
7. The speed of propagation of ultrasonic waves depends upon their frequency. The speed of ultrasonic waves increases with increase in frequency.

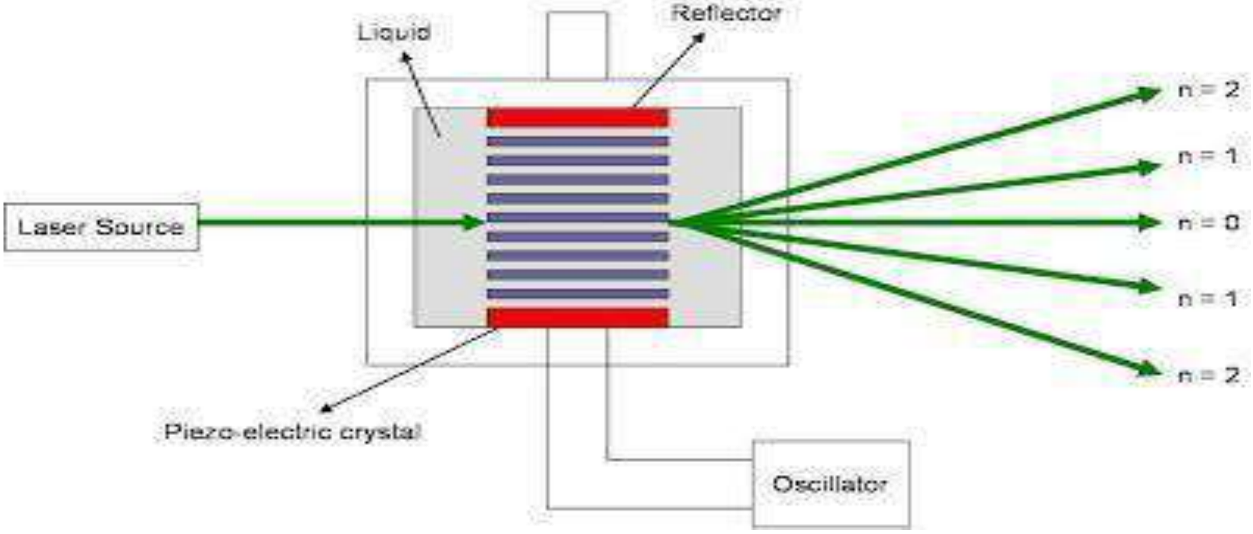
4. ACOUSTING GRATING

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 acoustical 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,

$$d \sin \theta_n = n\,\lambda \qquad \text{-----(1)}$$

where n = 0, 1, 2, 3, … 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, θn and λ, the value of d can be calculated from eqn. (1). If λa is the wavelength of the ultrasonic waves through the medium, then

$$d = \lambda a/2 \ \ (\text{ or }) \ \ \lambda a = 2d \qquad \text{-------(2)}$$

- If the resonant frequency of the Piezo-electric oscillator is N, then the velocity of ultrasonic wave is given by

$$v = N\,\lambda a = 2Nd \qquad \text{.......(3)}$$

- 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.

5. NON DESTRUCTIVE TESTING (NDT)

What is NDT?

- Ultrasonic waves were extensively used for non destructive testing of the material which is defined as ‘detecting the flaws (defects) without disturbing material properties’.

Most Common NDT Methods

- Visual Inspection Method
- Liquid Penetrant Method
- Magnetic Particle Inspection
- Ultrasonic Flaw Detection
- Eddy Current Testing
- X-Ray Diffraction Method

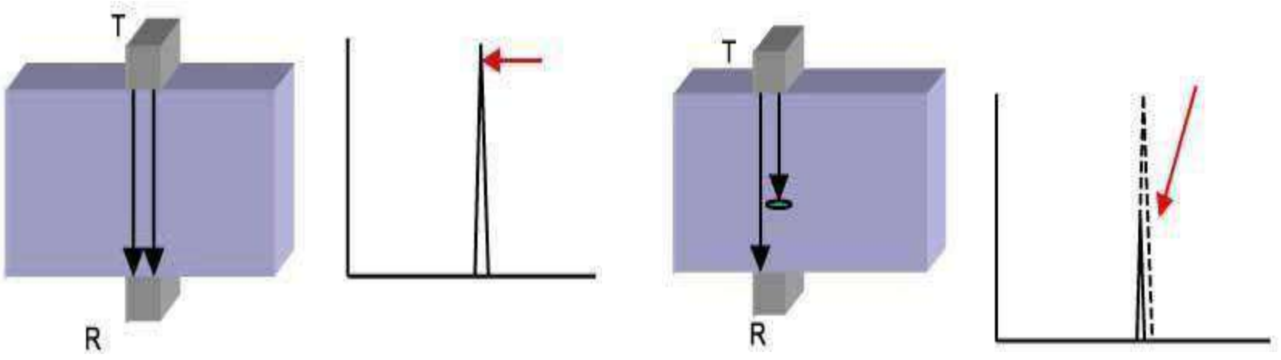
How is ultrasound used in NDT?

- 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

1. PULSE ECHO SYSTEM 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 probe ringing
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.

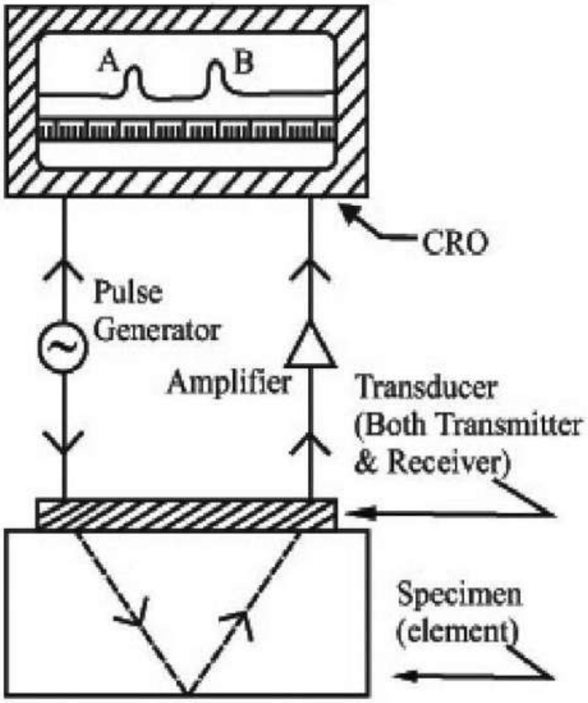
Disadvantages

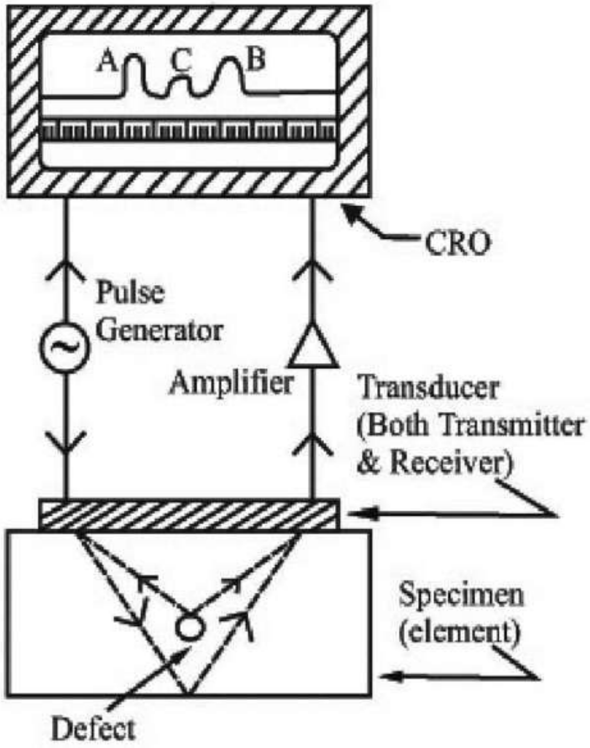
1. The defect cannot be located
2. The component surfaces must be parallel
3. Vertical defects do not show
4. Through transmission is useful in detecting discontinuities that are not good reflectors, and when signal strength is weak. It does not provide depth information
5. There must be access to both sides of the component.

2. 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.





- When there is a discontinuity (*such as a crack*) in the wave path, part of the energy will be reflected back from the flaw surface.
- 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 those 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.

7. MODE OF DISPLAYS (A, B and C)

- 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

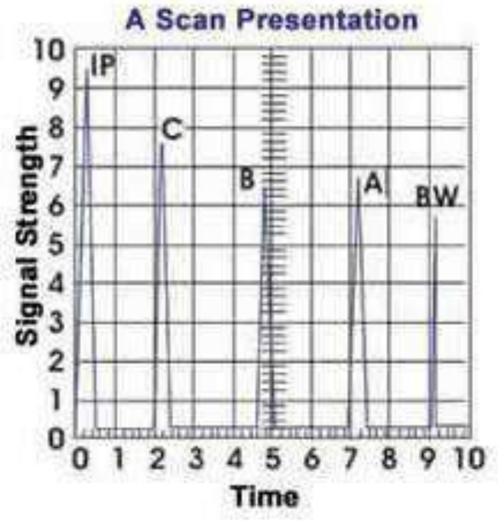
1. A-scan
2. B-scan and
3. C-scan presentations.

- 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.

1. A - Scan

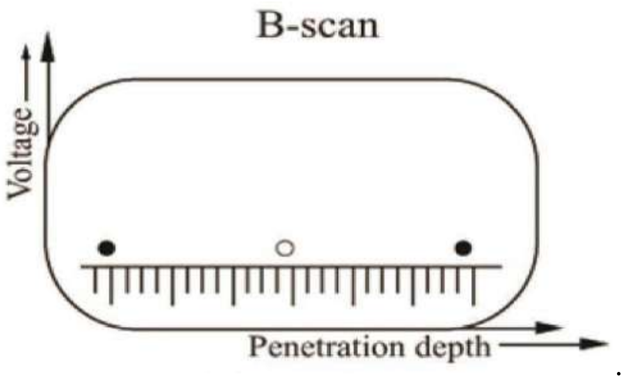
- The A-scan presentation displays the amount of received ultrasonic energy (amplitude mode) as a function of time.
- The relative amount of received energy is plotted along the vertical axis and the elapsed time (*which may be related to the traveled distance within the material*) is displayed along the horizontal axis.

- Reflector depth can be determined by the position of the signal on the horizontal time axis.
- It gives 1-D information.



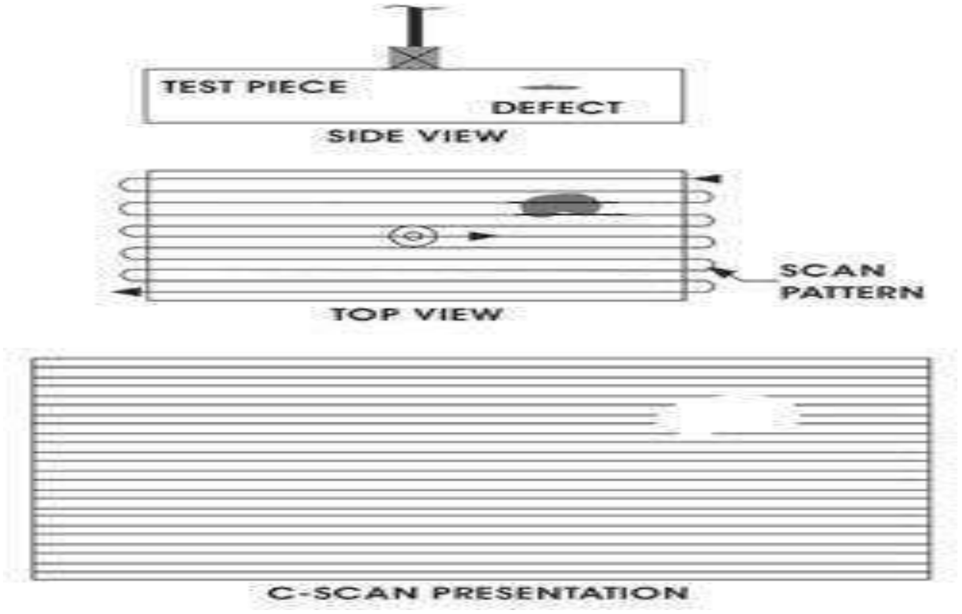
2. B - Scan

- It gives 2-dimensional image.
- The transducer can be moved.
- 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.

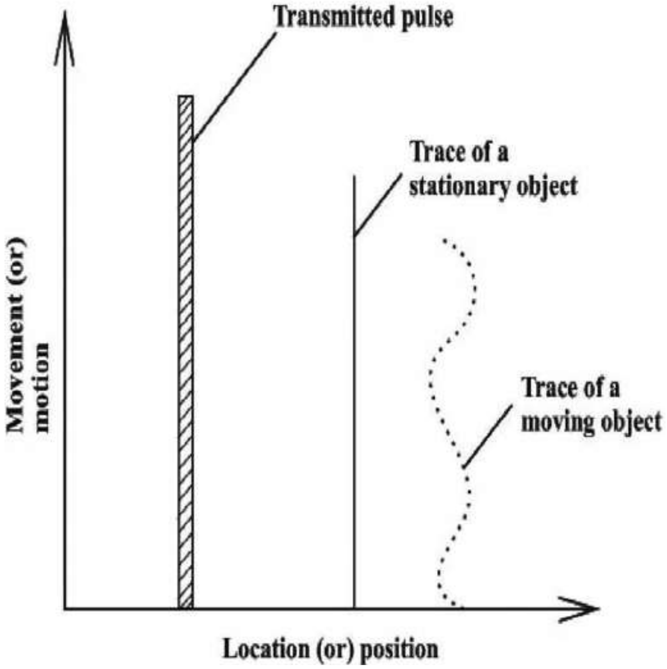


3. C – Scan

- It gives two-dimensional information.
- 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.

2. 8. Applications of Ultrasonics

Ultrasonic waves are used in

- Non destructive testing (NDT) i.e, detecting the flaws (defects) without disturbing the material properties.
- Drilling small holes in very hard materials.
- Almost all plastics and metals can be welded using ultrasonic wave’s suitable form of energy.
- For cleaning various parts of the machine, electronic devices, dental instruments, surgical instruments, jewellery, watches, lenses etc.
- Ultrasonic waves can act as catalytic agents to accelerate chemical reactions.

- Sound Navigation Ranging (SONAR) uses ultrasonic waves to identify the underwater objects like ships and submarines. It is used for fish finding application. Depth of the sea can be found using this technique.
- Date the pregnancy.
- 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-III

Chapter-1

Dielectric & Magnetic 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 materials 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.

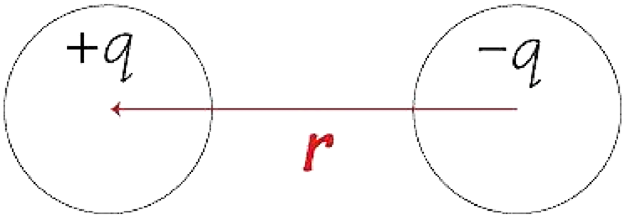
The difference between dielectric material and insulator depends on its application. Insulating materials are used to resist flow of current through it, on the other hand dielectric materials are used to store electrical energy. In contrast to the insulation aspect, the dielectric phenomena have become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

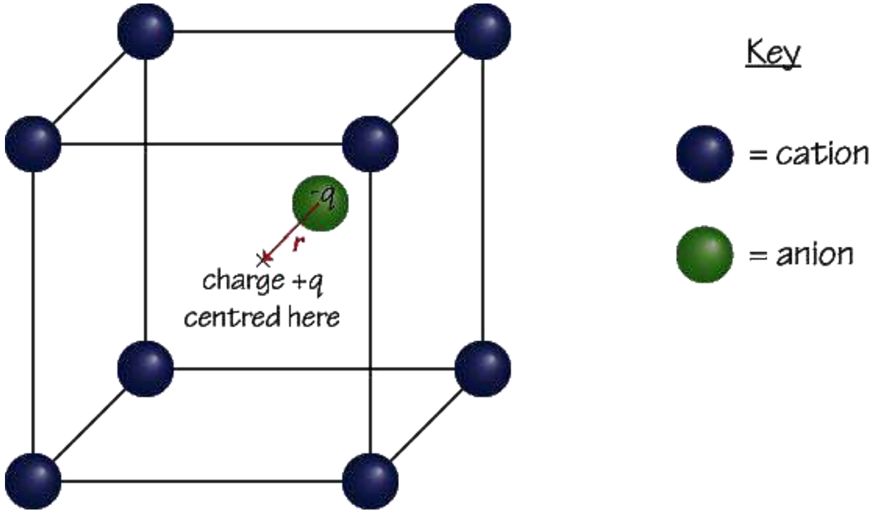
A dielectric supports charge by acquiring a polarisation in an electric field, whereby one surface develops a net positive charge while the opposite surface develops a net negative charge. This is made possible by the presence of electric dipoles – two opposite charges separated by a certain distance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

1. If two discrete charged particles of opposite charges are separated by a certain distance, a dipole moment $\boldsymbol{\mu}$ arises.



$$\mu = q\mathbf{r}$$

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 $\boldsymbol{\mu}$ 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.



$\mu = q\mathbf{r}$

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, $\boldsymbol{r}$ is a vector (the sign convention is that $\boldsymbol{r}$ points from negative to positive charge) therefore the dipole moment $\boldsymbol{\mu}$ is also a vector

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

Dielectric constant (□r)

The dielectric constant of a material is defined as the ratio of the permittivity of the medium (□) to the permittivity of free space (□o). It can also defined as the ratio of the capacitance with dielectric (Cd) and with air (CA) between the plates.

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

$C = q / V = A \varepsilon / d$ 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

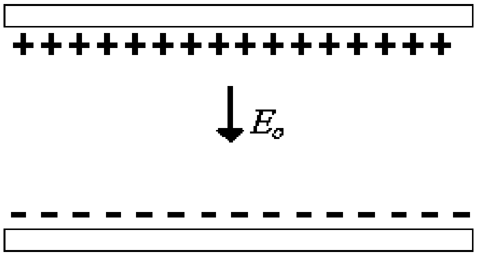
When an electric field is applied to a material with dielectrics, the positive charges are displaced opposite to the direction of the field and negative charges displaced in the direction of the field. The displacement of these two charges create a local dipole, creation of dipole by applying electric field is called as polarization.

Polarization is defined as induced dipole moment per unit volume.

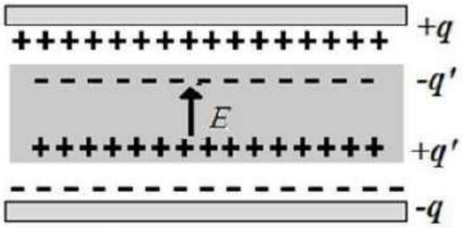
Polarisability

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

Relation between polarization and dielectric constant



Parallel plate condensor without dielectrics



Parallel plate condensor with dielectrics

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.

- 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..)

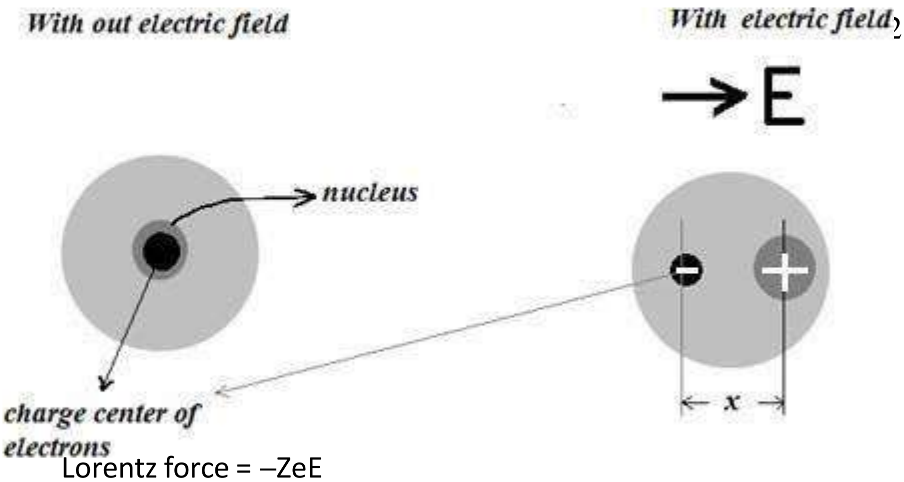
It is independent of temperature. …(1)

- It occurs only at optical frequencies (10^{15}Hz)
- Vast fast process: 10^{-15}~10^{-16}s.

Calculation of electronic polarizability:

Electronic polarization can be explained by classical model of an atom in gasses. 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.

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.



)

Lorentz force = –ZeE

Coulomb Force = Ze X *Ch* arg *eenclosed* int *hesphereofradiusx*

2

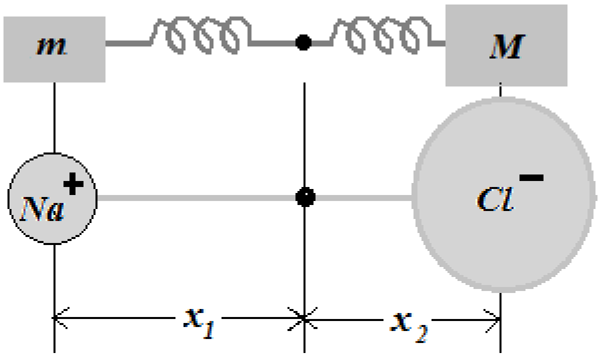
Ionic Polarization

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 i is produced.

Let x1 and x2 be the displacement of positive and negative ion respectively.

Then the induced dipole moment.

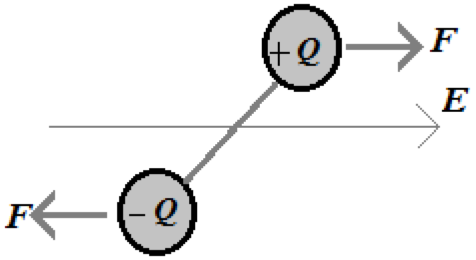


Orientation Polarization

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.

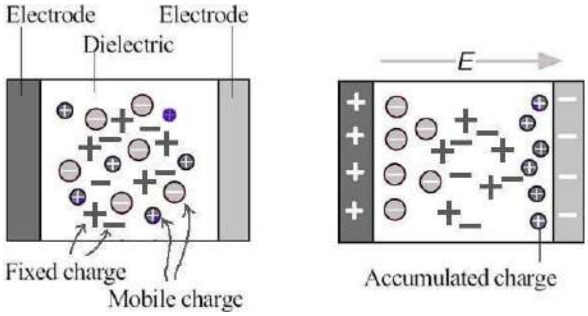


Space charge polarization

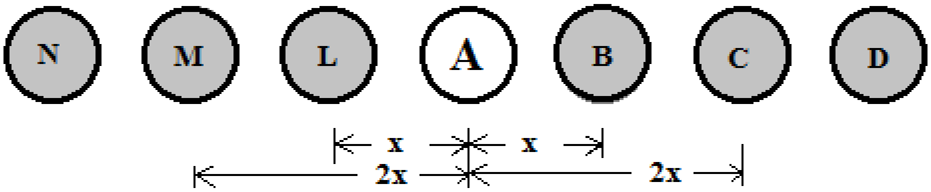
Space charge polarization occurs due to the accumulation of charges at the electrodes or at interfaces in a multiphase materials.

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 remains

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.



Consider an array of one dimensional atoms along x- axis. The all the atoms are similar, equally spaced and have induced electric dipole moment 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.



γ depends on the internal structure For a cubic symmetry crystal γ value is1/3

$$E_i = E + \frac{P}{3\mathcal{E}_o}$$

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

Clausius - Mosotti equation

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 δ 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. The polarization P(t) as a function of time t is given by

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

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

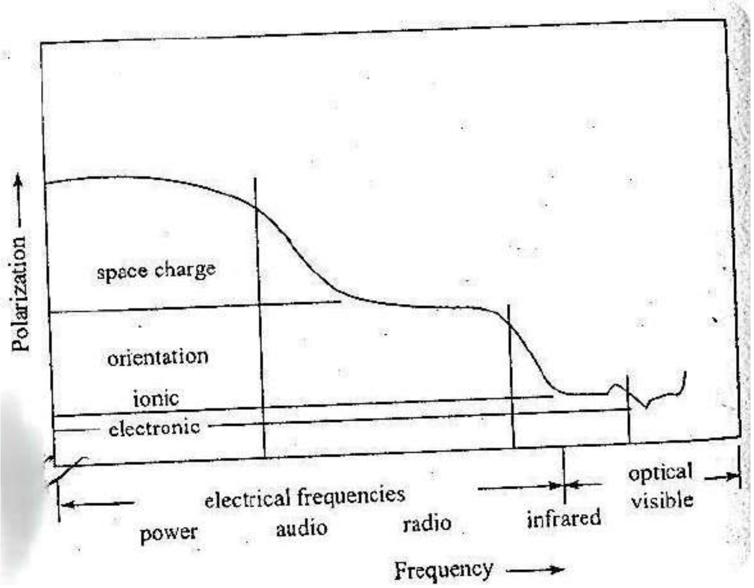
The relaxation time tr is a measure of the time scale of polarization process. It is the time taken for a polarization process to reach 0.63 of the max. value.

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 (≈1013Hz). Hence, at optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than 1013 Hz, the ions respond.

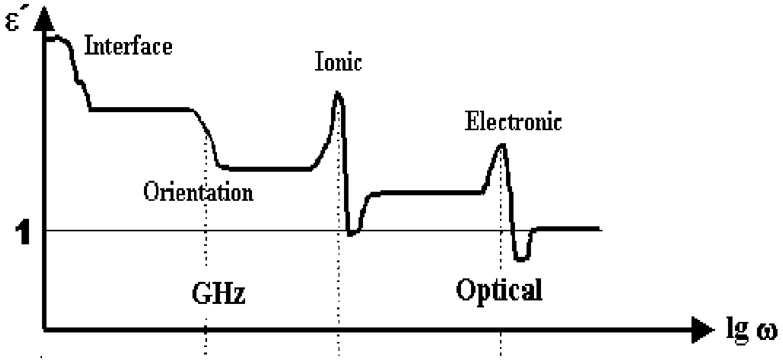
Orientation polarization is even slower than ionic polarization. The relaxation time for orientation polarization in a liquid is less than that in a solid. Orientation polarization occurs, when the frequency of applied voltage is in audio range (1010 Hz).

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 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 at low frequency i.e at radiofrequency region the dielectric constant will be due to all polarisability.

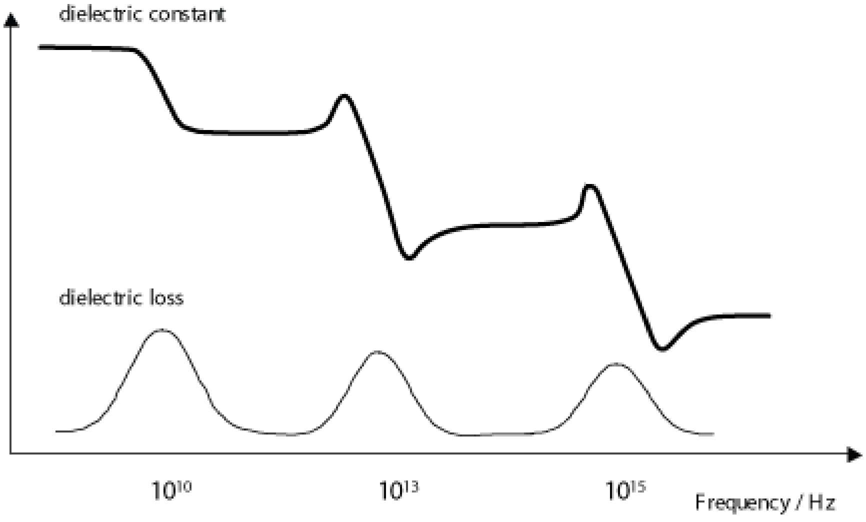
The orientation polarization, which is effective at low frequencies, is damped out for higher frequencies. In the microwave region the dipoles fail to follow the field and the polarisability reduces to (□ = □e + □i), as a result □*r* decreases to some amount.

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 (□ = □e) the □*r* still decreases and only electronic polarization exist.

For example at low frequency the dielecric 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.



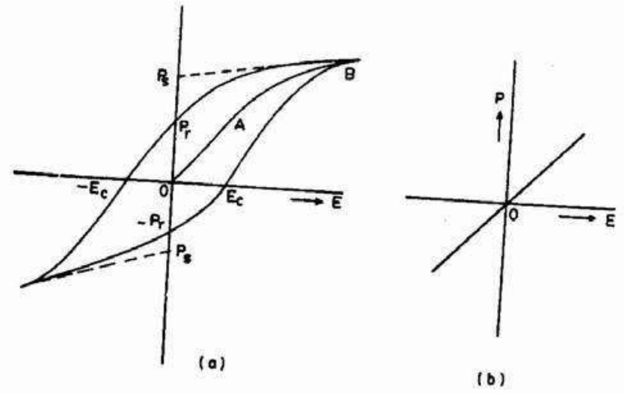
Ferroelectrics

Below certain temperature it is found that some materials spontaneously acquire an electric dipolemoment. 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 barium titanate, 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 ultrasonic waves.

Applications of Dielectric Materials:

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.

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.

Magnetic materials

1. Introduction

Magnetic materials play an important role in industrial and scientific research fields. Based on the response of materials in the external field, they ar4e divided classified into three types which are further classified into five important groups depending on the alignment of

magnetic moments with in the material. Thus, they are known as diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic and ferrimagnetic.

Magnetism

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

Basics of Magnetism

Magnet:

The magnets are materials which produces a magnetic field. The magnets are materials which attract the ferromagnetic materials like iron, Co, Ni etc.

Properties of Magnets:

1. Magnets attract ferromagnetic objects.
2. The magnetic field at the poles of a magnet is greater than at the middle of magnet.
3. The like poles of magnet repel each other while the opposite poles attract each other.
4. The magnet has a property that when it is suspended freely it’s South Pole and North Pole moves to the earth’s North and South Pole, respectively.

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” (2*l*).

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 2*l* **(magnetic length***)* constitute a magnetic dipole.

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

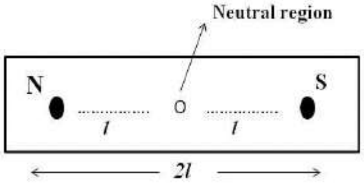


Fig : Magnetic dipole

3.2.2 Magnetic Dipole Moment:

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

(a)In the case of bar magnet:

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

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

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

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

(b) In the case of current loop:

A current carrying loop behaves as a magnetic dipole. Consider a current carrying conductor loop of wire as shown fig.

The current (I) establishes a magnetic field around the loop. By right hand palm rule, the upper face of the loop acts a N- pole and the lower face act as S- pole.

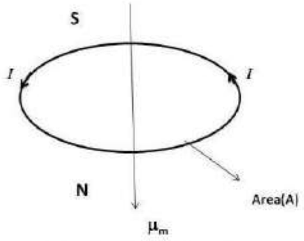


Fig : Current carrying conductor loop

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).

$$\mu_m \, \alpha \, I.A$$

$$\mu_m = K\,IA$$

$$\boxed{\mu_m = IA}$$

Where K is a proportionality whose value is one

Magnetic Field:

The space surrounding a magnet upto which it's influence can be felt is called 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.

Magnetic Flux:

A group of magnetic lines of force is called "magnetic flux".

The symbol for magnetic flux is Φ (phi).

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

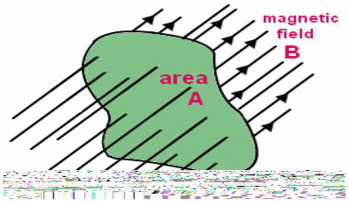
One Weber is equal to 1 x 10^8 magnetic field lines.

Magnetic Flux Density:

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

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

$$\boxed{B = \frac{\phi}{A} \text{ Tesla}}$$



3.2.3 Magnetization:

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 the material medium is to create the magnetic dipole moments.

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

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

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

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.

3.2.4 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.

$$M \alpha H$$

$$M = \chi_m H$$

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

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).

5. 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. $B \alpha H$

$$B = \mu H$$

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

Where "μ" is the permeability of a medium.

For vacuum:,

$$\boxed{B = \mu_0 H}$$

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

Relative permeability (μ_r):

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

$$\boxed{\mu_r = \frac{\mu}{\mu_o}}$$

$\mu_r = 1$ 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.**

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

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

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

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

$$\boxed{\mu_r = (1+\chi_m)} \qquad \text{Where } \chi_m = \frac{M}{H}$$

This is the relation between Relative Permeability and Magnetic Susceptibility.

6. Origin of Magnetism:

An electron is a good traveler because it has no fixed planes.

It has no desire to revolve around the nucleus, and yet it revolves and creates magnetism…

It revolves in the state of wei-wu-wei (action of non action).

- Magnetism is one of the manifestations of ultimate matter-energy.
- Magnetism is an intrinsic property of every charged particle.
- Every moving charged particle creates magnetic field in the creation.
- Magnetism manifests by itself in the material.
- Magnetism is an interdependence.

Science says:

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 moment (μ_{spin}).

- The motion of the protons and neutrons within the nucleus also contributes to the total magnetic moment (($\mu_{nucleus}$). But the magnitude of the nuclear magnetic moment is (about 10 $^{-3}$ times) very small compared with the magnetic moment of electron and is usually neglected.

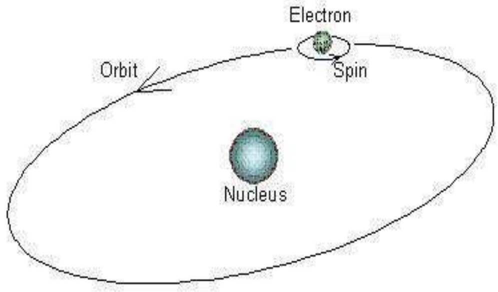


Fig: Motion of electron

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

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

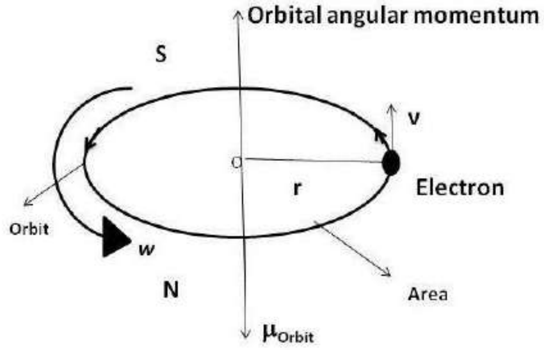


Fig : Orbital motion of electron

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

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

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

$$\text{i.e., } T = \frac{2\pi}{\omega} \qquad \xrightarrow{(2)}$$

Where *‘w’* is the angular frequency of the electron

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

$$v = r\,\boldsymbol{\omega}$$

$$\text{and } \boldsymbol{\omega} = \frac{v}{r} \qquad (3)\rightarrow$$

Substituting the equation (3) in (2),

$$T = \frac{2\pi}{r\,v} \qquad (4)\rightarrow$$

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

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

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

The Area of the orbit is **A** = πr^2 $\rightarrow(6)$

Then the corresponding magnetic dipole moment is given by

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

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

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

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

$$\mu_{\text{Orbit}} = \frac{-evr}{2} \text{ X } \frac{m}{m}$$

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

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

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

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

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

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

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

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

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

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

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

The electrons also rotate around their own axes. This motion of electrons is called spin motion as shown fig.

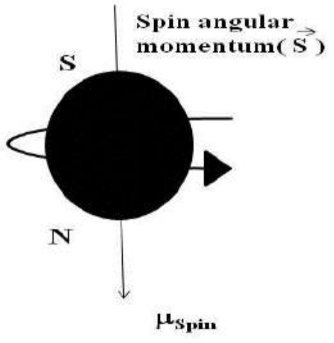


Fig: Spin motion of electron

The spinning electron constitutes a tiny current loop. This loop behaves as a magnetic dipole. The magnetic dipole moment arises due to its spin motion is called spin magnetic moment (μ_{spin}) and is given by

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

The – ve sign indicates that the spin angular momentum and spin magnetic dipole moment are in opposite directions. Its value is 9.4x $10-^{24}$ A-m^2.

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

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

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

$$\mu_{nuclear,\ spin} = \frac{eh}{4\pi M_n} = 5.525X1O^{-27} \text{ A-m}^2$$

Where M_n is the Mass of the proton.

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

7. Classification magnetic materials:

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

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

1.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

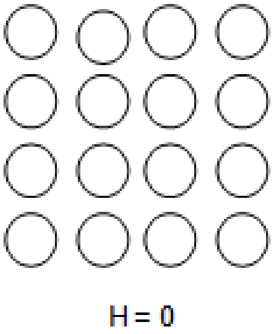
Examples:

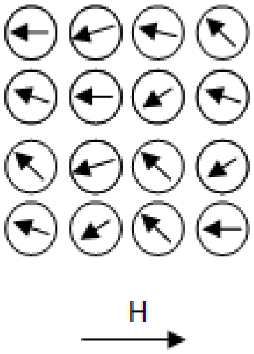
Bismuth, Copper, Zinc, Gold, Water, etc

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.





Properties:

- 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.
- The induced magnetic moments of atoms/molecule/ions are opposite to the applied magnetic field.
- 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.

2.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.

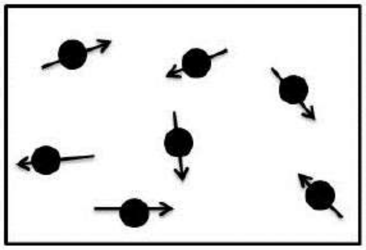


Fig: In the absence of external magnetic field (H=O)

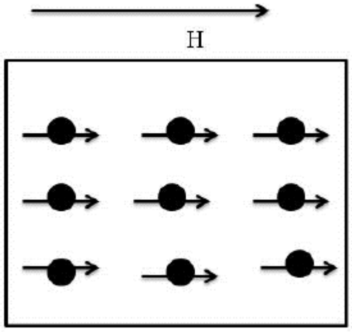


Fig: In the presence of external magnetic field

Properties:

- 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.
- 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.
- They possess permanent magnetic dipole moment.
- When a paramagnetic material is placed in a magnetic field, it is feebly or weekly magnetized in the direction of applied magnetic field.
- When a paramagnetic material is placed in a magnetic field, the magnetic lines force prefers to pass through the paramagnetic magnetic material rather than air.
- The magnetic flux density inside is greater than that in the free space. Hence the relative permeability $\mu_r > 1$.
- The magnetic susceptibility (χ_m) is positive and small.
- The magnetic susceptibility (χ_m) is inversely proportional to the temperature.

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

Where C → Curie constant

T → Absolute temperature and

θ_C → Curie temperature

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

3.Ferro magnetic materials:

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

Examples:

Iron, Steel, Nickel, Cobalt, etc

Cause of Ferro magnetism:

- In a Ferro magnetic material, the number of unpaired electrons is more and most of the magnetic dipole moments align parallel to each other even in the absence of magnetic field..Hence they possess permanent magnetic dipole moment even in the absence of magnetic field.
- In Ferro magnetic materials, atoms grouped into regions called *domains,* instead of acting independently like paramagnetic materials.

  *The region of space over which the magnetic dipole moments are aligned is called domain.*A typical domain contains 10^{17} to 10^{21} atoms and occupies a volume of 10^{-12} to 10^{-8} m^3.

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

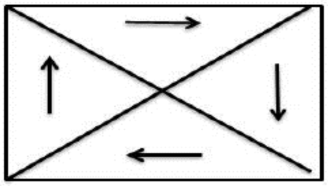


Fig: Without field

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

i) By the movement of domain walls

ii) By the rotation of domain walls.

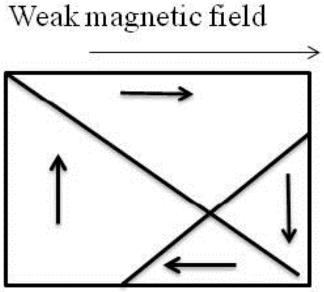


Fig: Displacement of domain walls With weak magnetic field

i) **By the rotation of domain walls**

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

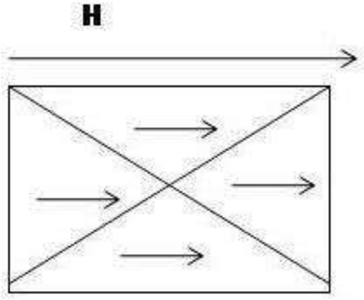


Fig: Rotation of domain walls in strong magnetic field

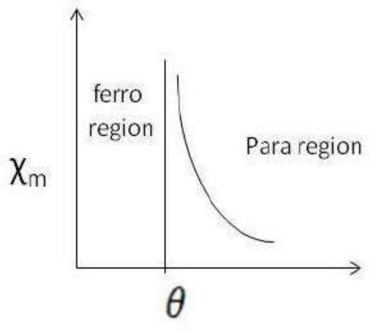
Properties:

- They possess permanent magnetic dipole moment.
- When a Ferro magnetic material is placed in a magnetic field, it is strongly magnetized in the direction of applied magnetic field.
- When a Ferro magnetic material is placed in a magnetic field, the magnetic lines force tend to crowed into the Ferro magnetic material.
- The magnetic flux density inside is very greater than that in the free space. Hence the relative permeability $\mu_r >> 1$.
- The magnetic susceptibility (χ_m) is positive and very high.
- The magnetic susceptibility (χ_m) is inversely proportional to the temperature.

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

Where C → Curie constant
T → Absolute temperature and
θ_C → Curie temperature

- 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.

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

4.Antiferromagnetic materials:

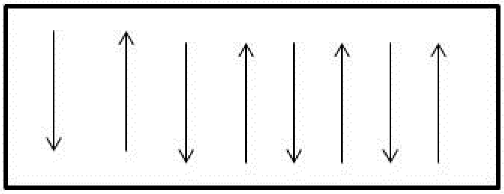
The materials which consist of anti parallel spin magnetic dipole moment with same magnitudes are known as anti ferromagnetic materials.

Examples:

Ferrous oxide (FeO),
Manganese oxide (MnO_4),
Manganese sulphide MnS),
Chromium Oxide (Cr_2O_3),
Ferrous Chloride ($FeCl_2$) etc

Properties:

- In this e aligned in anti parallel manner.

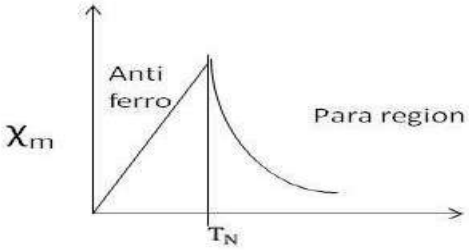


- The magnetic susceptibility is very small and positive
- The magnetic susceptibility is inversely proportional to temperature. The variation of susceptibility with temperature is shown in fig.

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

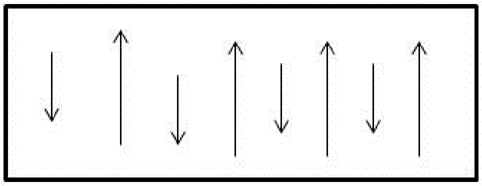
Where C → Curie constant
T → Absolute temperature and
θ_C → Curie temperature

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



5. Ferrimagnetic materials:

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



Examples:

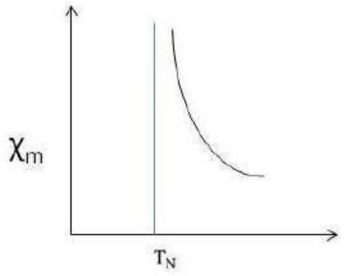
Ferrites-general formula: $Me^{+2} Fe^2O_4$
Where Me^{+2} =divalent metal ions (Zn,Cu,Ni).

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



3.2.8 Hysteresis:-

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

Definition of Hysteresis: *The phenomenon of lagging of flux density (B) behind the magnetizing force (H) in a ferromagnetic material subjected to cycles of magnetization is known as hysteresis*.

Explanation :

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

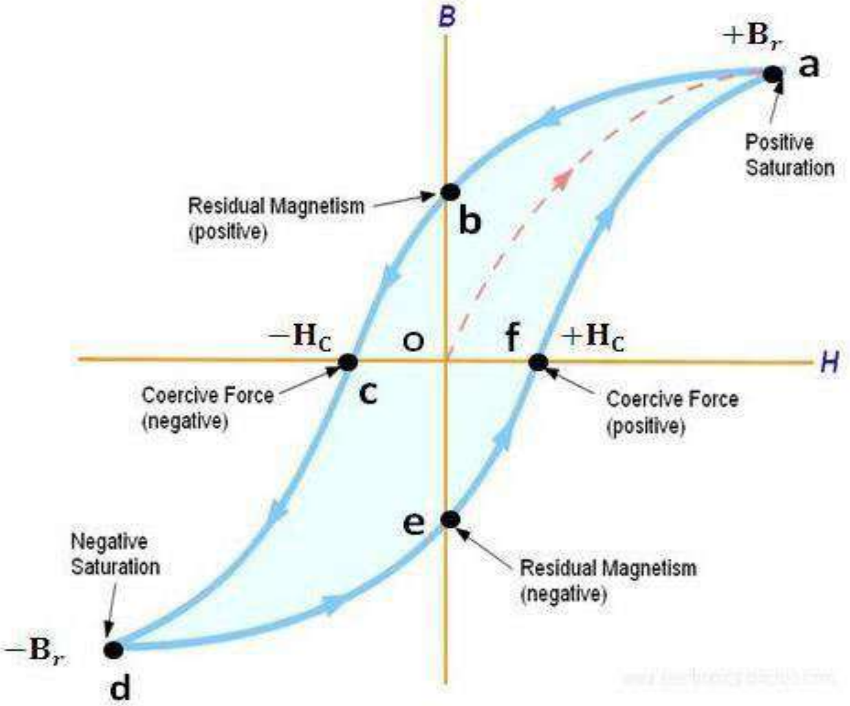


Fig: B-H Curve

(i) To start with, the toroid is unmagnetised and its situation is represented by point O 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.

(ii) 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.*

(iii) 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, he curve follows the path **bc**. At point c, B=0 and H= $-H_C$ .The value of *H* needed to wipe out residual magnetism is called coercive force (H_C).

(iv) 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.

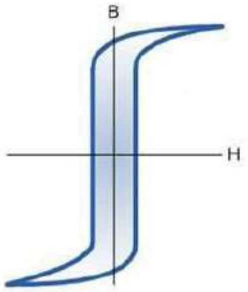
Based on the area of the hysteresis loop, the magnetic materials are classified into soft and hard magnetic materials.

9. Soft magnetic materials:-

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

Properties:

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



- The coercivity and retentivity values are small
- These materials are free from irregularities or impurities or imperfections

Examples:

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

Applications:

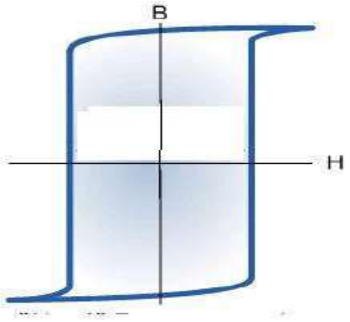
- They are used in switching devices, electromagnets,
- They are used in matrix storage of computers.
- They are used in motors, relays and sensors
- They are used to make the temporary magnets.

3.2.10 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.

Unit-IV
Chapter-1
LASERS

Introduction:

Laser is an acronym for ‘Light Amplification by Stimulated Emission of Radiation’. Laser radiation is due to stimulated emission of radiation process which improves (amplifies) the intensity of radiation. In general, when an electron moves from a higher energy orbit to a lower orbit, it emits radiation. This emission of radiation can be explained in terms of energy levels as when the electron transits from a higher energy level to a lower energy level, it emits radiation. According to Planck’s Quantum theory, the emission of radiation will be in the form of photon of energy hυ. The frequency (υ) term in the energy of the photon indicates the wave characteristics of the photon. The energy of the emitted photon is equal to the energy difference between the higher and lower energy levels. This loss of energy is attributed to the entire atom. As a result, it can be brought that the atom is moving from a higher energy state to a lower energy state.

When a large number of atoms transit to lower energy level, then each transition emit photons of same energy, same frequency and same wavelength.

$$v = \frac{E_2 - E_1}{h}$$

All the photons are in phase, and after reinforcement emit a high intensity monochromatic coherent radiation i.e, LASER radiation.

In laser, the intensity of light is amplified by a process called stimulated emission. Lasers find major applications in various fields such as medical, engineering, fiber communication, industries etc.

Lasers are more powerful than ordinary light radiation.

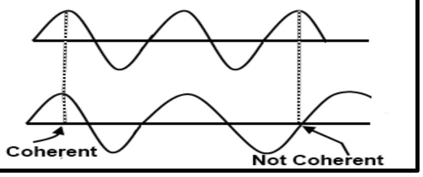
Characteristics of laser:

When compared with any conventional light (sun light, tube light, etc.,), Laser possesses few outstanding characteristics. They are

1] Coherence 2] High directionality 3] High intensity 4] High Monochromaticity

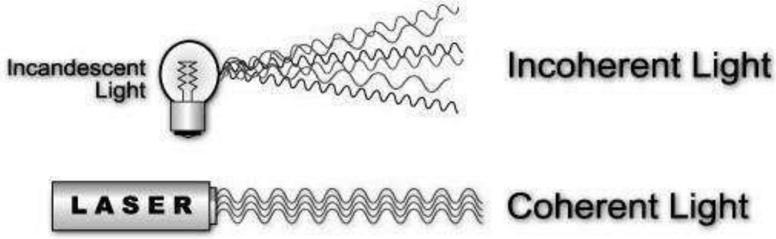
1] Coherence:

The property of existing either zero or constant phase angle difference between two or more waves is called as Coherence. The wave trains which are identical in phase and direction are called ‘coherent waves’.



In case of laser, the property of coherence exits between any two or more light waves of same type. On the other hand, the waves emitted by laser source will be in phase and are of the same frequency.

Therefore, light generated by laser is highly coherence. All the constituent photons of laser beam possess the same energy, momentum and propagate in same direction, the laser beam is said to be highly coherent.



Coherence is of two types: Spatial coherence and temporal coherence

Spatial Coherence: If there exists either zero or constant phase angle difference between two points on a wave front then wave is said to have spatial coherence.

Temporal coherence: If there exists either zero or constant phase angle difference between two light fields measure at two instants at the same point then wave is said to have temporal coherence.

2] High directionality:

Lasers emit light only in one direction. Laser travels as a parallel beam; that can travel over a long distance without spreading. During the propagation of laser its angular spreading will be less and occupies less area where it incident. It possesses high degree of directionality.

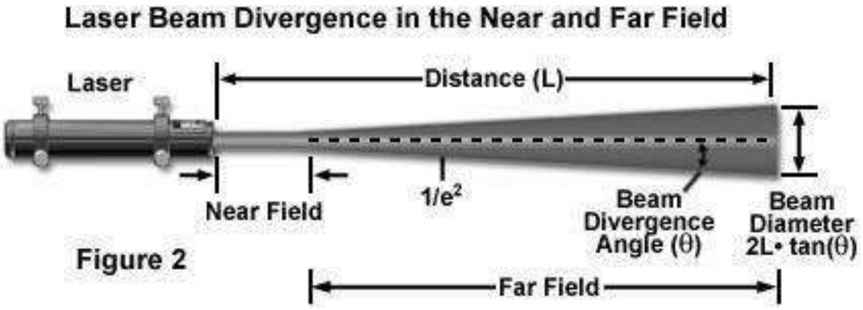


Figure 2

The laser light of wavelength ‘λ’ emerges through a laser source aperture diameter ‘2L tanθ’, then it propagates as a parallel beam upto d^2/λ (small value) and gets diverged. The angle of divergence of a laser beam is expressed as,

$$\phi = \frac{ar}{r\&dius} = 10^{-3} \text{ radians.}$$

EX: Laser beam of 10cm diameter is operated on to the moon (which is at a distance of 3, 84,000) when it doesn't spread over not more than 5km.

3] High intensity or brightness:

A laser emits light in the form of narrow beam which propagates in the form of plane waves. The energy is concentrated in very narrow region; its intensity would be tremendously high. Due to its directionality many beams of light incident in a small area. Therefore the intensity of light is high.

Let there be 'n' number of coherent photons of amplitude 'a' in the emitted laser radiation These photons reinforce with other and the amplitude of the resulting wave becomes 'na' and hence the intensity (I) is proportional to n^2a^2. Thus due to coherent additions of amplitude and negligible divergence, the intensity or brightness increases enormously.

$$I \propto A^2$$
$$I \propto (na)^2$$
$$I \propto n^2a^2$$

Eg: Typically estimated that the light from a 1-mW laser is 10,000 times brighter than the light from the sun at the earth.

4] High Monochromaticity:

The property of exhibiting a single wave length by a light is called monochromaticity. The light from normal monochromatic source spread over a wave length of the order of 100 Å to 100 Å. The laser light is highly monochromatic. The spread in wavelength is in the order of a few angstroms (<10 Å or 0.001 nm)). The laser emits continuous wave of very long duration.

On the degree of monochromaticity of light from some source we make use of line width (spectral width) of the source Δυ which is the frequency spread of a spectral line. Frequency spread Δυ is related to the wavelength spread Δλ as,

$$\Delta\lambda = -\left[\frac{c}{\upsilon^2}\right]\Delta\upsilon$$

Interaction of radiation with matter:

Introduction:

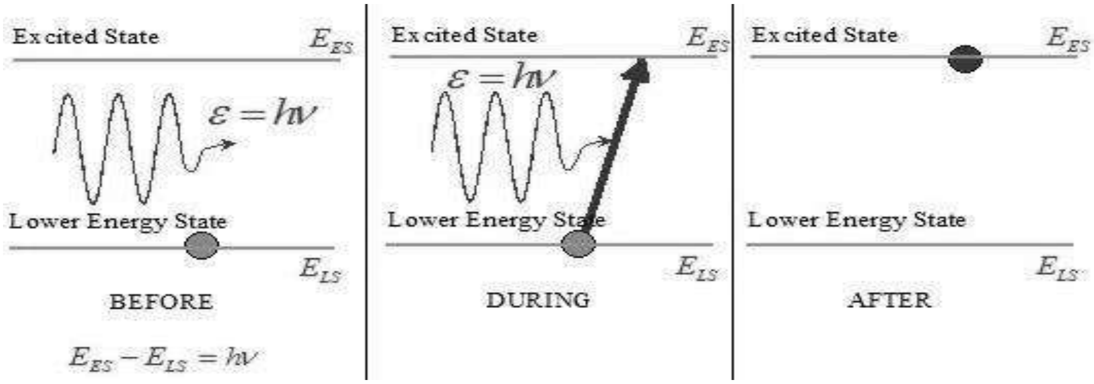
When the incident radiation (Photon) interacts with atoms in the energy levels then three distinct processes can takes place.

- Stimulated absorption of radiation
- Spontaneous emission of radiation

- Stimulated emission of radiation

1] Stimulated absorption of Radiation:

Let us consider a system in which two active energy levels are present whose energies are E_1 and E_2. Usually atoms are in the ground state as long as external forces are not applied. If a photon of energy $(E_1 - E_2 = h\upsilon)$ is incident on the atom in lower state. The atom absorbs incident photon and gets excited to the higher energy state E_2. This is called Stimulated or induced absorption of radiation.



$\boxed{A + h\upsilon \to A^*}$ A… Atom in the ground state A^*… Atom in higher state

The number of absorptions at any instant will be proportional to the number of density of atoms in lower state E_1 and the photon density (incident radiation density) in the incident beam. The more number of atoms in the lower state can undergo more number of absorption transitions. Similarly, the more number of photons in incident radiation, the more number of atoms can be excited to higher state.

The rate of absorptions R_{12} is proportional to the population of the lower energy level N_1 and to the density of photons in the incident radiation $\rho(\upsilon)$.

$$R_{12}\ \alpha\ N_1$$

$$R_{12}\ \alpha\ \rho(\upsilon)$$

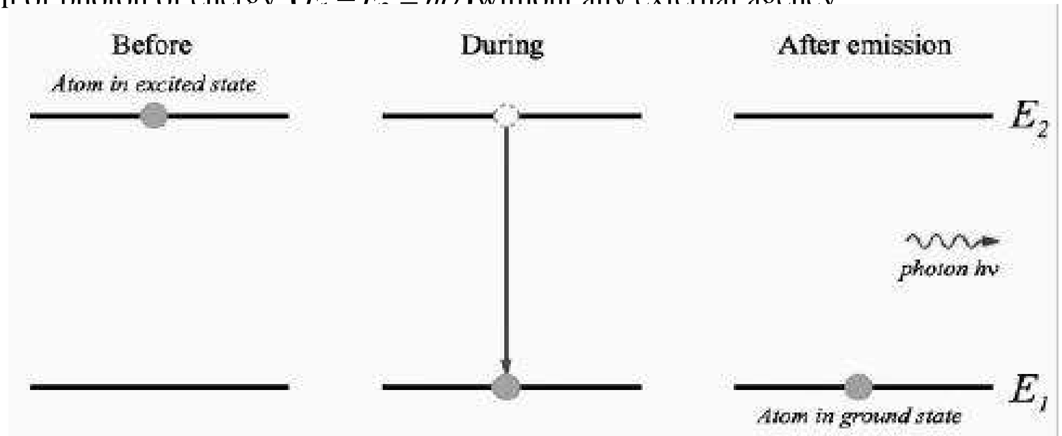
$$R_{12}\ \alpha\ N_1\ \rho(\upsilon)$$

$$\boxed{R_{12} = N_1 \rho(\upsilon) B_{12}}$$

B_{12}… Probability of absorption of radiation per unit time (or) Einstein's coefficient of stimulated absorption of radiation.

2] Spontaneous Emission of radiation:

It is the process, in which there is emission of radiation whenever an atom transits from a higher energy state to a lower energy state without external agency". For this process take place an atom initially present in the excited state, since the higher energy level is unstable, the excited atoms in the higher energy level E_2 spontaneously return to lower energy state E_1 with emission of photon of energy $(E_1 - E_2 = h\upsilon)$ without any external agency



$\boxed{A^* \rightarrow A + h\upsilon}$

A… Atom in the ground state and

A^*… atom in higher state

The instant of transition, the direction of emission of photon, the phase of photon, polarization state of photon are all random quantities. That is different atoms of the medium emit photons at different times and different directions. Hence there is no phase relationship among the emitted photons, so they are incoherent.

EX: Glowing tube light, Electric bulb, Candle flame, etc.,

The light from the conventional sources originates in spontaneous process and is incoherent. It contains a superposition of many waves of random phase.

The rate of spontaneous emission of radiation is proportional to the population at the higher energy level

$$R_{21} \alpha N_2$$

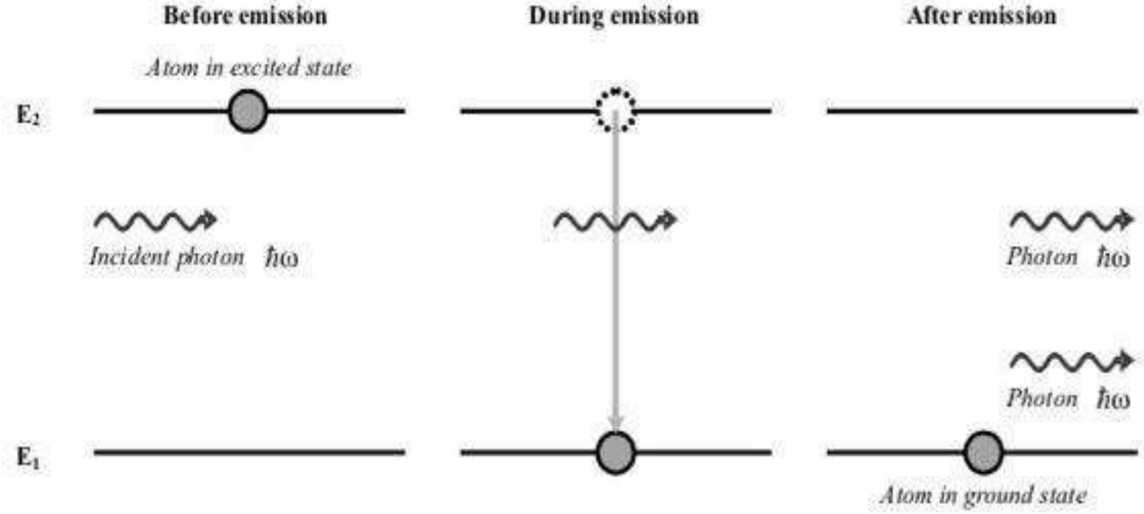
$$\boxed{R_{21} = N_2 A_{21}}$$

A_{21}…. Probability of spontaneous emission per unit time (or) Einstein's coefficient of spontaneous emission of radiation.

3] Stimulated emission of Radiation:

"It is a process in which there is an emission of photon whenever an atom transmits from higher energy state to lower energy state under the influence of an external agency". For this process also, atom should be already in a excited state. Let a photon having energy $(E_1 - E_2 = h\upsilon)$ interact with an atom in exciting state under such interaction an incident photon stimulates excited state atom in the level E_2 to transmit lower energy state E_1 resulting in the

emission of photon of energy $(E_1 - E_2 = h\upsilon)$.



$$\boxed{A^* + h\upsilon \rightarrow A + 2h\upsilon}$$

A… Atom in the ground state and A^* … atom in higher state

Inducing photon and emitted photon have same phase, energy and direction of movement. This type of emission is responsible for laser action. The stimulation emission of radiation is the principle used in the laser action.

The rate (number) of stimulated emission of radiation is proportional to the population at the higher energy state and to the density of inducing photon in incident radiation.

$$R_{21} \propto N_2 \quad \text{and} \quad R_{21} \propto \rho(\upsilon)$$

$$R_{21} \propto N_2 \, \rho(\upsilon)$$

$$\boxed{R_{21} = N_2 \rho(\upsilon) B_{21}}$$

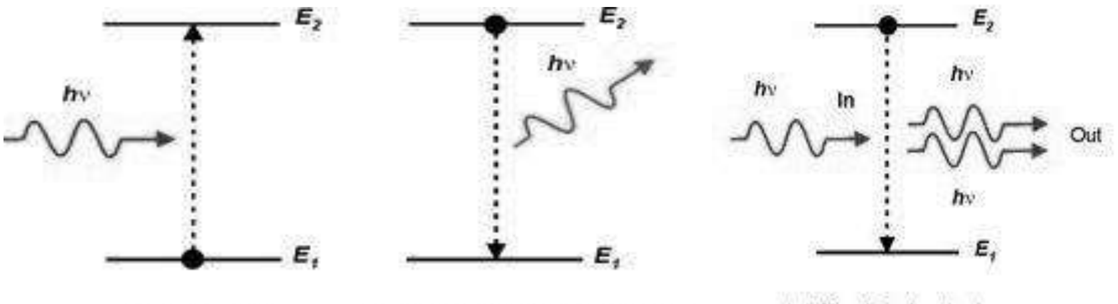
B_{21} … Stimulated emission of radiation per unit time. (or) stimulated emission of radiation.

Stimulated emissionof Radiation is characterized by some very interesting features:

1] The emitted photon is identical to the incident photon. It has same frequency as that of incident photon. It will be in phase with the incident photon. Both the photons travel in same direction. They will be in the same state of outside.
2] The stimulated emission controlled from outside.
3] One photon induces an atom to emit a second photon, these two travelling along the same direction de excite two atoms in their path producing a total four photons which stimulates four atoms generating eight photons and so on. The photons build up in avalanche manner.
4] Electromagnetic waves of extremely high amplitude could be generated by the combined stimulated emission from large samples of atoms.
5] The constructive interference of many waves travelling in same direction with a common frequency and common phase produce an intense coherent light beam.
6] The process of stimulated emission is the key to the operation of a laser.

The external radiation incident on the medium, the three process occur simultaneously. Atoms in the lower level E_1 will occasionally absorb radiation and make a transition to upper level E_2. Atoms in the upper level will occasionally radiate and make a transition to the lower level. In order to maintain N_1 and N_2 constant, the number of upward transitions must be equal to the number of downward transitions. Thus,

$$N_{Absorption} = N_{spon\tan eous} + N_{Stimulated}$$



(a) Absorption (b) Spontaneous emission (c) Simulated emission

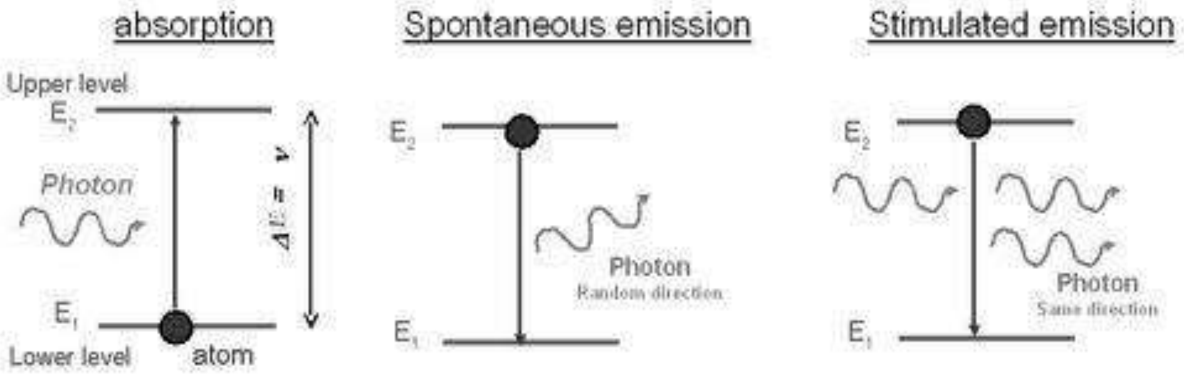
Difference between spontaneous emission of radiation and stimulated emission of radiation

Spontaneous Emission of radiation	***Stimulated Emission radiation***
1] Spontaneous emission takes place without any stimulus energy.	1] Stimulated emission takes place with the help of stimulus energy
2] It is independent of incident radiation density.	2] It is dependent on density of incident radiation.
3] Spontaneous emission takes place after 10^{-8} Second.	3] Stimulated emission takes place within 10^{-8} second.
4] Emitted radiations are incoherent radiation	4] Emitted radiations are coherent radiation
5] The radiations have low intensity and less directionality.	5] The radiations have high intense and more directionality.
6] Polychromatic radiation.	6] Monochromatic radiation.
7] It is uncontrolled process.	7] It is controlled process.

Einstein Coefficients:

Consider two energy levels E_1 and E_2 of an atomic system such that $E_2 > E_1$. Let N_1 and N_2 be number of atoms per unit volume (population) present at the levels E_1 and E_2 of any radiation of frequency (υ) falls on the atomic system, it can interact with matter in 3-distinct ways.

Absorption:



When the atom makes transition from E_1 to E_2 in the presence of external photon whose energy equal to $(E_1 - E_2 = h\upsilon)$ then the stimulated absorption takes place. The number of stimulated absorption per unit volume per second from level E_1 and E_2

$\boxed{R_{12} = N_1\rho(\upsilon)B_{12}}$…… [1]

B_{12}…Represent probability or absorption per unit time.

Spontaneous Emission: An atom in level E_2 can make spontaneous transition by jumping into lower energy level E_1. The number of spontaneous emissions per unit volume per second from level levels E_2 to E_1.

$$R_{21} = N_2 A_{21} \ldots\ldots [2]$$

Stimulated Emission:

When an atom makes transitions from E_2 to E_1 in the presence external photon whose energy equal to $\left(E_1 - E_2 = h\upsilon\right)$ stimulated emission takes place. The number of stimulated emission per unit volume per second from levels E_2 to E_1 is given as,

$$\boxed{R_{21} = N_2 \rho(\upsilon) B_{21}} \ldots\ldots [3]$$

$B_{21} \ldots$ Represents probability of stimulated emissions per unit volume.

$A_{21} \ldots$ Represents probability of spontaneous emissions per unit volume.

In the equilibrium conditions the number of transitions from E_2 to E_1 must be equal to number of transitions from E_1 to E_2. Thus,

Total number of upward transitions = Total number of downward transitions

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

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

$$N_2 A_{21} = \left(N_1 B_{12} - N_2 B_{21}\right) \rho(\upsilon)$$

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

$$\rho(\upsilon) = \frac{N_2 A_{21}}{N_2 B_{21} \left(\frac{N_1 B_{12}}{N_2 B_{21}} - 1\right)}$$

$$\rho(\upsilon) = \frac{\left(\frac{A_{21}}{B_{21}}\right)}{\left(\left(\frac{N_1}{N_2}\right)\left(\frac{B_{12}}{B_{21}}\right) - 1\right)} \ldots\ldots\ldots\ldots\ldots [4]$$

From Boltzmann distribution law $N_1 = N_2 e^{\left(\frac{E_2 - E_1}{k_B T}\right)}$

$$\frac{N_1}{N_2} = e^{\left(\frac{E_2 - E_1}{k_B T}\right)}$$

$$\frac{N_1}{N_2} = e^{\left(\frac{h\upsilon}{k_B T}\right)} \qquad \ldots\ldots\ldots\ldots\ldots\ [5]$$

From [4] and [5] ,we have

$$\rho(\upsilon) = \frac{\left(\frac{A_{21}}{B_{21}}\right)}{\left(\left(\frac{B_{12}}{B_{21}}\right) e^{\left(\frac{h\upsilon}{k_B T}\right)} - 1\right)} \ \ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [6]$$

According to Planck's radiation formula $\rho(\upsilon) = \left(\frac{8\pi h\upsilon^3}{C^3}\right)\left(\frac{1}{e^{\left(\frac{h\upsilon}{k_B T}\right)} - 1}\right)$ ……….. [7]

Compare [6] and [7] ,we get

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\upsilon^3}{C^3} \ \textbf{and}\ \frac{B_{12}}{B_{21}} = 1 \quad \frac{B_{12}}{B_{21}} = 1 \Rightarrow B_{12} = B_{21}$$

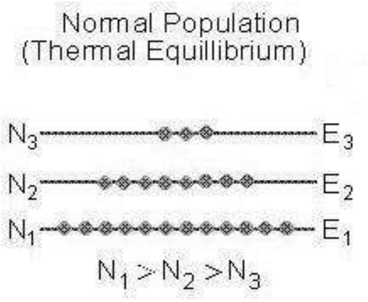
The probability of stimulated emission is same as induced absorption.

$\frac{A_{21}}{B_{21}} \alpha\ \upsilon^3$. The ratio of spontaneous emission and stimulated emission is proportional to υ^3. This shows that the probability of spontaneous emission increases rapidly with energy difference between two states.

Population

"The number of atoms per unit volume in an energy levels are called as population of that energy level. (OR) The number of active atoms occupying an energy state is called Population of that state."

N_1 And N_2 are the populations of the lower energy state E_1 and upper energy state E_2 respectively. In a state of thermal equilibrium, the populations of energy levels E_1 and E_2 are fixed by Boltzmann factor.



The population ratio is given by $\boxed{\frac{N_2}{N_1} = e^{-\left(\frac{E_2 - E_1}{kT}\right)} = e^{-\left(\frac{h\upsilon}{kT}\right)}}$

(OR)

$$\boxed{\frac{N_1}{N_2} = e^{\left(\frac{E_2-E_1}{kT}\right)} = e^{\left(\frac{h\upsilon}{kT}\right)}}$$

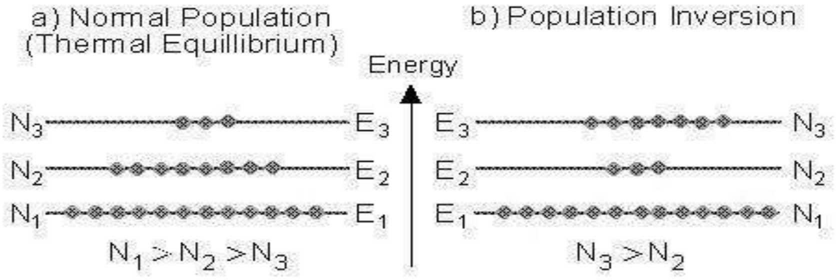
The negative exponential indicates $N_1 << N_2$ at equilibrium. It means more atoms are in lower energy state E_1. This state called Normal state.

Population inversion

In thermal equilibrium state more atoms in lower energy level than in the upper level. In order to achieve stimulated emission there must be more atoms in the upper level than in lower level. Therefore, a non equilibrium state is to be produced in which the population of the upper energy level exceeds the population in the lower energy level. When this situation occurs, the population distribution between levels E_1 and E_2 is said to be inverted, and the medium is said to have gone into the state of population inversion.

The population inversion is sometimes called as a negative temperature state that means the population inversion is a non-equilibrium state.
In practice the state of population inversion is obtained at ordinary temperature.

Consider 3-energy states in which 3-active energy levels E_1, E_2 and E_3 population in these energy states are, N_1 , N_2 and N_3 respectively.
In normal condition $E_1 < E_2 < E_3$ and $N_1 > N_2 > N_3$. E_1 is the ground state, its life time is unlimited. E_3 Is the highest energy level its life time is very less and have is most unstable state. Whereas E_2 is excited state and have more life time. Hence E_2 is metastable state.



When suitable form of energy is supplied to the system then the atoms excited from ground state E_1 to excited states E_2 and E_3. Due to instability, excited atoms will come back to ground state after the life time of respective energy states E_2 and E_3. If this process continued atoms will excite continuously to E_2 and E_3. E_3 is unstable state atoms will fall into E_2

immediately, at the stage the population in E_2 will becomes more than the population in ground state. This situation is called as ‘population inversion’.

Definition of Population inversion :

The stage of making population of the higher energy level to be greater than the population of lower energy level is known as ‘population inversion’.

Definition of Pumping:

The process of sending atoms from lower energy level (E_1) to higher energy level (E_2) to get population is called ‘Pumping’.

Conditions for population inversion:

1] The system should possess at least a pair of energy levels, separated by an energy equal to the energy of photon.

2] There should be a continuous supply of energy to the system such that the atoms must be raised continuously to the excited state.

3-Level pumping Scheme:

The state E_1 is the ground state and E_2 and E_3 are the excited states. When the medium is exposed to radiation of frequency υ a large no. of atoms will be excited to the higher energy level E_3. The E_3 level is not a stable state. Some of the atoms make spontaneous transition to the lower energy state E_1 but many of them make spontaneous transition to the metastable level E_2 through non-radiative transition.

The spontaneous transition from E_2 to E_1 occur rarely, the atoms trapped in the state E_2. The process continuous because of pumping and after same time there will be a large accumulation of atoms at E_2.

More than half of the ground state atoms accumulate at E_2 the population inversion id achieved between the states E_1 and E_2. Now, a photon of energy [$E_2 - E_1 = h\upsilon$] can tiger

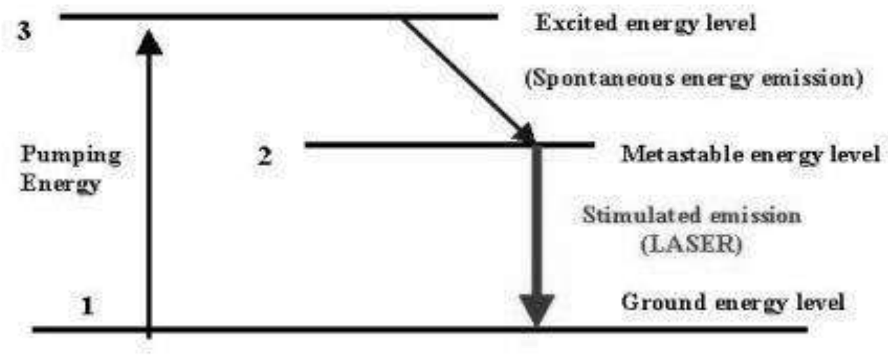


Fig. 3a: *Energy States of Three – level Active Medium*

stimulated emission of atoms at E_2 very high pump power is require in this type of pumping scheme because to achieve population inversion more than half of the ground state atoms pumped to the upper state.

4- Level pumping scheme:

Pump frequency lifts the active centers from the ground level E_1 to the upper most level E_4. From the pump level E_4 the atoms rapidly fall to the metastable state E_3. The population at this state goes rapidly while the level E_2 is virtually empty. Therefore the population is inversion is achieved between the states E_2 and E_3. The photon of energy $E_3 - E_1 = h\upsilon$ on start a chain of stimulated emission. Hence the atoms into the state E_2 from there atoms undergo non radiative transition subsequently to the ground state E_1 and will be available one to participate in this process.

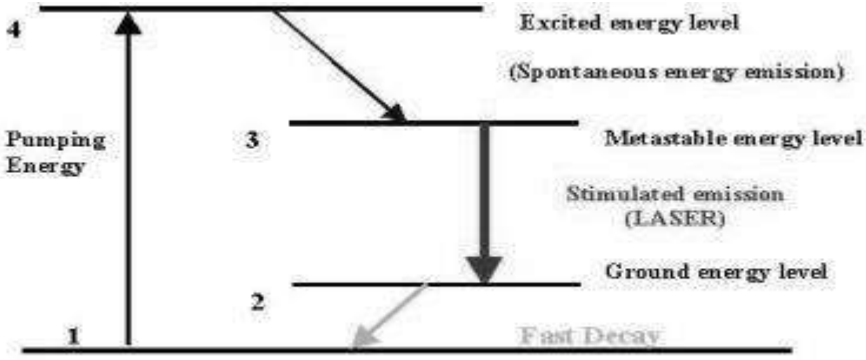
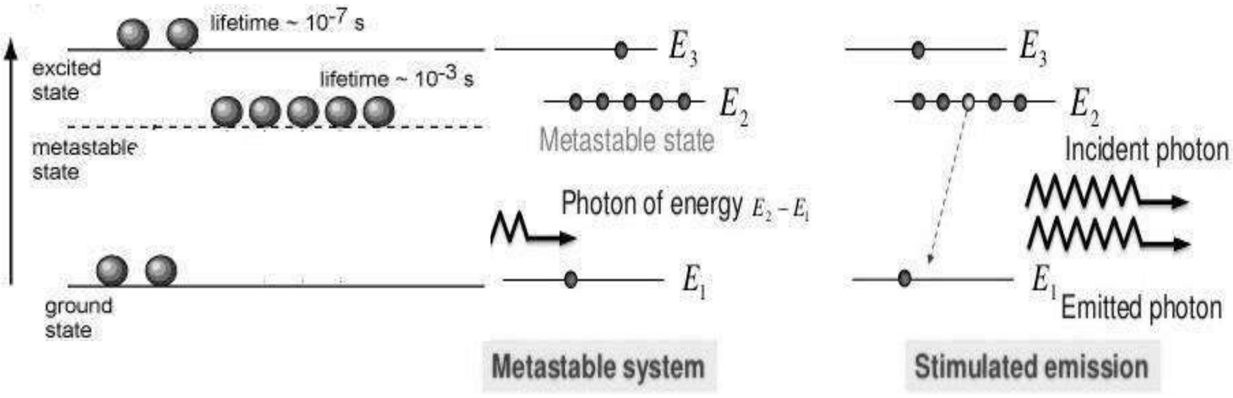


Fig. 3b: ***Energy States of Four – level Active Medium***

Meta Stable State

An atom can be excited to a higher level by supplying pumping energy; the excited atoms have short life time and release their energy in a matter of 10^{-9} sec though continuous emission. The atoms do not stay long enough at the excited state. Even though the pumping agent continuously raises the atoms to the excited level, they undergo spontaneous excitations and rapidly return to the lower energy level. Population inversion cannot be established in such circumstances. In order to establish population inversion the excited atoms are required to wait at the upper energy level till a large number of atoms accumulated at that level. It is necessary that the excited state has a large life time.

1] A Meta stable state is such state, atoms excited to meta stable state remains excited for appreciable time, which is of the order of $10^{-6}s$ (or) $10^{-3}s$. This is $10^{3}s$ or $10^{6}s$ times the life time of the ordinary energy level.



Excitation Mechanism (Methods to achieve Population inversion)

For laser action to takes place, we need the population inversion between the available energy levels of a system .To obtain population inversion ,the atoms in the lower energy level should be excited to higher energy levels by supply of additional energy in the form of excitation mechanism. The generally used various excitation mechanisms are detailed below.

(1)Optical Pumping :

In optical pumping, a light source is used to supply luminous energy to excite the atoms to higher energy levels to create population inversion for further laser emission of radiation. This type of pumping is widely used in solid state laser i.e., Ruby Laser and YAG: Nd Laser etc.

(2)Electric discharge:

In this method ,atoms are excited by collision with the fast moving accelerated electrons in an electric discharge. This mechanism is well suited for gaseous ion lasers. The electric field (kV/m) between the cathode and anode of discharge tube causes the emitted electrons by the cathode to be accelerated towards the anode. These electrons colloid with the gaseous atoms, ionize the gas and raise them to higher energy levels causing population inversion. The best example is Argon ion Laser.

3. Inelastic atom-atom collisions:

When the gaseous medium consists of two different atoms, then one atom is excited to the corresponding higher energy level by electric discharge. This excited atom colloid with the different atoms in the medium elastically transferring its energy to it and pumping it to the equivalent its higher energy levels. Population inversion is caused by the inelastic collisions between two various atoms of the gaseous medium. The best example is He-Ne Laser.

$$A + e \rightarrow A^{*} + e1$$

$$A^* + B \rightarrow A + B$$

Here A and B are two different gases.

4.Chemical Reaction:

In this method, the chemical energy released during the chemical process will excite the atoms to higher energy levels causing population inversion in the lasing system. For example, Hydrogen can react with Fluorine liberating heat energy. This heat energy will try to excite the atoms to the higher energy level.

5.Direct Conversion:

When a p-n junction is forward biased, then recombination of electron- hole pair across the junction emits radiations. In this process, the applied electric energy promotes the emission of radiation. The best example is Semiconductor Lasers.

Block diagram of a laser system:

The block diagram of laser system contains three parts, they

(i) are Source of energy
(ii) Active medium and
(iii) Optical resonator

(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, the pumping source is optical pumping that is helical xenon flash tube. In helium-neon laser, electrical pumping that is electric discharge is used.

(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 exited state to achieve population inversion is called as active centers.

For example in ruby laser, the active medium is Aluminum oxide (Al_2O_3) doped with Chromium oxide (Cr_2O_3). In which chromium ions (Cr^{3+}) act as active centers. In helium - neon laser it is the combination of helium and neon in the ratio of 10:1 in which Ne atoms act as active centers.

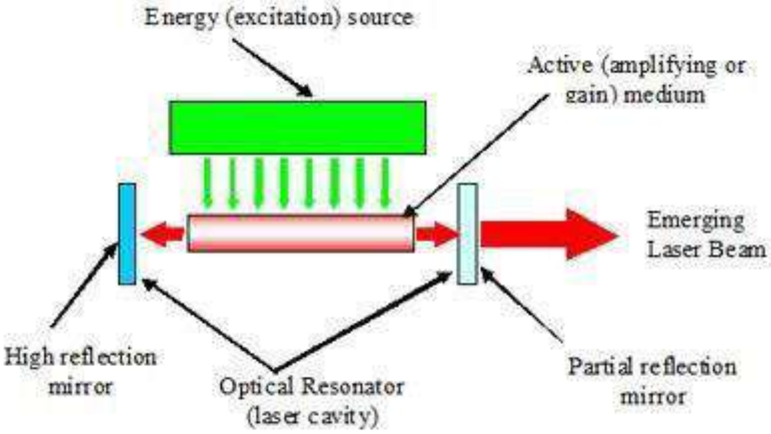


Fig: Components of LASER system.

Optical resonator or optical cavity:

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.

Different types of laser systems:

On the basis of active medium used in the laser system, lasers are classified into several types, and most popular methods are:

1] Solid state lasers (YAG-Nd Laser, Ruby laser)
2] Liquid lasers (Europium laser)
3] Gaseous lasers (He-Ne laser)
4] Dye lasers (Coumarium laser)
5] Semiconductor lasers (GaAs laser)

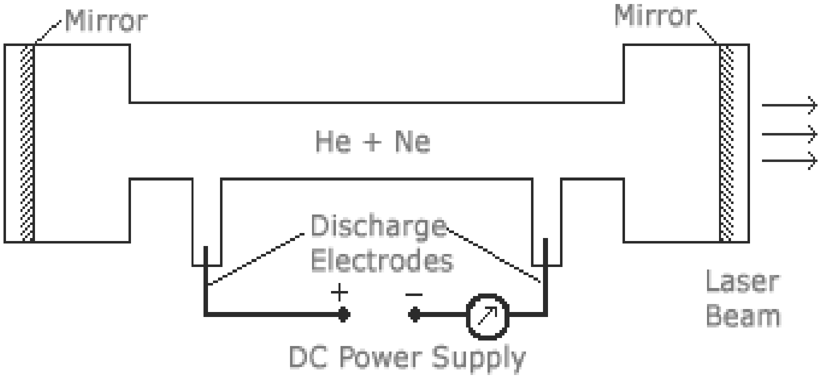
Most lasers emit light in the RED or IR region. Lasers can be operated in a continuous wave mode or in a pulsed mode with a higher output power.

He-Ne Laser

- He-Ne Laser is a gaseous laser system and is used to produce a continuous laser.
- This laser is highly directional, monochromatic, coherent and stable.
- The output of gas lasers is moderate and is generally few mill watts.
- The gas lasers are operating continuously with need of cooling.
- The first laser successfully operated is He-Ne gas laser.

Construction:

The He-Ne gas laser consists of fused quartz tube filled with mixture of neon under the pressure of 0.1mm of mercury and Helium under pressure of 1mm of mercury. The ratio of He-Ne is 10:1 hence the number of Helium atoms is greater than neon atoms. The output power from laser depends upon the length of the discharge tube and pressure of gas mixture.

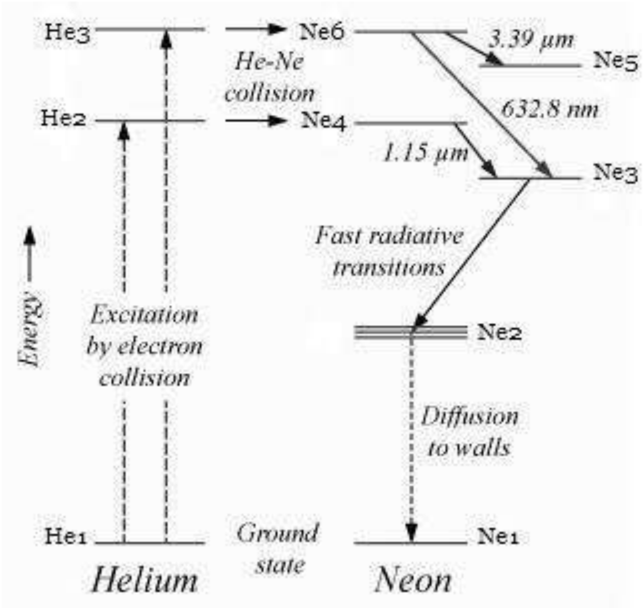


At one end of the tube, there is a perfect reflector while on the other end is partially reflector. The active medium in this laser is excited by a high frequency generator.

Working:

In He atom three energy levels are present, they are named as He_1, He_2 and He_3. In Neon atom six active energy levels, they are named as Ne_1 , Ne_2, Ne_3 , Ne_4, Ne_5 and Ne_6.

Here, it should be noted that He_2 and Ne_4 have same energy and life time similarly He_3 and Ne_6.



When a discharge is passed through the gas, the electrons accelerated towards the positive electrode. During their passage they collide with He atoms and excite them into upper states labeled He_2 and He_3. These are Meta stable states in Helium atoms.

Thus the He atoms remain in these energy levels for sufficiently long time. Now these atoms interact with neon atoms, which are in ground state.

The interaction excites the Neon atoms to their metastable states labeled as Ne_4 and Ne_6 while helium atoms return to their ground state. As the energy exchange is continuously between He and Ne atoms, the population of neon atoms in the excited states Ne_4 and Ne_6 increases more and more. At the stage population inversion will be achieved in the Meta stable states Ne_4 and Ne_6.

After achieving population inversion:

1] Few Neon atoms de excite from Ne_6 to Ne_5. During this transition electromagnetic radiation of wavelength of 3390 Å will be emitted.

2] Many other Neon atoms de excite from Ne_6 to Ne_3. During this transition electromagnetic radiation of wavelength 6328 Å will be emitted. This is important and major wavelength in this laser system.

3] In continuation atoms in the excited state Ne_4 de excite to Ne_3, where an electromagnetic radiation of wavelength 1150 Å is emitted.

4] After reaching all the Neon atoms to Ne_3, spontaneously those will de excite to Ne. During this transition, an electromagnetic radiation of wavelength 6000 Å will be emitted.

5] Finally Neon atoms take non radiative transition by making collisions with walls of the tube from Ne_2 to Ne_1 .

He-Ne Laser - Characterstics

1] Type:	Gas laser
2] Active medium:	He-Ne gas mixture
3] Active centres:	Ne - Atoms
4] Pumping mechanism:	Electric discharge
5] Output:	100mW
6] Nature of output:	continuous wave
7] Wavelength emitted:	6328 Å

Advantages of He-Ne Laser

1.It is a continuous Laser which emits high monochromatic and high directional laser light when compared to solid state Lasers.

2. Due to end window set at Brewester's angle, we get linearly polarized Laser.

GaAs semiconductor laser:-

The GaAs laser was constructed by Hall.

Characteristics:-

Type	: Semiconductor laser
Active medium	: P-N junction diode
Active centre	: Re combination of electrons and holes
Pumping method	: Direct pumping
Optical resonator	: Junction of Diode ends Polished
Nature output	: pulsed (or) continuous waveform
Power output	: 1mw
Wave length	: 8200Å -9000 Å
Band gap	: 1.44 ev

Active medium:The active medium in GaAs laser is GaAs. But it is also commonly said that depletion region is the active medium in semiconductor laser. The thickness of the depletion layer is usually very small (0.1 μm).

Pumping Source: Forward biasing is used as pumping source. The p-n junction is made forward biased that is p side is connected to positive terminal of the battery and n side to negative terminal. Under the influence of forward biased electric field, conduction electrons will be injected from n side into junction area, while holes will enter will enter the junction from the p side. Thus, there will again be recombination of holes and electrons in depletion region and thus depletion region becomes thinner.

Optical resonator system: The two faces of semiconductor which are perpendicular to junction plane make a resonant cavity. The top and bottom faces of diode, which are parallel to junction plane, are metalized so as to make external connections. The front and back faces are roughened to suppress the oscillations in unwanted direction.

Principle: - When a p-n junction is formed across a p and n-type semiconductor, then it results in the formation of depletion region across the junction. When the junction is forward biased, the width of depletion region decreases allowing more number of electrons from n-type to across the junction and recombine with holes in p-type. This, recombination of hole pairs across the junction emits the radiation (as shown in figure 7.25).

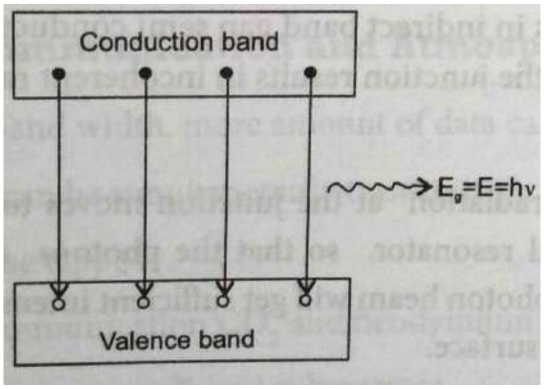


Figure: Principle of semiconductor laser

Construction:-

- A typical GaAs laser is shown in fig.
- A rectangular block of Ga-As semiconductor is converted into p and n-type by proper doping of impurities into the block. The upper region acts as p-type and the lower portion as n-type .Between these two regions, we have a p-n junction. To achieve population inversion p and n-regions are heavily doped with the impurities. The p-n junctions act as active medium. The two faces of the block, one fully polished and the other partially polished act as an optical resonator (or) cavity.

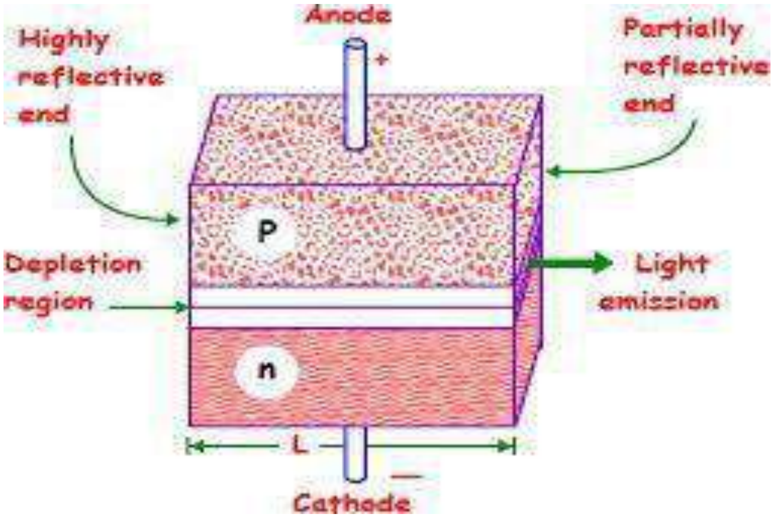


Figure: Construction of semiconductor diode Laser.

Working:

When the p-type is connected to the positive terminal of the battery and the n-type is connected to the negative terminal then the p-n junction will be in forward biased condition, then there will be injection of electrons into the conduction band along n-side and production of more holes in valence band along p-side of the junction. Thus, there will be more number of electrons in conduction band comparable to valence band, so population inversion is achieved. Therefore, when the electrons and holes are injected into the junction region from opposite sides with forward biasing, then population inversion is achieved between levels near the bottom of the conduction band and empty levels near the top of the valence band.

When electrons recombine with the holes in junction region, then there will be release of energy in the form of photons. This release of energy in the form of photons happens only in special types of semiconductors like Gallium Arsenide (GaAs). Otherwise in semiconductors like silicon and germanium, whenever holes and electrons recombine, energy is released in the form of heat, thus Si and Ge cannot be used for the production of laser.

The spontaneously emitted photon during recombination in the junction region of GaAs will trigger laser action near the junction diode. The photons emitted have a wavelength from 8200 Å to 9000 Å in the infrared region.

Calculation of wavelength:

Band gap of GaAs =1.44 ev (1ev=1.6× 10^{-19} J)

$$E_g = h\square = h\frac{\square}{\square} \qquad (c = \square\square)$$

$$\square = \frac{\square}{\square}$$

$$\lambda = \frac{hc}{E_g} = \frac{6.625\times10^{-34}\times3\times10^{8}}{1.44\times1.6\times10^{-19}}$$

$$\lambda = 8626\ \text{Å}$$

The wavelength is near IR region.

Advantages:-

- It is easy to manufacture
- The cost is low.
- The efficiency of GaAs laser is high.

Disadvantages:

- It produces low power output.
- The beam has large divergence.

Nd:YAG Laser:

- Nd-YAG laser is one of the most popular types of solid state laser. It is a four level laser.
- Yttrium aluminum Garnet ($Y_3Al_5O_{12}$), commonly called YAG is an optically isotropic crystal.
- Some of the Y^{3+} ions in the crystal are replaced by neodymium ions, Nd^{3+}.
- Doping concentrations are typically in the order of 0.725% by weight.
- The crystal atoms do not participate in the lasing action but serve as a host lattice in which the active centers, namely Nd^{3+} ions reside.

Construction:

- Figure illustrates a typical design of Nd:YAG laser. The system consists of elliptically cylindrical reflector housing the laser rod along one of its focus line and a flash lamp along the other focus line.
- The light leaving one focus of the ellipse will pass through the other focus after reflection from the silvered surface of the reflector. Thus the entire lash lamp radiation gets focused on the laser rod.
- The YAG crystal rods are typically of 10cm in length and 12mm in diameter. The two ends of the laser rods are polished and silvered and constitute the optical resonator.

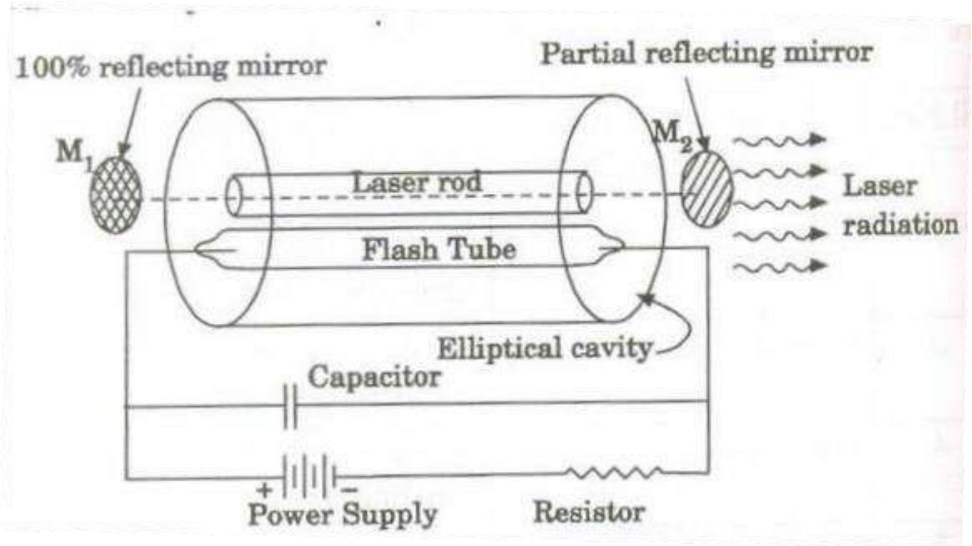


Figure: Construction of Nd:YAG Laser

Working:

A simplified energy level diagram for the neodymium ion in YAG crystal is shown in figure. The energy level structure of the free neodymium atom is preserved to a certain extent because of its relatively low concentration. However the energy levels are split and the structure is complex.

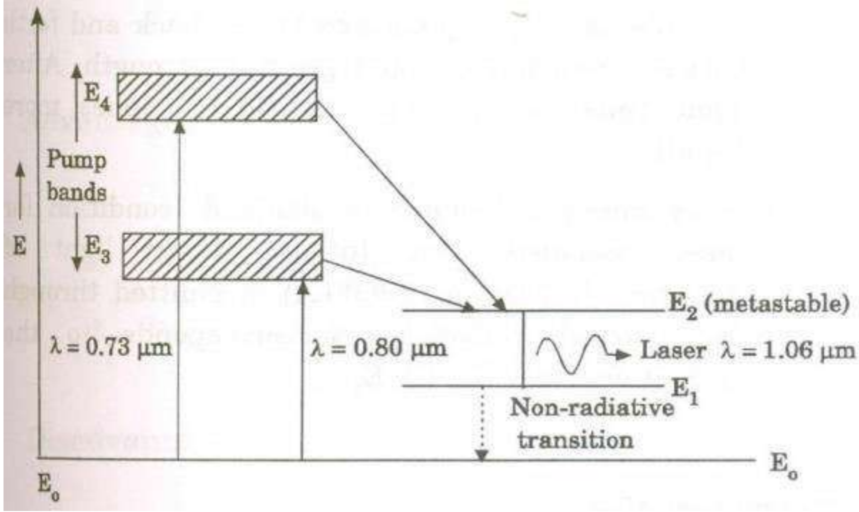


Figure: Energy level diagram for the neodymium ion in YAG crystal

The Pumping mechanism:

- ❖ When the krypton flash lamp is switched on, the Nd^{3+} ions are excited to the upper energy band E_4 and E_5.
- ❖ The Nd^{3+} ions make a transition from these energy levels to level E_3 by non- radiative transition.E_3 is metastable state.
- ❖ The metastable level E_3 is the upper laser level.

Population Inversion:

- ❖ The upper laser level E_3 will be rapidly populated, as the excited Nd^{3+} ions quickly make downward transitions from the upper energy bands.
- ❖ The lower laser level E_2 is far above the ground level and hence it cannot be populated by Nd^{3+} ions through thermal transitions from the ground level.
- ❖ Therefore the population inversion is readily achieved between the E_3 level and E_2 level.

Lasing:

- ❖ A chance photon is produced when an Nd^{3+} ion makes a spontaneous transition from E_3 level to E_2 level. This spontaneous photon stimulates another excited atom to make a downward transition.
- ❖ This stimulated photon and initial photon trigger many excited atoms to emit photons.
- ❖ Photons thus generated travel back and forth between the two end mirrors and gain in strength very rapidly.
- ❖ On attaining sufficient energy, the laser beam emerges out through the partially reflecting mirror.
- ❖ The laser emission occurs in infrared (IR) region at a wavelength of about 10,600 A^0 (1.6 μm).
- ❖ The Nd^{3+} ions return to the ground state E_1 from the lower lasing level E_2 on their own through non-radiative transitions.

Salient Features:

- Uses four level pumping schemes.
- The active centers are Nd^{3+} ions.
- Light from a Xenon or Krypton flash lamp is the pumping agent.
- Low efficiency and moderate power output.
- Operates in CW/pulse mode.

Application of Laser :

Industry :

(1) With increased power output, lasers can be used as a welding tool. Dissimilar metals can be welded using lasers with minimum distortions. Lasers are used to cut glass and quartz.
(2) Lasers are used to drill holes in ceramics.
(3) Lasers are used to drill aerosol nozzles and control orifices within the required precision.
(4) Lasers are used for heat treatment in the tooling and automotive industry.
(5) Lasers are used in electronic industry in trimming the components of ICs
(6) In plastic industry, polymers are obtained by irradiating monomers by lasers.

Medicine:

(1) Ophthalmologists use laser for attaching the retina in retinal-detachment cases.
(2) Lasers are used for cataract removal.
(3) Lasers are used for eye lens curvature corrections.
(4) Lasers are used for bloodless surgery.
(5) Lasers are used in angioplasty for removal of artery block.
(6) Lasers are used in cancer diagnosis and therapy.
(7) Lasers are used in destroying kidney stones and gallstones.
(8) Lasers are used in plastic surgery, skin injuries and to remove moles and tumours developed in skin tissue.
(9) Lasers are used in the treatment of mouth diseases.
(10) Lasers are used in the treatment of liver and lung diseases.
(11) Laser Doppler velocimetry is used to measure blood velocity in blood vessels.

Scientific Field :

(1) Lasers are used for isotope separation.
(2) Lasers are used in recording and reconstruction of a hologram.
(3) Lasers are used to create plasma.
(4)Lasers are used to produce chemical reactions.
(5) Lasers are used to study the internal structure of microorganisms and cells.
(6) Lasers are used in air pollution, to estimate the size of the dust particles.
(7) Lasers are used to develop hidden fingerprints and to clean delicate pieces of art.

Unit-IV- chapter-2
Fiber optics

Introduction:

The developments in the fields of communication and information technology demand very easy and transmission of data over longer distances. Fiber optic technology is increasingly replacing wire transmission lines in communication systems and is expected to be as common as electrical wiring even in our vehicles and house very shortly.

Optical fiber lines offer several important advantages over wire lines. Optical fibers are light equitant of microwave guides with the advantage of very high bandwidth and hence very high information carrying capacity .Though at the beginning fiber optic communication systems were more expensive than equivalent wire or radio system, now the situation has changed very much. Fiber optic systems have become competitive with other systems in price and eventually started replacing them.

Fiber optics is a branch of optics which deals with the study of propagation of information in the form of light (rays or modes) through transparent dielectric optical fibers.
The term optical fiber was first coined by N.S.Kapany.

Optical fiber:

The word fiber comes from Latin *fibra* which means a thin thread like piece of material. Therefore; Optical fiber means a thin thread like piece of visible material.
Optical fiber is a thin and transparent guiding dielectric medium or material which guides or transmits the information as light waves, using principle of total internal refection.

Definition of an optical fiber

Optical fiber is a thin and transparent guiding medium or material which guides the information carrying light waves.

Principle of optical fiber:

An optical fiber works on the principle of total internal reflection.
John Tyndall observed that the propagation of light through the optical fiber will be in the form of multiple total internal reflections.

Definition of Total internal reflection:

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

Explanation:

Consider a light ray passing from a denser medium of refractive index (n_1) into a rarer medium of refractive index (n_2) as shown in fig. Assuming that $n_1 > n_2$ and that the angle of incidence and refraction with respect to normal to the interface are **i** and **r** respectively.

Then according to Snell's law, $n_1 \sin i = n_2 \sin r$………………… (1).

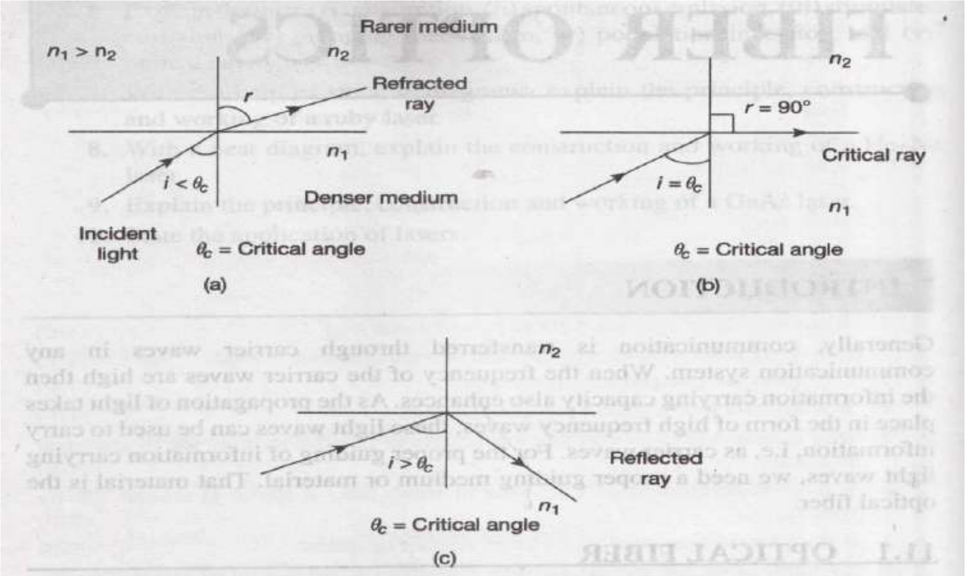


Fig: (a) Normal refraction (b) Critical angle (c) Total internal reflection.

The refracted ray bends away from the normal as it travels from denser medium rarer medium with increase of angle incidence.

As $n_1 > n_2$, if we increase the angle of incidence **i,** the angle of refraction r will go on increasing until a critical situation is reached, when for a certain value of **i= θ**$_c$, **r** becomes $\frac{\square}{2}$ and refracted ray passes along interface. This angle **i = θ**$_c$ is called critical angle [see fig (b)].

If angle of incidence I is further increased beyond **θ**$_c$, the ray is no longer refracted but is reflected back into the same medium [see fig (c)].this is called total internal reflection.

From the equation (1); $n_1 \sin i = n_2 \sin r$.

$$\text{When } i = \theta_c \text{ then } r = \frac{\square}{2} = 90^0.$$

$$\text{Therefore; } n_1 \sin \theta_c = n_2 \sin 90^0 .$$

$$n_1 \sin \theta_c = n_2 .$$

$$\sin \theta_c = n_2/n_1$$

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

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

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

Conditions for total internal reflection:

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

Optical fiber structure and construction:

A typical structure of optical fiber as shown in fig.

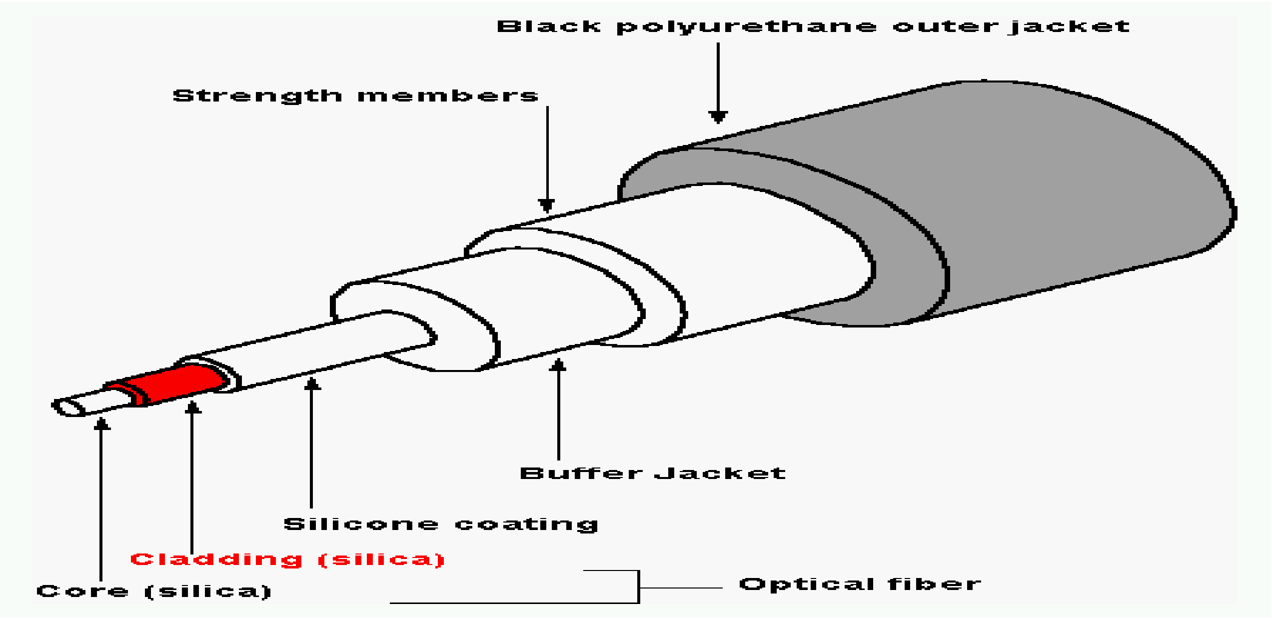


Fig: Structure of optical fiber.

The optical fiber mainly consists of the following six parts as shown in fig.

1. Core and cladding:

An optical fiber consists of a central cylindrical material layer called core with high refractive index n_1, surrounded by a second cylindrical material layer called cladding with a lower of

refractive index n_2. ($n_1 > n_2$)

The core is the inner part of the fiber, which guides or transmits the light and cladding keeps the light waves within the core because the refractive index of the cladding is less than that of the core. (Core acts as denser medium and cladding act as rarer medium). The core and cladding are made of either plastic or glass.

2.Silicon coating: it is provided between cladding and buffer- jacket in order to improve the quality of transmission of light.

3.Buffer jacket: it is covered over silicon coating which is made up of plastic material and protects the fiber from moisture and abrasion.

4.Strength members: this layer is arranged over the buffer jacket to provide necessary toughness and tensile strength to the fiber.

5.Black polyurethane outer jacket: Finally a block polyurethane outer layer is provided to avoid damages during hard pulling, bending, stretching or rolling of the fiber in the real field.

Acceptance angle and acceptance cone:

The maximum angle at which the light can suffers total internal refection is called as acceptance angle.

The acceptance cone is derived by rotating the acceptance angle about the fiber axis.

Explanation:

Let us consider a cross-sectional view of an optical fiber. It consists of core of refractive index n_1 and cladding of refractive index n_2 respectively.

Let n_o be the refractive index of the medium (air) in which the optical fiber is placed. The incident ray travels along AO and enters the core at an angle θ_i to the fiber axis. The ray is refracted along OB at an angle θ_r in the core as shown in fig. In core it travels along AB and is incident at point B on core-cladding interface. Let θ be angle of incidence at B.

When θ is greater than the critical angle θ_c then the total internal reflection takes place into core and light takes the path BD. Due to multiple total internal reflections the propagation of light ray takes place through the fiber

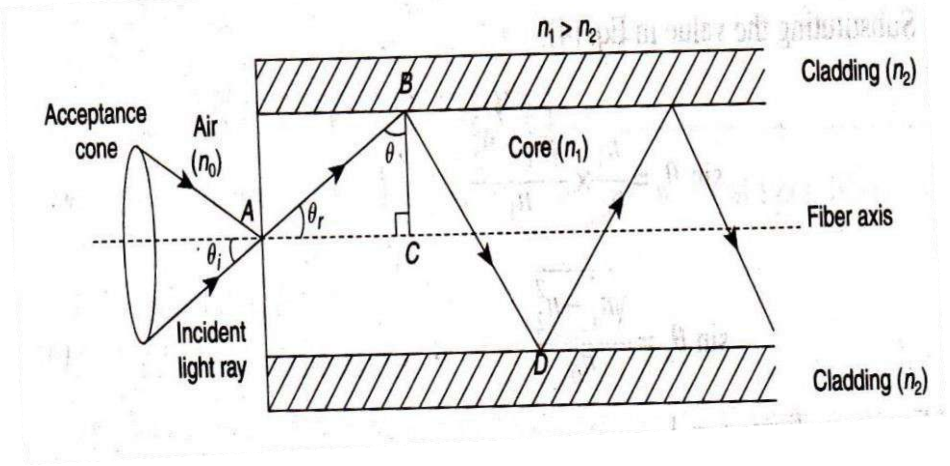


Fig: Cross-sectional view of optical fiber

Applying Snell's law at a (core-air interface)

$$n_0 = \frac{1}{\sin \Theta_i}$$

$$n_1 = \frac{1}{\sin \Theta r}$$

$$\frac{n1}{n0} = \frac{\sin \Theta i}{\sin \Theta r}$$

$$n_0 \sin \Theta i = n_1 \sin \Theta r \;..............................(1)$$

Let a normal BC drawn from the point B to fiber axis. Then the from ΔABC, we get

$$\Theta r + \Theta = 90^0$$

$$\Theta r = 90^0 - \theta \;........................(2)$$

Substituting the above value in equation (1)

$$n_0 \sin \Theta i = n_1 \sin (90^0 - \Theta)$$

$$n_0 \sin \Theta i = n_1 \cos \Theta \;............................. (3)$$

To get toatl internal reflection at point b(core-cladding interface) the incident angle Θ should be greater than or equal to Θc (critical angle).

Let the maxium angle of incidence at point A be $\Theta = \Theta a$ for which $\Theta \geq \theta c$.

From equation (3),we get,

$$n_0 \sin \Theta a = n_1 \cos \theta_c$$

$$\sin \Theta a = \frac{n1}{n0} \cos \theta_c \;.............................(4)$$

$$\text{But} \qquad \sin \theta_c = \frac{n2}{n1}$$

$$\cos \theta_c = \sqrt{1 - \sin^2 \Theta c} = \sqrt{1 - \frac{n_2^2}{n_1^2}}$$

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

$$= \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \;.................. (5)$$

Substituting the values in equation (4)

$$\sin \Theta_a = \frac{n1}{n0} \text{ x } \frac{\sqrt{n_1^2 - n_2^2}}{n1}$$

$$\sin \Theta_a = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \;....................................(6)$$

For air medium $n_0=1$

$$\sin \Theta a = \sqrt{n_1^2 - n_2^2} \;...........................(7)$$

$$\Theta a = \sin^{-1} \sqrt{n_1^2 - n_2^2} \;..............................(8)$$

In the above expression, Θa is the maximum angle of incidence of light at the core and light can suffers total internal reflection.

Thus the maximum angle at which the light can suffers total internal refection is called as acceptance angle.

Acceptance cone:

Rotating the acceptance about the fiber axis, we get an incident light cone with semi-vertical angle asΘa. This incident light cone at core of an optical fiber will be accepted by the fiber for

guidance through it, and is known as acceptance cone.

Numerical aperture (N.A):

Numerical aperture represents the light gathering power of an optical fiber. It is a measure of the amount of light that can be accepted by a fiber. The value of NA ranges from 0.13 to 0.50. A large NA implies that a fiber will accept large amount of light from the source.

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

$$N.A = \sin \Theta a.$$

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

$$= \sqrt{(n_1 + n_2)(n_1 - n_2)} \ldots\ldots (9)$$

Numerical aperture is also defined as fractional index change **Δ**. It is the ratio of refractive index difference in core and cladding to the refractive index of core**.**

$$\text{i.e.,} \quad \Delta = \frac{n_1 - n_2}{n_1} \quad \ldots\ldots\ldots (10)$$

This parameter is always positive because n1 must be larger than n2 for the total internal reflection condition. In order to guide light rays effectively through a fiber, Δ<<1.Typically Δ is of the order of 0.01.

From the equation (9)

$n_1 - n_2 = \Delta n_1$………… (11)

Substituting equation (10) in equation (9)

$$N.A = \sqrt{(n_1 + n_2)\Delta n_1}$$

For all optical fibers, $n_1 \approx n_2$, so

$$N.A = \sqrt{2 n_1^2 \Delta}$$

$$N.A = n_1 \sqrt{2\Delta} \ldots\ldots\ldots\ldots\ldots (12)$$

This is the relation between Numerical aperture and fractional index change.

Types of optical fibers:

Based on type of material used in core and cladding, optical fibers can be classified into two types. They are

(1) Glass fiber
(2) Plastic fiber

(1)Glass fiber :

If optical fibers are made by fusing mixtures of metal oxides and silica glasses, then it is known as ‘glass fiber. The resulting material is randomly connected by molecular network rather than well defined ordered structures as found in crystalline materials.

The most common material used in glass fiber is silica (oxide glasses).It has a refractive index of 1.458 at 850 nm. To produce two similar materials having slightly different indices of refraction for the core and cladding, either fluorine or various oxides such as B_2O_3 , GeO_2 or P_2O_5. are added to silica.
Examples of fiber compositions are:

1. $GeO_2 – SiO_2$ core; SiO_2 cladding
2. P_2O_5-SiO_2 core ; SiO_2 cladding
3. SiO_2 core : P2O5-SiO_2 cladding

Another type of silica glasses are the low melting silicates .Such optical fibers are made of soda Lime silicates, germanosilicates and various borosilicates.

(2)Plastic fibers :

The plastic fibers are typically made of plastics are of low cost and can be easily handled without special care due to their toughness and durability.
Examples of plastic fibers are as follows:

1. Polystyrene core ($n_1 = 1.6$) and methylmethacrylate cladding ($n_2=1.49$)
2. Polymethylmethacrylate core ($n_1= 1.49$) and cladding made of its co-polymer ($n_2=1.40$)

Again based on variation of refractive index of core of an optical fiber, optical fibers are classified into two types. They are

(1) Step index optical fiber
(2) Graded index optical fiber

Again based on number of paths (Modes) , available for the light rays inside the core, these optical fibers are further divided into two types , they are

(1)Single mode optical fiber
(2) Multimode optical fiber

In single mode optical fiber, the width or diameter of the core is smaller when compared to the width of the cladding. As a result, only a single path (mode) is available for the light ray through the optical fiber.
When the width of the core is greater than the cladding, then the large number of paths (modes) is available for the light ray through the fiber and fiber and it is known as multimode optical fiber.

(1) Step index optical fiber – Refractive index profile:

- In a step index optical fiber, the refractive index of the core remains constant throughout the core and decreases from step to n_1 to n_2 at the core cladding interface. Thus it is known as Step-index optical fiber.
- The transmission of information will be in the form of signals or pulses.
- For single mode step index optical fiber, a single light ray from the signal enters into the fiber and traverses a single path and forms the output signal. In this case two signals match with each other as shown in figure 11.5
- In a multimode step index optical fiber, due to large width of core, greater number of light rays from the input signals enters into the core and takes multipath as shown in figure 11.6.
- The light ray (1) which greater angle with the fiber axis suffers more reflections through the fiber and takes more time to traverse the optical fiber, where as the light ray (2) makes less angle with the axis suffers less number of reflections and within a short time, it traverses the optical fibers.

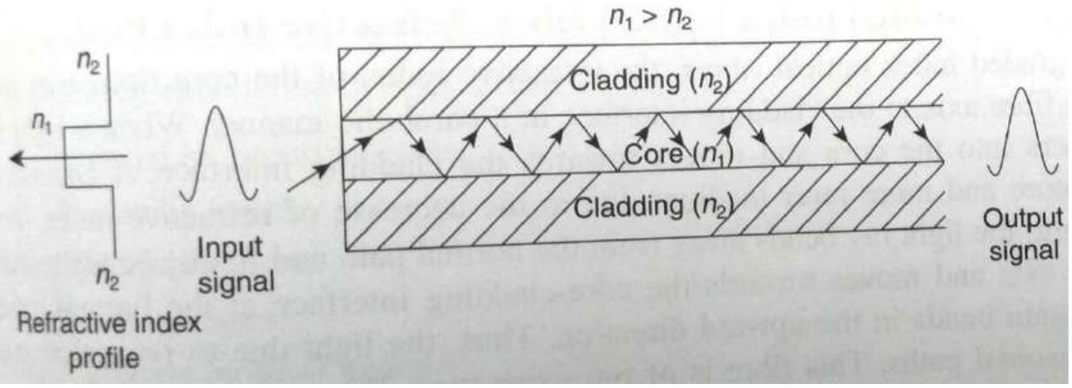


Figure: Single mode step index optical fiber.

- At the output end we receive ray (2) first and later we get ray (1). Due to the path difference between the light rays when they superimpose to form the output signals, the signals are overlapped. In this we get signal distortion known as ' intermodal dispersion'.

- It is difficult to retrieve the information carried by the distorted output signal. In a step index fiber, the propagation of light ray is due to multiple reflections, so it is reflective type.

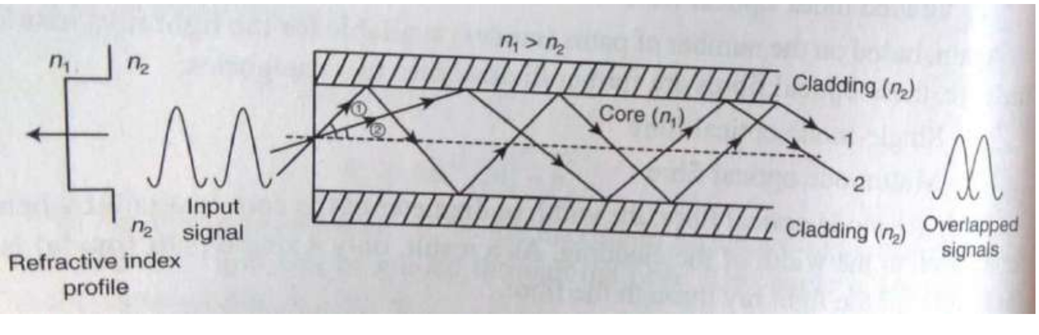


Figure: Multimode step index optical fiber.

The number of possible propagation modes in the core is given by the V-number as,

$$V = \frac{2\pi}{\lambda} a\,(NA)$$

Where λ = Wavelength of light
a = radius of the core
NA = Numerical aperture

Number of modes through step index fiber = $\frac{V^2}{2}$

Note :

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

(2) Graded index optical fiber – Refractive index profile:

- In graded index optical fiber, the refractive index of the core decreases from the fiber axis to the cladding surface in a parabolic manner.
- When a light ray enters into the core and moves towards the cladding interface, it encounters a more and more rarer medium due to decrease of refractive index.
- As a result, the light ray bends more away from the normal and finally bends towards the axis and moves the core-cladding interface at the bottom. Again it bends it bends in the upward direction.
- Thus the light due to refraction takes sinusoidal paths. This fiber is of refractive type. When two light rays (1) and light ray (2) making different angles with the axis enters into the fiber , they adjust their velocities (due to variations of refractive index) and come to focus at the same point.
- As a result, all the light rays will be received at the output end at the same time. There is no intermodal dispersion and the output signals match with input signal. It is easy to retrieve the information from the signals. In this fiber we get a refocusing effect of light rays.
- The number of possible modes through graded index fiber = $\frac{V^2}{2}$ where V is the V-number.

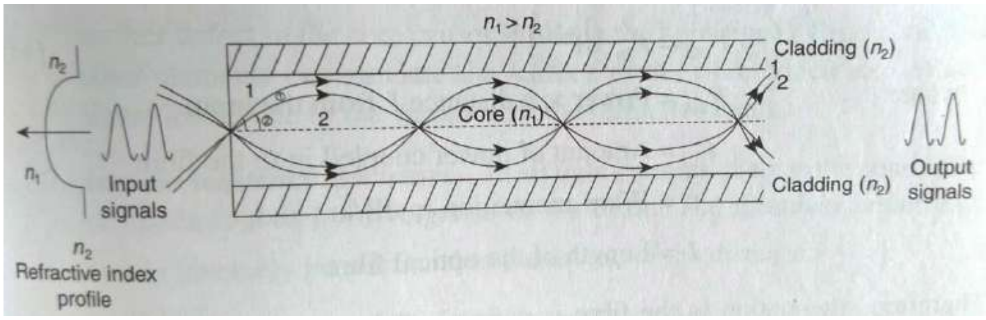


Figure: Graded index optical fiber.

Attenuation and losses in fibers:

When the light signal propagates in the optical fibers, losses arise due to different factors and these losses are referred to attenuation in optical fiber.

Losses are expressed in decibles per kilometer (dB/km). The attenuation loss (α) is given by,

$$\alpha = \frac{10}{l}\log\left(\frac{\log(p\ in)}{\log(p\ out)}\right) \text{ dB/km}$$

Where P_{out} = Power at a distance L from the input

P_{in} = Amount of power coupled in the fiber

A = Fiber attenuation in dB/km

L = length of the optical fiber

Definition of Attenuation in optical fiber :

The ratio of the optical power input (P_{in}) fed to the optical fiber to the optical power output (P_{out}) obtained from a fiber of length ‘L’ is called Attenuation of an optical fiber.
The various factors causing attenuation in optical fiber are:

1) Material (or) impurity losses
2) Scattering losses
3) Absorption losses
4) Bending losses
5) Radiation induced losses
6) Inherent defect losses
7) Inverse sequence law losses
8) Transmission losses
9) Core and cladding losses.

1.Material (or) impurity losses :

The doped impurities present in the fabrication of an optical fiber in order to vary the refractive index causes losses in the light signal propagation through the fiber.

2.Scattering losses :

In glass fiber, the fiber glass contains many microscopic inhomogeneities and material content. Due to this, a portion of light signal passing through the glass fiber gets scattered. This scattering loss varies inversely with the fourth power of the wavelength.

$$\text{Scattering loss } \alpha \ \frac{1}{\lambda^4}$$

3.Absorption losses :

Absorption loss is caused by the nature of the core material and varies inversely to the transparency of the material. For glass fibers, ion-resonance absorption ultra violet absorption and infrared absorption are three separate mechanisms which contribute to total absorption losses.

4.Bending losses:

Whenever a fiber deviates from a straight line path , radiative losses occur.These losses are prominent for improperly installed single mode optical cable

5.Radiation induced losses:

When the glass molecular matrix interacts with the electrons, neutrons, X-rays and gamma rays, the structure of the molecules is altered and the fiber darkens. This introduces additional losses which increase with amount, type, dose and exposure time of radiation..

6. Inherent defect losses:

The inherent defect present in the core and cladding causes losses of the propagating light signal through it. The surface defect in the core causes losses in the light signal. Grease, oil and other contaminates on the surface of the fiber also causes signal losses due to variation of refractive index.

7. Inverse sequence law losses:

In all light systems, there is the possibility of losses caused by divergence of the beam. The illuminance per unit area is inversely proportional to the square of the distance.

The illuminance per unit area α $\frac{\square}{\square^{\square}}$

8.Transmission losses:

The losses are caused by light which is caught in the cladding material of the optical fibers. This light is either lost to the outside or is trapped in the cladding layer and is thus not available for propagation in the core of the fiber.

9.Core and cladding losses:

In a fiber, core and cladding have different refractive indices as they have different compostions.so the core and the cladding have different attenuation coefficients, causing the power losses in the fiber.

Block diagram of optical fiber communication system:

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

Transmitter:

The information signal source may be audio, video, and data etc, which is in analog form to be transmitted, is converted from analog signal to electrical signal.

The transmitter consists of a drive circuit and a light source. The drive circuit transfers the electric input signal into digital pulses and the light source (LED/LASER) converts that optical pulses and are focused into the optical fiber.

Fiber–optic cable:

It acts as a waveguide and transmits the optical pulses towards receiver, by the principle of total internal reflection.

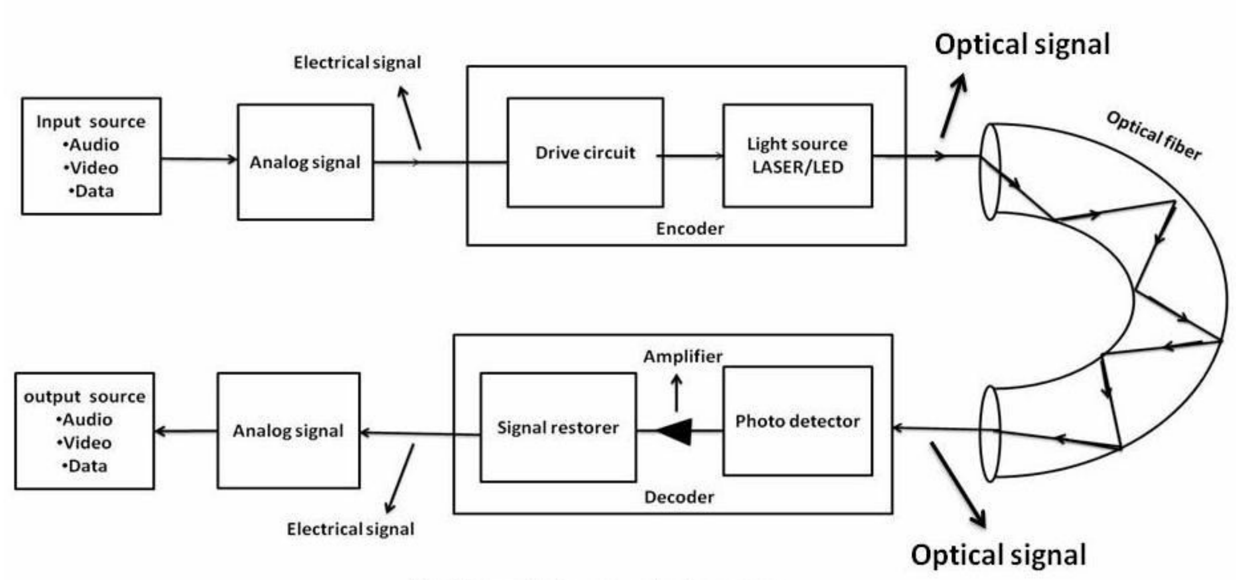


Fig: Fiber optical communication system

Receiver:

The receiver consists of a photo detector, amplifier and signal restorer. The photo detector receives the optical pulses and converts into electrical pulses. Further the signals are *amplified (distortion & noise are filtered out)* by an amplifier. These electrical signals are decoded i.e., converted from digital to analog signal. Thus original signal is obtained, in analog form, with the same information. In this way information is transmitted from one end to other end.

Advantages of Optical fiber in communication:

Let us see the advantages of optical fiber communication over conventional communication system.

(1) Enormous band width:

The information carrying capacity of a transmission system is directly proportional to the carrier frequency of the transmitted signals. The optical carrier frequency is in the range of 10^{14}

Hz while the radio frequency is about 10^6 Hz and microwave frequency is about 10^{10} Hz. Thus the optical fibers have enormous transmission bandwidths and high data rate. Using wavelength division multiplexing operation, the data rate or information carrying capacity of optical fibers is enhanced to many orders of magnitude.

(2)Low transmission loss :

Due to the usage of ultra low loss fibers and the erbium doped silica fibers as optical amplifiers, one can achieve almost loss less transmission .Hence for long distance communication fibers of 0.002 dB/km are used. Thus the repeater spacing is more than 100 km.

(3)Immunity to interference and less cross talk:

Since optical fibers are dielectric wave guides, they are free from any electromagnetic interference (EMI) and radio frequency interference (RFI) . Since optical interference among different fiber is not possible , cross talk is negligible even many fibers are cabled together.

(3)Electrical isolation :

Optical fibers are made from silica which is an electrical insulator. Therefore they do not pick up any electromagnetic wave or any high current lightening.It is also suitable in explosive environment.

(4)Small size and weight :

The size of the fiber ranges from 10μm to 50 μm which is very small. The space occupied by the fiber cable is negligibly compared to conventional electric cables. Optical fibers are light in weight. These advantages make them to use in aircrafts and satellites more effectively.

(5)Signal security:

The transmitted signal through the fiber does not radiate. Unlike in copper cables, a transmitted signal cannot be drawn from fiber without tampering it. Thus the optical fiber communication provides 100 % signal security.

(7) Ruggedness and flexibility :

The Fiber cable can be easily bend or twisted without damaging it. Further the fiber cables are superior than the copper cables in terms of handling, installation, storage, transportation, maintenance, strength and durability.

(8)Low cost and availability :

Since the fibers are made of silica which is available in abundance. Hence there is no shortage of material and optical fibers offer the potential for low cost communication.

(9)Reliability :

The optical are made from silicon glass which does not undergo any chemical reaction or corrosion .Its quality is not affected by external radiation. Further due to its negligible attenuation and dispersion, optical fiber communication has high reliability. All the above factors also tend to reduce the expenditure on its maintenance.

Industrial applications of optical fibers:

(i) Applications of Optical fibers in Communication :

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

- For example, a local area network (LAN) is a computer network that interconnects computers in a limited area such as a home, school, computer laboratory, or office building using network media to exchange the information. They are used for short distances about 1to 2 km.
- **Long haul communication**: They are used for long distances, 10 km or more. Tele phone cables in which Optical fibres are used in to exchange of information between various places.
- They are used for exchange of information in cable television, space vehicles, submarines, etc**.**
- Nearly 10000 information carrying signals can be transmitted simultaneously through the optical fiber.
- They are used for guiding weapons and submarine communication systems.
- As the optical fiber is highly immune to temperature, moisture etc, without any environmental effects the information can be delivered.
- During the war time they are used for secret communication.

(ii) Applications of Optical fibers in Medicine :

1.Fiberscope in endoscopy is one of the widely used optical techniques to view the internal parts of the disease affected body. In this optical fibre plays a major role in visualization of internal portions of human body but also in the selective cauterisation of tissues using laser beam.

2.This technique is widely used for the diagnosis of interior of lungs, stomach and other human body parts.

3.This method is used for the examination of gastrointestinal tract for diagnosis of ulcers, cancers etc.
4. Optical fibres are used in photodynamic thrapy for cancer.
5. They are used in treatment of lung disorders.
6. They are used in treatment of bleeding ulcers.
7.They are used in arthroscopic surgery for damaged cartilage, ligaments, and tendons in major joints such as knees and shoulders.
8. They are used in the investigation of heart , respiratory system and pancreas.

Optical fiber in sensors:

Fiber optic sensor is a transducer which converts any form signal into optical signal in measurable form. They can used for measuring physical parameters such as Temperature, pressure, Flow, liquid level, displacement, velocity, acceleration, Force, Rotation, Vibration, Radiation, pH, humidity, strain, Acoustic fields, Electric fields and Magnetic fields etc. A fiber optic sensor consists of a light source which generates light signals. These signals passes through the suitable optical fiber placed in the sensing fields and then passes through the light detector. The variation in the light signal is caused by sensing field and is detected by the detector as shown in fig.

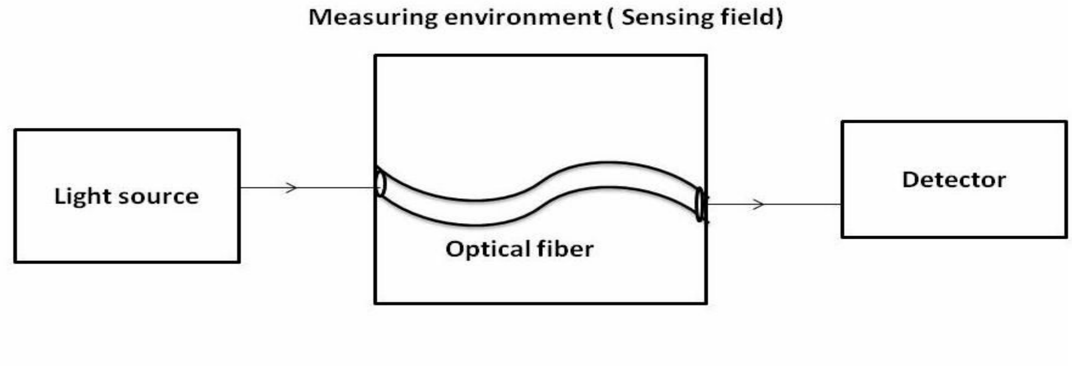


Fig .Block diagram of fiber optic sensor

(1) Temperature and pressure sensor:

It is an example of active sensors.

Principle:

It is based on the principle of interference between the beams emerging out from the reference fiber and the test fiber kept in the measuring environment.

Description:

- The block diagram of Temperature and pressure sensor as shown in fig.
- It consists of a laser source to emit light.
- A beam splitter arranged at 45^0.It splits the incident beam into two beams: Main beam and split beam.
- In which two fibers are used.
- Reference fiber which is isolated from the measuring environment.
- Test fiber kept in the environment to be sensed.
- Double convex lens are provided to convergent the beam.

Working:

A monochromatic source of light is emitted from the laser source.

- The beam splitter kept at 45^0 which divide the beam emerging from the laser source into beams (i) main beam (ii) spitted beam, exactly at right angles to each other.
- The main beam passes through the lens L_1 and is focused onto the reference fiber which is isolated from the environment to be sensed.
- The beam after passing through the reference fiber then falls on the lens L_2.
- The split beam passes through the lens L_3 and is focused onto the test fiber kept in the environment to be sensed.
- The beam after passing through the test fiber then falls on the lens L_2.
- The two beams after passing through the fibers, produces a path difference due to the change in parameters such as pressure, temperature etc., in the environment.
- Therefore a path difference is produced between the two beams, causing the interference pattern as shown in fig.
- Thus the change in pressure or temperature can be accurately measured with the help of the interference pattern obtained.

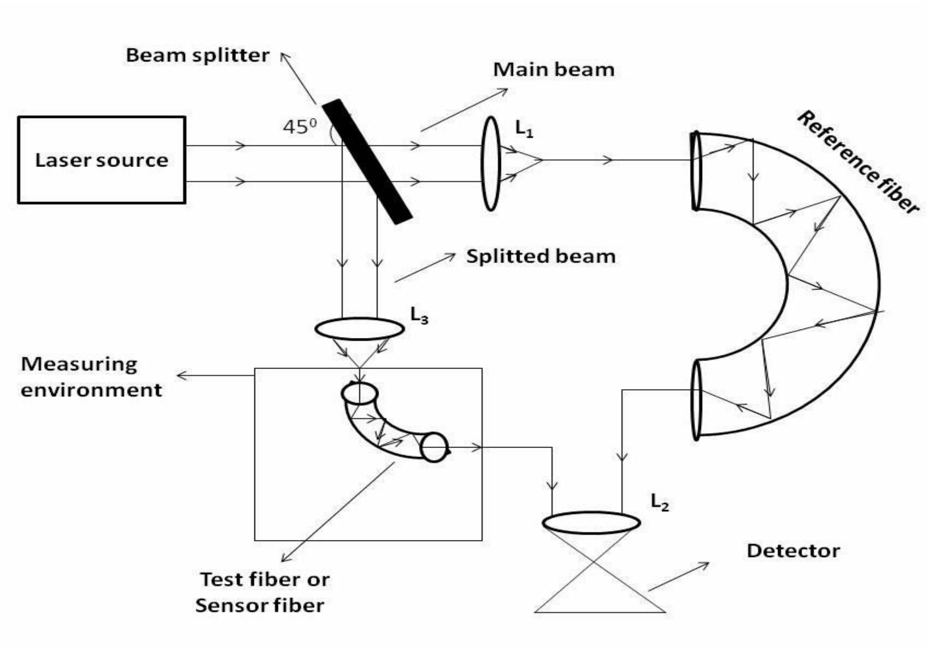


Fig: Temperature and pressure sensor

(3) Liquid flow level detector:

It is an example of active sensor.

Principle:

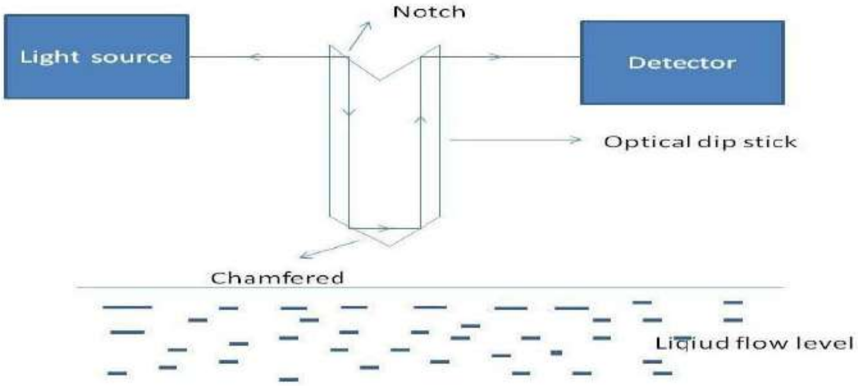
The liquid level detector described here is based on the principle of total internal reflection.

Description:

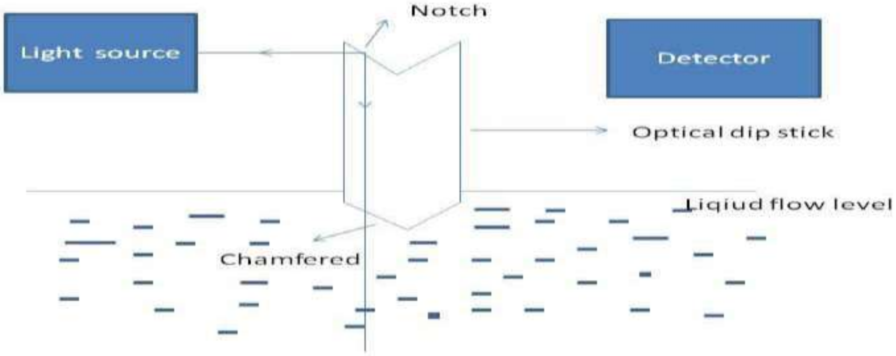
- A simple liquid detector is shown in fig.
- A notch is made of one end of multimode optical fiber and its other end is chamfered as shown in fig.
- A light source sends light onto the fiber and a photo detector on the other side measures light emerging out from the fiber.

Working:

- The optical fiber is arranged at the desired height in a vessel.
- The refractive index of the fiber is chosen to be less than that of the liquid whose level is to be detected.
- Light from the light source is made to be incident on one of the inclined faces of the notch.
- The light turns through 90^0 and travels through the fiber.



- On reaching the chamfered end of the fiber, it gets internally reflected, if the liquid is below the desired level. Then, it is again turned through 90^0 at the opposite face, travels back through the fiber to be turned once again through 90^0 and is detected at the detector.
- When the liquid rises and touches the fiber end, total internal reflection ceases and light is transmitted into the liquid. Hence photo detector does not receive any light.
- Thus, an indication of the liquid level is obtained at the detector.



(4) Displacement sensor:

It is an example of a passive sensor.

Principle:

In this method, two separate sensors are used for transmitting the light on the moving object and other, to receive the reflected light from the object. Light is sent through a transmitting fiber and is made to fall on a moving object. The reflected light from the target is sensed by a detector. Based on the intensity of light reflected from it the displacement of the object is measured.

Description:

- The displacement sensor consists of a light source, a transmitting fiber, a receiving fiber, an object and the detector as shown in fig.
- The transmitting optical fiber consists of bundle of fibers coupled to the laser source and receiving optical fiber is also consists of bundle of fibers coupled to the detector.

Working:

- The light energy from the He-Ne laser source is transmitted through the transmitting fiber and is made to incident on the moving object.
- The light reflected from the moving object is made to pass through the receiving fiber and the same is detected by the detector.
- Based on the intensity of light received ,the displacement of object can be measured,
For example, if the object is moving towards the sensor, the intensity of light increases and if the object is moving away from the sensor, the intensity of light decreases.
- Thus the change in intensity of the light is used to measure the displacement of the object.

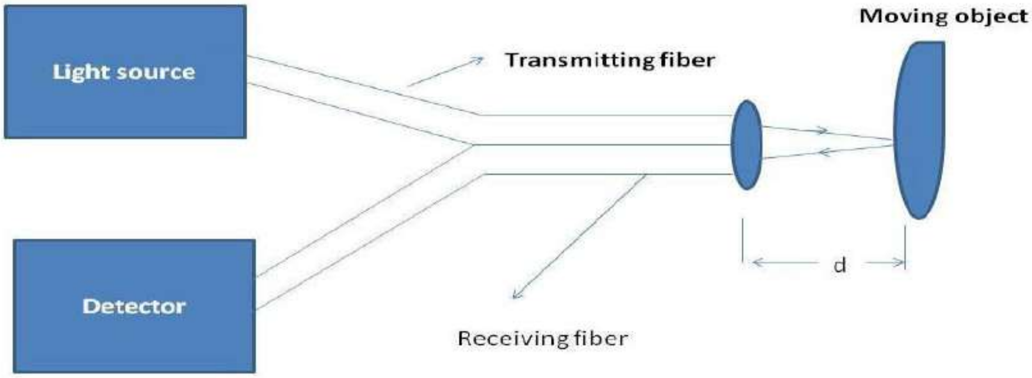


Fig .Displacement sensor

Unit-V
Sensors

1.Strain Gauge Sensor

construction

- Bonded strain gauge sensors are sensors that are fabricated by bonding a strain – resistive sensor to a metallic diaphragm.
- These sensors have a built in advantage that they don't have to be isolated from the working medium.
- Since there must be a diaphragm to bond the strain gauge resistors, the diaphragm also isolate the resistors from the working medium.
- These diaphragms are generally stainless steel or some other resistant material.
- Both semiconductor and metal foil resistors are used as sensing elements.
- The diaphragm dimensions determines the pressure range of the transducer (high pressures up to 10,000 psi.
- The very high pressure devices have small diameter pressure passages to minimize the force the package has to withstand.
- The low and mid range sensors have larger diaphragms and larger pressure diameter ports. The sensor housing is generally made from stainless steel and the entire assembly is welded together to give a strong, medium resistant sensor as shown in figure 7.2(a).

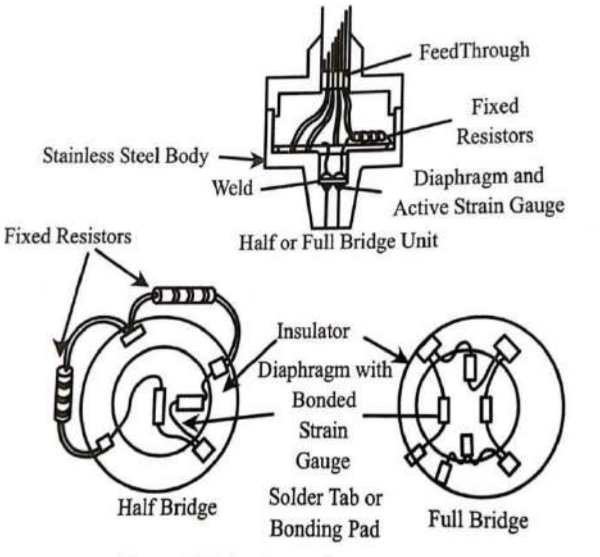


Figure 7.2(a) : Sensor Construction

Operating Principle

- The resistors are not strain sensitive and used for bias purpose only. The resistors on each side of the bridge should have the same temperature coefficient to minimize the off set temperature coefficient of the bridge.
- The two strain sensitive resistors are aligned so that one is in compression and other is in tension.
- The resistor in tension increases with applied pressure, while the resistor in compression decreases unbalancing the bridge. It measures + and – pressures.
- When a –ve pressure is applied to the sensor, the diaphragm strained in the opposite direction and the resistor that was in tension goes into compression. This gives sign reversal at output. (If no pressure is applied to the sensor output is ‘0’).
- When a +ve pressure is applied to the sensor, the differential output increases or if a vacuum is applied, the differential output decreases.

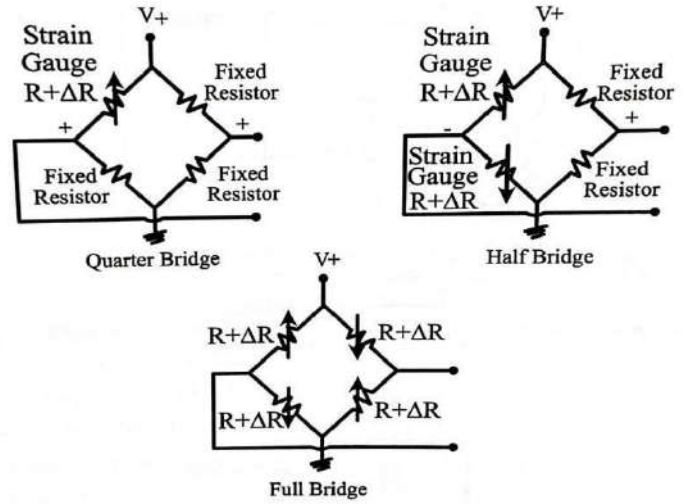


Figure 7.2(b): Bridge Configurations

2. Piezoelectric Sensor

- The piezoelectric effect refers to a change in electric polarization that is produced in certain materials when they are subjected to mechanical stress. Piezo is a Greek word which means ‘pressure’ or ‘squeeze’.

- A sensor that uses the piezoelectric effect to measure the changes in the acceleration, strain, pressure, and force by converting them into electrical charge is called a piezoelectric sensor.
- Piezoelectric sensor require no external power and are used for dynamic measurements.
- These sensors have very high natural frequencies and low noise. Most accelerometers are piezoelectric because of their high frequency response.
- Piezoelectric accelerometers are available with frequency responses ranging from 1Hz to 200kHz.
- Piezoelectric pressure sensors are generally used to measure very fact pressure changes such as shock waves from explosions or a very fast pressure spike.
- Piezoelectric sensors also used in microphones due to their small change and wide frequency response.

Operating Principle

- In the early designs of piezoelectric sensors, a solid piece of quartz was cut and two surfaces were metalized for electrical contact.
- This structure was then mounted in a metallic housing that preloaded the crystal and was used as the electrical ground for the circuit. The end of the sensor was flexible to couple the pressure change to crystal.
- When properly cut and oriented to its crystallographic axis, a piece of quartz or polycrystalline ceramic will generate a small electric change when strained. Stack of thin crystal wafers to increase sensitivity.
- The crystals are stacked in sereies, single electric contact is made from the crystal through a connector with the housing acting as the signal return.
- As shown in the figure, pressure is applied to the diaphragm , which applies a compression force to the crystal element. As the crystal is compressed, a change proportional to the pressure is generated.

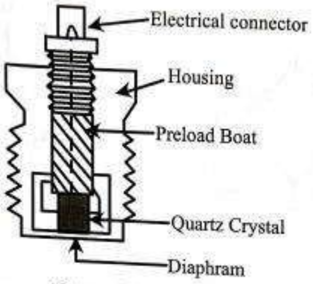


Figure 7.3: Early Design

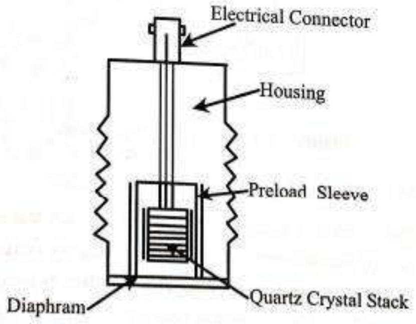


Figure7.4:Piezoelectric Sensor Construction

Sensitivity

- The output is linear over a wide range, typically 0.7 Kpa to 70 Mpa (0.1 to 10000 psi)with an accuracy of about 1 %. Ceramic sensors are subject to a loss of sensitivity over time. But this is usually quite small; typically less than 1 % per year.
- There may also be a small loss in sensitivity when first exposed to high pressure and temperature. The effects of this can be avoided by cycling the sensor through the maximum expected pressure and temperature before deploying them.
- The frequency response of piezoelectric sensor drops off at low frequencies because the generated change cannot be retained.
- At high frequencies there is a peak corresponding to the resonant frequency of the piezoelectric element.
- The sensor is normally used within the flat region of the response curve between these two extrmes.

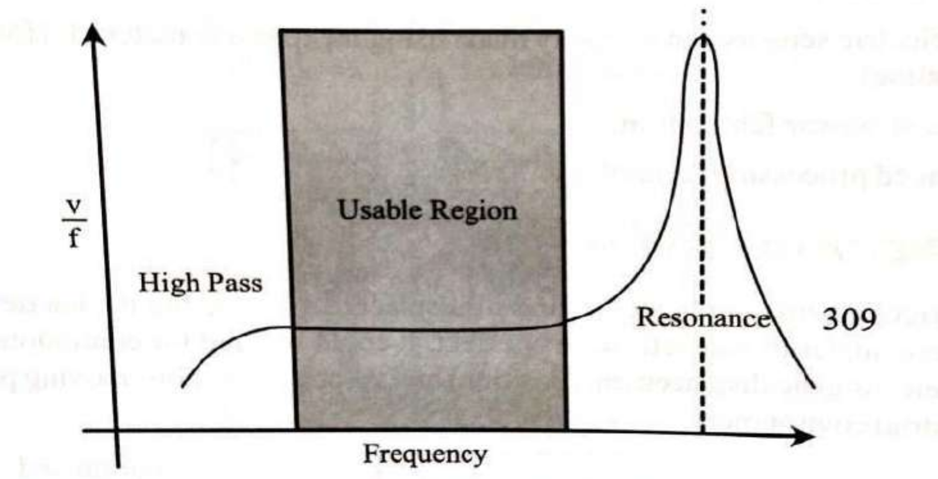


Figure7.5: The Frequency Response of Piezoelectric Sensor

Applications of piezoelectric sensor

- The piezoelectric sensor measuring dynamic pressure, for example in turbulence, blast and engine combustion.
- Their sensitivity and low power consumption also makes them useful for some medical applications. For example, a thin film plastic sensor can be attached to the skin and used for real-time monitoring arterial pulse.
- Health care industry.
- Aerospace industry.
- Industrial products.
- Consumer products.
- Telecommunication etc.

Advantages of piezoelectric sensor

- Piezoelectric pressure sensors is their ruggedness. This makes them suitable for use in a variety of harsh environment.
- Piezoelectric sensors can be used at high temperatures. Some materials will work at up to 1000 °C.
- The output signal is generated by the piezoelectric element itself, so they are inherintly low power devides.
- Piezoelectric sensors can be easily made using inexpensive materials.
- Low cost sensor fabrication
- Advanced processing technology.

3. Magnetostrictive Sensor

- Magnetostrictive sensor indicates a kind of displacement detecting device developed based on ferromagnetic material Magnetostrictive effect. It could be used for contineously, precisely and real time detecting the displacement (position) and velocity of various moving parts under abominably industrial environment .
- Magnetostrictive sensors based on the Villari effect, this technique utilizes the change in permeability of ferromagnetic materials with applied stress. A stack of laminations forms a load bearing colum through holes oriented as shown in figure.
- Coil A is excited with an AC voltage, and coil B provides the signal voltage. In the unstressed condition, the permeability of the material is uniform throughout the structure.
- Since the coils are oriented 90° with respect to each other, little or no coupling exists between coil A and coil B. Hence no output signal is developed.
- When the column is loaded, the induced stresses cause the permeability of the column to be non uniform, resulting in corresponding distortions in the flux pattern within the magnetic material.

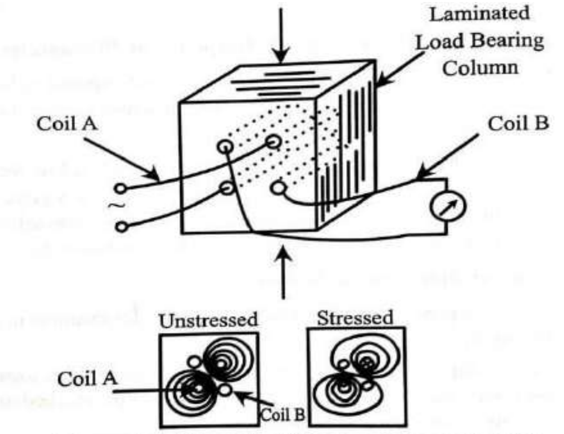


Figure 7.6 :Magnetostrictive sensing principle

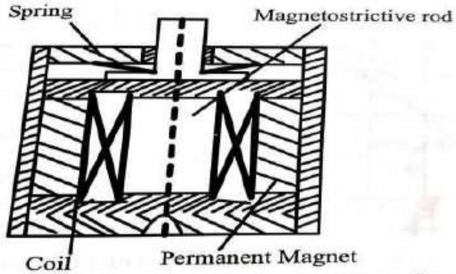


Figure 7.7: Magnetostrictive Construction

Construction

- The magnetostrictive rod surrounded by a cylidrical coil is premagnetized by a permanent magnet and mechanically pre-stessed with a disc spring. The magnetic circuit is achieved with two magnetic plates at the bottom and top of the coil.
- Electrochemical equalent circuit diagram and amplitude responses of the actuator and sensor transfer characteristic in small-signal operation is given by.

- **Large- Signal characteristic:** The interaction between the driving current I and the magnetic flux ϕ within the magnetostrictive transducer and the displacement is highly hysteric and show the characteristics as shown in figure.
- The changes in the magnetic flux ϕ and the displacements which are produced by the mechanical load F can also be observed in figure.
- **Operating range and operating point:** In magnetostrictive transducers the positive branch of the relationship between the displacements and the current is normally used.
- The magnetic operating point is usually placed in the middle of the operating range. It is set by a bias current via a magnetic coil or by permanent magnets.
- The relationship between ϕ and I displays a highly sensitive inherent sensory effect in the magetic operating point shown in figure.
- Starting with the choice of the magnetic operating range of the transducer maximally extents to the reversal point of the δ-I characteristic on the left hand side and on the
  right hand side to the amplitude range in which ferromagnetic saturation effects

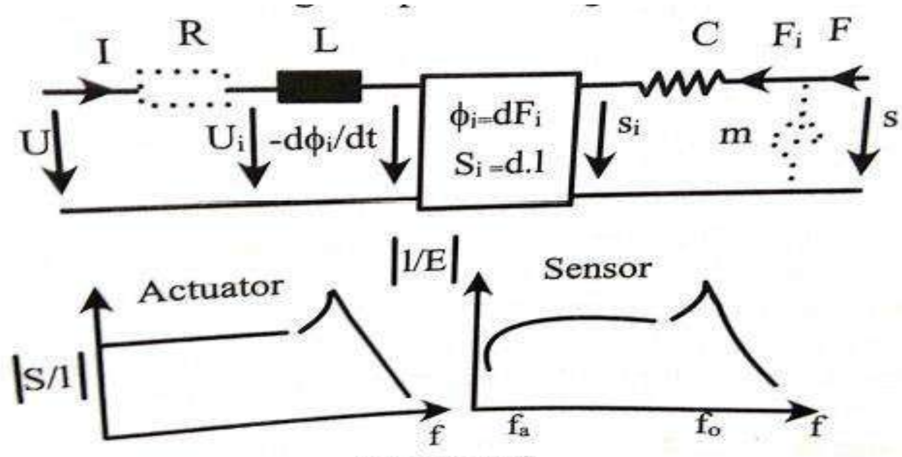


Figure 7.8

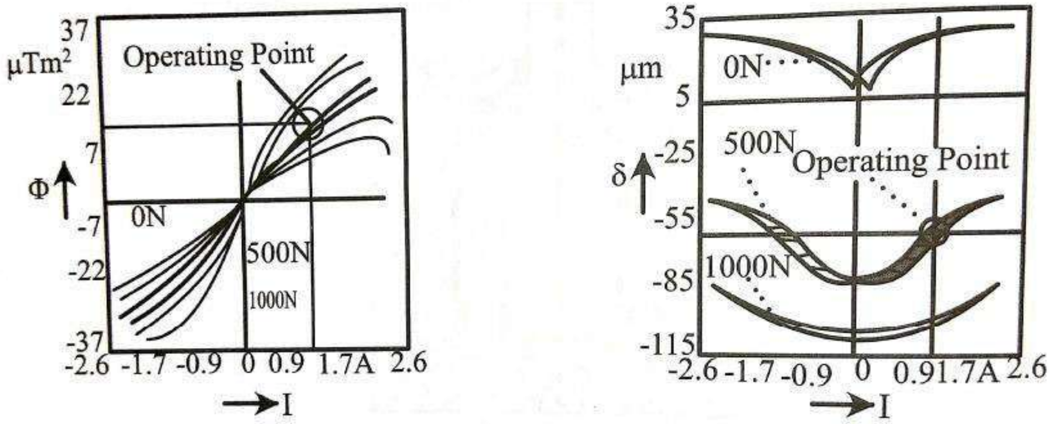


Figure 7.9: Typical hysteretic characteristics of a magnetostrictive transducer for different mechanical loads with the marked operating region and the operating point.

4. Fiber optic methods of pressure sensing

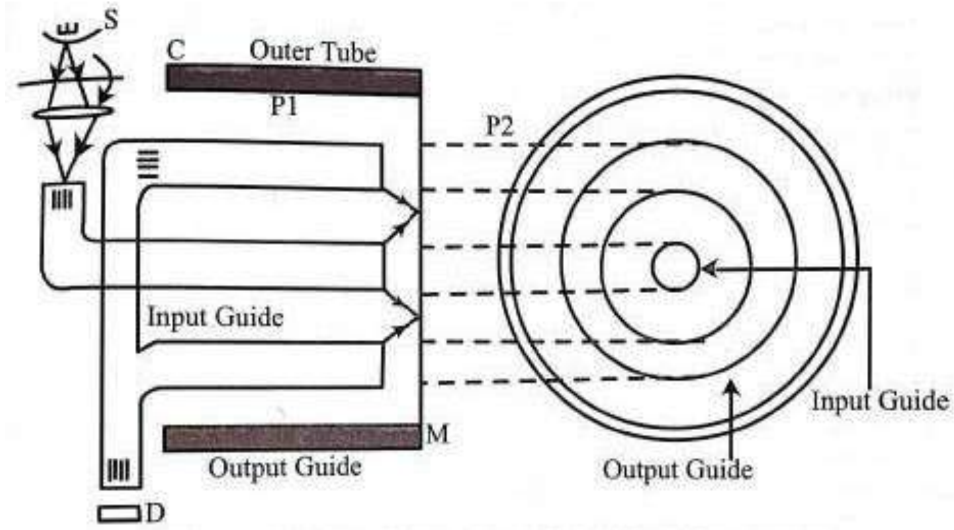


Figure 7.10: Fibre Optic Type Pressure Measurement System

- The fiber optic type pressure measurement is versatile in many applications. Its adaptability in biomedical area in which it can be used to monitor pressure in the human circulatory system.
- The basic diagram of the system is shown in figure.
- In this measurement system input and output optical guides arranged as shown in figure.
- Whenever we passed a light from input guide, which on emergence is reflected from a flexible membrane.
- The membrane may be made of aluminized plastic formed as a film. With pressures P1 and P2 equal, the position of the membrane with respect to the input guide is so kept that 50% of the reflected light falls on the surrounding annular output guide.
- If P2>P1, the membrane becomes convex towards the guides and more light falls on the output guide. If P2<P1, the reverse occurs.
- A detector set at the other end of the output guide correspondingly receives varied amount of light with changing pressure. The detector can be calibrated for pressure.
- There are technologies are presently for pressure measurement fiber-optic sensors.

(1) Intensity – based

(2) Fiber Bragg gratings

(3) Fabry – Perot.

(1) Intensity – based :

- Intensity – based pressure sensors are probably one of the first pressure OFS. The principle behind in this type of sensors is “ the light emitted by a multimode optical fiber tip is collected by another after reflecting on a diaphragm deflecting with pressure”.
- The intensity of the collected light is dependent on the core diameter and position of the optical fibers as well as on their numerical aperture, but it is also directly related to the distance separating the fiber ends and the reflecting diaphragm allowing direct pressure measurement.
- The light intensity increases rapidly from zero to reach a maximum when the diaphragm plane matches the position where the solid angles of the numerical aperture of both fibers overlaps the most.

- As the diaphragm plane moves further away, less light could be collected and the light intensity decreases slowly back to zero.
- By properly designing the sensor for a selected pressure range providing that only a monotone region of the light intensity curve is used, a unique pressure could be derived from light intensity once the sensor has been calibrated.

(2) Fiber Bragg gratings:

- Fiber Bragg grating (FBG) sensors are commonly used by two ways. One consists of attaching the FBG fiber to a flexible diaphragm either orthogonally or in the diaphragm plane in areas where the strain is maximal.
- In both cases such designs always imply bulky sensors, often limited to high pressure ranges which are however acceptable for applications in civil engineering or in the oil and gas industry where sensor size is not a real issue.
- Another type consists of mounting the FBG sensor in cylindrical assemblies so that increased pressure sensitivity is achieved through mechanical amplification schemes. Many designs are proposed in variations in coatings and assembly.
- They are always comprising size and sensitivity and to achieve sensor outer diameters (1 mm or less) usually much smaller than the first approach.
- Since the length of the FBG itself is generally 5-10 mm range, encapsulated FBG pressure sensors are not really suitable for true-point sensing pressure in very small regions.
- Also the lack of very high sensitivity to hydrostatic pressure of such sensors limits their use in most applications requiring better performances.
- However some interesting ones involving FBG sensors could be found in the biomedical field, mostly related to evaluation of pressure in rigid structures involving bones or dental implants.

(3) Fabry - Perot:

- The fabry perot interferometer is an important application of multiple wave interference in optics.

- Each time the light encounters one of the surfaces, a portion of it is transmitted out

And the remaining part is reflected back.

- The net effect is to break a single beam into multiple beams which interfere with each other.

- The resulting interference patterns may be used to analyse the spectral character of the incident beam.
- If the additional optical path length of the reflected beam is an integral multiple of the light's wavelength, then the reflected beam will interfere constructively.
- More is the number of reflection inside the cavity, sharper is the interfernce maximum.

5. TEMPERATURE SENSORS

- Temperature is the most often measured environment quantity. Temperature sensing can be done either through direct contact with the heating source, or remotely, without direct contact, with the source using radiated energy instead.
- There are a wide variety of temperature sensors are on the market today including thermocouples, resistance temperature detectors (RTDs), thermistors, infrared and semiconductor sensors.
- A temperature sensor consists of two basic physical types:

(a)Contact temperature sensor : These types of sensors are required to be in physical contact with the object being sensed and use conductions to monitor changes in temperature.

(b)Non-contact temperature sensor : These type of temperature sensor use convection and radiation to monitor changes in temperature.

By taking into account, there are 4 types of temperature sensors.

(i) **Negative temperature coefficient (NTC) thermistor :** An NTC thermistor provides a very high resistance at low temperatures. As temperature increases, the resistance drops quickly. Because an NTC thermistor experiences such a large change in resistance per degree Celsius, small change in temperature are reflected very fast and with high accuracy (0.05-1.5 °C). Because of its exponential nature, the output of an NTC thermistor requires linearization. The effective operating range is -50 to 250°C for gas encapsulated thermistors or150 °C for standard.

(ii) **Resistance temperature detector (RTD) :** Resistive temperature detectors have positive temperature coefficients (PTC). An RTD, also known as a resistance thermistor, measures temperature by correlating the resistance of the RTD element with temperature. An RTD consists of a film or, for greater accuracy, a wire wrapped around a ceramic or glass core. The most accurate RTDs are made using platinum but lower cost. RTDs are made from nickel or

(iii) or copper. However nickel and copper are not stable or repeatable. Platinum RTDs offer a fairly linear output that is highly accurate (0.1 to 1°C) across -200 to 600 °C.

(iv) While providing the greatest accuracy, RTDs also tend to be the most expensive of temperature sensors.

(v) **(iii) Thermocouple :** This temperature sensor type consists of two wires of different metals connected at two points. The varying voltage between these two points reflects proportional changes in temperature. Thermocouples are nonlinear, requiring conversion when used for temperature control and compensation typically accomplished using a look up table. Accuracy is low, from 0.5 to 5 °C. However, they operate across the widest temperature range from -200 to 1750 °C. The voltage being the temperature difference between the two similar junctions

(vi) Vout = V1-V2

(vii) **(iv) Semiconductor based sensors:** A semiconductor based temperature sensor is placed on integrated circuits(ICs). These sensors are effectively two identical diodes

with temperature sensitive voltage vs current characteristics that can be used to monitor changes in temperature. They offer a linear response but have the lowest accuracy of the basic sensor type at 1 to 5 °C. They also have the slowest responsiveness (5 to 60 seconds) across the narrowest temperature range (-70 to 150 °C). The ordinary semiconducting diode may be used as a temperature sensor. The diode is the lowest cost temperature sensor and can produce more than satisfactory result. The circuit diagram of a semiconductor based sensor is shown in figure. The bias current should be held as a constant as possible using constant current source, or a resistor from a stable voltage source.

1. Thermostat

- ❖ A thermostat is a component which senses the temperature of a system so that the system's temperature is maintained near a desired set point.
- ❖ It is a closed loop control device as it seeks to reduce the error between desired and measured temperatures.

- ❖ The thermostat is a contact type electro-mechanical temperature sensor or switch that basically consists of two different metals such as nickel, copper, aluminimum tungsten etc, that are bonded together to form a bimetallic strip.

1. The bi-metallic thermostat

- ❑ A thermostat has two pieces of different metals bolted together to form a bimetallic strip. The strip works as a bridge in an electrical circuit connected to heating system.

- ☐ The strip carries electricity through the circuit, and the heating is on. When the strip gets hot, one of the metals expands more than the other so the whole strip bends very slightly. The circuit diagram is shown in figure.
- ☐ The thermostat consists of two thermally different metals stuck together back to back. When it is cold, the contacts are closed and current passes through the thermostat.
- ☐ When it gets hot, one metal expands more than the other and the bonded bi-metallic strip bends up (or down) opening the contacts preventing the current from flowing.

How a bi-metallic thermostat switches work???

(1) The dial is connected through a circuit to the temperature sensor which switches an electrical circuit ON and OFF by bending more or less.

(2) The bimetal (two metal) strip is made of two separate metal strips fastened together: a piece of brass bolted to a piece of iron.

(3) Iron expands less than brass as it gets hotter, so the bimetal strip curves inward as the temperature rises.

(4) The bimetal strip forms part of an electrical circuit (gray path). When the strip is cool, it is straight, so it acts as a bridge through which electricity can flow. The circuit is on and so is heating. When the strip is hotter, it bends and breaks the circuit, no electricity can flow. Now the circuit is OFF.

6.Hall effect sensor

Principle:

When a magnetic field is applied perpendicularly to the direction of an electric current flowing in a conductor or semiconductor, an electric field arises that is perpendicular to both the direction of the current and the magnetic field.

$VH \alpha IB$

Where VH = Hall voltage, B = Magnetic field, I = current

- ➢ Figure illustrates the basic principle of Hall effect. It shows a thin sheet of semiconducting material through which a current is passed. The output connections are perpendicular to the direction of current.
- ➢ When no magnetic field is present, current distribution is uniform and no potential difference is seen across the output.

- When a perpendicular magnetic field is present is seen in below figure, a Lorentz force is exerted on the current. This force disturbs the current distribution, resulting in potential difference (voltage) across the output. This voltage is the Hall voltage (VH) .

Basic Hall effect sensors:

- These are simple, inexpensive, electronic chips that are used in all sorts of widely available gadgets and products. The hall element is the basic magnetic field sensor.
- It requires signal conditioning to make the output usable for most applications. The signal conditioning electronics needed are an amplifier stage and temperature compensation.
- Voltage regulation is needed when operating from an unregulated supply. The below figure illustrates a basic Hall effect sensor.
- If the Hall voltage is measured when no magnetic field is present, the output is zero. However if the voltage at each output terminal is measured with respect to ground, a non zero voltage will appear.
- This is the common mode voltage, and is the same at each output terminal. The amplifier drawn in below figure must be a differential amplifier so as to amplify only the potential difference (Hall voltage).

- The hall voltage is a low level signal in the order of 30 microvolts in the presence of a one gauss magnetic field. This low level output requires an amplifier with low noise, high input impedance and moderate gain.
- A differential amplifier with these characteristics can be readily integrated with the Hall element using standard bipolar transistor technology. Temperature compensation is also readily integrated.
- As from the equation, the Hall voltage is function of the input current. The purpose of the regulator is below figure is to hold this current constant so that the output of the sensor only reflects the intensity of the magnetic field.
- As many systems have a regulated supply available, some Hall effect sensors may not include an integral regulator.
- When an electric current flows through a material, electrons move through it pretty much a straight line. Put the material in a magnetic field and the electrons inside it are in the field too.

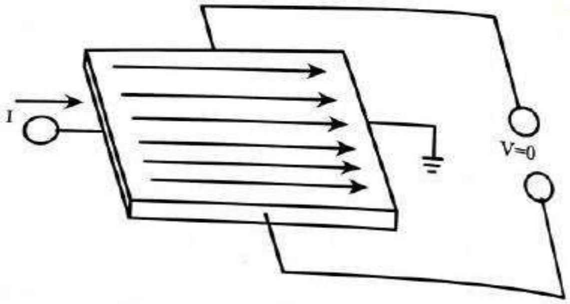


Figure 7.18: Hall Effect Principle

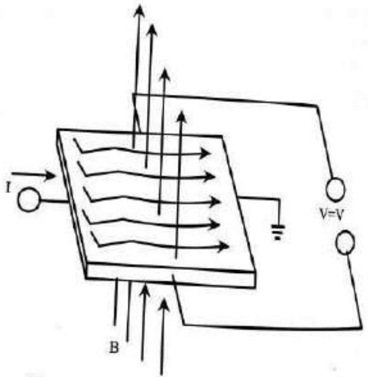


Figure 7.19: Hall Effect When Magnetic Field Present

- A force acts on them (Lorentz force) and makes them deviate from their straight line path. Now looking from above, the electrons in this example would bend as shown: from their point of view, from left to right.
- With more electrons on the right side of the material than on the left, there would be a difference in the potential difference between the two sides as shown in the figure.
- The size of this voltage is directly proportional to the size of the electric current and the strength of the magnetic field.

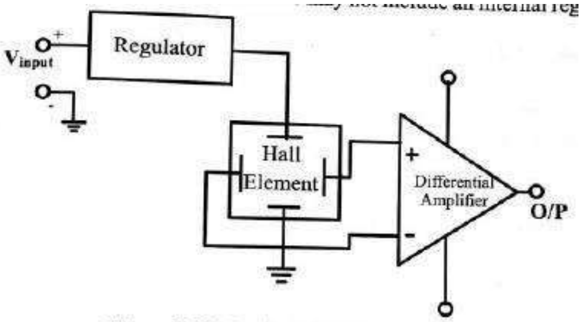


Figure7.20: Basic Hall Effect Sensor

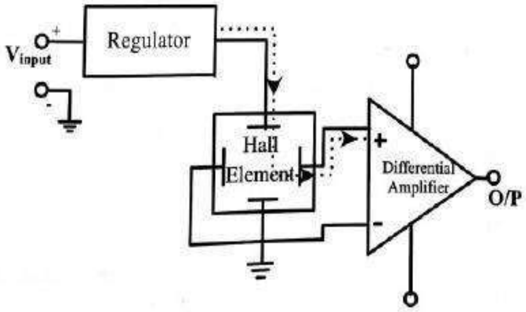


Figure 7.21

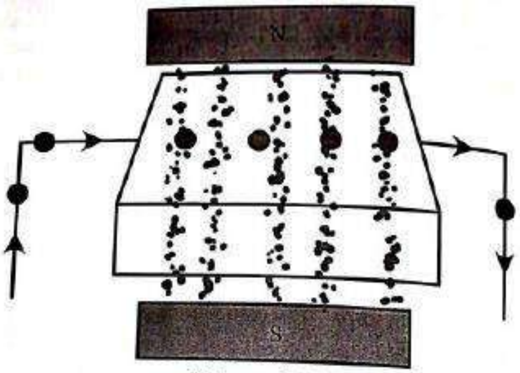


Figure 7.22

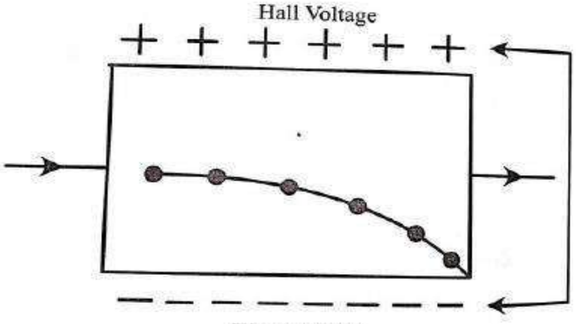


Figure 7.23