MODULE-3
LASER

LASER: Light Amplification by Stimulated Emission of Radiation.

It was invented by American Scientist Maiman in the year 1960.

Today there are about hundred different kinds of lasers.

Characteristics of Laser beam

The following important properties of laser make it different from other ordinary source of light.

1) **Laser is highly monochromatic.**

   The laser beam is emitted in a very narrow frequency band.

2) **Laser light is spatially coherent.**

   The laser is highly coherent due to stimulated emission of radiation.

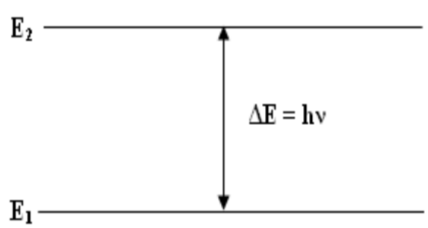
3) **Laser light extremely high directionality or unidirectionality**.

   The laser beam has very small divergence due to the resonant cavity. Hence light intensity does not decrease as fast with distance as it does in ordinary source of light.

4) **The laser beam is extremely bright or intense.**

   Light from laser is much brighter than other ordinary sources of light.

Principle and Production of Laser:



Radiation interacts with matter under appropriate conditions. The interaction leads to an abrupt transition of the Quantum system such as an atom or molecule from one energy state to another. If the transition is from a higher state to a lower one, the system gives out a part of its energy and if the transition is in reverse direction, then it absorbs the incident energy.

In order to understand the manner in which radiation can interact with matter, consider two energy states E_1 and E_2 of a system. If the energy difference between the two energy levels is ΔE,

Then $\Delta E = E_2 - E_1$

Max planck suggested that if an electromagnetic radiation of frequency 'ν' with value

$$\nu = \frac{\Delta}{h} = \frac{2 - 1}{h} \quad \text{-------(1)}$$

is incident on the system which is in the energy state E_1 , then the system moves from E_1 to the energy state E_2 (from lower to higher) by absorbing the energy. On the other hand, if the system is in state E_2, then it emits an electromagnetic radiation of frequency 'ν' given by eq(1) then energy of the system changes to E_1.

There are three possible ways through which interaction of radiation and matter can takes place:

- Induced Absorption
- Spontaneous Emission
- Stimulated Emission

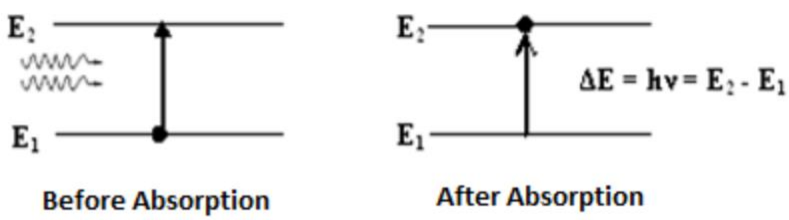
Induced Absorption:

It is a process in which an atom in the ground state undergoes transition to the higher energy state by absorbing an incident photon.

The process can be represented as

Atom + Photon ➔ Atom *

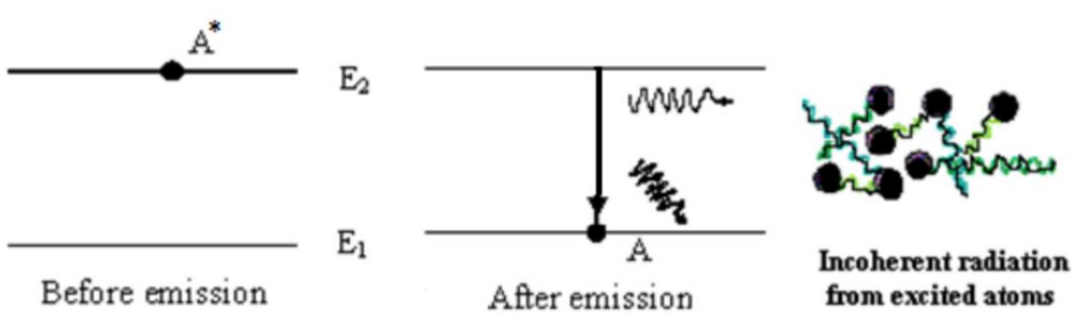
Where Atom* indicates an excited atom



Spontaneous Emission:

It is a process in which an atom in the excited state undergoes transition to the ground state by emitting a photon <u>without any aid of external agency</u>. As shown in the figure, consider an atom in the excited state E_2. It makes a transition to the ground state E_1 by the emission of a photon of energy **hν**. It may be represented as

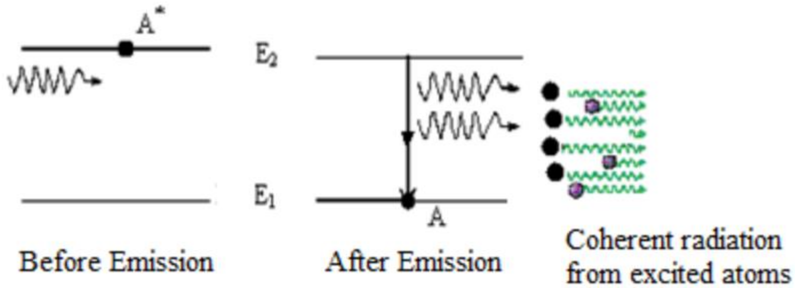
Atom* ➔ Atom + Photon



Stimulated Emission:

It is a process in which an atom in the excited state undergoes transition to the ground state by the influence of a passing photon. During this process a stimulated photon is emitted along with the incident photon and these photons are found to be coherent.

Atom * + Photon atom + 2 Photons (Photon + Photon)



Einstein's Coefficients:

(Expression for energy density of photons in terms of Einstein's Coefficients under thermal equilibrium condition)

* Consider two energy states E_1 and E_2.

* Let E_1 be the lower energy state and E_2 be the higher energy state.

* Let N_1 be the number of atoms per unit volume in the energy state E_1 and N_2 be the number of atoms per unit volume in the energy state E_2.

* Let be the energy density of radiations.

1. Induced Absorption:

In this case, an atom in the lower energy state E_1 undergoes transition to the higher energy state E_2 by absorbing a photon.

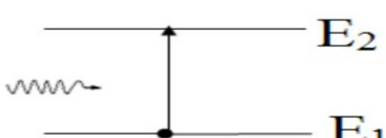
The number of such absorptions per unit time per unit volume is called Rate of induced absorption.

Rate of induced absorption ∝ N_1

$$= B_{12} N_1 \quad \ldots\ldots\ldots\ldots (1)$$

Where N_1 is number of atoms in the state E_1,

is the energy density in frequency range and + d and B_{12} is called Einstein coefficient of induced absorption.

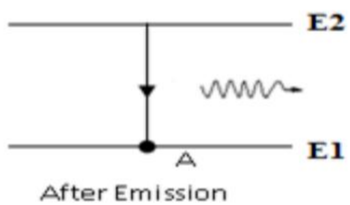


2. Spontaneous Emission:

In this case, an atom in the higher energy state E_2 undergoes transition to the lower energy state E_1 by emitting a photon without any aid of external agency. The number of such spontaneous emissions per unit volume per unit time is called Rate of spontaneous emission.

Rate of spontaneous emission $\propto$ **N2**

$$= \mathbf{A_{21} N_2} \text{ -------- } \mathbf{(2)}$$

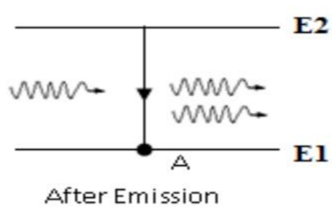


Where, $\mathbf{A_{21}}$ is called Einstein's coefficient of spontaneous emission.

3. <u>Stimulated Emission</u>:

In this case, an atom in the higher energy state E_2 undergoes transition to the lower energy state E_1 under the influence of passing photon.

During this process a stimulated photon is emitted along with the incident photon.



The number of such stimulated emissions per unit time per unit volume in called the Rate of stimulated emission.

Rate of stimulated emission $\propto$ **N2**

$$= B_{21} \mathbf{N_2} \quad \text{------ } \mathbf{(3)}$$

Where, $\mathbf{B_{21}}$ is called the Einstein coefficient of stimulated emission

At thermal equilibrium, the number of upward transitions must be equal to the number of downward transitions.

Rate of absorption = Rate of spontaneous emission + Rate of stimulated emission

$$B_{12} N_1 = A_{21} N_2 + B_{21} N_2$$

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

=

$$=$$

$$= \frac{\quad}{[\ \frac{\quad}{\quad} -]}$$

$$\frac{\quad}{\frac{\quad}{\quad}} \qquad \text{...........(4)}$$

By Boltzmann law, we have

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

∴ (4) becomes,

$$E_\nu = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}}{B_{21}}e^{\frac{h\nu}{KT}}-1}\right] \quad \text{................(5)}$$

According to Planck's law, the equation for energy density of radiation at given temperature, is

$$E_\nu = \frac{8\pi h\nu^3}{C^3}\left[\frac{1}{e^{\frac{h\nu}{KT}}-1}\right] \quad \text{..................(6)}$$

Comparing equation (5) and (6), we get

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \text{ and } \frac{B_{12}}{B_{21}} = 1 \text{ or } B_{12} = B_{21}$$

This means that the probability of induced absorption is equal to the probability of stimulated emission. By neglecting the subscripts, A_{21} and B_{21} can be represented as A and B respectively i.e., A_{21} = A and B_{21} = B.

Then at thermal equilibrium, the equation for energy density is

$$\boxed{E_\nu = \frac{A}{B\left[e^{\frac{h\nu}{KT}}-1\right]}}$$

Energy states of atoms:

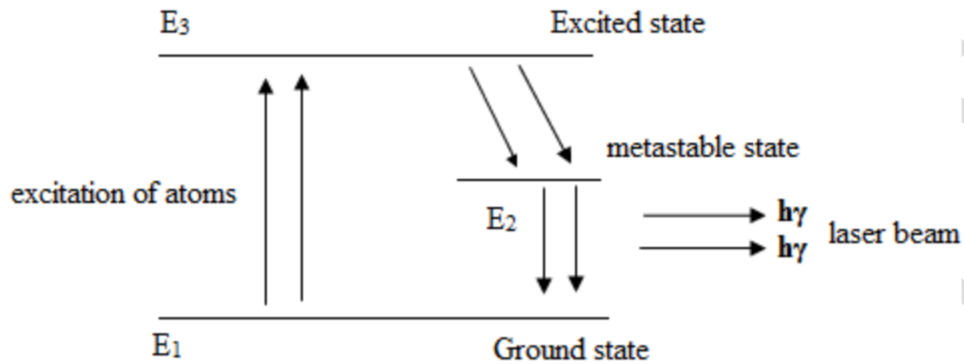
Ground state: It is the lowest possible energy state of an atom which is the most stable state. Atoms can remain in this state for unlimited time.

Excited state: These are the possible energy states of an atom which are higher than the ground state. Atoms remain in these energy states for a very short time called the lifetime typically of the order of 10^{-8} s to 10^{-9} s.

Metastable State: These are excited states of an atom with relatively large lifetime of the order of 10^{-3} s.

CONDITION FOR LASER ACTION:

(Population inversion and metastable state)



"Population inversion is the state of a system at which the population of a particular higher energy state is more than that of a lower energy state". To achieve population inversion a special kind of excited state called **metastable state** are used and it can be explained as follows.

Atoms in the ground state undergo transition to the higher energy state E_3 by absorbing incident photons. Since E_3 state is ordinary excited state, atoms in the E_3 state don't stay over a long time, as a result the atoms immediately undergoes spontaneous downward transitions to the E_2 state. Since E2 is metastable state, atoms in the E_2 state stay over a long duration of about 10^{-2} to 10^{-3} seconds. Under these conditions a stage will br reached where the population in E2 overtakes that of E1. This condition is called population inversion.

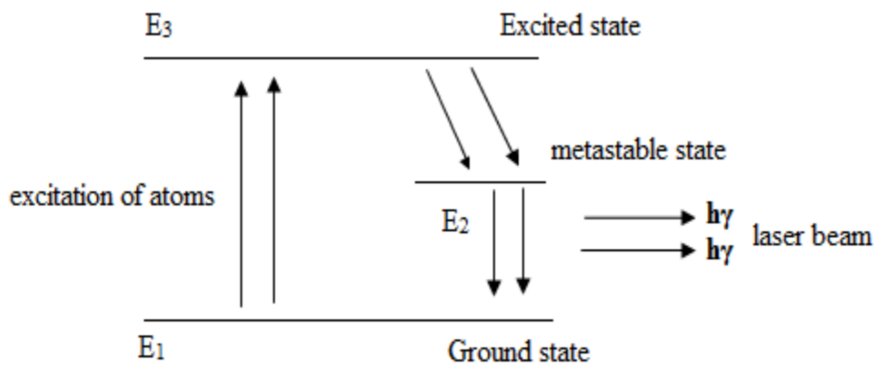
REQUISITES OF A LASER SYSTEM:

There are three requisites of laser systems.

1. An excitation source for pumping action
2. An Active medium to achieve population Inversion
3. An Optical resonant cavity or laser cavity

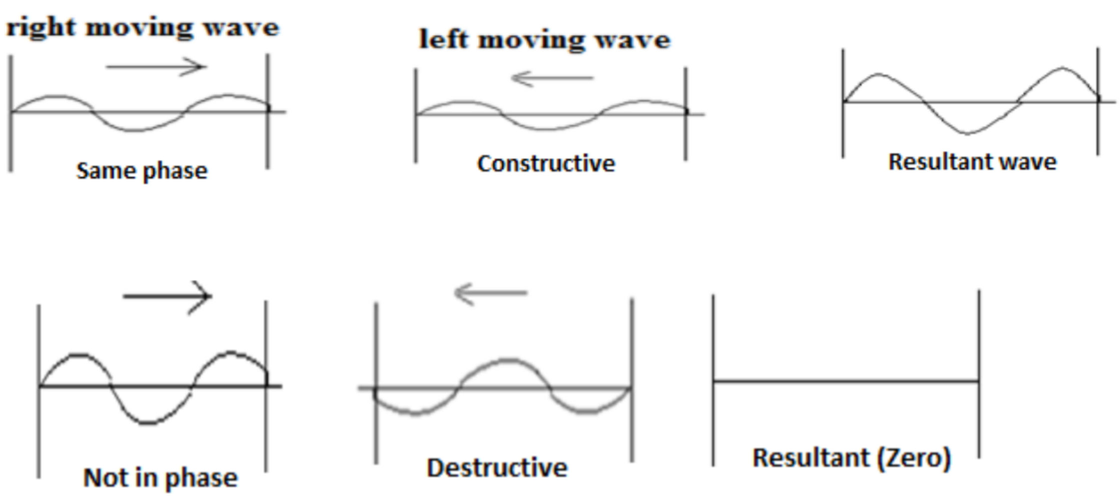
1. **<u>An Excitation source for pumping action</u>:** The process of supplying energy to the medium to excite an atom from lower energy state to a higher energy state is called pumping.
   Energy can be supplied to atoms in different forms like Optical pumping, Electrical pumping and Chemical Pumping

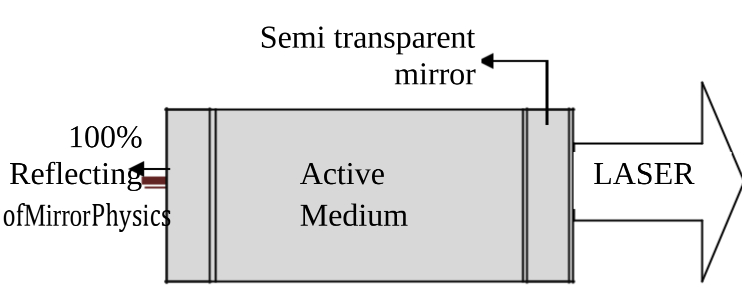
2. **<u>An active medium to achieve Population Inversion</u>:**



Active medium refers to the medium in which the laser action takes place. The energy levels of the atoms or molecules which are involved in laser action are identified. Accurate information about the energy levels and their lifetimes helps in identifying the level between which the population inversion can be achieved.

3. **<u>An Optical resonant cavity or laser cavity:</u>**





A laser device consists of an active medium bound between two mirrors. The mirrors reflect the photons to and fro through the active medium. A photon moving in a particular direction represents a light wave moving in the same direction. Thus, the two mirrors along with the active medium form a laser cavity.

CARBON DIOXIDE LASER [CO_2 LASER]:

Construction and working with the help of energy level diagram:

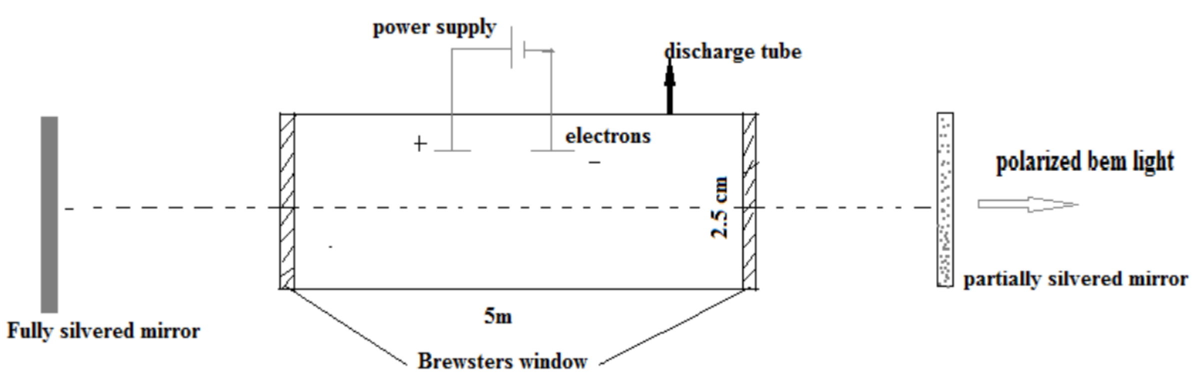
Introduction:

CO_2 Lasers belong to the class of molecular gas laser. This operates in the far IR region involving a set of **rotational vibrational transitions**.

CO_2 laser was developed by C.K.N. Patel in the year 1963.

Construction:

1) A CO_2 laser consists of a discharge tube of length 5m and diameter nearly 2.5cm.
2) The tube is filled with a mixture of CO_2, N_2 and He gases in the ratio of 1:2:3
3) The pressure inside the tube is 6-17 torr.
4) Also water vapour is added to the discharge tube. Water vapour additives help to deoxidize CO to CO_2 in case CO_2 molecules break into CO and O during discharge.
5) The two ends of the tube are sealed with flat Quartz plate which functions as Brewster window(to get the linearly plane polarized light)
6) Two optically plane mirrors are fixed on either sides of the tube, one of the mirrors is fully silvered and can reflect the light 100% and other is partially silvered helps to transmission of laser beam.



Working:

When the suitable voltage is applied across the two electrodes, a glow discharge of the gases is initiated in the tube. During discharge, electrons gets free from the gas atoms and starts moving towards the positive electrode and begin colliding with N_2 molecule in their path.The collision belong to collision of 1st kind. N_2 molecules are raised to the 1st vibrational level ν = 1 which is a metastable state. The process is represented as

$$\mathbf{e_1 + N_2 \rightarrow e_2 + N_2^*}$$

Where, $\mathbf{e_1}$ and $\mathbf{e_2}$ are energy values of the electrons before and after collision.

N_2 and N_2^* are energy of N_2 molecules in ground state ν = 0 and ν =1 state respectively. Hence population inversion is achieved in ν =1 of N_2 and molecules stay for about 10^{-3} to 10^{-2} seconds.

There is a close coincidence in energy of 001 state of CO_2 and ν =1 state of N_2. Therefore, N_2^* collides with CO_2 at ground state. This leads to the transition of CO_2 to 001 state and de-excitation of N_2 to ground state. This type of collision belongs to collision of 2nd kind. 001 state is metastable state for CO_2 molecule. Hence population inversion is achieved in CO_2 molecule in 001 state. This process can be represented by

$$\mathbf{N_2^* + CO_2 \rightarrow CO_2^* + N_2}$$

Where,

N_2^* and N_2 are energies of N_2 molecule in ν = 1 state and ground state respectively.

CO_2 and CO_2^* are energies of CO_2 molecule in ground state and 001 state respectively

Let us designate the (010) state, (020) state, (100) state and (001) state as E_2, E_3, E_4, E_5 levels respectively as shown in the figure.

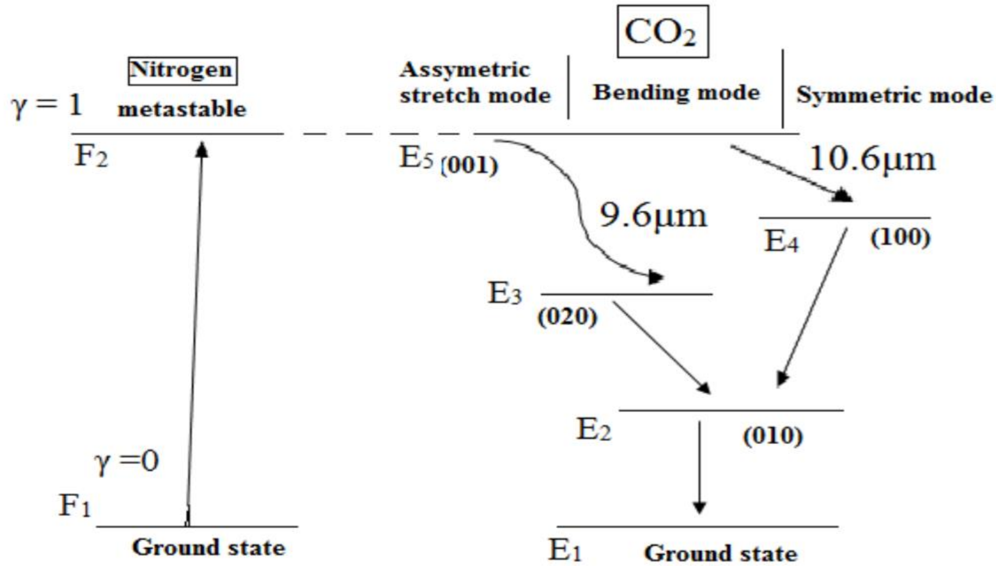
Once population inversion is established in E_5 level the CO_2 molecule undergoes stimulated emission to E_3 and E_4 levels:

(a) Transition from E_5 level to E_4 with a wavelength of 10.6 which is in far IR region.

(b) From E_5 level to E_3 level with a wavelength of 9.6 which is also in far IR region.

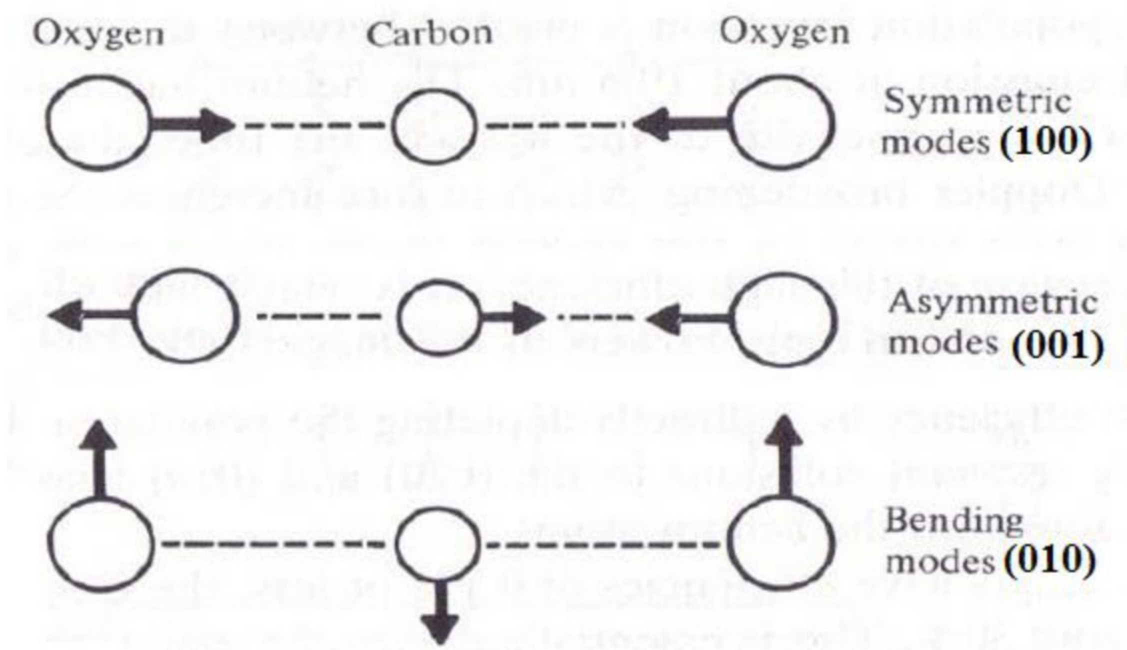
Molecule (CO_2) from E_4 level and E_3 level undergoes inelastic collision with unexcited CO_2 molecules and de -excite to E_2 level. Later CO_2 molecule in E_2 level undergoes collision with He and water vapour molecules and came down to the ground state E1.

CO_2 laser has an efficiency of up to 30%.



VIBRATIONAL ENERGY LEVELS OF A CO_2 MOLECULE:

A carbon dioxide molecule has two oxygen atoms between which there is a carbon atom. It has 3 different modes of vibration.



1) **Symmetric stretching** mode: In this mode, oxygen atoms vibrate along the molecular axis, either approaching towards or departing from the carbon atom . The carbon atoms remains stationary.
   The vibration state is given by (100)
2) **Asymmetric stretching mode**: During the vibration in this mode, all the 3 atoms oscillate along the molecular axis. But, the two oxygen atoms move in one direction while the carbon atom moves in the opposite direction.

This vibrational state represented as (001).

3) **Bending mode:** In bending mode, all the 3 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. The state is (010)

SEMICONDUCTOR LASER (GALLIUM ARSENIDE LASER):

Principle: A Semiconductor diode laser is a specially fabricated p-n junction diode which emits light when it is forward biased. The 'n' junction is the active medium.

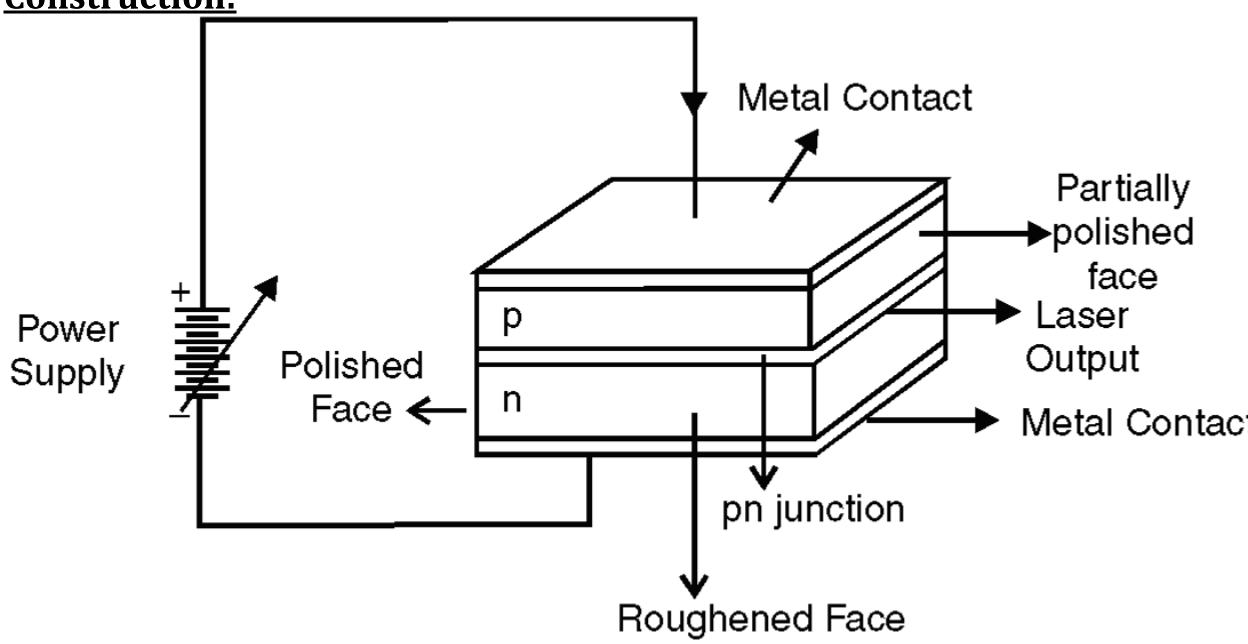
Recombination is the main principle: **R**ecombination is the process wherein electrons and holes meet each and result in the release of heat energy. It's actually the transition of an electron from conduction band to valence band.

Recombination occurs due to forward biasing the system and occurs in the p-n junction (depletion region).Hence it is called as **Active medium.**

We make use of **Direct Band gap and degenerate semiconducting** materials Direct band gap semiconductors are the materials where, there is no lose of energy and the released energy will be in visible region. .Semiconductors that are highly doped are called degenerate semiconductors. The p-region is degenerate in holes and the n-region in electrons.

Example GaAs (Gallium Arsenide),CdSe (Cadmium Selenide).

Construction:



GaAs diode is a single crystal of Ga and As.
Consists of heavily doped n and p sections.
N-section is formed by doping with Tellurium and p-section with Zinc.
Doping concentration is 10^{17} to 10^{19} dopant atoms/cm^3
Size of the diode is very small. Sides are 1mm and junction width is 1μm to 100μm.
A pair of parallel planes is polished and these play the role of reflecting mirrors. They provide sufficient reflection to sustain the lasing action.
Other two sides are roughed surface to suppress the reflections of the photons.
End surfaces of p-n sections parallel to the plane of junction are provided with the electrodes in order to facilitate application of a forward bias voltage with the help of voltage source.

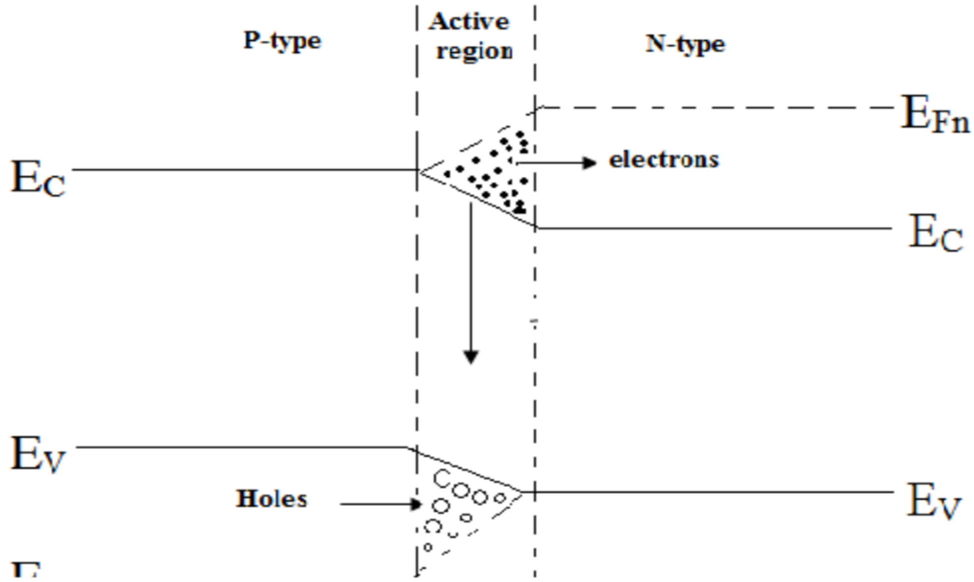
Working:

- Suitable forward bias voltage is applied to the diode to overcome the potential barrier. Due to forward biasing, more and more electrons are injected into the n-region. This leads to the increase in population of electrons in n-region and population of holes in the p-region. When the current crosses certain value called threshold current, electrons from n-type come to higher energy level of the depletion region and population inversion is attained.
- Once the populations of charge carriers in the depletion region increases, the electrons are made to recombine with the holes in the lower energy level of depletion region.
- At this stage, a photon released by spontaneous emission may trigger stimulated emissions over a large no of recombinations leading to the buildup of laser radiation of high power.

  Thus, the current flow provides pumping in semiconductor laser.
- The wavelength of emitted light is

$$= \frac{h}{\ } = \frac{6.626 \ 10^{-34} \ 3 \ 10^{8}}{1.4 \ 1.6 \ 10^{-19}} = 8874 \ A_o$$

The energy gap of Ga As is 1.4 eV.

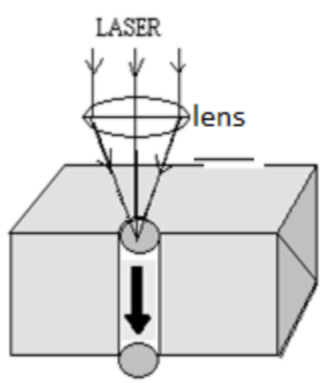


Applications of semiconductor laser:

1) Used in optical communication
2) Used as reading devices for compact disc players.
3) Semiconductor lasers are used in laser printers.
4) Semiconductor lasers are used in medicine, interferometry and barcode scanners.

APPLICATIONS OF LASERS:

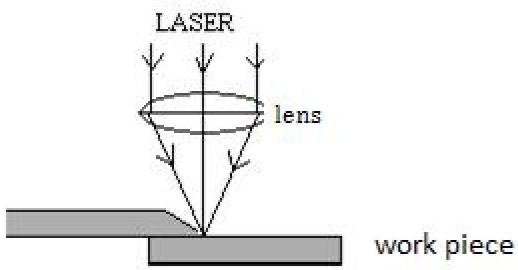
1) **Laser drilling:**



Drilling of holes is achieved by subjecting the material to powerful light pulses. The pulses will be of 10^{-4} to 10^{-3} second duration. The heat generated by the pulse evaporates the material locally and thus makes a hole. Nd-YAG (Neodymium Yttrium Aluminium Garnet) laser is used to drill

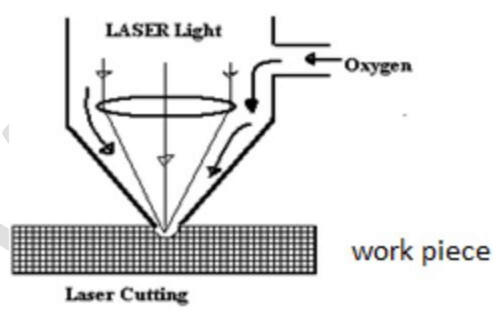
holes in metals whereas CO_2 laser is used in both metallic and Non-metallic materials.
This process has high accuracy, ability to produce holes of small diameter (0.5 to 05mm) , wear out of tools is avoided.

2) Laser welding:



In laser welding, the laser beam is focused on the spot which is to be welded. Due to the heat generated, the material melts. The heat produced by the beam is so intense that impurities in the material float up on the surface. On cooling, the material becomes a homogenous solid structure. This makes stronger joint. CO_2 laser is used for laser welding
Using this technique, spots can be located precisely and no foreign material has chance to get into the welded joint.

3) Laser cutting:



Laser cutting of metals is generally done by blowing oxygen gas along with the laser beam. The laser focusing part is surrounded by nozzle into which oxygen gas is fed. The combustion of gas burns the metal and the tiny splinters along with the molten part of the metal will be blown away by the oxygen jet. The blowing action increases the depth and also speed of cutting. In laser cutting, the cut edges will be of very high quality. Usually

CO_2 laser is used for laser cutting.

a) The cutting process could be programmed which results in high production rates.
b) The quality of cutting is very high.
c) There will be no thermal damage and chemical change when the cutting is done in inert atmosphere.
d) Cutting a complicated profile even in 3-dimension is possible.

MEASUREMENT OF POLLUTANTS IN THE ATMOSPHERE:

Various pollutants present in the atmosphere include oxides of nitrogen, carbon dioxide, carbon monoxide, sulphur dioxide, Dust, smoke, etc. Using LASER one can study and measure the pollutant concentration and other aspects in atmosphere. The data obtained by conventional method is not the real time data because the atmosphere is subjected to slow and continuous variation. This limitation is overcome when measurements are done using laser.

In the application of laser for measurement of pollutants, laser is made use the way a RADAR system is used hence it is often referred as LIDAR (LIGHT DETECTION AND RANGING).

LIDAR operates on the same principle as RADAR except that it uses light rather than radio waves to collect information. There are 3 types of LIDAR

1) Range finders: used to determine the distance of a solid or hard target
2) Differential absorption LIDAR (DIAL): used to measure chemical concentrations in the atmosphere.
3) Doppler LIDAR: used to measure the velocity of a moving target.

LIDAR (light detection and ranging) is used in the measurement of atmospheric pollutants

LIDAR can give information about the distance and velocity of the pollutant object.

A LIDAR system contains transmitting part and receiving part.

The transmitting part consists of pulsed laser and receiving part consists of the following:

a) A concave mirror which receives the reflected light pulses.
b) A photo detector which converts optical energy to electrical energy.
c) A narrow band filter which cuts off the background noise and extraneous light.
d) A data processor which gives information about the dimensions of the object.

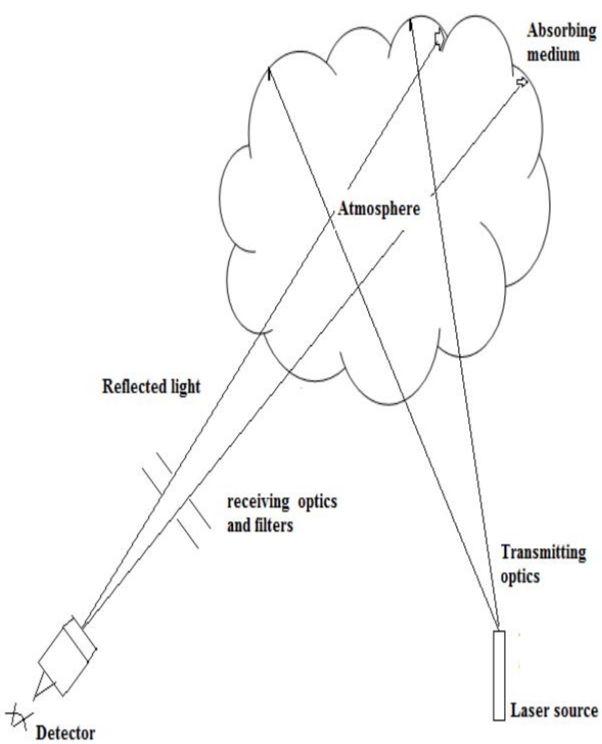
While measurements are carried out, the laser beam undergoes scattering at places where pollutants are to be measured. A back scattered light is received by the concave mirror and finally the compositions of the pollutants of the sample can be measured by the following method.

1) Absorption technique:

The laser beam is passed through the sample collected from the atmosphere. When the beam passes through the sample, it undergoes absorption. Depending upon the absorption pattern, composition of the pollutants can be determined.

2) Raman Back Scattering:

In this method also laser beam is passed through the sample and spectrum of the transmitted light is obtained. Due to the Raman scattering, in the spectrum, we will see not only one but several lines; one line of high intensity corresponding to the incident light's wavelength. The other lines of low intensity lie symmetrically to this line. These additional spectral lines are called side bands. This depends on the oscillating frequencies of different types of molecules. Thus by observing Raman spectra of the back scattered light in the sample, the composition of pollutants can be measured.



<u>HOLOGRAPHY</u>:

Holography was discovered by Dennis Gabor in 1948.
Holography is a process of capturing pictorial details of 3-dimensions on a 2-dimensional recording aid by using the phenomenon of interference".
The technique amounts for complete recording and hence it is called Holography after the Greek words 'Holos' and 'Graphos' which means 'complete' and 'writing' respectively. The recording aid is called a hologram.
PRINCIPLE: The principles underlying holography are interference and diffraction. Therefore, to produce hologram highly coherent beams are required and laser serves the purpose.
Holography can be explained in two steps

1) Recording of a Hologram
2) Reconstruction of the Hologram.

Recording of a Hologram:

*A broadened laser beam from a laser source is obtained. The object whose hologram is to be recorded and a mirror are placed one next to the other as shown in fig.
*The expanded laser beam is then directed on this arrangement in which a part of the beam is incident on the mirror and the rest of the beam is incident on the object.
* A photographic plate is placed in such a position that it receives the light reflected from the mirror and the object.
* The reflected light from the mirror is incident on the photographic plate and will be in the form of plane wavefronts. This is called **reference beam**.
* The reflected light from the object gives rise to spherical wavefronts as every point on the object scatters the incident light. This is called **object beam**.
* The surface of the photographic plate is photo sensitive and responds to the resultant effect of interference between the spherical wavefronts of the object beam and the plane wavefronts of the reference beam.
* The superposition of these two beams (Reference beam + Object beam) produces an interference which is recorded on the plate. The pattern consists of concentric circular rings called **GABOR ZONE PLATE**. The recording consists of countless number of zone plates.
* The photographic plate carrying interference pattern is called a **hologram**.

Reconstruction of the image:

*The original laser beam is directed at the hologram in the same direction as the reference beam was incident on it at the stage of recording.
* This beam undergoes diffraction in the hologram. Because of diffraction, secondary wavelets originate from each zone plate which interferes constructively in certain directions and generates both real and virtual image.
* Each and every zone plate participates in this process to generate the image of the object as the beam is incident on the entire hologram.

Applications of Holography:

1) Holographic interferometry
2) Holographic Diffraction Gratings
3) Information coding
4) Thick holograms
5) Acoustical Holography
6) It finds application in microscopy called holographic microscopy
7) It is used to produce three dimensional images in cinematography

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NOTE:

1. The ratio of populating two energy states is given by the Boltzmann factor,

$$\frac{N_1}{N_2} = e^{-\frac{h\nu}{KT}} = e^{-\frac{\Delta E}{KT}}$$

2. Let the energy difference between two states is E which is equal to the energy of each of the emitted photon. If M is the no of photons emitted per second. And P is the power generated in each pulse then.

Power (P) = N   E

Energy of each pulse can be written as.

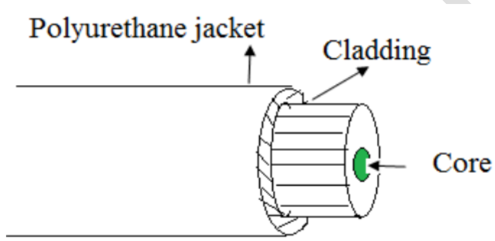
E = Power   duration of the pulse.

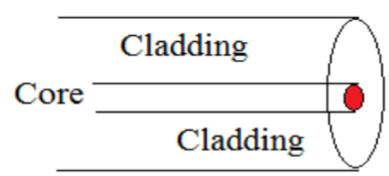
E = P   t

OPTICAL FIBERS

- Fiber optics is an overlap of science and technology which deals with transmission of light waves into optical fibers, their emission and detection.
- It is a waveguide through which light can be transmitted with very little leakage through the sidewalls.
- These are essentially light guides used in optical communications as waveguides.
- ***The principle behind the transmission of light waves an optical fiber is TIR(Total internal Reflection)***
- They are transparent dielectrics and able to guide visible and infrared light over long distances.

CONSTRUCTION OF OPTICAL FIBER:





An optical fiber is cylindrical in shape

It has two parts **a)** inner part and **b)** outer part.

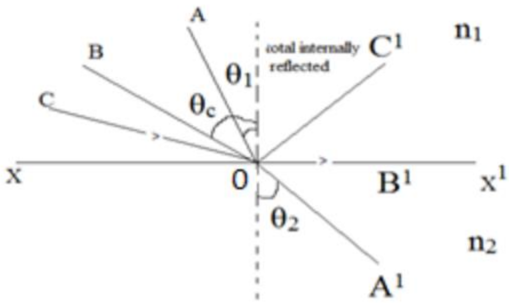
The inner part is made of glass or plastic and its cylindrical in shape, it is called **core**. Core is having high refractive index.

Outer part is a concentric cylinder surrounding the core, and is called **cladding**. Cladding is also made of same material with little lesser refractive index.

The polyurethane jacket is used to enclose cladding which safeguards the fiber against chemical reaction with surroundings and also crushing. Many fibers which are protected by individual jackets are grouped to form a cable. A cable may consist of one to several hundred such fibers.

TIR (TOTAL INTERNAL REFLECTION):

It is the principle behind the transmission of light waves in an optical fiber which is a well known optical phenomenon in physics.

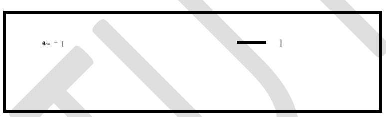


A ray **AO**, travelling in a medium of refractive index n_1 is separated by the boundary XX_1 , from another medium of lower refractive index n_2. So $n_1 > n_2$
The incident ray **AO** makes an angle **θ_1** with the normal in the medium of refractive index n_1. The same **AO** undergoes **refraction** into the medium of refractive index n_2 and it bends away from the normal, since **$n_1 > n_2$** . **θ_2** is the angle made by the refracted ray with the normal.
If we increase **θ_1** for certain value of **$\theta_1 = \theta_c$** called critical angle, $\theta_2 = 90$, for such a case, the refracted ray grazes along the boundary of separation along **OB_1** while incident ray is along **BO.**
If **$\theta_1 > \theta_C$** , incident ray **CO** always gets reflected back into the same medium in which it is incident on the boundary. These takes place as per the law of reflection.
For refraction, we have the Snell's law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

For $\theta_1 = \theta_C$ and $\theta_2 = 90^0$

$$n_1 \sin\theta_C = n_2 \sin 90^0 = n_2 \qquad (\sin 90_0 = 1)$$



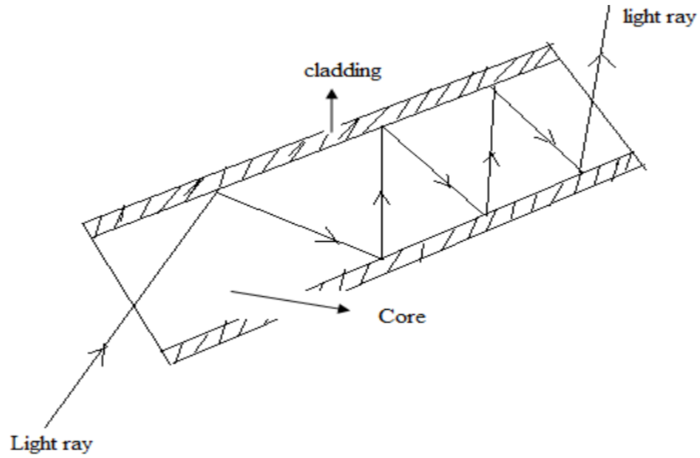
PROPAGATION MECHANISM:

Explain mechanism of light propagation in optical fibers.

(Or)

Explain how optical fibers work as waveguides.

"Optical fibers are the devices used to transmit light effectively along any desired path."



Optical fibers work on the principle of total internal reflection (TIR)

For total internal reflection there are two essential conditions, they are

1) The light ray must pass from denser to rarer medium.
2) The angle of incidence must be greater than the critical angle **i > c**

A waveguide is a tubular structure through which energy of some sort could be guided in the form of waves.

The waveguide as a light guide. also called fiber waveguide or fiber light guide

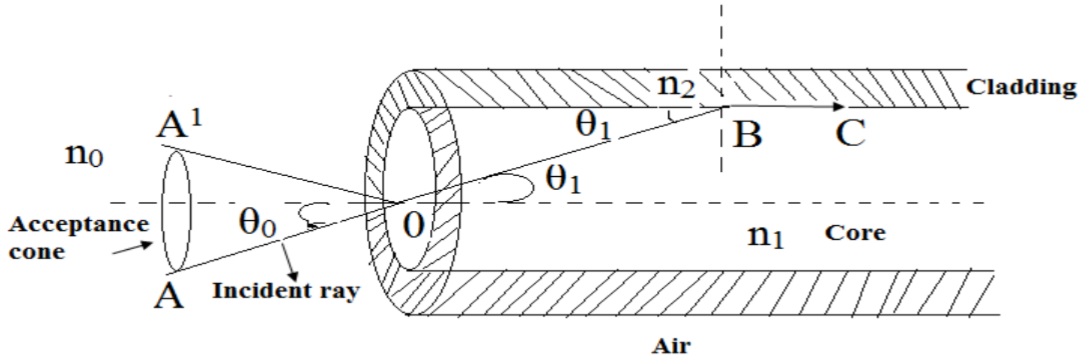
An optical fiber consists of a core and cladding.

In any optical fiber the refractive index of cladding is always lesser than that of its core to achieve TIR, i.e. R.I cladding < R.I of core

When a light is incident at one end of the fiber, it undergoes total internal reflection and finally emerges at the other end of the fiber. It is found that intensity of emergent light is almost same as that of incident light. In this way optical fibers transmit light effectively along any desired path.

RAY PROPAGATION IN THE FIBER. ANGLE OF ACCEPTANCE AND NUMERICAL APERTURE.

Q: **Explain with a neat diagram Acceptance angle and numerical Aperture of an optical fiber. Hence derives an expression for numerical aperture.**



Consider a ray **AO** entering into the core at an angle **θ_0** to the fiber axis. Then it is **refracted along OB** at an angle **θ_1** in the core and further falls at critical angle of incidence (equal to 90 - θ_1) at **B** on the interface between core and cladding. Since the incidence is critical angle of incidence, the ray is refracted at **90_0** to the normal drawn to the interface i.e. **<u>grazes along BC.</u>**

Any ray that enters into the core at an angle of incidence less than **θ_0** will have refractive angle less than **θ_1** because of which its angle of incidence **90_0-θ_1** at the interface will become greater than the critical angle of incidence and hence undergoes **<u>total internal reflection.</u>**

On the other hand any ray that enters at an angle of incidence greater than **θ_0** , will have to be incident at the interface at an angle less than the critical angle, it get **refracted i**nto the cladding region. Then it travels across the cladding and emerges into the surroundings and will be lost.

If now **OA** is rotated around the fiber axis keeping **θ_0** same, it describes a conical surface.

Therefore if a beam converges at a wide angle into the core, then those rays which are funneled into the fiber with in this cone will only be totally internally reflected, and thus confined within for propagation..

θ_0 is called waveguide acceptance angle or the acceptance cone half angle.

Sinθ_0 is called Numerical aperture (N.A) of the fiber.

"**The light gathering capacity of an optical fiber is known as <u>Numerical aperture.'</u>**

<u>Condition for propagation;</u>

Let **n_0 , n_1 , n_2** be the refractive indices of surrounding medium, core and cladding respectively.

For refraction at the point of entry of the ray **"AO"** into the core, we can apply Snell's law, i.e., at point **A**

$$n_0 \sin \theta_0 = n_1 \sin \theta_1 \quad \text{--------} \quad (1)$$

At the point **B**

The angle of incidence $=90_0-\theta_1$

Apply Snell's Law

$n_1 \sin(90^0-\theta_1) = n_2 \sin 90^0$

$n_1\cos\theta_1 = n_2$ $(\sin 90^0 = 1)$

Cos θ1= 2 ------- (2)

quation (1) can be written as

Sin θ0 = 1 sin θ1

= 1√(1− 2θ1)

= 1√1−(2)2

= 1√12 − 22

=1

Sin θ0 =√12 − 22

If the medium surrounding the fiber is air then $n_o=1$

Therefore, Sin θ_0 =√ 2 − 2

i.e.

N.A=√ −

If $\boldsymbol{\theta_i}$ is the angle of incidence, then the ray will propagate if $\boldsymbol{\theta_i < \theta_0}$

(Or) $\sin\theta_i < \sin\theta_0$

(Or) sin θi < √ 12 − 22

$\sin\theta_i <$ N.A

→Condition for propagation

Note: for light propagation, angle of incidence is less than $\boldsymbol{\theta_0}$

FRACTIONAL INDEX CHANGE (Δ):

The fractional index change Δ is the ratio of the refractive index difference between the core and cladding to the refractive index of core of an optical fiber.

Δ = − **---(3)**

RELATION BETWEEN N.A. AND Δ :

From equation (3) (n1 − n2) = n1 Δ ------- (4)

$$N.A = \sqrt{\,_1^2 - \,_2^2}$$

$$= \sqrt{(\,_1 + \,_2)(\,_1 - \,_2)}$$

$$= \sqrt{(\,_1 + \,_2)\,_1\Delta} \text{ from eq(4)}$$

Since, $n_1 \approx n_2$, $(n_1 + n_2) = 2n_1$

i.e $N.A = \sqrt{2\,_1^2\Delta}$

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

MODES OF PROPAGATION:

MODE is,

The pattern of motion in a vibrating body.

The light ray paths along which the waves are in phase inside the fiber.

In simple terms these modes can be visualized as the possible number of allowed paths of light in an optical fiber.

Through it is expected that all the rays which enter into the core at an angle less than the acceptance should travel in the core, it is not even theoretical. By the application of Maxwell's equation, we can get to know that , out of the light that enters into the core within the waveguide acceptance angle, only the light waves in terms of certain number of modes will be sustained for propagation in the fiber.

V-NUMBER:

"The number of modes supported for the light propagation in the optical fiber is known as V- number."

V – Number is given by

V= $\sqrt{}$

Where, d is the diameter of the core, is the wavelength of light

n_1 is the R.I of the core n_2 is the R.I of the cladding

(Or) **V= N.A**

If the fiber is surrounded by a medium of R.I n_0, then the expression is

V= $\sqrt{}$

For V>>1

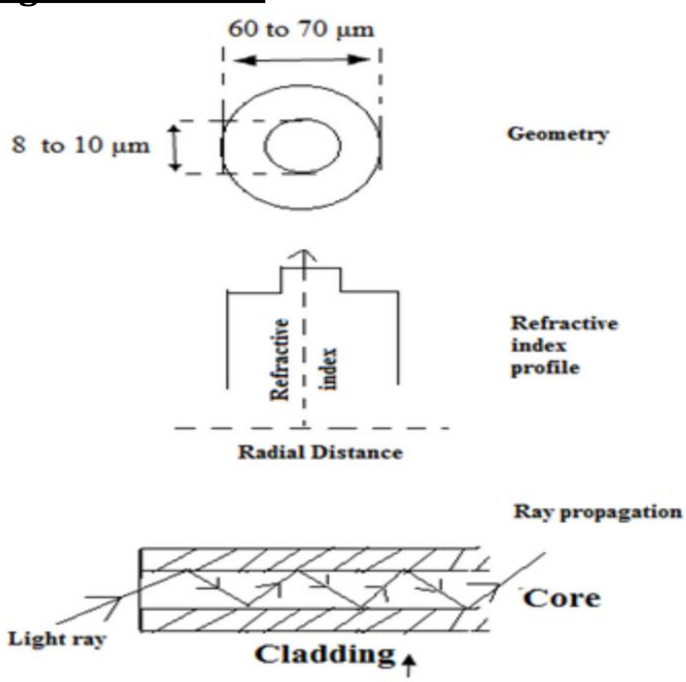
Number of modes =

TYPES OF OPTICAL FIBERS:

Optical fibers are classified into 3 major categories based on the materials used for making optical fibers, number of modes transmitted and the R.I profile of the fibers.
In any optical fiber, the whole material of the cladding has a uniform refractive index value but the refractive index of core material may either remain constant or subjected to variation in a particular way. (R.I of the core changes in graded index multimode fiber)
The curve which represents the variation of refractive index with respect to the radial distance from the axis of the fiber is called the **Refractive Index Profile**.

a) Single mode fiber
b) Step index multimode fiber
c) Graded index multimode fiber

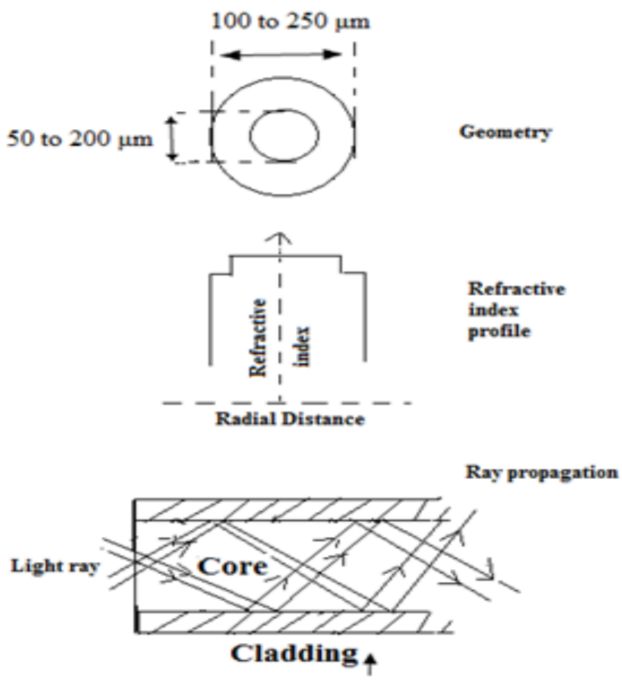
Single mode fiber:



Here core material has uniform refractive index value.
Cladding also has uniform refractive index but of little lesser value than that of core. This results in a sudden increase in the value of R.I from cladding to core.
R.I profile takes the shape of a step.
Diameter of the core is 8 to 10 m.

Diameter of the cladding is 60- 70 m
Since the core is very narrow, it can guide just a single mode. Hence it is called single mode fiber.
These are the most extensively used ones and constituent 80% of all the fibers that are manufactured.
They need lasers as the source of light
It is less expensive, but very difficult to splice. Used in submarine cable system.

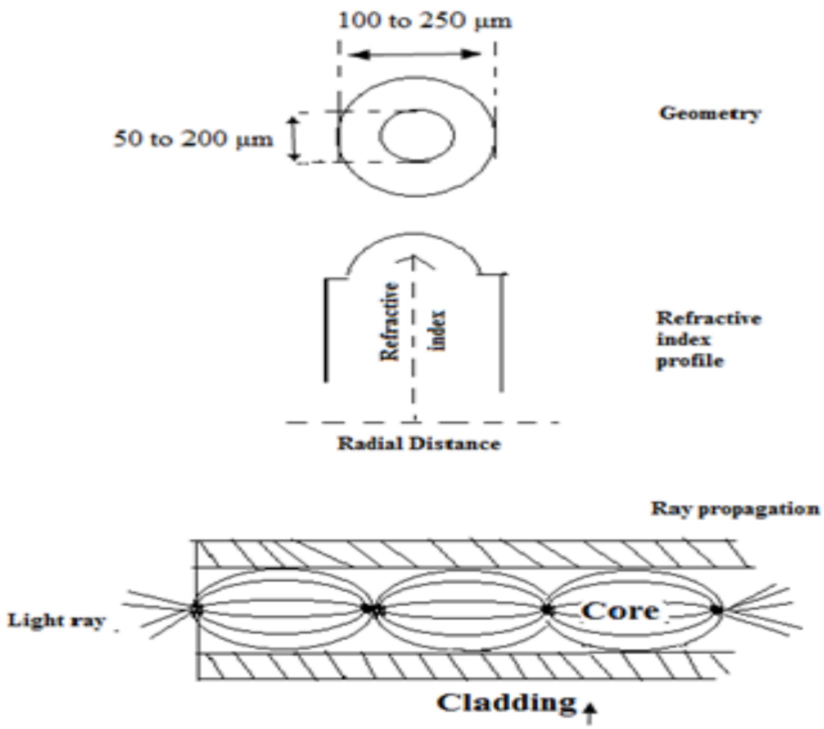
<u>Step index multimode fiber</u>:



Here, the core material has uniform refractive index value.
Cladding also has uniform refractive index but of little lesser value than that of the core. This results in a sudden increase in the value of R.I from cladding to core.
R.I profile takes the shape of a step.
Diameter of the core is 50 to 200 m.
Diameter of cladding is 100- 250 m
Here the core material has a much larger diameter, which supports propagation of large number of modes.
R.I profile is also similar to single mode optical fiber. Uses LED or laser as source of light.

It is least expensive all and is used in data links which has lower band width requirements

Graded index multimode optical fiber:



It is also denoted as GRIN.

The geometry of GRIN is same as that of step index multimode fiber.

The special feature of the core is that its R.I value decreases in the radially outward direction from the axis, and becomes equal to that of the cladding at the interface. But the R. I of the cladding remains uniform.

Diameter of the core 50 to 200 m.

Diameter of cladding 100- 250 m

Uses LED or laser as source of light

Application is in the telephone trunk between central offices.

***ATTENUATION (POWER LOSS OR FIBER LOSS)*:**

The power loss suffered by the signal when it propagates through the fiber is called **Attenuation**. It is also known as fiber loss.

Types of losses in fiber are:

i) Absorption
ii) Scattering
iii) Radiation loss

i) Absorption loss:

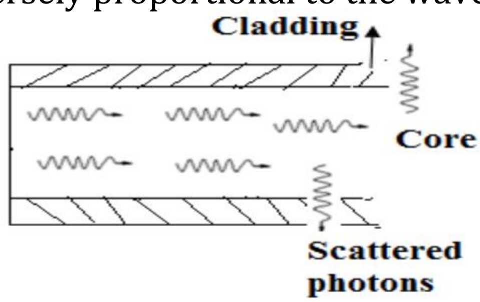
a. Absorption by impurities: Iron, Chromium, Cobalt and Copper are some of the impurities generally present in the glass fiber. When signal propagates through the fiber, a few photons associated with the signal are absorbed by the impurities present in the fiber. This results in power loss.

b. Intrinsic absorption: The absorption that takes place in the fiber material assuming that there are no impurities in it.

ii) Scattering loss:

a. Rayleigh scattering:

When a signal propagates through the fiber, a few photons associated with the signal are scattered by the scattering objects such as impurities present in the fiber. The dimensions of the scattering objects are very small compared to the wavelength of light. This type of scattering is similar to Rayleigh scattering. It is found that the co-efficient of scattering is inversely proportional to the wavelength of the object.

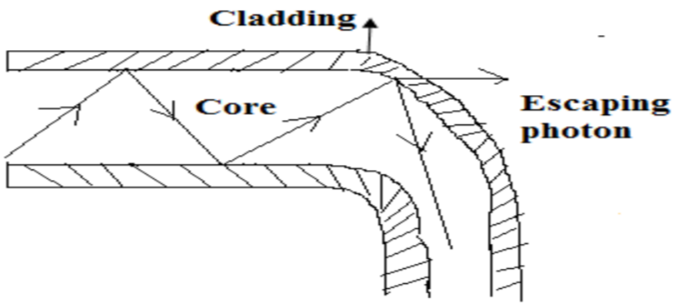


b. Others: Scattering also occurs due to trapped gas bubbles, unreacted starting materials and some crystallized region in the glass.

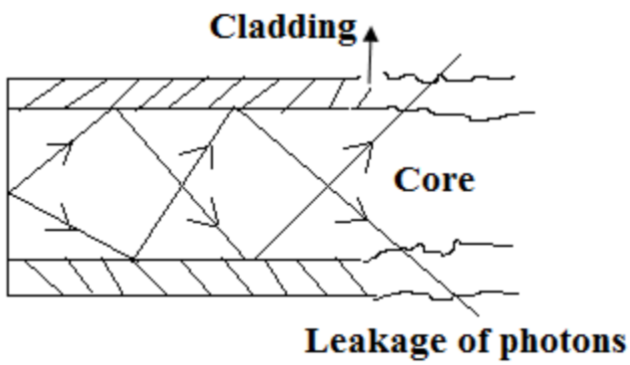
iii) Radiation loss:

It is due to the bending of fibers and it can be explained as follows:

a) Macroscopic bending: They are the bends with radii much larger compared to fiber diameter. It occurs while wrapping the fiber on a spool or turning it around a corner. If the bending is too sharp then the power loss becomes very high.



b) <u>Microscopic bending</u>: It occurs due to the non uniformity in the fibers while manufacturing. Because of this a few modes undergo leakage which results in power loss.



<u>EXPRESSION FOR ATTENUATION CO-EFFICIENT ( )</u>:

By lamberts law "The rate of decrease of intensity with distance ( ) is directly proportional to the initial intensity P".

i.e. - P ----- (1)

(-ve sign indicates that it is a decrement)

- = P

Where α is a constant called Attenuation co-efficient.

$= - \alpha \, dL$

By integrating both sides we have

$\int = - \alpha \int$ ------ (2)

An optical fiber of length L

If P_{in} is the initial intensity with which the light is launched into the fiber.

and P_{out} is the intensity of the light received as output end of the fiber.

Equation (2) $\int = - \alpha \int_0$

$[\log\ ] = - \alpha L$ (Apply the lower limit and upper limit)

$\log_e p_{out} - \log_e P_{in} = - \alpha L$

$\alpha = -^1 \log_e [\ ]$

$$\alpha = -\frac{1}{\ } \log_{10} \left[\frac{\ }{\ } \right] \text{ --- Bel /unit length}$$

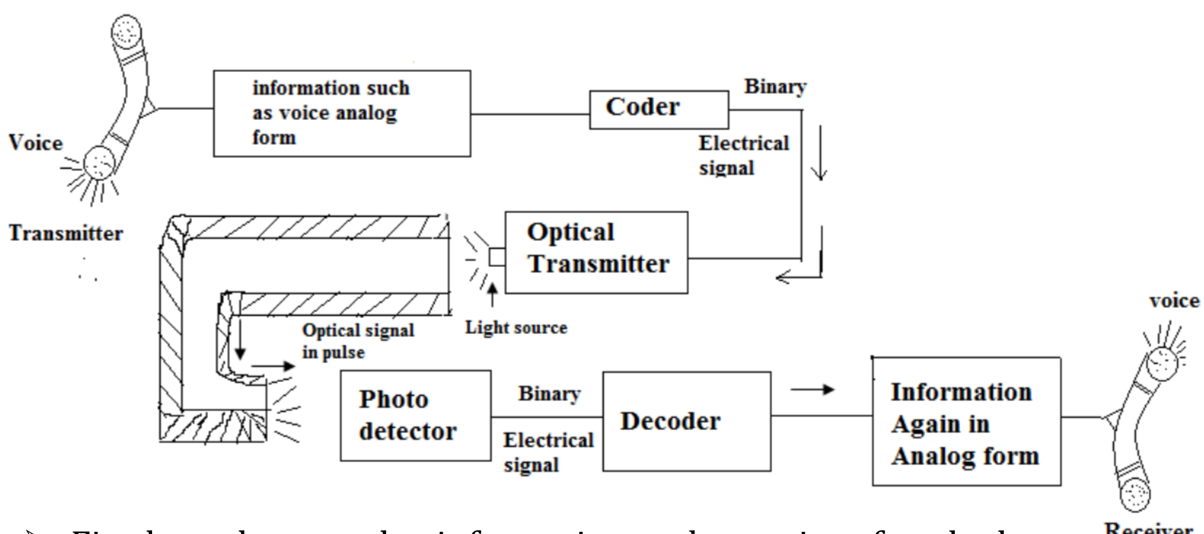
An optical fiber technology it is expressed α in terms of decibel / Kilometer (dB/Km). hence it follows that

1) The length of the fiber is expressed in Km.
2) The unit of Bel is 10 dB   (1 Bel=10 Decibel)

$$\alpha = -\frac{\ }{\ } \log_{10} \left[\frac{\ }{\ } \right] \text{X 10dB/Km}$$

DISCUSS THE POINT TO POINT COMMUNICATION SYSTEM USING OPTICAL FIBERS:

Optical fiber communication is the transmission of information by propagation of optical signal through optical fibers over the required distance which involves driving optical signal from electrical signal at the transmitting end and conversion of optical signal back to electrical signal at the receiving end.



- Firstly we have analog information such as voice of a telephone user. The voice gives rise to electrical signals in analog form coming out of the transmitter section of the telephone.
- The analog signal is converted to binary data (digital) with the help of an electronic system called **Coder.**
- These electrical pulses are converted into optical pulses by modulating the light emitted by an optical source, in the binary form. This unit is called **<u>optical transmitter</u>(**converts electrical signals into light signals**)**
- This optical Signal is fed into the fiber.

- Out of the incident light which is funneled into the core within the half angle acceptance cone, only certain modes will be sustained for propagation within the fiber by means of total internal reflection. While propagating signal undergoes attenuation and delay distortion. Delay distortion is the reduction in the quality of signal with time. These effects cause degradation of the signal as the light propagates and may reach a limiting stage beyond which it may not be possible to retrieve the information from the light signal.
- The receiver section uses **<u>Photo detector</u>** which converts the optical signal into corresponding electrical signal then electrical signal is amplified and recast in the original form by means of an electrical regenerator, which is part of receivers section.
- Lastly using the **<u>Decoder</u>,** the binary electrical signal is converted back to analog electrical signal, which will be same information such as voice, which was there at the transmitting end.

<u>QUESTION BANK</u>

1) Obtain an expression for energy density of radiation under equilibrium condition in terms of Einstein co-efficients.
2) Describe briefly the application of laser in welding, cutting and Drilling
3) Describe the recording and reconstruction process in HOLOGRAPHY with the help of suitable diagrams.
4) Describe the construction and working of semiconductor laser.
5) Describe the construction and working of carbon dioxide laser .with the help of energy level diagram.
6) What is numerical aperture? Obtain an expression for numerical aperture in terms of refractive indices of core and cladding, and then arrive at the condition for propagation
7) Discuss the point to point communication system using optical fibers with the help of a block diagram.
8) Explain the types of optical fibers.
9) Write a note on measurement of pollutants in atmosphere using laser.