2.9 Concept of Laser

The photon emitted during stimulated emission has the same energy, phase, frequency and direction as that of the incident photon.

Thus, we have two coherent photons. Now, these two photons are incident on two other atoms in the state E_2. This results in induced emission of two more photons.

Now, there are four coherent photons of same energy. These four photons induce further transitions with four other atoms in the energy state E_2. This gives stimulated emission of eight coherent photons of same energy.

If the process continues in a chain, ultimately enable to increase the intensity of coherent radiation enormously.

Stimulated emission is multiplied through a chain reaction. This multiplication of photons through stimulated emission leads to coherent, powerful, monochromatic, collimated beam of light. The light is known as laser light.

Thus for laser action, stimulated emission is most important. It is achieved by population inversion.

OPTICAL RESONATOR

An optical resonator consists of a pair of reflecting surfaces in which one is fully reflecting (R_1) and the other is partially reflecting (R_2). The active material is placed in between these two reflecting surfaces.

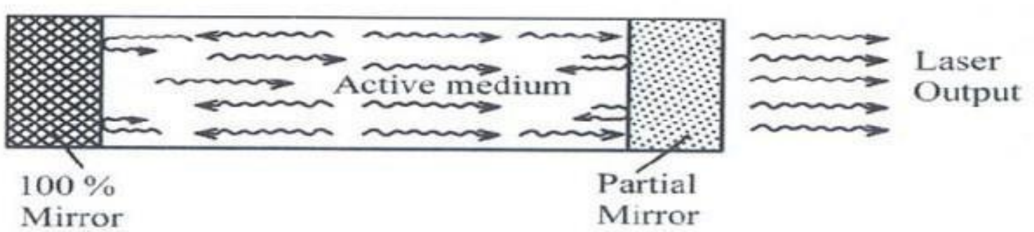


fig:2.9.1-Optical Resonator

The photons generated due to transitions between the energy states of active material are bounced back and forth between two reflecting surfaces.This will induce more and more stimulated transition leading to laser action.

Optical Resonator

The optical resonator constitutes an active medium kept between a fully reflecting mirror and a partially reflecting mirror as shown in figure.

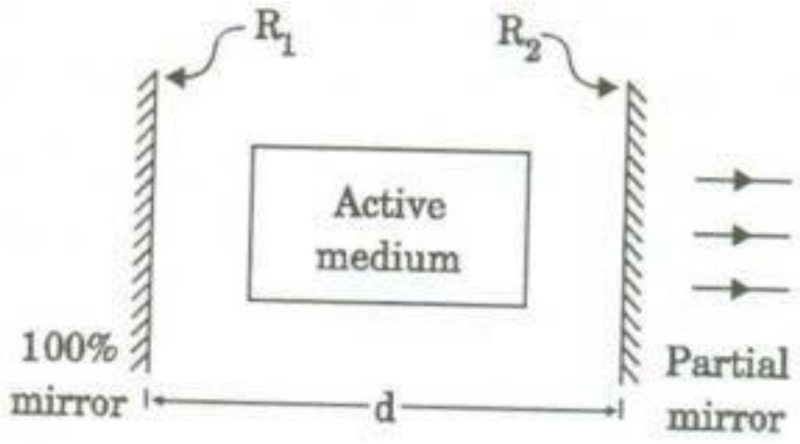


fig:2.9.2 Mirrors in laser action

This optical resonator acts as a feedback system in amplifying the light emitted from the active medium, by making it to undergo multiple reflections between the 100% mirror and the partial mirror. Here the light 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 figure.

ENGINEERING PHYSICS

UNIT II

WAVES AND FIBRE OPTICS

2.4. Damped Oscillations

2.4.1 Differential Equation And Its Solution

2.4.Damped Oscillations:

When a body is in vibration ,if the amplitude of vibration goes on decreasing and finally the oscillation die. This type of oscillation is said to be a damped oscillation. In this oscillation, the body vibrates with natural frequency.

Examples:

When a pendulum is displaced from its equilibrium position, it oscillates with decreasing amplitude and finally it come to rest.

2.4.1 Differential Equation And Its Solution

Let us consider a mass system . Let 'm' is the mass suspended over the spring. Due to the applied mass (load), the system exhibits two types of forces on it, namely Restoring force and Friction force.

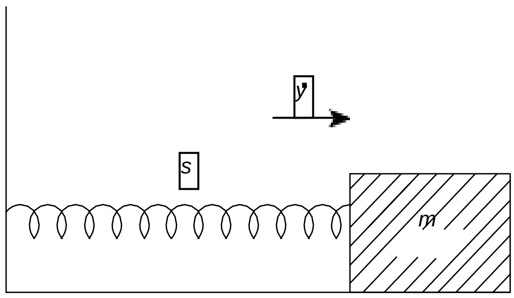


Fig 2.4.1 Damped Oscillations

(source: "The Physics of vibration and vibration" by H.J.Pain Page-38)

Restoring force:

A restoring force is the force which is opposite to the direction of displacement(y).

$$F1 \propto -y$$

$$F1 = -ky \_\_\_\_\_\_\_\_\_\_ (i)$$

Where, K is the force constant and y is the displacement. Here the negative sign indicates that the restoring force acts in the opposite direction to the displacement.

Friction force:

Friction force or damping force is due to presence of air resistance, which is opposite to the direction of velocity

$$F_2 = -r\frac{dy}{dx} \text{-----------------(2)}$$

Total force

$$F = F_1 + F_2 \text{-----------------(3)}$$

Sub (i) & (2) in (3)

$$F = -ky - r\frac{dy}{dt} \text{-----------------(4)}$$

But according to Newton's law

$$F = ma$$

$$\text{Here } F = m\frac{d^2y}{dt^2} \text{-----------------(5)}$$

Where $\frac{d^2y}{dt^2}$ *is the acceleration*

From (4) & (5)

$$m\frac{d^2y}{dt^2} = -ky - r\frac{dy}{dt}$$

Divide by m

$$\frac{d^2y}{dt^2} = -\frac{k}{m}y - \frac{r}{m}\frac{dy}{dt}$$

$$\frac{d^2y}{dt^2} + \frac{r}{m}\frac{dy}{dt} + \frac{k}{m}y = 0$$

Put $r/m = 2b$ & $k/m = \omega^2$

$$\frac{d^2y}{dt^2} + 2b\frac{dy}{dt} + \omega^2 y = 0 \text{-----------------(6)}$$

The solution for this equation is

$$y = Ae^{\alpha t} \text{-----------------(7)}$$

Where, A and α are the arbitrary constants

On differentiating (7)

$$\frac{dy}{dt} = Ae^{\alpha t}\alpha \text{-----------------(8)}$$

$$\frac{d^2y}{dt^2} = Ae^{\alpha t}\alpha^2 \text{-----------------(9)}$$

Sub equations 7,8 & 9 in 6 we get

$$A\alpha^2 e^{\alpha t} + 2b\, Ae^{\alpha t}\, \alpha + \omega^2 Ae^{\alpha t} = 0$$

$$Ae^{\alpha t}\, (\alpha^2 + 2b\, \alpha + \omega^2) = 0$$

$Ae^{\alpha t}$ is not equal to zeo

$$\alpha^2 + 2b\, \alpha + \omega^2 = 0$$

On solving the above equation we get

$$\alpha = -b \pm \sqrt{b^2 - \omega^2}$$

Then the general solution for the damped equation is

$$y = Ae^{(-b \pm \sqrt{b^2-\omega^2})\, t}$$

$$y = A_1 e^{(-b+\sqrt{b^2-\omega^2})\, t} + A_2 e^{(-b-\sqrt{b^2-\omega^2})\, t}$$

A_1 & A_2 are arbitrary constant.

Change of amplitude with respect to displacement is shown in figure 2.4.2

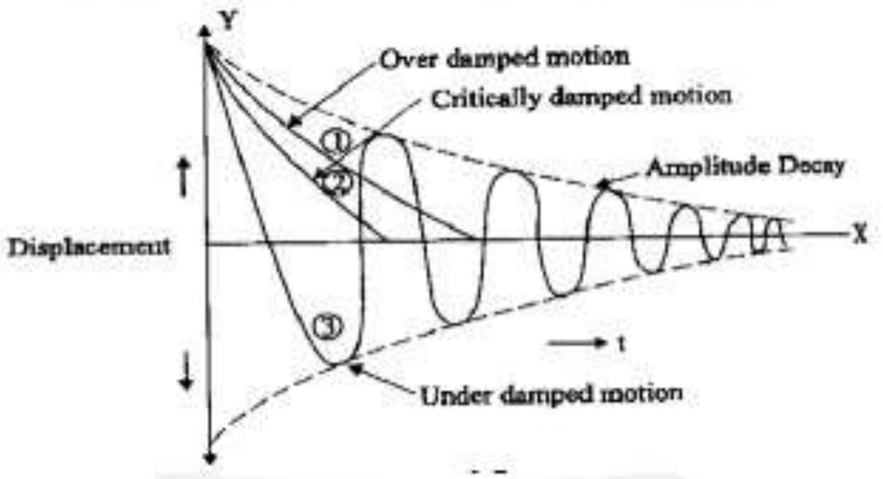


Fig 2.4.2.Damping

2.8 Einstein's A and B Coefficients (Derivation)

Einstein's theory of absorption and emission of light by an atom is based on Planck's theory of radiation. Also under thermal equilibrium, the population of energy levels obey the Boltzmann's distribution law.

Under thermal equilibrium,

$$\text{Rate of absorption} = \text{Rate of emission} \quad \ldots\ldots (1)$$

The rate of absorption R_{12} (SA) is proportional to the energy density of incident radiation (ρ) and number of atoms in the ground state (N_1)

$$R_{12}\,(SA) \;\alpha\; \rho N_1$$

$$R_{12}\,(SA) = B_{12}\,\rho\, N_1 \ldots\ldots\ldots (2)$$

Where, B_{12} is a constant which gives the probability of absorption transition per unit time.

The rate of spontaneous emission R_{21}(Sp.E) is proportional to the population of the higher energy level N_2. Therefore, we have,

$$R_{21}(Sp.E) = A_{21}N_2 \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where, A_{21} is the proportionality constant known as the probability of spontaneous emission per unit time.

The rate of stimulated emission R_{21} (St.E) is proportional to the population of the higher energy level N_2 and energy density of incident radiation (ρ). Therefore, we have,

$$R_{21}\,(St.E) \;\alpha\; \rho N_2$$

$$R_{21}\,(St.E) = B_{21}\rho N_2 \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where, B_{21} is the proportionality constant known as the probability of stimulated emission of radiation per unit time.

The coefficients B_{12}, A_{21} and B_{21} in the expressions for the rate of absorption and emission are called the Einstein's coefficients.

Substitute equations (2), (3) and (4) in equation (1), we get,

$$B_{12}\,\rho N_1 = A_{21}N_2 + B_{21}\rho N_2$$

$$\rho\,[B_{12}N_1 - B_{21}N_2] = A_{21}N_2$$

$$\rho = \frac{A21N2}{B12N1 - B21N2}$$

(or)

$$\rho = \frac{A21}{B12\frac{N1}{N2} - B21} \text{------------------} (5)$$

According to Boltzmann distribution law, the number of atoms N_1 in energy states E_1 and E_2 in thermal equilibrium at temperature T is given by,

$$N1 = N0\ e^{-E1/KBT}$$

$$N2 = N0\ e^{-E2/KBT}$$

$$\frac{N1}{N2} = e^{\frac{E2-E1}{KBT}}$$

$$\text{since} E2-E1 = h\nu, \text{we have}$$

$$\frac{N1}{N2} = e^{\frac{h\nu}{KBT}} \text{..............................} (6)$$

Substituting equation (6) in equation (5), we get

$$\rho = \frac{A21}{B12(e^{\frac{h\nu}{KBT}}) - B21}$$

(or)

$$\rho = \frac{A21}{B21} \frac{1}{\frac{B12}{B21}(e^{\frac{h\nu}{KBT}})-1} \text{---------------} (7)$$

According to Planck's theory of black body radiation is

$$\rho = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{KBT}}-1} \text{----------------------} (8)$$

Comparing the equations (7) and (8)

$$B_{12} = B_{21} \text{--------------------} (9)$$

and

$$\frac{A21}{B21} = \frac{8\pi h v^3}{c^3} \text{-------------------------} (10)$$

Equation (10) shows that the Einstein's Coefficients A and B.

i) $B_{12} = B_{21}$, the probability of stimulated emission is the same as that of absorption.

ii) $A_{21} / B_{21} \propto v^3$, the ratio of spontaneous emission and stimulated emission is proportional to v^3. It means that the probability of spontaneous emission dominates over induced emission more and more as the energy difference between the two states increases.

ENGINEERING PHYSICS

UNIT II

WAVES AND FIBRE OPTICS

2.5. Forced Oscillation

2.5.1. Differential Equation And Its Solution Of Forced Oscillations

2.5.Forced Oscillation

Oscillation in which the body vibrates with a frequency other than natural frequency due to the external force applied in equal interval of time is called Forced Oscillation.

2.5.1.Differential Equation And Its Solution Of Forced Oscillations

Let as consider a mass "m" connected to a spring and an external force is applied to this. Then there are three types of forces acting on it.

Restoring Force, Frictional force External force as in figure 2.5.1

Restoring force:

A restoring force is the force which is opposite to the direction of displacement(y).

$$F1 = -ky \quad \text{\_\_\_\_\_\_\_\_\_\_\_(i)}$$

Where, K is the force constant and y is the displacement. Here the negative sign indicates that the restoring force acts in the opposite direction to the displacement.

Friction force:

Friction force or damping force is due to presence of air resistance, which is opposite to the direction of velocity

$$F_2 = -r \text{ - - - - - - - - - - - - (2)}$$

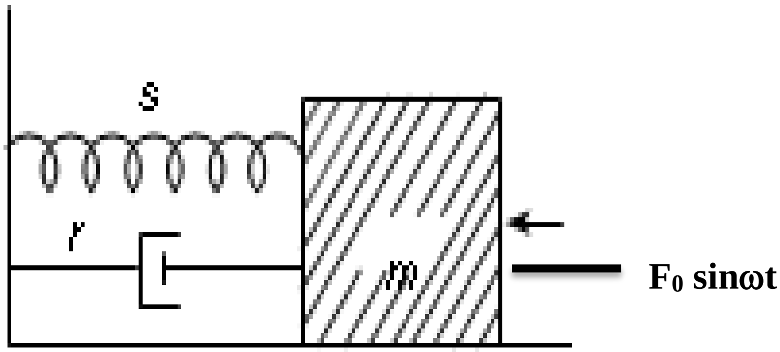


Fig 2.5.1 Forced Oscillations

(Source-"Physics of vibration and waves" by H.J.Pain page 57)

Applied force

$F_3 = F_0$ sinωt -------------- (3)

Total force

$F = F_1+F_2+ F_3$ --------------- (4)

Sub (i) & (2) & (3) in (4)

F=- ky -r + F_0 sinωt -------------(5)

But according to Newton's law

F = ma

Here F= m ----------------- (6)

Where —

From (4) & (5)

m =- ky -r + F_0 — sinωt

Divide by m = y — — — + sinωt

— — — —y sinωt

Put $r/m = 2b$ & $k/m = \omega_0^2$ & $F_0/m = f$

$$— \quad — \quad \omega \quad y \quad \omega \square (7)$$

The solution for this equation is

$$y = A\sin(\omega t - \theta) \text{ ------------ } (8)$$

Where, A is the amplitude and **θ** is the angle at which the displacement lags behind the applied force.

Differentiating twice (8)

We get $\omega \quad (\omega t-\theta) \text{ ---------------} (9)$

$$— \quad \omega \quad (\omega t-\theta) \text{--------} (10)$$

Sub (8),(9) &(10) in (7)

$$\omega\ (\omega t-\theta) + \omega\ (\omega t-\theta) + A\omega \sin(\omega t-\theta) = \omega\ -\theta+\theta)$$

$$= \omega\ -\theta)\cos\theta) + \omega\ -\theta)\sin\theta \text{---} (11)$$

Comparing the equations

$$\omega\ \omega\ )\ \theta \text{------} (12)$$

$$\omega = \theta \text{------} (13)$$

Squaring & adding (12) & (13)

$$\omega\ \omega\ )\ \omega\ \theta + \theta \text{-------} (14)$$

$$\omega\ \omega\ )\ \omega\ )$$

$$= \frac{}{\omega \quad \omega\ )\ \omega\ )}$$

$$A = \frac{}{\sqrt{\omega \quad \omega\ )} \quad \omega}$$

Divide (13) by (12)

$$\frac{\omega}{\omega\ \omega\ )} = \tan\theta$$

$$\theta \qquad (\frac{\omega}{\omega \quad \omega\ )})$$

The amplitude and phase of the forced oscillation depends on ω ω

2.7 Introduction of LASER

Light waves can also be amplified and is termed as 'LASER' which is an acronym for "***L**ight **A**mplification by **S**timulated **E**mission of **R**adiation*".

T.H. Maiman was discovered Ruby laser in 1960. Which lead to many types of lasers due to the lasting action with atoms, ions, molecules, etc., in gases, solids and liquids. The light beam from laser has frequency up to 10^{14} Hz leads to many applications in the scientific world.

Basic definitions

Stimulated Absorption:

When external photon energy is incident on the atom in the lower state, it can be raised to higher state by absorbing photon energy. This process is called the stimulated absorption.

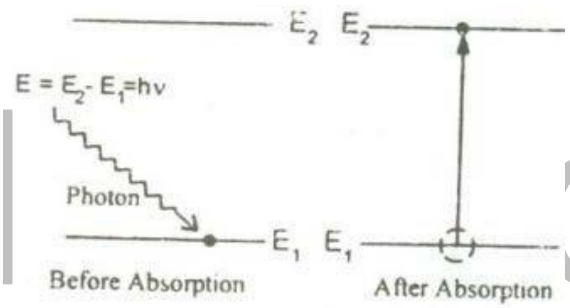


Fig:2.7.1 Stimulated Absorption

Stimulated Emission

Induced emissions of photons are produced by the transformation of

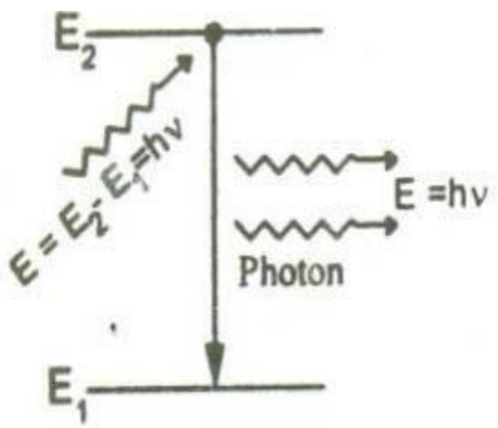


Fig 2.7.2 Stimulated Emission

an atom from excited state to ground state with the applied external photon energy is known as stimulated emission.

Spontaneous Emission

Induced emissions of photons are produced by the transformation of an atom from excited state to ground state without applied external photon energy is known as spontaneous emission.

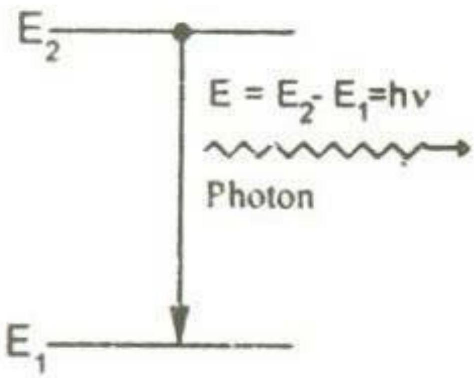


Fig:2.7.3 Spontaneous Emission

Population Inversion

The establishment of a situation in which the number of atoms in higher energy level is more than that in lower energy level is called population inversion. It is an essential requirement for producing a laser beam. It is achieved by pumping action.

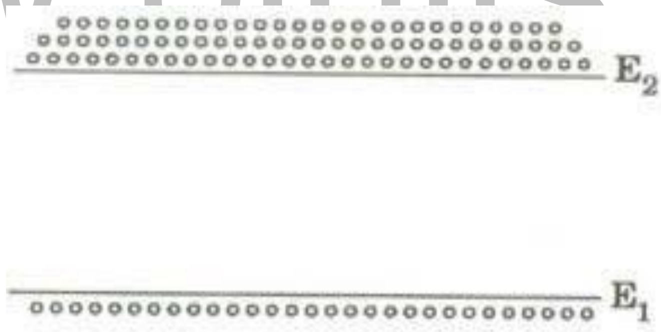


Fig:2.7.4 Population Inversion

Active medium

The medium in which the population inversion takes places is called active medium.

Active centre

The material in which the atoms are raised to excited state to achieve population inversion is called as active centre.

Pumping action

The process of creating a population inversion in the atomic state is known as pumping action. It is essential requirement for producing a laser beam.

There are several methods by which the population inversion (pumping) can be achieved.

Some of the most commonly used methods are

(a) Optical pumping

(b) Direct electron excitation (Electric discharge)

(c) Inelastic atom-atom collision.

(d) Direct conversion

(e) Chemical process

(a) Optical pumping:

The atoms are excited with the help of photons emitted by an external optical source. The atoms absorb energy from the photons and raises to excited state.

(e.g.) Ruby Laser, Nd-YAG Laser.

(b) Direct electron excitation:

The electrons are accelerated to very high velocities by strong electric field and they collide with gas atoms and these atoms are raised to excited state

(e.g) Gaseous ion lasers (argon laser), Helium-Neon (He-Ne) laser, CO_2 laser etc.

(c) Inelastic atom-atom collision:

A combination of two types of gases are used, say A and B both having same and nearly coinciding excited states A* and B*. During electric discharge 'A' atoms get excited due to collision with electrons. The excited A* atoms now collide with 'B' atoms so that B goes to excited state B* (e.g) Helium-Neon laser, CO_2 laser

$$e^- + A \rightarrow A^*$$

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

(c) **Direct conversion:** Due to electrical energy applied in direct band gap semiconductor like GaAs etc, the combination of electrons and holes takes place and electrical energy is converted into light energy directly. (e.g.) Semiconductor laser.

(d) **Chemical method:** Due to some chemical reactions, the atoms may be raised to excited state. (e.g.) Dye laser.

Differences Between Stimulated and Spontaneous Emission of Radiation.

S.No	Stimulated emission	Spontaneous emission
1.	Emission of light radiation is triggered by external source.	Emission of light radiation is not triggered by external influence.
2.	The emitted photon move in same direction and is highly directional.	The emitted photons move in all directions and are random.
3.	The radiation is high intense, monochromatic and coherent.	The radiation is less intense and is incoherent.
4.	The photons are in phase.	The photons are not in phase.
5.	The rate of transition is given by $R_{21}(St) = B_{21}\ \rho_v\ N_2$	The rate of transition is given by $R_{21}\ (Sp)=A_{21}\ N_2$

Characteristics of laser

1. It is highly coherent.
2. It is highly powerful.
3. It is directional and monochromatic.
4. It is extremely bright.
5. It is not easily absorbed by the water.
6. It is travel long distance without energy loss.

Differences between Ordinary Light and Laser Beam

S.No	Ordinary light	Laser beam
1.	In ordinary light the angular spread is more	In laser beam the angular spread is less.
2.	They are not directional	They are highly directional
3.	It is less intense	It is highly intense
4.	It is not a coherent beam and is not in phase	It is a coherent beam and is in phase.
5.	The radiations are polychromatic.	The radiations are monochromatic
6.	Eg. Sunlight, mercury vapour lamp etc.	Eg. He-Ne laser, CO_2 laser etc.

2.13 Losses in Optical fibres

When light propagates through an optical fibre, a small percentage of light is lost through different mechanisms. The loss of optical power is measured in terms of decibels per kilometre for attenuation losses.

Attenuation:

It is defined as the ratio of the optical power output (P_{out}) from a fibre of length 'L' to the power input (P_{in}).

$$\text{Attenuation} \quad (\alpha) = \frac{-10}{L} \log \frac{Pout}{Pin} \frac{dB}{Km}$$

Since attenuation plays a major role in determining the transmission distance, the following attenuation mechanisms are to be considered in designing an optical fibre.

(1) Absorption

(2) Scattering and

(3) Radiative losses.

(4) Distortion and Dispersion

Absorption

Usually absorption of light occurs due to imperfections of the atomic structure such as missing molecules, (OH^-) hydroxyl ions, high density cluster of atoms etc., which absorbs light. Absorption also depends on the wavelength of the light used.

Scattering

Scattering is also a wavelength dependent loss, which occurs inside the fibres. Since the glass is used in fabrication of fibres, the disordered structure of glass will make some variations in the refractive index inside the fibre. As a result, if light is passed through the atoms in the fibre, a portion of the light is scattered (elastic scattering). This type of scattering is called Rayleigh scattering.

$$\text{Rayleigh scattering Loss} \propto \frac{1}{\lambda^4}$$

Radiative losses

Radiative loss occurs in fibres, due to bending of finite radius of curvature in optical fibres. The types of bends are

(a) Macroscopic bend and

(b) Microscopic bend

Macroscopic bends:

If the radius of core is large compared to fibre diameter as shown in figure, it may cause large- curvature at the position where the fibre cable

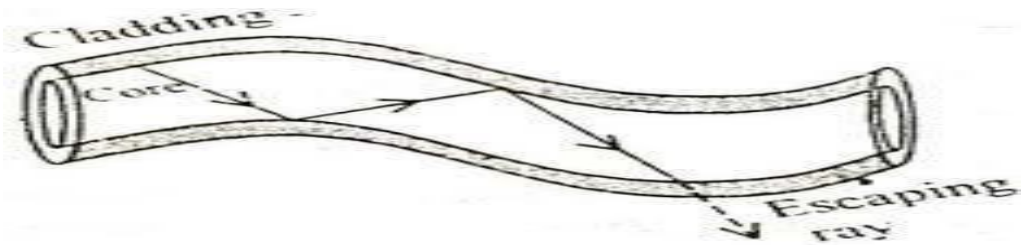


Fig 2.13.1 Macroscopic bends

turns at the corner. At these corners the light will not satisfy the condition for total internal reflection and hence it escapes out from the fibre. This is called as macroscopic/macro bending losses. Also note that this loss is negligible for small bends.

Microscopic bends:

Micro-bends losses are caused due to non-uniformities or micro-bends inside the fibre as shown in figure. This micro bends in fibre appears due to non-uniform pressures created during the cabling of the fibre or even during the manufacturing itself. It leads to loss of light by leakage through the fibre.

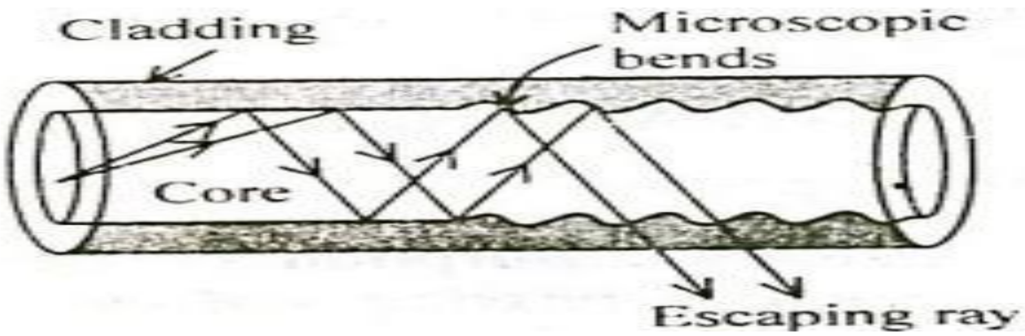


Fig 2.13.2 **Microscopic bends**

Remedy:

Micro-bend losses can be minimised by extruding (squeezing out) a compressible jacket over the fibre. In such cases, even when the external forces are applied, the jacket will be deformed but the fibre will tend to stay relatively straight and safe, without causing more loss.

Distortion and Dispersion

The optical signal becomes increasingly distorted as it travels along a fibre. This distortion is due to dispersion effect.

Dispersion

When an optical signal or pulse is sent into the fibre the pulse spreads/broaden as it propagates through the fibre. This phenomenon is called dispersion as shown in figure.

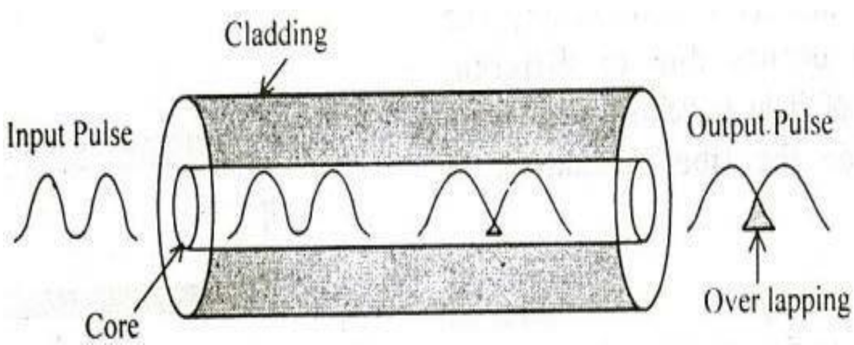


Fig 2.13.3 Dispersion

From figure we can see that the pulse received at the output is wider than the input pulse. Hence the output pulse is said to be distorted, due to dispersion effect.

The pulse broadening or dispersion will occur in three ways, viz,

(1) Inter-modal dispersion
(2) Material dispersion or chromatic dispersion
(3) Waveguide dispersion.

Inter-modal dispersion

When more than one mode is propagating through a fibre, then inter modal dispersion will occur. Since, many modes are propagating, they will

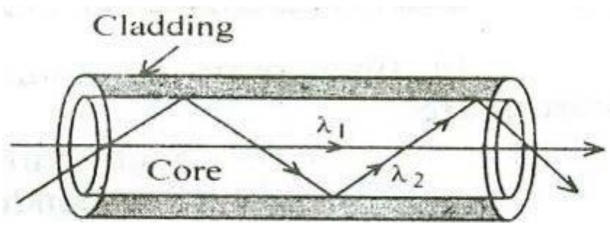


Fig 2.13.4 Inter-modal dispersion

have different wavelength and will take different time to propagate through the fibre, which leads to inter-modal dispersion.

Explanation:

When a ray of light is launched into the fibre, the pulse is dispersed in all possible paths through the core, so called different modes. Each mode will be of different wavelength and has different velocity as shown in figure. Hence, they reach the end of the fibre at different time. This results in the

elongation or stretching of data in the pulse. Thus causes the distorted pulse. This is known as inter- modal dispersion.

Material dispersion/ Chromatic dispersion

In material dispersion, the dispersion occurs due to different wavelength

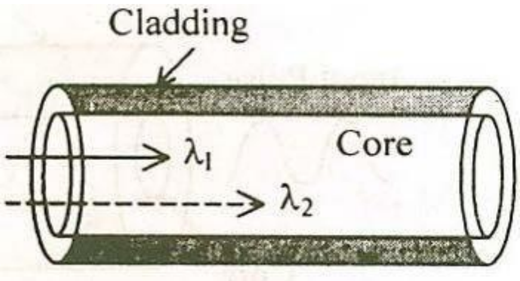


Fig 2.13.5 Material dispersion

of light travelling at different speed inside the fibre as shown in figure.

Remedy:

The material dispersion can be minimised at certain wavelengths say 870 nm, 1300 nm and 1550 nm, these wavelengths are termed as Zero Dispersion Wavelength (ZDW). When the light wavelength is lesser than the zero dispersion wavelengths (ZDW), it travels slower and when it is higher than ZDW it travels faster. Thus the speed is altered and adjusted in such a way that all the waves passing through the fibre will move with constant speed and hence the material dispersion is minimised.

Wave guide dispersion

The wave guide dispersion arises due to the guiding property of the fibre and due to their different angles at which they incident at the core-cladding interface of the fibre as shown in figure.

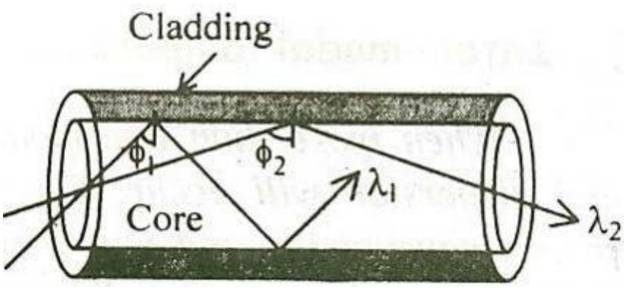


Fig 2.13.6 Wave guide dispersion

In general

Inter-modal dispersion > Material dispersion > Waveguide dispersion

2.11Derivation for Acceptance angle and Numerical aperture

Consider the light ray propagate in an optical fibre. The incident ray AO enters into core at an angle θ_0 to fibre axis. Let n_1, n_2 and n_o be the refractive indices of the core, cladding and surroundings.

Angle of incidence $\theta_c = 90 - \theta_r$

Applying Snell's law of refraction at the point B we have

$$n_1 \sin(90^\circ - \theta_r) = n_2 \sin 90^\circ$$

$$n_1 \cos\theta_r = n_2$$

$$\cos\theta_r = \frac{n2}{n1} \text{.....(2)}$$

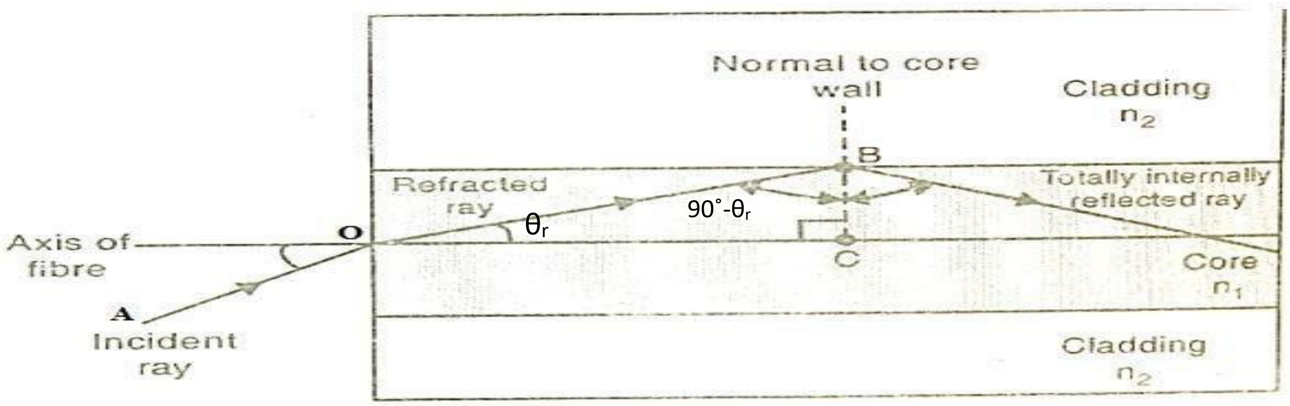


Fig 2.11.1propagation of light in fiber

Applying Snell's law of refraction at the point O we have

$$n_o \sin\theta_o = n_1 \sin\theta_r$$

$$\sin\theta_o = \frac{n1}{n0} \sin\theta_r$$

$$\sin\theta_o = \frac{n1}{n0} \sqrt{1 cos^2\theta - \theta_r} \text{ -----------------------(1)}$$

At the point B on the interface of core and cladding, Substituting equation (2) in equation (1) we have

$$\sin\theta_o = \frac{n1}{n0}\sqrt{1-\frac{n_2^2}{n_1^2}}$$

$$\sin\theta_o = \frac{n1}{n0}\sqrt{\frac{n_1^2-n_2^2}{n1}}$$

$$\sin\theta_o = \frac{n1}{n0n1}\sqrt{\frac{n_1^2-n_2^2}{1}}$$

$$\sin\theta_o = \frac{\sqrt{n_1^2-n_2^2}}{n0}$$

the medium surrounding the fibre is air, then $n_o = 1$

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

$$\theta_o = \sin^{-1}\sqrt{n_1^2-n_2^2} \quad \text{.........................(3)}$$

$$NA = \sin\theta_o \quad \text{.........................(4)}$$

This is the final expression of acceptance angle and numerical aperture.

The condition for propagation of light within the fibre is

$$\mathbf{\sin\theta_i < NA}$$

Acceptance angle

The maximum angle at or below which a ray of light can enter through one end of the fibre still be total internal reflection is called as acceptance angle. The cone is referred as acceptance cone.

$$\theta_o = \sin^{-1}\sqrt{n_1^2-n_2^2}$$

Numerical Aperture (NA)

Sine of the acceptance angle of the fibre is known as numerical aperture. It denotes the light gathering capability of the optical fibre.

$$NA = \sin\theta_o$$

Fractional Index Charge (Δ)

It is the ratio of refractive index difference in core and cladding to the refractive index f core.

$$\Delta = \frac{n1 - n2}{n1}$$

ENGINEERING PHYSICS

UNIT II

WAVES AND FIBRE OPTICS

2.6.PLANE PROGRESSIVE WAVES AND ITS WAVE EQUATION

Definition:

A wave which travels continuously in a medium in the same direction without any change in its amplitude is called a progressive wave or a travelling wave.

Explanation:

A Plane Progressive wave equation can be obtained to represent the displacementof a vibrating particle in a medium through which a wave passes. Each particle of a progressive wave executes simple harmonic motion of the same period and amplitude but differing in phase from each other.

(i) Displacement of Point O:

Let us assume that a progressive wave travels from the origin (O) along the x direction from left to right (Fig.). The displacement of a particle at a given instant.

$$y = A \sin \omega t \text{------}(1)$$

Where, A is the Amplitude and ω is the angular frequency of the particle, it is given by

$$\omega = \frac{2\pi}{T} \text{-----------}(2)$$

Where, T is the time period, it is defined as the total time take by the particle to complete one oscillation.

Sub eqn. (2) in (1), we get

$$y = A \sin \frac{2\pi t}{T} \text{------}(3)$$

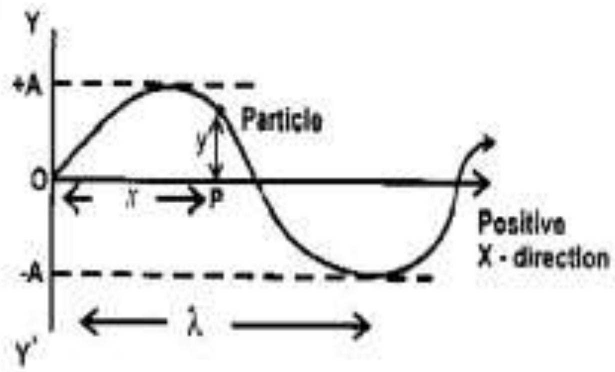


Fig 2.6.1. Plane progressive waves

(source:askiitians.com)

(ii) Displacement of Point P:

Now, assume that the particle is displaced to a distance (x) from point O to P with some time. Then the displacement of the particle at a distance x from O at a given instant is given by,

$$y = A\sin\frac{2\pi}{T}(t - \frac{x}{v})$$

$$T = \lambda/v$$

$$y = A\sin\frac{2\pi}{\lambda}(vt - x)\text{-------}(4)$$

Thus, eqn.6 shows the complete form of wave equation for plane progressive wave with respect to velocity **(v)** in the x- direction.

Definition: It is defined as the rate of change of displacement (y) of the particle with time (t).

From eqn.6, we can write

$$y = A\sin\frac{2\pi}{\lambda}(vt - x)$$

Differentiating eqn.4 with respect to t, we have

$$\frac{dy}{dt} = A\cos\frac{2\pi}{\lambda}(vt - x)\,X\,\frac{2\pi}{\lambda}v\text{------}(5)$$

When particle velocity is high, then

$$\cos\frac{2\pi}{\lambda}(vt - x) = 1$$

$$\frac{dy}{dt} = A\frac{2\pi}{\lambda}v$$

Differentiate (4) with respect to x

$$\frac{dy}{dx} = A\cos\frac{2\pi}{\lambda}(vt - x)\,X\,\frac{-2\pi}{\lambda} \quad \text{---------}(6)$$

$$\cos\frac{2\pi}{\lambda}(vt - x) = 1$$

$$\frac{dy}{dx} = -A\frac{2\pi}{\lambda}$$

Comparing (7) & (8)

$$\frac{dy}{dt} = -v\,\frac{dy}{dx}\text{---------}(7)$$

Thus, from eqn. 7, the particle velocity is directly depends on the wave velocity and the slope of the displacement of the particle.

Diff (5) & (6) again

$$\frac{d^2y}{dt^2} = -A\sin\frac{2\pi}{\lambda}(vt - x)\ X(\frac{2\pi}{\lambda})^2 v^2$$

$$\frac{d^2y}{dx^2} = -A\sin\frac{2\pi}{\lambda}(vt - x)\ X(\frac{2\pi}{\lambda})^2$$

On comparing

$$\frac{d^2y}{dx^2} = \frac{d^2y}{dt^2}v^2$$

This is the differential equation for progressive waves

2.10 Types of Lasers

Lasers are classified into five major categories based on the type of active medium.

(i) Solid state laser

Example: Ruby, Nd-YAG laser

(ii) Gas Lasers

Example: CO_2, He-Ne and Ar laser

(iii) Semiconductor laser

Example: GaAs, GaAsP, GaAlAs, InP lasers

(iv) Liquid lasers

(v) Dye laser

Homojunction Semiconductor LASER (GaAs)

Characteristics

Type	- Homojunction Semiconductor laser
Active medium	- P-N junction diode
Active centre	- Recombination of electrons and holes
Pumping method	- Direct pumping
Optical Resonator	- Junction of diodes - polished
Power output	- 1 mW
Nature of output	- Pulsed or Continuous waveform
Wavelength	- $8400A^0 – 8600A^0$
Band gap	- 1.44 eV

Principle:

The electron in conduction band combines with a hole in the valence band and hence the recombination of electron and hole produces energy in the form of light. This

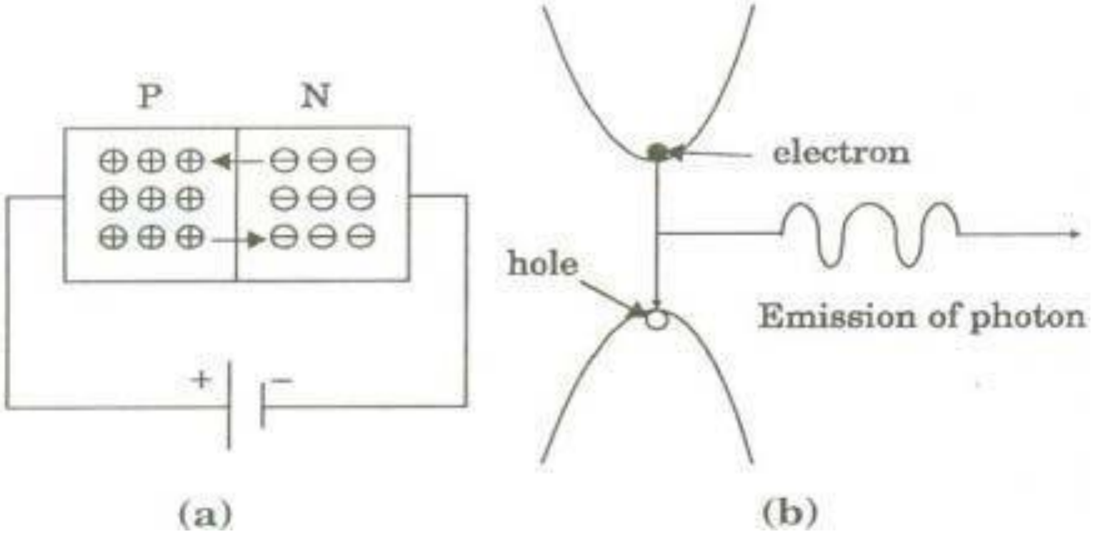


fig:2.10.1 (a)semiconductor laser principle,(b)Emission of photon

photon, in turn may induce another electron in the conduction band (CB) to valence band (VB) and thereby stimulate the emission of another photon.

Construction:

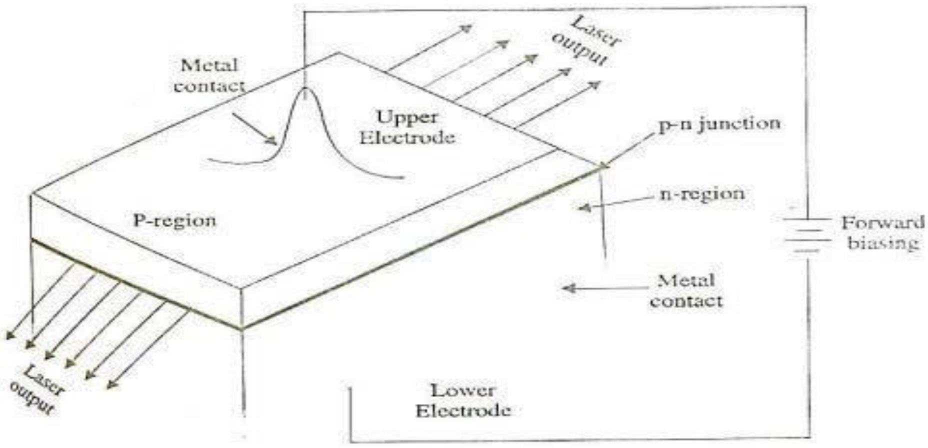
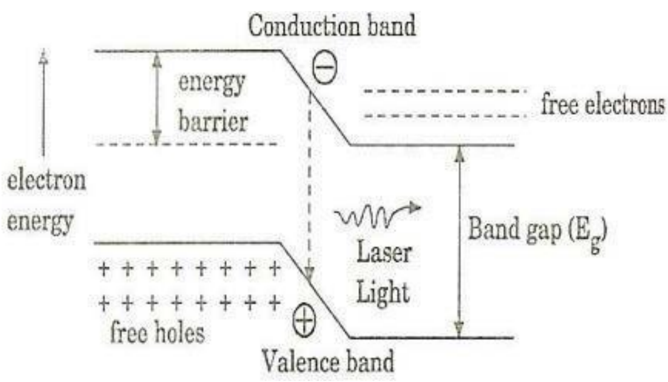
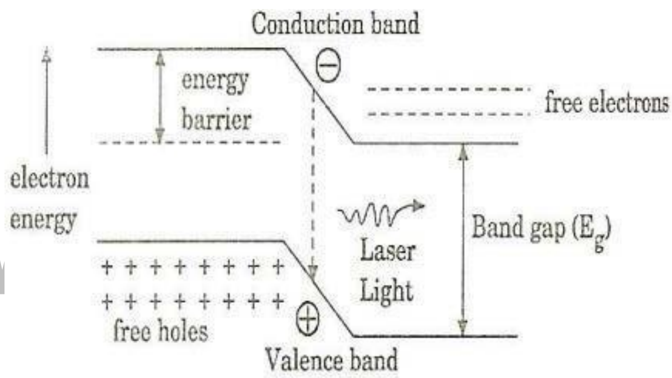


fig:2.10.2 Homojunction Semiconductor laser

The active medium is a p-n junction diode made from a single crystalline material i.e. Gallium Arsenide in which p-region is doped with germanium and n-region with Tellurium. The thickness of the p-n junction layer is very narrow so that the emitted laser radiation has large divergence. The junctions of the ‘p’ and ‘n’ are well polished and are parallel to each other as shown in figure. Since the refractive index of GaAs is high, it acts as optical resonator so that the external mirrors are not needed. The upper and lower electrodes fixed in the ‘p’ and ‘n’ region helps for the flow of current to the diode while biasing.

Working





1. Fig:2.10.3 Band gap diagram

1.The population inversion in a p-n junction is achieved by heavily doping ‘p’ and ‘n’ materials, so that the Fermi level lies within the conduction band of n type and within the valence band of ‘p’ type as shown in figure.

2. If, the junction is forward biased with an applied voltage nearly equal to the band gap voltage, direct conduction takes place. Due to high current density, active region is generated near the depletion region.
3. At this junction, if a radiation having frequency (v) is made to incident on the p-n junction then the photon emission is produced as shown in figure.
4. Thus the frequency of the incident radiation should be in the range

$$\underline{Eg} < \frac{EF_C - EF_V\, h}{h}$$

5. Further, the emitted photons increase the rate of recombination of injection electrons from

the n region and holes in p region by inducing more recombination.

6. Hence the emitted photons have the same phase and frequency as that of original inducing photons and will be amplified to get intense beam of LASER.
7. The wavelength of emitted radiation depends on i) the band gap and ii) the concentration of donor and acceptor atoms in GaAs.

Advantages

i) It is easy to manufacture the diode.

ii) The cost is low.

Disadvantages

i) It produces low power output.

ii) The output wave is pulsed and will be continuous only for some time.

iii) The beam has large divergence.

iv) They have high threshold current density.

Applications

1. It is widely used in fibre optic communications
2. It is used to heal the wounds by IR radiation.
3. I t is also used as a pain killer.
4. It is used in printers, CD writing and reading.

Heterojunction Semiconductor LASER (GaAlAs)

Characteristics

Type	- Heterojunction Semiconductor laser
Active medium	– p-n junction diode (with various layers)
Active centre	- Recombination of electrons and holes
Pumping method	- Direct pumping
Optical Resonator	- Polished junctions of diode
Power output	- 10 mW
Nature of output	- Continuous waveform
Wavelength	- 8000 Å
Band gap	- 1.55 eV

Principle:

The electron in conduction band combines with a hole in the valence band and hence the recombination of electron and hole produces energy in the form of light. This photon, in turn may induce another electron in the conduction band (CB) to valence band (VB) and thereby stimulate the emission of another photon.

Construction:

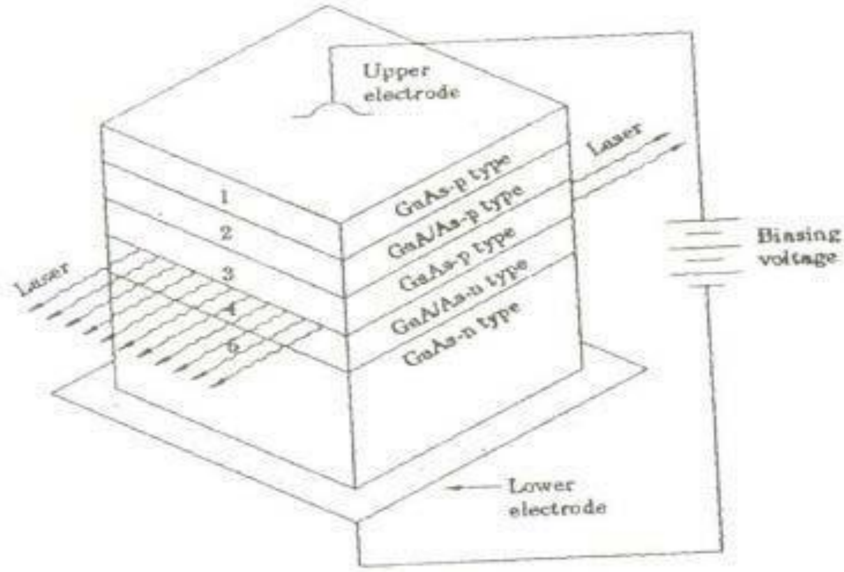


Fig 2.10.4 Heterojunction semiconductor laser

It consists of five layers as shown in figure. A layer of GaAs- p type (3rd layer) which has a narrow band gap will act as the active region. This layer (3rd layer) is sand witched between the two layers having wider band gap viz. GaAlAs – p-type (2nd layer) and GaAlAs – n-type (4th layer). A contact layer made of GaAs-p-type (1st layer) is made to form at the top of the 2nd layer for necessary biasing. All these four layers are grown over the substrate (5th layer) made of GaAs-n-type. The junctions of GaAs-p-type (3rd layer) and GaAlAs-n-type (4th layer) are well polished and hence it acts as an optical resonator. The upper and lower electrode helps in forward biasing the diode.

Working

The working of a hetero junction laser is similar to that of the working of a homo junction laser.

1) The diode is forward biased with the help of upper and lower electrodes.
2) Due to forward biasing the charge carriers are produced in the wide band gap layers (2 and 4).

3) These charge carriers are injected into the active region(layer 3).

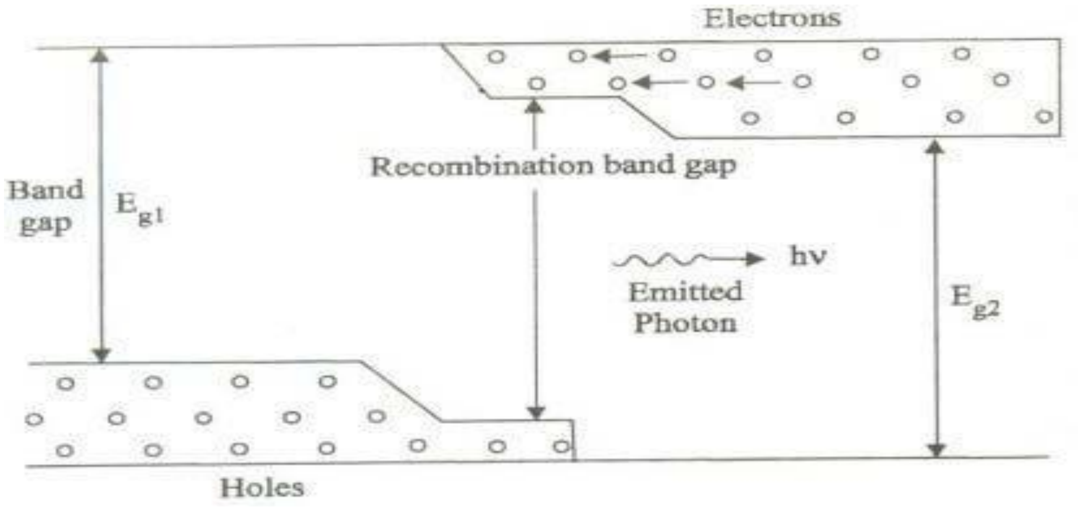


Fig 2.10.4 Band gap diagram

The charge carriers are continuously injected from 2nd and 4th layer to the 3rd layer, until the population inversion is achieved.

4) At this state some of the injected charge carriers recombines and produces spontaneously emitted photons.
5) These spontaneously emitted photons stimulate the injected charge carriers to emit photons.
6) As a result, more number of stimulated emissions arises and thus large number of photons is produced.
7) These photons are reflected back and forth at the junction and hence an intense, coherent beam of LASER emerges out from the P-N junctions of active region i.e. between layr-3 and layer-4 as shown in figure.

3) These charge carriers are injected into the active region(layer 3).

Applications of LASER

1. It is used in microelectronics.
2. It is used to deposit semiconductor films on dielectric substrate.
3. High power laser is used to write the data in the CD/DVD.
4. Laser is used as a tool to cut thin metal sheets by property of focusing.
5. It is used make weld, drill and perforate holes, even up to 0.2 to 0.5 μm of thickness.
6. It is used in the treatment of detached retina.
7. It is used to coagulation in diabetic retinopathy.
8. It is used in the treatment of nerves in skull and spine.
9. It is used in the treatment by coagulation of lower gastro intestinal fat.
10. Removal of skin imperfections by laser irradiation.
11. It is used to fallopian tube reconstruction.
12. It is also used in surgery.

2.14 Types of Sensors

There are two types of sensors. They are

(i) Intrinsic Sensors or Active sensors

(ii) Extrinsic Sensors or Passive sensors

Displacement sensor

Definition

It is a sensor which is used to sense and measure the displacement of an object.

Construction

It consists of a bundle of transmitting fibers connected to a laser source and a bundle of receiving fibers connected to a detector. (figure)

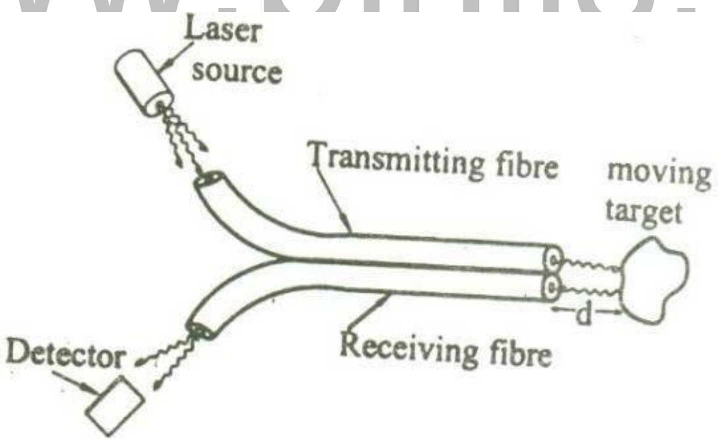


Fig 2.14.1 Displacement sensor

Working

First the light from the laser source is transmitted through transmitting fiber and it falls on the moving target.

The reflected beam from the target is made to passes through the receiving fiber and this light is detected by the detector. The intensity of the light received back depends on the displacement of the target.

If the received intensity increases, it denotes that the target is moving towards the sensor. If the intensity of light received decreases, it denotes that the target is moving away from the sensor.

Thus, the displacement of the target

Pressure Sensor

Principle :

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

Description:

It consists of a Laser source to emit light.A beam splitter, made of glass plate is inclined to an angle of 45 degrees with respect to the direction of laser beam.There are two fiber namely

i)Reference fiber- which is isolated from the environment.

i) Test fiber – Seperate lens systems are provided to spit and to collect the beam.

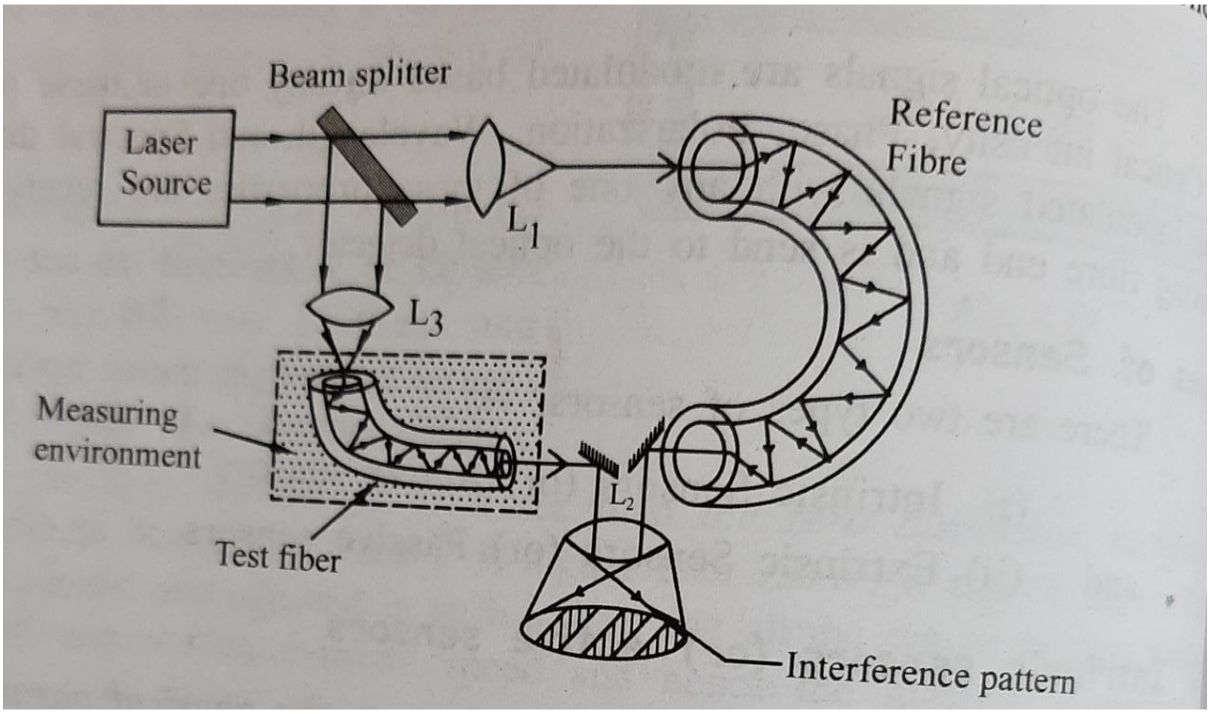


Fig 2.14.2 Pressure Sensor

Working:

1.Monochromatic source of light is emitted from the laser source.

2.The beam splitter kept at 45 degrees divides the beam emerging from the laser source into two beams

i)Main beam

ii)Splitted beam

3)The main beam passes through the lens L1 and is focussed onto the reference fibre.

4) The beam ,after passing through the reference fibre,falls on the lens L2.

5)The splitted beam passes through the lens L3 and is focussed onto the test fibre.

6) The splitted beam after passsing through the the test fibre is made to fall on the lens L2.

7) The two beams ,after passing through the fibre,produces a path difference,due to the change in pressure and temperature .

8)Therefore a path difference is produced between the two beams,causing the interference pattern.

9)Thus the change in pressure can be accurately measured with the help of the interference pattern obtained.

2.12Types of Optical Fibre Based on the materials

1. Glass fibre
2. Plastic fibre

Based on the mode

1. Single mode fibre
2. Multi-mode fibre

Based on the refractive index

1. Step index fibre
2. Graded index fibre

Glass fibres

The fibres are made up of mixture of metal oxides and silica glasses. The glass fibres can be made by any one of the following combinations of core and cladding.

1. **Core:** SiO_2; **Cladding:** $P_2O_3 - SiO_2$
2. **Core:** $GeO_2 - SiO_2$ **Cladding:** SiO_2

Plastic fibres

If the fibres are made up of plastics which can be handled without any care due to its toughness and durability it is called plastic fibre. The plastic fibres are made by any one of the following combinations of core and cladding.

1. **Core:** Polymethyl methacrylate;
   Cladding: Co-polymer
2. **Core:** Polystyrene;
   Cladding: Methyl methacrylate

In general, the single mode fibres are step index fibres. These types of fibres are made from doped silica. It has a very small core diameter so that it can allow only one mode of propagation and hence called single mode fibres. The cladding diameter must be very large compared to the fore diameter. Thus in the case of single mode fibre, optical loss is very much reduced. The structure of a single mode fibre is as shown in figure.

Fig 2.12.1 Single mode fibres

Structure

Core Diameter : 5- 10 μm

Cladding Diameter : Generally, around 125 μm

Protective layer : 250 to 1000μm Numerical

Aperture : 0.08 to 0.10

Band Width : More than 50 MHz km

Application

Because of its high band width, they are used in long haul communication systems.

Multi-Mode fibres

The multimode fibres are useful in manufacturing both for the step index and graded index fibres. The multimode fibres are made by multi-component glass compounds such as Glass-clad Glass, Silica-clad Silica, doped silica etc. Here the core diameter is very large compared to single mode fibres, so that it can allow many modes to

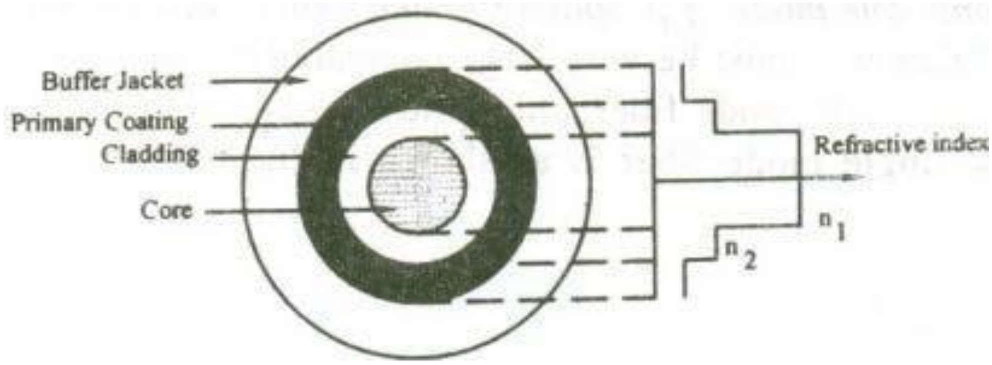


Fig 2.12.2Multi mode fibres

propagate through it and hence called as multi-mode fibres. The cladding diameter is also larger than the diameter of the single mode fibres. The structure of the multimode fibre is as shown in figure.

Structure

Core Diameter : 50 - 350 µm

Cladding Diameter : 125 -500 µm

Protective layer : 250 to 1100µm

Numerical Aperture : 0.12 to 0.5

Band Width : Less than 50 MHz km

Application

Because of its less band width it is very useful in short haul communication systems.

Differences between Single and Multimode Fibre

S.No	**Single mode fibre**	**Multi-mode fibre**
1.	In single mode fibre only one mode can be propagated.	Large number of modes for light to pass through it.
2.	The single mode fibre has a smaller core diameter. and	The core diameter is large.
3	Difference in refractive index of core and cladding is small.	The core and cladding refractive indices difference is large
3.	No dispersion	Dispersion is more
4.	Information can be carried to longer distances only.	Informationcan be carried to shorter distances only.
5.	Launching of light and connecting two fibres are difficult.	Launching of light and also connecting two fibres is easy.
6.	Installation is more costly.	Installation cost is low.

Step index fibre

Single mode fibre

A single mode step index fibre consists of a very thin core of uniform refractive index surrounded by a cladding of refractive index lower than that of core. The refractive

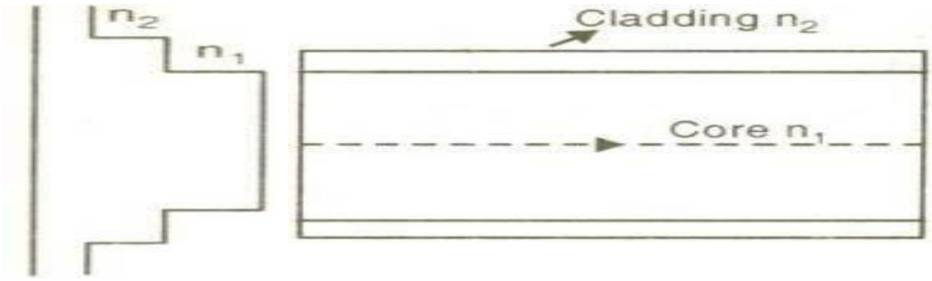
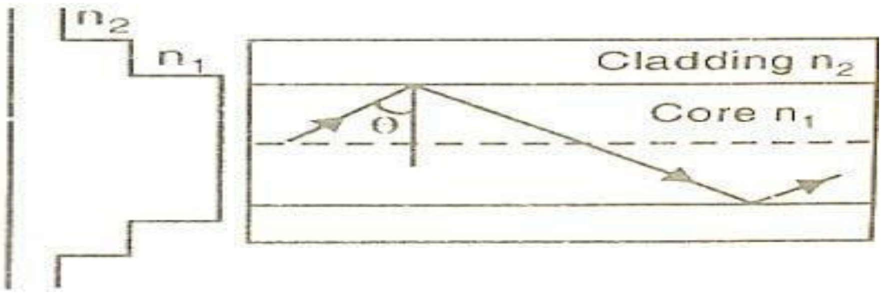


Fig 2.12.3 Step index fibre Single mode fibre

index abruptly changes at the core cladding boundary. Light travels along a side path, i.e., along the axis only. So zero order modes are supported by Single Mode Fibre.

Multi-mode fibre

A multimode step index fibre consists of a core of uniform refractive index surrounded by cladding of refractive index lower than that of the core. The refractive index abruptly changes at the core cladding boundary. The core is of large diameter. Light follows zigzag paths inside the fibre. Many such zigzag paths of propagation are permitted in multi-mode fibre. The numerical aperture of a multi-mode fibre is larger as the core diameter of the fibre is larger.



2.12.4 Step index fibre Multi mode fibre

Graded index fibre

GRIN fibre is one in which refractive index varies radially, decreasing continuously in a parabolic manner from the maximum value of n_1, at the centre of the core to a constant value of

n_2 at the core cladding interface.

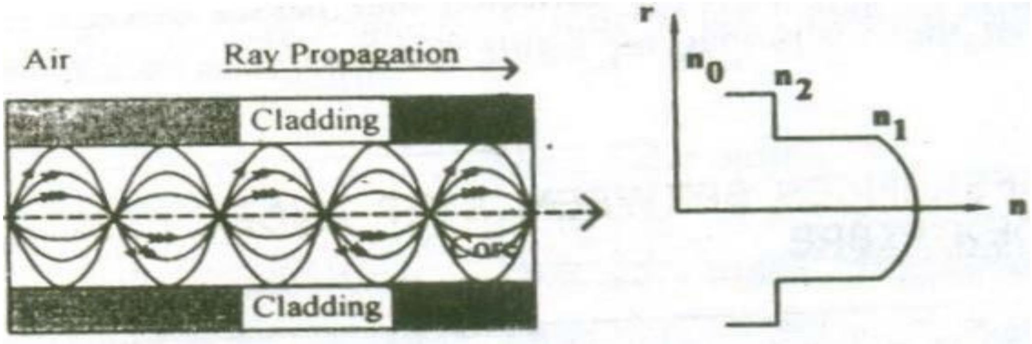


Fig 2.12.5 Graded index fibre

In graded index fibre, light rays travel at different speeds in different parts of the fibre because the refractive index varies throughout the fibre. Near the outer edge, the refractive index is lower. As a result, rays near the outer edge travel faster than the rays at the centre of the core.

Because of this, rays arrive at the end of the fibre at approximately the same time. In effect light rays arrive at the end of the fibre are continuously refocused as they travel down the fibre. All rays take the same amount of time in traversing the fibre. This leads to small pulse dispersion.

Propagation of light in GRIN fibre

Let n_a, n_b, n_c, n_d etc. be the refractive indices of different layers in the graded index fibre with $n_a > n_b > n_c > n_d$ etc. Then the propagation of light through the graded index fibre is as shown in figure.

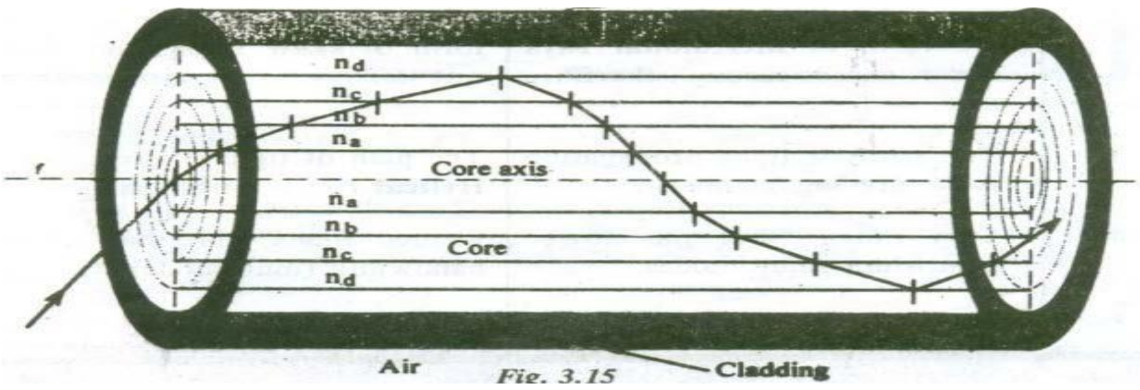


Fig 2.12.6 Propagation of light in GRIN fibre

Here, since $n_a > n_b$ the ray gets refracted. Similarly, since $n_b > n_c$, the ray gets refracted. In a similar manner, due to decrease in refractive index the ray gets gradually curved towards the upward direction and at one place, where it satisfies the condition for total internal reflection, ($\phi > \phi_c$) it is totally internally reflected. The reflected ray travels back towards the core axis (but not crosses it) and without crossing the fibre axis, it is refracted towards downwards direction and again gets totally internally reflected and passes towards upwards direction. In this manner the ray propagates inside the fibre in a helical or spiral manner.

Differences between Step Index Fibre and Graded Index Fibre

S.No	**Step index fibre**	**Graded index fibre**
1.	Change in refractive index is abruptly at the core and cladding interface.	Change in refractive index is gradually at the core and cladding interface.
2.	Propagation light rays are in the form of meridional rays.	Propagation of light rays is in the form of skew rays.
3.	The path of light propagation is in Zig-zag manner.	The path of light propagation is Helical.
4.	Step index fibre has lower bandwidth.	Graded index fibre has higher bandwidth.
5.	Distortion is more	Distortion is less
6.	Numerical aperture is more.	Numerical aperture is less.

ENGINEERING PHYSICS

UNIT II

WAVES AND FIBRE OPTICS

Contents

2.1. Oscillatory motion

Basic Definitions

Motion

When the position of the body in the space changes with times, the body is said to be in motion.

Types of motion

1. Translational motion
2. Rotational motion.
3. Periodic motion
4. Vibrational or Oscillatory motion

Translational motion

If an object is moving linearly with time, then the motion is said to be in Translational motion.

Example: Car moving in a road. Train moving in a track, Rocket launching etc.

Rotational motion

If an object rotates about an axis then the motion is said to in Rotational motion.

Example: Bob moving around the pendulum.

Periodic motion

If the body repeats its movement at regular intervals of time then it is said to be in periodic motion.

Example: Motion of planets round the sun, rotational motion of the earth about its own

Oscillatory motion

When a body rotates to and fro movement repeatedly then the motion is said to be oscillatory motion.

Example: Motion of a pendulum, oscillation of loaded spring, to and fro motion of the prongs of tuning fork.

2.2. SIMPLE HARMONIC MOTION

Definition

If the acceleration of particle is directly proportional to its displacement from its equilibrium position and it is always directed towardsequilibrium position, then the motion of the particle is said to Simple Harmonic Motion

Types of Simple Harmonic Motion:

(i) Linear Simple Harmonic Motion

(ii) Angular Simple Harmonic Motion

(i) **Linear Simple Harmonic Motion**

If the displacement of the particle executing simple harmonic motion is linear then it is linear SHM

Example: Motion of simple pendulum.

(ii) **Angular Simple Harmonic Motion**

If the displacement of the particle executing simple harmonic motion is Angular then it is angular SHM.

Example: Torsional oscillation.

2.3. CHARACTERISTIC OF SIMPLE HARMONIC MOTION

a) Amplitude

The maximum displacement of the particle from its mean position is known as the amplitude.

b) Displacement:

The distance moved by the particle from its mean position is called displacement.

Displacement (y) = A sin ωt

c) Time Period:

The time taken for the particle to complete one oscillation is known as Period.. It is given the symbol *T*.**Time Period,**

d) Frequency:

Number of oscillations occurred in one second is called frequency.

e) Phase:

The position and direction of motion of a vibrating particle is expressed by a physical quantity called the phase.