MODULE 3
LASER

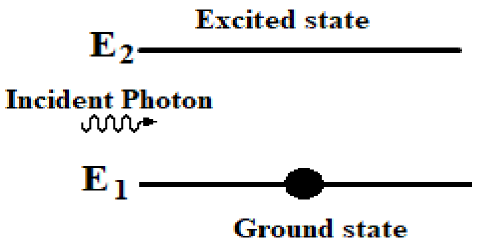
The term LASER is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Laser is a device that produces a highly coherent, monochromatic, intense beam of light with very small divergence. Production of laser light is a particular consequence of interaction of radiation with matter. The interpretation of the interaction is done on the basis of ideas related to energy levels of the concerned system from which light is derived.

Interaction of radiation with matter:

There are three possible ways through which the interaction of radiation with the matter can take place.

(1) Induced absorption: **Induced absorption is the absorption of an incident photon by a system as a result of which the system is elevated from a lower energy state to a higher energy state, wherein the difference in energy of two states is precisely the energy of the photon.**

Let us assume that the atom is in the lower energy state E_1. Let a photon having energy $h\nu = E_2 - E_1$ be incident on the atom. The atom absorbs the energy and go to the higher energy state E_2. This process is known as induced absorption.



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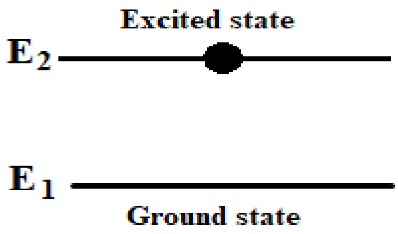

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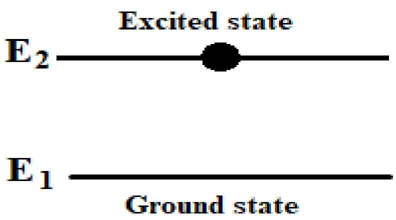
(2) Spontaneous emission: **Spontaneous emission is the emission of a photon, when a system transits from a higher energy state to a lower energy state without the aid of any external agency.**

Consider the atom in the higher energy state E_2. It makes a transition to the lower energy state E_1 by emitting a photon of energy $h\nu=E_2-E_1$ without the help of external source of energy. This process is called spontaneous emission.



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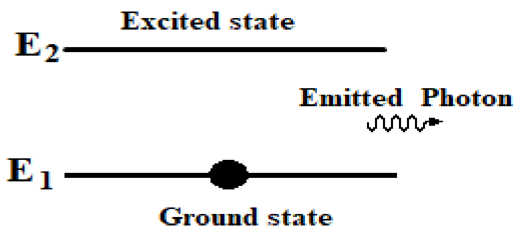

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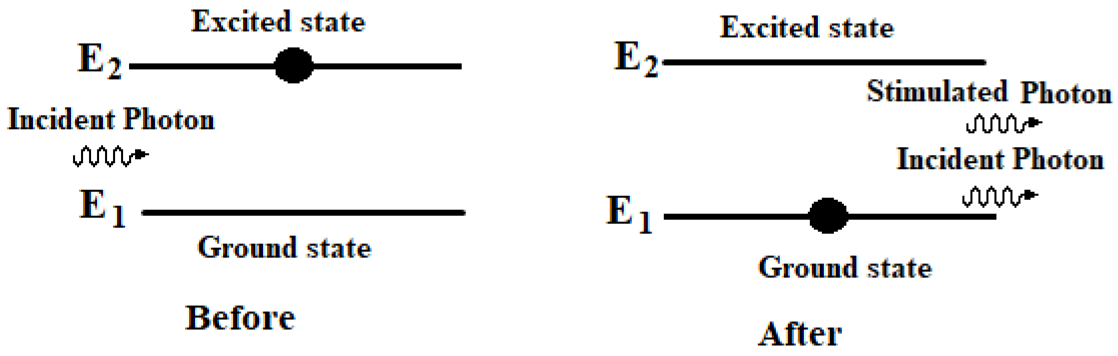
The photons are emitted in all directions in this process. They do not have any phase relationship between them. Hence the emitted radiations are incoherent. It can be represented as atom* $\rightarrow$ atom + photon.

(3) Stimulated emission: Stimulated emission is the emission of photon by a system under the influence of a passing photon of just the right energy, due to which the system transits from higher energy state to the lower energy state.

Consider a photon having energy $h\nu = E_2 - E_1$ interacts with an atom which is in the higher energy state E_2, by passing in its vicinity. Under such stimulation the atom undergoes transition to the lower energy state E_1 by emitting another photon of same energy $h\nu$. This process is called Stimulated emission.

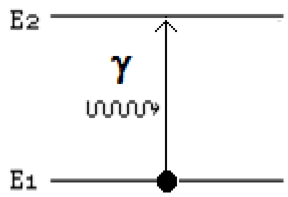


In this process two photons will have the identical phase and thus they are coherent. It can be represented as atom* + photon → atom + photon + photon. This kind of emission is responsible for laser action.

Einstein's Co-efficient:

An Einstein coefficient gives the probability of emission or absorption. Consider two energy states E_1 and E_2 of system of atoms ($E_2 > E_1$). Let there be N_1 no. of atoms with energy E_1 and N_2 is the no. of atoms with energy E_2. N_1 and N_2 are called number density of atoms in the states 1 and 2 respectively. Let $U_\nu d\nu$ is the energy incident per unit volume of the system whose frequency lie in the range ν and $\nu + d\nu$. Then U_ν represents the energy density.

1. Case of induced absorption



Induced Absorption

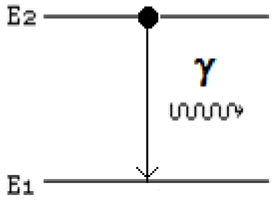
In this case an atom in the ground state at an energy E_1 can go to the excited state E_2 by absorbing a photon of frequency $\nu = E_2 - E_1 / h$. The number of such absorption per unit time per unit volume is called rate of induced absorption. Rate of induced absorption is proportional to (a) No of atoms in the lower energy state i.e. N_1. (b) Energy density U_ν.

Rate of induced absorption α $N_1 U_\nu$

$\therefore$ Rate of induced absorption = $B_{12} N_1 U_\nu$ ---------- (1)

Where B_{12} is the proportionality constant called Einstein's coefficient of induced absorption.

2. Case of spontaneous emission:



Spontaneous Emission

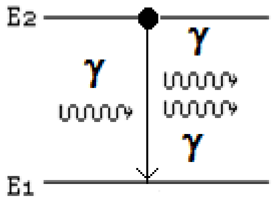
In this case atom in the higher energy state E_2 undergoes transition to the lower energy level E_1 voluntarily by emitting a photon of energy $h\nu = E_2 - E_1$. The Number of spontaneous emissions per unit time per unit volume is called rate of spontaneous emission. Rate of spontaneous emission is proportional to the number atom in the higher energy state E_2 i.e. N_2.

Rate of spontaneous emission α N_2

$\therefore$ Rate of spontaneous emission = $A_{21} N_2$. -------(2)

Where A_{21} is the proportionality constant called Einstein's coefficient for spontaneous emission.

3. Case of stimulated emission.



Stimulated Emission

In this case atoms in the higher energy level E_2 come to the lower energy level E_1 by the emission of photon of energy $h\nu$ under the influence of the incoming photon of energy $h\nu$. The number stimulated emissions per unit time per unit volume is called rate of stimulated emission The rate of stimulated emission is proportional to (a) number of atoms N_2 in the higher energy state E_2. (b) the energy density U_ν.

Rate of stimulated emission α $N_2 U_\nu$.

$\therefore$ Rate of stimulated emission= $B_{21}N_2 U_\nu$. --------(3)

Where B_{21} is the proportionality constant called Einstein's coefficient of stimulated

At thermal equilibrium, rate of induced absorption = rate of spontaneous emission + rate of stimulated emission.

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

i.e. $$B_{12} N_1 U_\nu - B_{21} N_2 U_\nu = A_{21} N_2$$

i.e. $$U_\nu (B_{12}N_1 - B_{21}N_2) = A_{21}N_2$$

i.e. $$\mathbf{U_\nu = \frac{A_{21}N_2}{(B_{12}N_1 - B_{21}N_2)}}$$

i.e. $$\mathbf{U_\nu = \frac{A_{21}N_2}{B_{21}N_2\left(\frac{B_{12}}{B_{21}}\frac{N_1}{N_2} - 1\right)}}$$

i.e. $$\mathbf{U_\nu = \frac{A_{21}}{B_{21}}\left(\frac{1}{\frac{B_{12}}{B_{21}}\frac{N_1}{N_2} - 1}\right)} \quad \text{----------------------(4)}$$

When the system is in thermal equilibrium, the population of different energy states is related to each other by a term known as Boltzmann factor which is given by

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/kT} \quad \text{where k is Boltzmann constant}$$

i.e. $\frac{N_2}{N_1} = e^{-h\nu/kT}$ (since $(E_2 - E_1) = h\nu$)

or $\frac{N_1}{N_2} = e^{\,h\nu/kT}$

Using this in eqn.(4) we get

$$U_\nu = \frac{A_{21}}{B_{21}}\left(\frac{1}{\frac{B_{12}}{B_{21}}\ e^{\frac{h\nu}{kT}}-1}\right) \qquad \text{----------------} \ (5)$$

Since the system is in a black body radiation field, we can use Planck's law of Blackbody radiation.

i.e. $$U_\nu = \frac{8\pi h\nu^3}{c^3}\left(\frac{1}{e^{\frac{h\nu}{kT}}-1}\right) \qquad \text{------------------} \ (6)$$

From eqn.(5) and (6) we can write,

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

and $\frac{B_{12}}{B_{21}} = 1$

i.e. $B_{12} = B_{21}$

i.e. the probability of induced absorption is equal to the probability of stimulated emission. Because of this, the subscripts could be dropped. Hence A_{21} and B_{21} can be written simply as A and B in eqn. (5).

Thus we get

$$\boldsymbol{U_\nu = \frac{A}{B}\left(\frac{1}{e^{\frac{h\nu}{kT}}-1}\right)}$$

This is the equation for energy density at thermal equilibrium.

<u>Conditions for lasing action:</u>

1. Population inversion:

From Boltzmann factor, we have

$$\frac{N_2}{N_1} = e^{-h\nu/kT} = e^{-(E_2-E_1)/kT} \qquad \text{-------}(1)$$

where E_1 & E_2 are the energies of lower and higher energy levels respectively.

i.e. $E_2 > E_1$ Thus $N_2 < N_1$ from eqn. (1)

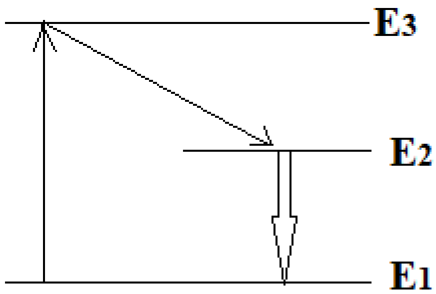
i.e. the number of atoms is more in the lower energy state than that in the higher energy state.

If a photon having energy (E_2-E_1) is incident on a system, the probability of induced absorption is more than that of stimulated emission. To increase the probability of stimulated emission, the number of atoms in the higher energy state must be made greater than number of atoms in lower energy state. ***The state in which there are a larger number of atoms in the higher energy state than the lower energy state is called population inversion.*** This is achieved by using the concept of metastable state. A system in which population inversion is achieved is called active medium. The state of population inversion is not an equilibrium state of the system.

2. Metastable state:

Metastable state is the special type of excited state where the life time of atom is more than that of the normal excited state.

In real physical system, the population inversion condition doesn't exist under normal conditions. The population inversion is achieved in certain systems which possess a special kind of excited energy state called metastable state. The life time of a metastable state is few milliseconds. (Life time of an excited state is few nano second)



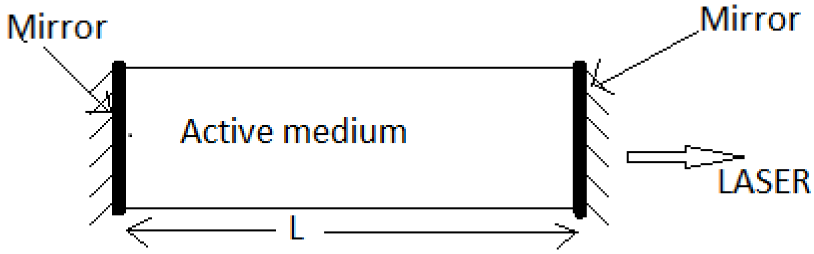
Consider three energy levels E_1, E_2, and E_3, of which E_1 is the ground state, E_3 is the excited state and E_2 is the intermediate metastable state. Let the atom be excited from E_1 to E_3 by supply of appropriate energy from the external source. From E_3 state atoms undergo spontaneous transition to E_2 and E_1. Since E_2 is metastable state it allows accumulation of a large number of excited atoms at that level. Because of which population of E_2 state increases. Under such conditions a stage will be reached where the population of E_2 state overtakes that of E_1 which is known as population inversion

<u>Requisites of a laser system.</u>

(i) An excitation source for pumping action- To achieve a state of population inversion, the atoms in the lower energy state have to be pumped to the higher energy state by providing energy. Energy can be supplied to atoms in different forms. The source of energy used for pumping process is known as excitation source. The process of raising the atoms from a lower energy state to higher energy state to create population inversion is called pumping.

(ii) An active medium – The quantum medium which supports the population inversion and promotes stimulated emission leading to light amplification.

(iii) A laser cavity: A laser consists of an active medium bound between two mirrors. The mirrors reflect the photons to and fro through the active medium. The two mirrors along with active medium form a laser cavity.



Within the laser cavity interference of light waves take place. To achieve constructive interference the distance between the two mirrors should be such that the cavity should support an integral no of half wavelengths. If L is the length of the laser cavity, then

$L = \frac{m\lambda}{2}$ where m > 0 is an integer and λ is wavelength of light

Thus $\lambda = \frac{2L}{m}$

Note: Frequency difference between adjacent modes of vibration:

We know that $L = \frac{m\lambda}{2} = \frac{mv}{2\upsilon}$ (since $v = \vartheta\lambda$)

Or $\upsilon = \frac{mv}{2L}$

Then $\Delta\upsilon = \frac{(m+1)v}{2L} - \frac{mv}{2L} = \frac{v}{2L}$ where Δυ is Frequency difference between adjacent modes of vibration.

Carbon Dioxide laser:

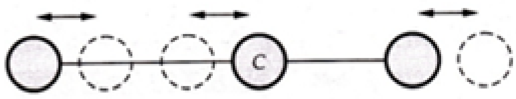
It is a molecular gas laser which operates in the middle IR region involving a set of quantized rotational vibrational transitions. It is a four level laser producing both continuous and pulsed output. This was devised by CKN Patel in 1964.

The CO_2 molecule has three modes of vibration. They are

(i) Symmetric stretching mode: In this mode, the oxygen atoms oscillate along the molecular axis either approaching towards or departing from the carbon atom simultaneously. The carbon atom remains stationary. In spectroscopy this is referred as 100 state.

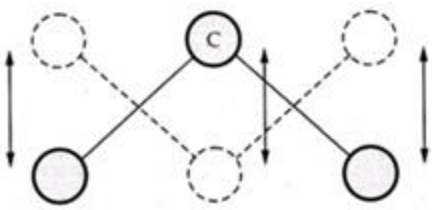
Symmetric stretching mode

(ii) Asymmetric stretching mode: In this mode, all the three atoms oscillates along the molecular axis. But the two oxygen atoms move in one direction while the carbon atom moves in the opposite direction and vice- versa. This state is referred as 001 state in spectroscopy. The molecule possesses highest energy in this state of vibration.



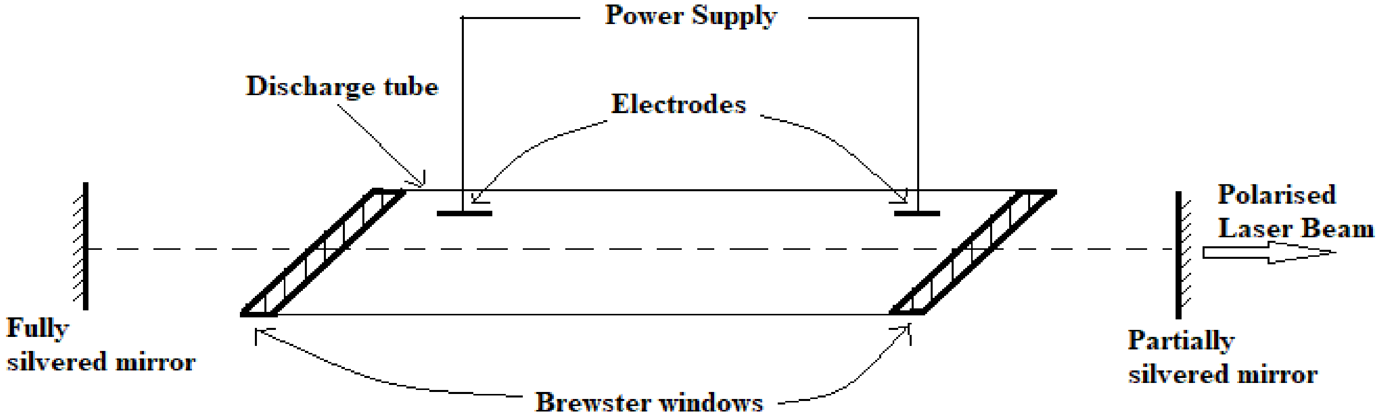
Asymmetric stretching mode

(iii) Bending mode: In this mode, all the three atoms oscillate normal to the molecular axis. While vibrating, the two oxygen atoms pull together in one direction as the carbon atom is displaced in the opposite direction. This state is referred as 010 state in spectroscopy.



Bending mode

Construction: A typical carbon dioxide laser consists of a laser cavity of 2.5cm in diameter and 5m in length. The cavity is water cooled and filled with a mixture of CO_2, N_2 and He gases in the ration 1:2:3. Sometimes traces of hydrogen or water vapour is added. The pressure inside the cavity is 6-17 torr. The actual size, pressure and the proportion of gases vary with the particular application of the laser. Two optically plane mirrors are fixed on either side of the cavity normal to its axis as shown in the figure.



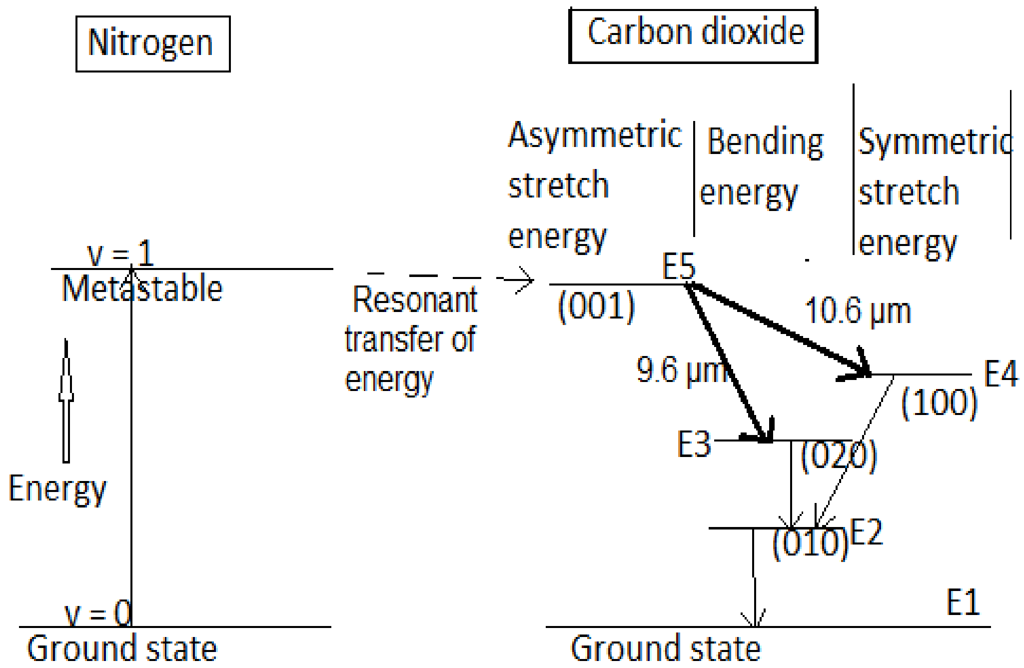
Working: When a suitable voltage (1kV) is applied across the two electrodes, gas discharge take place rendering free electrons. These accelerated free electrons collide with N_2 and CO_2 molecules. The collisions belong to the first kind of collision. Hence the N_2 molecules are raised to the first vibrational level v_1, which is a metastable state and CO_2 molecules raised to 001(E_5 state which is not a metastable state.

These processes can be represented as

$e_1 + N_2 = e_2 + N_2^*$

$e_3 + CO_2 = e_4 + CO_2^*$

Since v_1 is metastable state for nitrogen, its population increases. The energy level diagram is shown in the figure.



In CO_2 gas the energy of its 001 state approximately same as that of v_1 state of N_2 molecule. Therefore, the N_2 molecule in v_1 state collides with ground state CO_2 molecule, because of the matching of the energy levels, resonant transfer of energy takes place from N_2 to CO_2 molecule. As a result, CO_2 molecule gets excited to 001 state and N_2 molecule de-excited to its ground state. This type of collision belongs to the second kind of collision, which can be represented as

$$N_2^* + CO_2 \rightarrow CO_2^* + N_2$$

Thus the population of 001 state (E5 state) of CO_2 increases rapidly which leads to the population inversion condition.

Once the population inversion is established between the E5 (001) level with respect to the E3 (020) level & E4 (100) level, we can observe two laser transitions.

(i) Transition from E5 (001) level to E4 (100) level which gives a radiation of wavelength 10.6 μm in far IR region.

(ii) Transition from E5 (001) level to E3 (020) level which gives a radiation of wavelength 9.6 μm in far IR region.

Along with these two transitions, the CO_2 molecules in the levels E3 & E4 levels undergo transition to E2 level. Hence population of E2 level increases and that of E3 & E4 level decreases. Also by absorbing thermal energy, CO_2 molecules from level E1, get excited to level E2, it will increases its population further. This inturn adversely affects the population inversion condition for E5 level. The CO_2 molecules in E2 level undergo collision with He and water vapour molecules and come down to the ground state, hence population of E_2 level decreases.

The efficiency of this laser is 30%. Power output is of few kilowatt.

Note: (i) The electric discharge breaks down CO_2 in to O_2 and CO. The water vapour in the mixture regenerates CO_2 from CO & O_2.

(ii) The Brewster windows are provided to give plane polarized light.

Advantages:

1. CO_2 laser emit energy in far infrared region.
2. Output power can be increased by increasing the diameter.

Disadvantages:

1. The efficiency is only 30%
2. Increasing the output power increases the heating produced.

Applications:

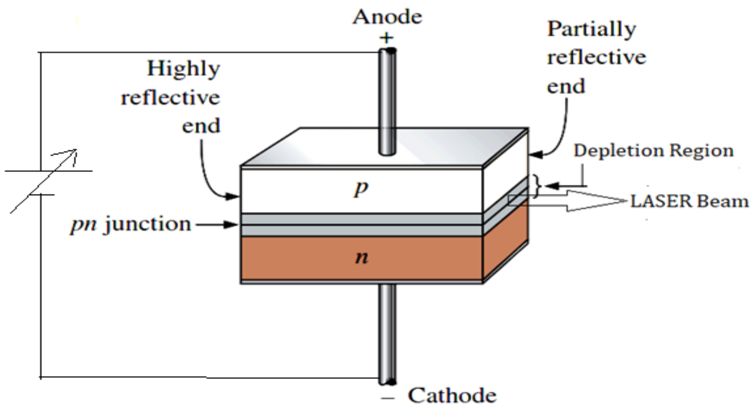
1. Used for optical fiber communication(attenuation is less for IR radiations)
2. They are used for LIDAR.

Semiconductor laser (GaAs Laser):

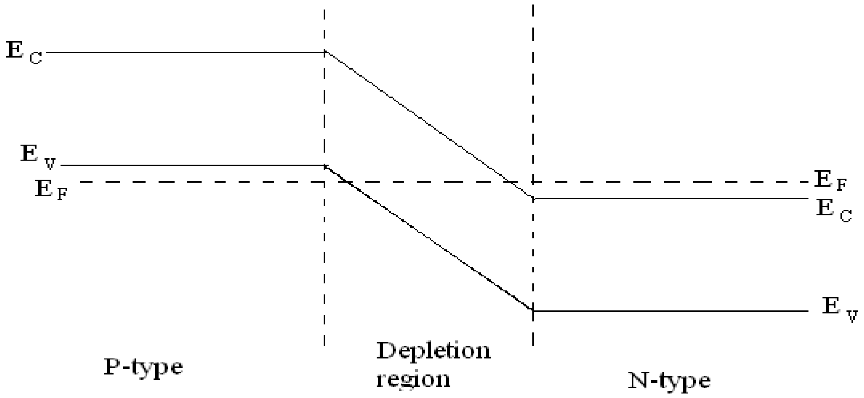
Principle: When a p-n junction is forward biased within the depletion region, the conduction band electrons from n-type combine with the valance band holes and radiation is emitted. The pn junction is heavily doped and a large current is made to flow through the junction to create population inversion. Laser can be obtained by using a resonant cavity for such junction.

Construction: The GaAs laser is a single crystal of GaAs and consists of heavily doped n and p sections. The n- region is obtained by doping with tellurium and p-region is obtained by doping with zinc. The doping concentration is very high and is of the order 10^{17} to 10^{19} atoms /cm^3. The size of the GaAs crystal is of the order of 1mm. The width

of the pn junction varies from 1μm to 100 μm depending on the temp & diffusion conditions.
The metallic contacts are provided to the p and n types in order to apply a forward bias voltage with the help of a voltage source. Two opposite faces which are perpendicular to the plane of the junction are polished which play the role of reflecting mirrors and constitute the resonant cavity. The remaining two faces are roughened to prevent lasing action in that direction.

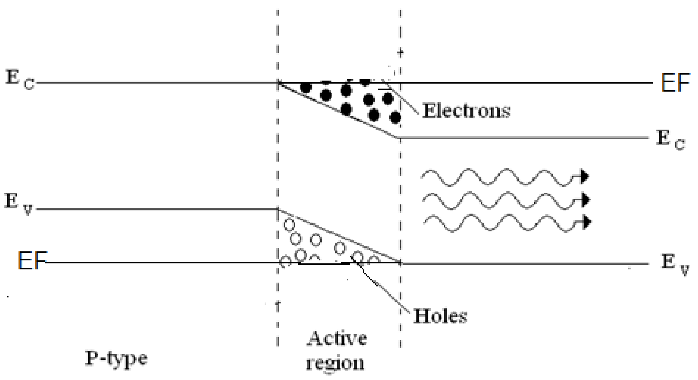


Working: As the p and n type materials are heavily doped, the fermi level (E_F) in n type lies in the conduction band and in p- type lies in the valance band. The fermi level is uniform throughout the unbiased pn junction as shown below.



Heavily doped p-n junction

When the junction is forward biased, the energy levels shifts as shown.



Forward biased p-n junction

The width of the depletion region decreases due to injection of electrons and holes. At low forward currents, the electron hole recombination causes spontaneous emission of photons and the junction acts as LED. When the current reaches a threshold values, population inversion is achieved in the depletion region due to the large concentration of electrons in conduction band and holes in valance band. The narrow depletion region where population inversion is achieved is known as the active region where lasing action takes place. The spontaneously emitted photons travelling in the junction stimulate recombination of electron holes pairs due to which the intensed coherent light builds up along the axis of the cavity.

Since the energy gap of the GaAs is 1.4 eV, wavelength of the emitted light is $\lambda = \frac{hc}{E_g} = 8400$ A.

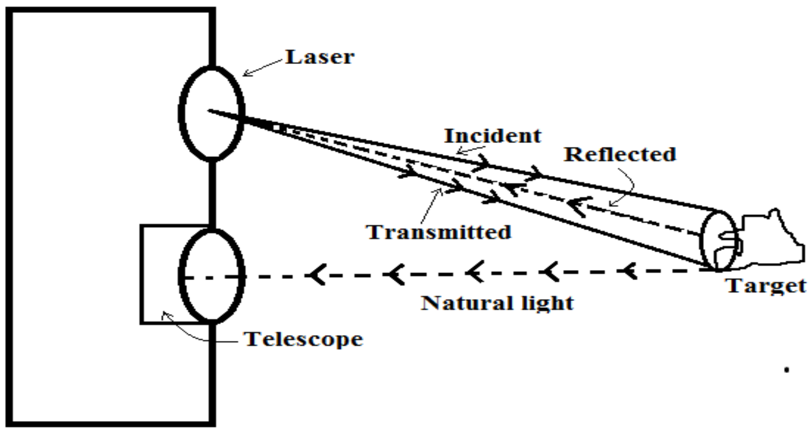
Note: Forward biasing power applied to the junction is the pumping source.

Applications of Laser:

1. Laser Range finder in Defense:

In defense it is important to have accurate data about the distance of the enemy target to have the first hit chance. Because of its high intensity and very low divergence even after travelling quite a few kilometres, laser is ideally suited for this purpose. These laser range
finders are light weight and have higher reliability and superior range accuracy as compared to the conventional range finders. The laser range finder works on the principle of a radar. Hand held range finder is an inseparable aid to the modern infantry. In today's military all battle tanks are fitted with laser rangefinder interfaced with computers to provide information in digital readout form. The rangefinders are also used for continuous tracking and ranging of missiles and aircraft from ground or from air.

Principle: A collimated pulse of the laser beam is directed towards a target and the reflected 1ight from the target is received by an optical system and detected. The time taken by the laser beam for the to and fro travel from the transmitter to the target is measured. When half of the time taken for to and fro travel from the transmitter is multiplied by the velocity of light, the product gives the range.



Working: A typical laser range finder can be functionally divided into four parts: (i) transmitter, (ii)receiver, (iii) display and readout, and (iv) sighting telescope.

The transmitter uses Nd:YAG laser which sends out single, collimated and short pulse of laser radiation to the target. A scattering wire grid directs a small sample of light from the transmitter pulse on to the photodetector, which after amplification is fed to the counter. This sample of light starts the counter. The reflected pulse, received by the telescope, is passed through an interference filter to eliminate any extraneous radiation. It is then focused on to another photodetector. The resulting signal is then fed to the counter. A digital system converts the time interval into distance. The range, thus determined by the counter, is displayed in the readout. The sighting telescope permits the operator to read the range while looking at the target

Medical applications:

Eye surgery:

LASIK is the most commonly performed laser eye surgery to treat myopia (nearsightedness), hyperopia (farsightedness) and astigmatism. The LASIK procedure reshapes the cornea to enable light entering the eye to be properly focused onto the retina for clearer vision.

First, very thin, superficial flap is created in the cornea with the help of laser. Then hinged flap folded back to access the underlying cornea (called the stroma) and removes some corneal tissue using laser.

lasers create a cool ultraviolet light beam to remove ("ablate") microscopic amounts of tissue from the cornea to reshape it so light entering the eye focuses more accurately on the retina for improved vision.

For near-sighted people, the goal is to flatten the cornea; with farsighted people, a steeper cornea is desired. Lasers also can correct astigmatism by smoothing an irregular cornea into a more normal shape.

After the laser ablation reshapes the cornea, the flap is then laid back in place, covering the area where the corneal tissue was removed. The flap seals to the underlying cornea during the healing period following surgery.

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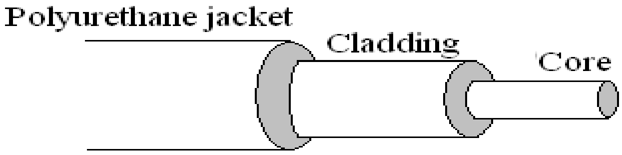
OPTICAL FIBERS

Optical fibers are long thin transparent dielectric materials made up of glass or plastic and able to guide the visible and infrared light over long distances.

An optical fiber mainly made up of two parts one is the inner cylindrical material made up of glass or plastic called **core**. The core is surrounded by a cylinder called **cladding** which is also made up of glass or plastic with lower refractive index than the core material. There is a material continuity between the core and the cladding. The cladding is enclosed by polyurethane jacket which prevents the fiber from the chemical reaction with the surroundings and also against abrasion and crushing. An optical fiber is very thin comparable to the human hair. Many such fibers are each one protected by individual jacket is grouped to form a cable. A cable may consist of one to several hundred such fibers.

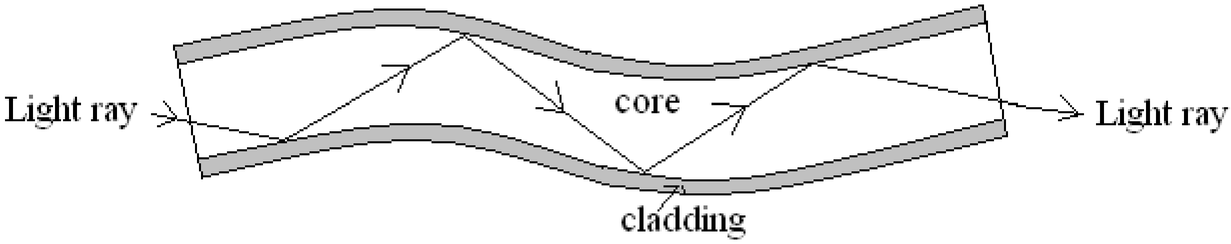


Propagation mechanism in an optical fiber

Figure gives the schematic representation of an optical fiber which is used as a wave guide for the propagation of light. It works on the principle of total internal reflection. The optical fiber is made up of core of high refractive index transparent material which is surrounded by a cladding of low refractive index transparent material.

The light signal that enters into the core can strike the interface of the core and the cladding with an angle greater than the critical angle. It suffers total internal reflection and reflected back into the core and again it strikes the core cladding interface. Again its angle of incidence is greater than the critical angle, it undergoes total internal reflection. After series of such total internal reflections it emerges out of the core at the other end. In the case of total internal reflections there is absolutely no absorption of light energy at the reflecting surface. The entire incident energy is returned along the reflected light. Therefore optical fibers are able to sustain the light signal even though it is undergoing multiple reflections within the core of the fiber. Thus the optical fiber functions as waveguide.

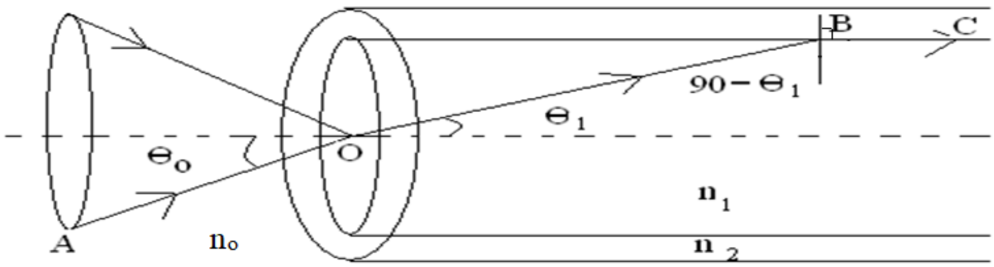
The propagation of light continues as long as the fiber is not bent too sharply, since for sharp bends light fails to undergo the total internal reflection.



Angle of acceptance and Numerical Aperture and Condition for propagation

Consider a ray of light entering an optical fiber at one end which suffers critical incidence at the core –cladding interface. A ray AO enters into the core with an angle θ_0 with the fiber axis. Let angle of refraction at 'O' is θ_1. After refraction the ray falls on the interface between core and cladding mediums at point B at an angle equal to critical angle θ_c [θ_c =(90 - θ_1)]. Now the ray travels along the interface between core and the cladding mediums as shown in figure.

Any ray that enters the core with an angle of incidence less than θ_0 will incident at the interface with an angle greater than the critical angle of incidence. Thus it undergoes total internal reflection. Any ray which enters the core with an angle of incidence greater than θ_0 will enter the interface with an angle less than the critical angle. Hence the ray escapes through the cladding into the surrounding medium. The angle θ_0 is called the angle of acceptance. If AO is rotated around the fiber axis keeping θ_0 constant it produces a conical surface. The beam of light which are funneled into the fiber within this cone only be totally internally reflected and thus coffined within the core for propagation. Rest of the rays emerges from the sides of the fiber. Hence θ_0 is also known as the acceptance cone half angle.



Acceptance angle is defined as the maximum angle that a light ray can have relative to the axis of the fiber which propagates through the fiber.
The Numerical Aperture (NA) is defined as the light gathering capacity of an optical fiber which is expressed as sin of angle of acceptance that is,

NA = sin θ_0

Let the refractive indices of the surrounding medium is n_0, core is n_1 and cladding is n_2.
Now for the refraction at the point of entry of ray AO into the core, we have from Snell's law

$n_0 \sin \theta_0 = n_1 \sin \theta_1$ ---------- (1)

At point B on the interface angle of incidence is 90-Θ_1 and angle of refraction is 90. Again from Snell's law

$n_1 \sin (90-\theta_1) = n_2 \sin 90$

$n_1 \cos\theta_1 = n_2$

or $\cos\theta_1 = \frac{n_2}{n_1}$ ----------- (2)

$\therefore sin\theta_1 = \sqrt{1 - cos^2}\theta_1$

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

$= \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}$ ---------------(3)

Substituting Equation (3) in (1) we get,

$$n_0 sin\theta_0 = n_1\sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}$$

$$sin\theta_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \quad \text{----- (4)}$$

If the fiber is surrounded by air then n_0 = 1, then

$sin\theta_0 = \sqrt{n_1^2 - n_2^2}$

$NA = \sqrt{n_1^2 - n_2^2}$ -------- (5) since NA = sin θ_0

If θ_i is the angle of incidence of an incident ray then the ray will be able to propagate if $\theta_i < \theta_0$

Or Sin θ_i < Sin θ_0

Or $sin\theta_i < \sqrt{n_1^2 - n_2^2}$

This is the condition for propagation of light.

Fractional Index Change (Δ)

It is defined as the ratio of the refractive index difference between the core and cladding to the refractive index of the core.

$\Delta = \frac{n_1 - n_2}{n_1}$ ------ (6)

$\Delta n_1 = n_1 - n_2$ ---------(7)

Numerical aperture can be expressed in terms of 'Δ' as

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

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

$= \sqrt{\Delta n_1 (n_1 + n_2)}$ from equation (7)

Since the difference between the refractive indices of core and the cladding is very small one can assume that $n_1 = n_2$

$\therefore \quad (n_1 + n_2) = 2n_1$

Then

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

$NA = n_1\sqrt{2\Delta}$ ------ (8)

From the above equation it can be observed that increasing the value of 'Δ', one can increase the light gathering capacity of an optical fiber. But a large value of 'Δ' leads to intermodal dispersion, which causes signal distortion.

Modes of propagation:

On the basis of geometrical optics though it is expected that all rays which enter into the core of the fiber with the angle less than angle of acceptance should travel in the core, it is not so even theoretically. The application of Maxwell's equation shows that only certain directions are allowed to propagate. The allowed directions corresponds to the modes the fiber. In a simple terms modes can be visualized as the possible number of paths of light in an optical fiber. The number of modes supported for the propagation in the fiber is determined by a parameter called V- Number. If the surrounding medium is air then V-number is given by

$V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}$

Where d is the diameter of the core, n1 and n2 are refractive indices of core and cladding,λ is the wavelength of the light propagating in the fiber. If the fiber is surrounded by the medium of R.I. n_0 then

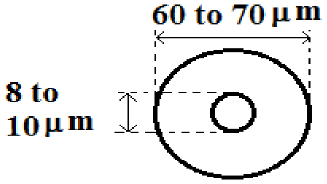
$V = \frac{\pi d}{\lambda}\frac{\sqrt{n_1^2 - n_2^2}}{n_0}$

For V >> 1 the number of modes supported by the fiber is given by $n = \frac{V^2}{2}$

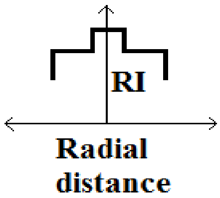
Types of optical fibers

The curve which represents the variation of refractive index with the radial distance from the axis of the fiber is called refractive index profile. Depending on the refractive index profile and number of modes the optical fiber are classified into three categories.

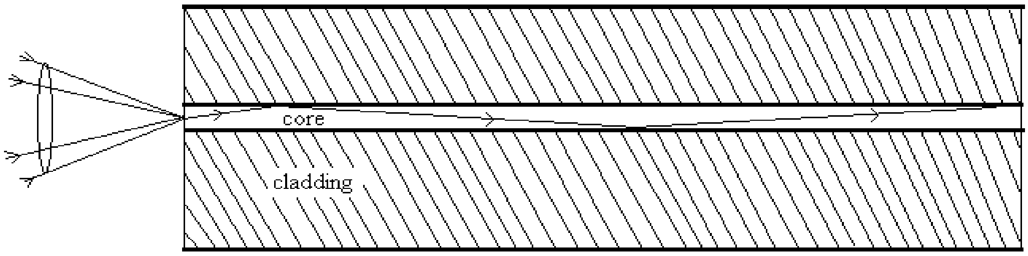
1. Step index single mode fiber



Geometry



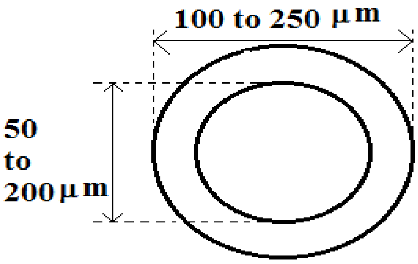
Refractive index Profile



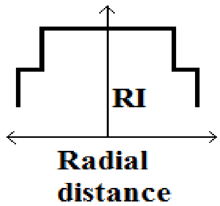
Ray Propagation

Single mode step index optical fiber is made up of core of diameter of 8 to 10 μm. and cladding having outer diameter of 60 - 70 μm. It has core material of uniform refractive index value. Similarly cladding also has uniform refractive index but of lesser value. This results in sudden increase in the value of refractive index from cladding core. Thus refractive index takes the shape of the step. Because of smaller core diameter the optical fiber, it can guide only single mode. Since there is no intermodal dispersion and signal broadening effect, this fiber is extensively used. The signal propagates almost along the axis of the core. Lasers are used as source of light. These are widely used in sub marine cable systems.

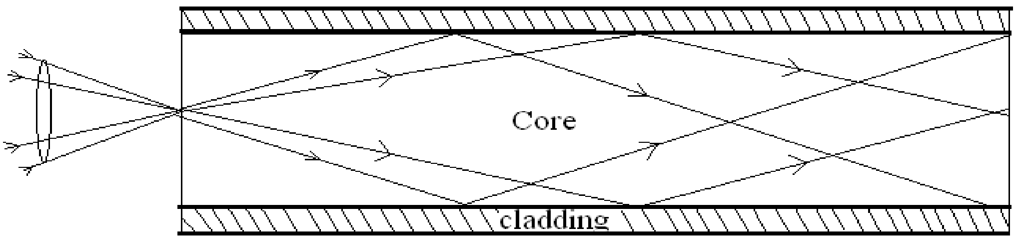
2. Step index multimode fiber



Geometry



Refractive index Profile

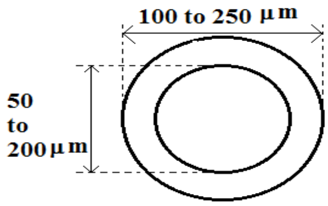


Ray Propagation

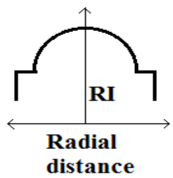
This fiber has a core diameter 50-200 μm and cladding diameter of the order of 100-250 μm. This also has uniform core and cladding refractive indices. Its refractive index profile is also similar to that of a single mode fiber but with a larger plane region for the core. Because of the larger core diameter this fiber allows many modes to propagate through it. Light follows zig-zag path inside the fiber in which the high angle modes travel a longer distance as compared to low angle modes causing intermodal dispersion. This in turn restricts the bandwidth of the optical fiber. These fibers can use LED's. as a source of light in addition to lasers. These are basically used in DATA links, which don't require very large bandwidths.

3. Graded index multimode fiber:

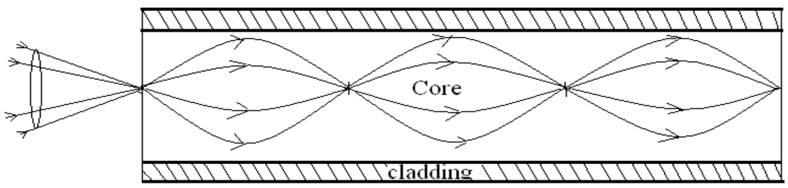
This fiber has a core diameter 50-200 μm and cladding diameter of the order of 100-250 μm. In this fiber the refractive index of the core is maximum at the center of the core and decreases gradually across the core diameter and becomes equal to that of the cladding at interface. The refractive index of the cladding is remains uniform. Though the signals take different distances through the fiber the signal distortion is not seen as they travel through the medium with different refractive indices. The one that covers more distance travels through low refractive index than the one that covers less distance. Hence the travel time of different modes will be same. Either laser or LED can be used as the source of light. It's typical application is in the telephone trunk between the central offices.



Geometry



Refractive index Profile



Ray Propagation

Attenuation:

The loss of power suffered by the optical signal as it propagates through the fiber is called attenuation. It is also called as fiber loss. The net attenuation is given by a factor called attenuation coefficient. The coefficient of attenuation α in dB/Km is

$$\alpha = -\frac{10}{L} log \frac{P_{out}}{P_{in}}$$

Where P_{in}, Pout and L are input power, output power and the length of the fiber respectively.

There are mainly three mechanisms through which attenuation or the fiber loss takes place. They are

1. Absorption loss
2. Scattering loss
3. Radiation loss

1. Absorption loss:

In this case the loss of signal power occurs due to absorption of photons associated with the signal. The absorption of the photons associated with the signal are

1. Due to the presence of impurities.
2. Due to the intrinsic absorption by the glass.

Impurities like iron, chromium, cobalt, copper or hydroxyl ions are trapped with in the glass at the time of manufacturing. During the signal propagation when photons interact with these impurities the electrons of the impurities absorb the photons and get excited to higher energy level. Later these electrons give up their absorbed energy either as heat energy or light energy. The emitted light is in different wavelength or in different phase with respect to the signal, hence it is lost.

The fiber itself has a tendency to absorb light energy at certain wavelengths. It is the inherent property of the glass itself and is called intrinsic absorption. It is the lower limit of absorption takes place even if no impurities present and no inhomoginity.

2. Scattering loss

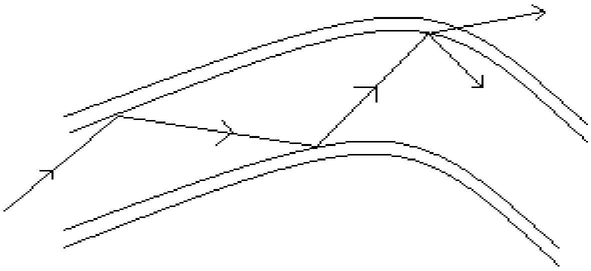
However best the material may be, it is impossible to have its density uniform through out. The variation in the density leads to the variation in the refractive index. While signal travels through the fiber the light may be scattered because of the sharp changes in refractive index value inside the glass over distances that are comparable with the wavelength of the light. It is known as Rayleigh's scattering. Since Rayleigh's scattering is inversely proportional to the fourth power of the wavelength, scattering is more for shorter wavelength. Thus Rayleigh's scattering sets the lower limit on the wavelength of the light that can be transmitted by the glass fiber.

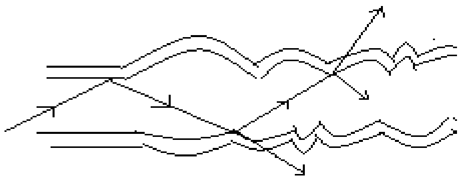
3. Radiation losses

Radiation loss occurs due to bending of light. A bend in the fiber may result in the modification of the angle of incidence on the core cladding interface and hence may lead to signal loss. There are two types of bending

Macroscopic bends: In this case bends have radius larger compared to the fiber diameter. It occurs while wrapping the fiber on a spool or when turning it around corner. This loss is negligible for small bends.

Microscopic bends: These are the small scale fluctuation in the linearity of the fiber. This may occur due to the non-uniformities in the manufacturing of the fiber or by non-uniform lateral pressure created during the cabling of the fiber. It can be minimized using compressible jacket over the fiber.





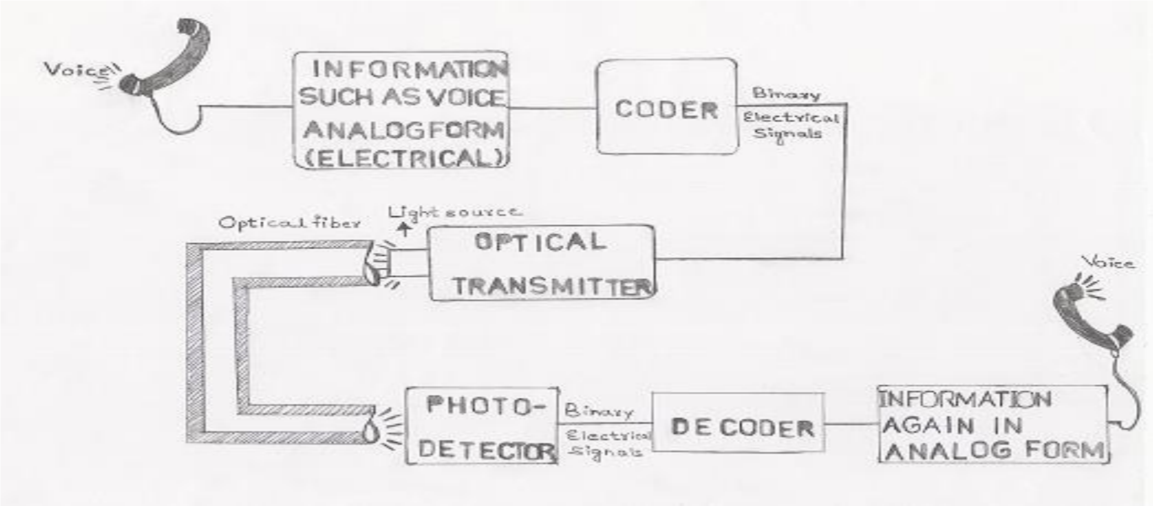
Application of optical fibers:

Point to point communication:

The optical fibers are widely used in various fields like communications, Medical, Domestic etc.

One of its applications in **point to point communication** is discussed in detail here.

In optical fiber communication, the signal can be transmitted through the fiber only in the form of optical signal. A basic communication system consists of transmitter, a receiver and the communication medium i.e. optical fiber.



Normally the information to be communicated is a non electrical signal such as voice of a telephone user. This is converted into electrical analog signals with the help of transducer in the telephone. These analog signals are fed in to a coder where they get converted into binary form. This binary data is made to enter in to an optical transmitter where these get converted into optical signals by modulating the light emitted from the optical source (LED or Laser). These optical signals are fed into the optical fiber with in the angle of acceptance.

The light pulses inside the fiber undergo total internal reflections and reach the other end of the cable. At the other end of the fiber, optical signals are fed into a photo detector which converts them into binary form and then into a decoder, where the signal is converted into analog form. Finally it gets converted into useful form such as voice of a telephone user.

As the signal propagates through the optical fiber there may be loss of signal due to attenuation and also the signal may be distorted due to the spreading of pulses with time which is mainly because of the variation in the velocity of the different spectral components through the optical fiber. With distance the loss of the signal becomes more. Hence before the entire signal gets lost it is necessary to have a repeater which amplifies the signal. But there is no such device which can directly amplify the optical signal and therefore at each repeater the optical signal needs to be converted into electrical signal then amplify and again convert it back into optical signal and then fed in to the fiber. This process has to be followed at every repeater, which restricts the speed of the signal transmission.

Optical fiber sensors

A sensor is a device that converts one form of physical parameter into another form of physical parameter that can be conveniently and accurately measured. The optic fiber sensors generally consist of a light source coupled with an optical fiber and light detector held at the receiver end. The optic fiber sensors are used to measure pressure, temperature, displacement, force etc.

There are two types of optical fiber sensors active and passive sensors.

In **active optical fiber sensors** fiber itself acts as sensors and any one physical parameters of light such as intensity, phase, polarization, wavelength etc. is modulated within the fiber.

Example: Temperature sensor based on phase modulation

In **passive optical fiber sensor** modulation takes place outside the sensors and optical fiber merely carries the light beams.

Example: Intensity based displacement sensor.

Temperature sensor based on phase modulation:

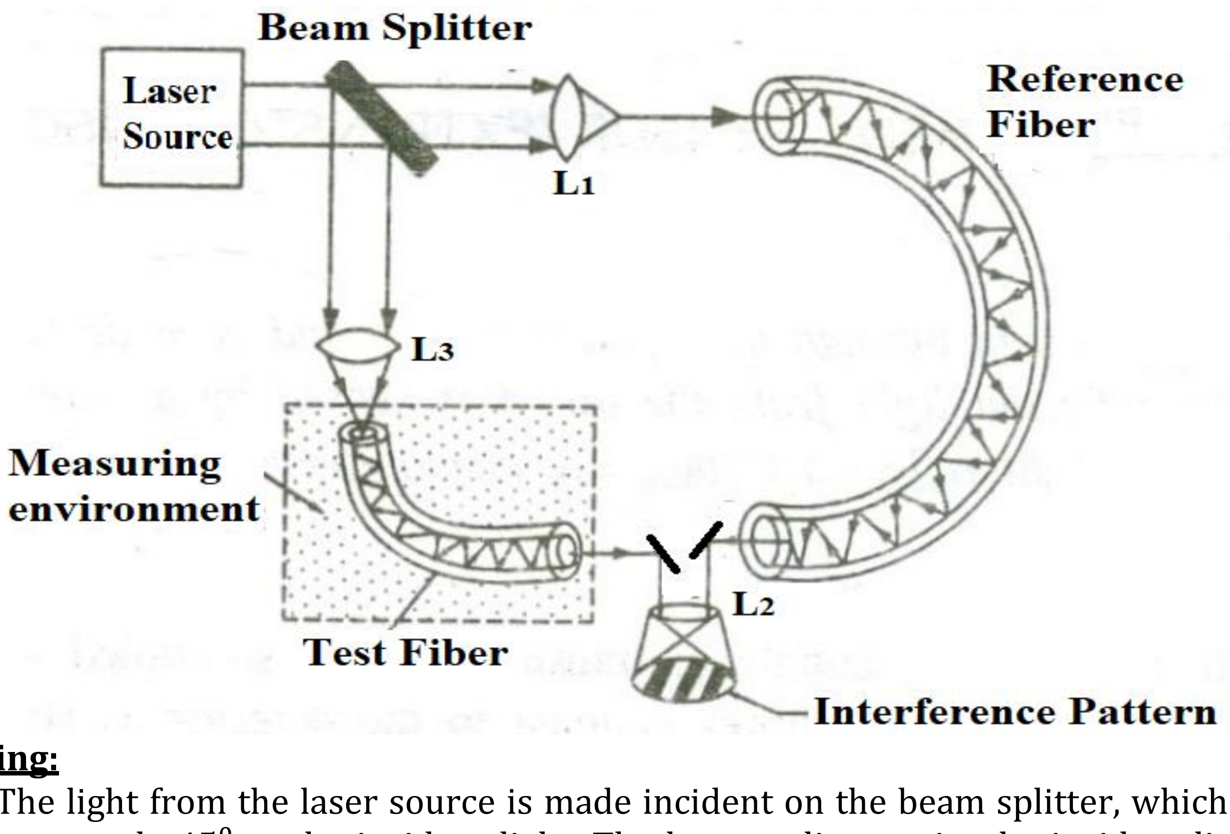
Principle:

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

Construction:

It consists of a laser source to emit light. A beam splitter, made of glass plate is inclined to an angle of $45^0$with respect to the direction of laser beam. Two fibers

(i) **Reference fiber**, which is isolated from the environment and
(ii) **Test fiber**, kept in the environment to be sensed, and are placed as shown in figure. Separate lenssystem is provided to split and to collect the beam.



Working:

The light from the laser source is made incident on the beam splitter, which is kept at an angle 45^0 to the incident light. The beam splitter spits the incident light into two components. The light beam emerging out of the beam splitter is made to pass through the reference fiber with the help of converging lens L1. The reference beam is isolated from the environment to be sensed. The Beam after passing through the reference fiber falls on the lens L2. The beam which is reflected from the beam splitter is made to pass through the test fiber using the converging lens L3. The test fiber is exposed to the environment. Any changes in temperature makes the corresponding change in the phase of the laser light which is passes through the test fiber. The laser light emerging from the test fiber is made to incident on the lens L2.

The two beams after passing through the fibers, produces a path difference due to the change in temperature in the environment. The path difference produced between the two beams causes the interference pattern as shown in figure. Thus, change in temperature can be accurately measured with the help of the interference pattern obtained.

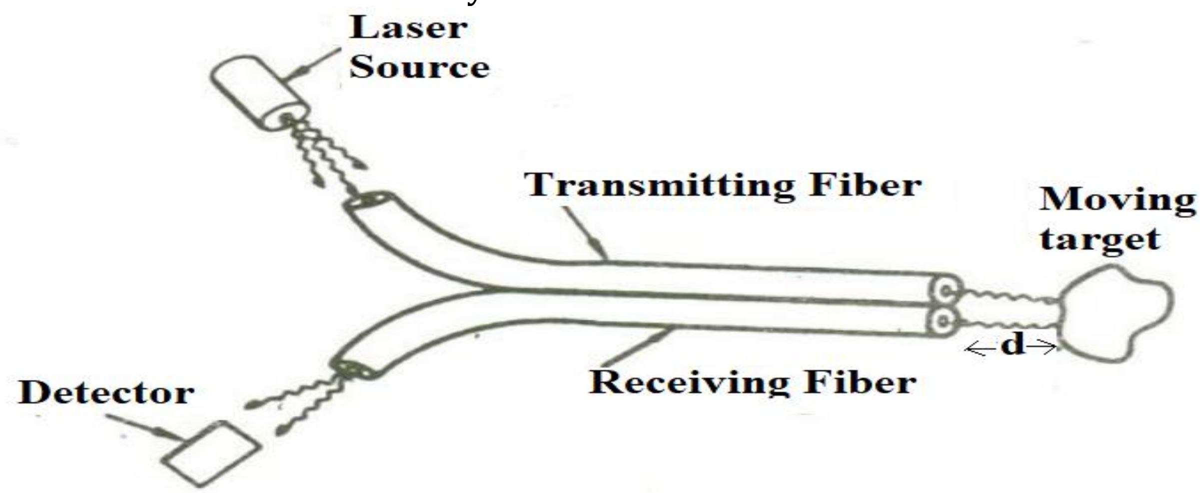
Intensity based displacement sensor

Principle:

Light is sent through a transmitting fiber and is made to fall on the moving target. The reflected light from the target is sensed by a detector. With respect to intensity of light reflected from it the displacement of the target is measured.

Construction:

It consists of a bundle of transmitting fibers coupled to the laser source and a bundle of receiving fibers coupled to the detector as shown in figure. The axis of transmitting fiber and the receiving fiber with respect to the moving target can be adjusted to increase the sensitivity of the sensor.



Working:

Light from the source is transmitted through transmitting fiber and is made to fall on the moving target. The light reflected from the target 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 the target can be measured. if the received intensity is more, then we can say that the target is moving towards the sensor and if the intensity is less, we can say that the target is moving away from the sensor.

Advantages:

Optical fibers have many advantageous features.

1. Optical fibers have a wider band width

The optical carrier frequency used for communication is in the range from 10^{13} to 10^{15} Hz which is many orders of the magnitude higher than the frequency of the carrier waves used in conventional communication. Therefore greater volume of information can be carried over the fiber optic system.

2. **Optical fibers are small in size, light in weight, flexible and mechanically strong.**
3. **Optical fibers are not hazardous**.

This is because optical fibers are made out of insulating materials. Therefore only the light and not electricity is being conducted.

4. **Optical fibers are immune to Electromagnetic interference.**
   In optical fibers information is carried by photons and photons are electrically neutral. They can not be disturbed by high voltage fields, lightning etc. Therefore fibers are immune to externally caused background noise generated through electromagnetic interference.
5. **Longer life span.**
   The life span of optical fibers is considerably high at 25-30 years as compared to around 15 years of life of copper wires.
6. **Security**
   The light waves propagating along the fibers are completely trapped within the fiber and cannot leak out and light cannot couple into the fiber from its sides. Signal taping is not possible.

Limitations:

1. Cable splicing:
   The joining of the ends of the two optical fibers to correctly transmit the light waves is called splicing effective splicing operation costs both time and money
2. Thermal instability:
   The expansion and contraction of the optical fibers under the varying environmental conditions may affect the alignment at the splices and causes transmission losses.
3. Bend losses:
   When the optical fiber is bent severely a part of the light will escape out through the cladding causing signal loss. The copper cables bending has no effect on the signal strength.

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Engineering Physics
Question Bank
(CBCS Scheme-2021-22)
Module – 3

1. **What is Laser?**
2. **Explain the terms (a) Induced absorption (b) spontaneous emission, (c) stimulated emission (d) population inversion (e) active medium (f) resonance cavity and (g) metastable state**
3. **Derive the expression for energy density in terms of Einstein's coefficient.**
4. **Explain the requisites of the laser system.**
5. **Explain the condition for Laser action.**
6. **Mention the three different vibration modes of CO_2 molecule. With a neat energy level diagram explain the construction and working of CO_2 laser**
7. **With a proper energy level diagram explain the principle and working of Semiconductor laser.**
8. **What is a laser range finder? Give the qualitative explanation of construction and working of laser range finder.**
9. **Explain the medical applications of Laser**
10. **Describe propagation mechanism of light through an optical fiber.**
11. **Define angle of acceptance and numerical aperture (NA).**
12. **Explain Fractional index change and V- number.**
13. **Obtain the condition for light propagation in an optical fiber.**
14. **With neat diagrams explain different types of optical fiber.**
15. **What is attenuation? Explain three types of attenuation/fiber loss in optical fiber. Give the expression for attenuation coefficient.**
16. **With the help of Block diagram, explain point to point communication using optical fiber.**
17. **Explain with basic principle, construction and working of any one type of Optical fiber sensors**
18. **Mention the merits and demerits of optical fiber communications**