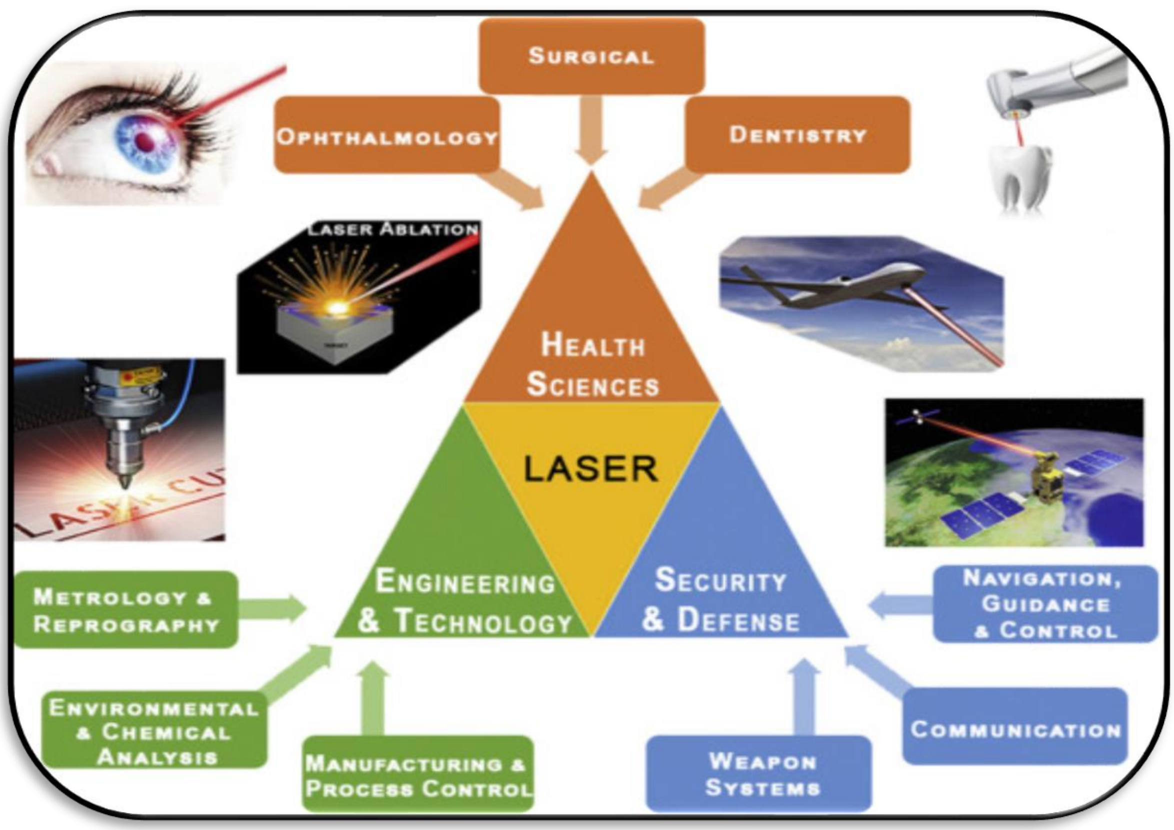
MODULE-1: LASER

LASER : Basic properties of a LASER beam, Interaction of Radiation with Matter, Einstein's A and B Coefficients, Laser Action, Population Inversion, Metastable State, Requisites of a laser system, He-Ne Laser, Applications: Bar code scanner, Laser Printer, Laser Cooling, Numerical Problems

Pre requisite: Properties of light



LASER (Light Amplification by Stimulated Emission of Radiation)

Fundamentals of Lasers:

Introduction:

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.

For any matter, whether it is characterized by energy bands (matter in solid state) or by discrete energy levels (matter in gas state), the energy quantization rules always hold good.

Interaction of radiation with matter:

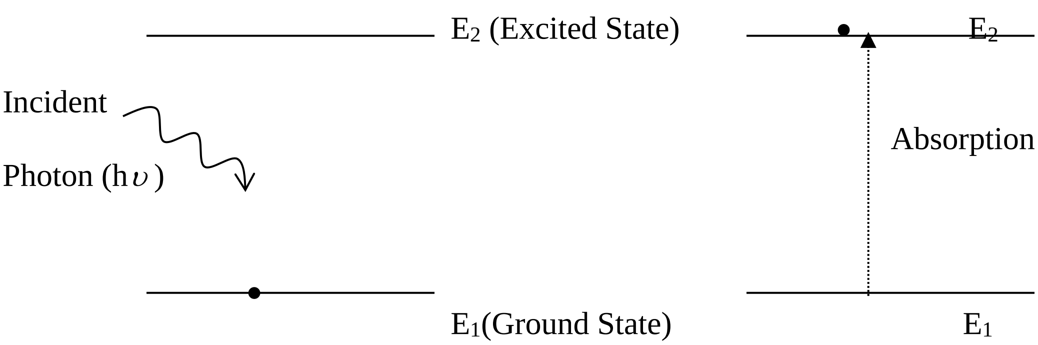
The working principle of laser is based on the phenomenon of interaction of radiation with matter. To understand this interaction, consider a simple system may be atom or molecule, consisting of two energy levels.

Radiation interacts with matter under appropriate conditions i.e.

- ➔ Frequency (γ) of the incident radiation should be equal to the energy gap (ΔE) between which the transitions are taking place.
- ➔ One photon can interact with one atom/molecule.

There are three possible ways through which interaction of radiation and matter can take place. They are

(1) Induced Absorption:

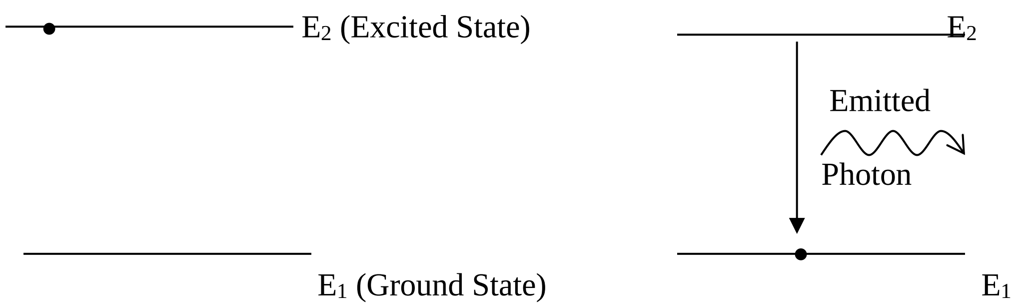


Let E_1 and E_2 are the energy levels of an atom system. Assume that the atom is in the lower energy level, which could be called as ground state. Let a photon of energy ΔE (=E_2-E_1) be incident on the atom under which, the atom absorbs the photon. As a result, its energy becomes $E_2 = E_1 + \Delta E$. Hence, it is shown in the level E_2. In such a condition, the atom is said to have made transition to the excited state. This is called as induced absorption and it can be defined as: induced absorption is the absorption of an incident photon by a system as a result of which the atom/molecule shifted from lower energy state to higher state and can be represented as,

$$\text{Atom} + \text{photon} \rightarrow \text{Atom}^*$$

The rate of absorption depends on number photons in the incident radiation and also on the number of atoms in the ground state.

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.

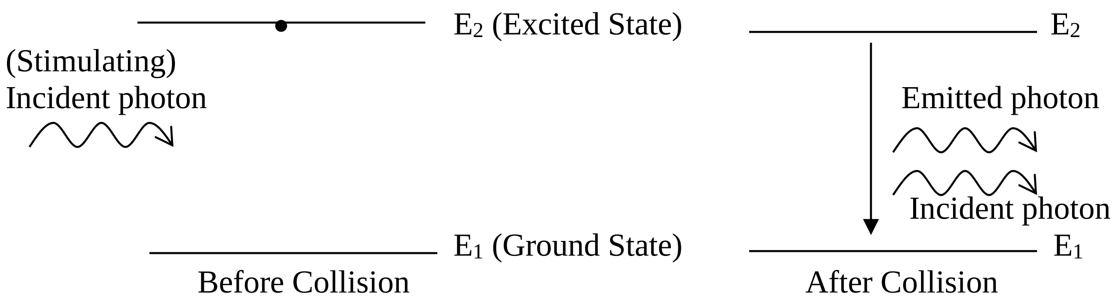
Consider an atom in the excited state. We know that for any system to attain the least available energy state, the atom emits a photon of energy ΔE (=E_2-E_1) itself. Then the energy of the atom becomes E_1. This phenomenon is called spontaneous emission. Two photons, which are emitted spontaneously by two atoms under identical conditions, may not have any phase similarities and may not move in the same direction. Hence, they are incoherent. The process can be denoted as

$$\text{Atom}^* \longrightarrow \text{Atom} + \text{photon}$$

The rate of emission depends on number of atoms available in the excited state only.

3. Stimulated emission:

Consider an atom in the excited state. Let a photon with energy ΔE = E_2-E_1, interact with the atom by passing in the vicinity. Under such stimulation, the atom emits a photon and transits to the lower energy state. The two photons travel in the same



Direction, with same energy and phase, thus they are coherent. The process can be represented as

$$\text{Atom}^* + \text{Photon} \longrightarrow \text{Atom} + (\text{Photon} + \text{Photon})$$

This is kind of emission is responsible for laser action.

The rate of stimulated emission depends on number photons in the incident radiation and number of atoms in the excited state.

Defn: The stimulated emission is the emission process, when an external photon of suitable frequency interacts with an excited atom and forces to emit another photon of the same frequency, in the same direction and in the same phase.

Einstein's Co-efficients:

Planck's Law: If a body can absorb radiation of certain frequency, then, when temperature increases, it will also be able to emit a radiation of same frequency. Max Planck gave a satisfactory theory to explain the blackbody spectrum.

According to Max Planck, if Uν is the energy density emitted by the blackbody through radiation of frequency ν at a temperature T, then

$$U_\nu = \frac{8\pi h\nu^3}{c^3}\left[\frac{1}{e^{h\nu/kT}-1}\right]$$

Boltzmann Factor:

The population of different energy states of any physical system are related to each other, provided, the system is in thermal equilibrium. The relation is given by Boltzmann factor. If we consider any two energy states E_1 and E_2 with population N_1 and N_2 respectively, and if $E_2 > E_1$, then the Boltzmann factor is the ratio (N_2/N_1) given by

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/kT}$$ Where k is Boltzmann's constant

Since $E_2 > E_1$, hence $e^{-(E_2-E_1)/kT} < 1$

Therefore $N_2 < N_1$

Hence, for a system in thermodynamic equilibrium, it is mandatory that the population of any higher state is always lesser than that in any of the lower states.

Thermodynamic Equilibrium: It is a state of system, in which the energy exchange due to emission and absorption processes occur such that the population of each state remains unaltered. i.e. the temperature of the quantum system must be constant.

Expression for Energy density in terms of Einstein's Coefficients:

Einstein explored the basic mechanism involved in the interaction between radiation and matter. He assumed that matter is in thermodynamic equilibrium with a black body radiation field. Einstein coefficients give the probability associated with the absorption and emission processes.

Consider two energy states E_1 and E_2 of a system of atoms.

Let N_1 and N_2 are called the number density of atoms in the states 1 and 2 with energy E_1 and E_2.

Let $U_\gamma d\gamma$ be the energy of the radiation incident/unit volume of the system considering only those radiations whose frequencies lie in the range ν and $\nu + d\nu$.

Let us consider the absorption, and the two emission processes case by case.

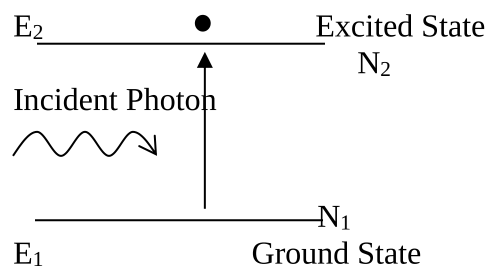
(i) Case of Induced Absorption:

In the case of induced absorption, an atom in the level E_1 can go to the level E_2, when it absorbs a suitable frequency of radiation.

The rate of absorption i.e. the number of absorptions per unit time, per unit volume, depends on

a) the number of density of lower energy state (N_1)

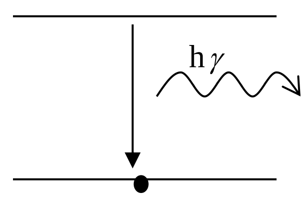
b) the energy density i.e. $U\gamma$ i.e. Rate of absorption α $N_1U\gamma$



Or Rate of absorption = $B_{12}N_1U\gamma$

Where B_{12} is the constant of proportionality called Einstein co-efficient of induced absorption.

(ii) Case of Spontaneous Emission:



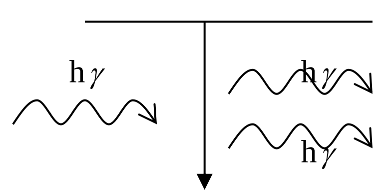
In case of spontaneous emission, an atom undergoes transition from higher energy to lower energy state itself by emitting a photon.

The rate of spontaneous emission is independent of energy density of the incident radiation but it is proportional to the number of density of in the higher energy state i.e. N_2

Rate of spontaneous emission = $A_{21}N_2$

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

(ii) Case of Stimulated Emission:



The system requires an external photon of appropriate frequency to stimulate the atom for the corresponding downward transition, and thereby cause emission of stimulated photons.

The rate of stimulated emission is proportional to

a) the number density of the higher energy state i.e. N_2

b) the energy density i.e. $U\gamma$

i.e. rate of stimulated emission α $N_2U\gamma$

Or rate of stimulated emission = $B_{21}N_2U\gamma$

Where B_{21} is the constant of proportionality called the Einstein's co-efficient of stimulated emission.

At thermal equilibrium

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

$$B_{12}N_1 U\gamma = A_{21}N_2 + B_{21} N_2U\gamma$$

Or $$U\gamma (B_{12} N_1 - B_{21} N_2) = A_{21}N_2$$

$$U_\gamma = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

By rearranging the above equation, we get

$$U\gamma = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}N_1}{B_{21}N_2} - 1}\right] \quad . \quad . \quad . \quad (5)$$

But, by Boltzmann's law, we have

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

$$\therefore \quad \frac{N_1}{N_2} = e^{\frac{h\nu}{kT}}$$

$\therefore$ Equation (5) becomes

$$U\gamma = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}}{B_{21}} e^{\frac{h\nu}{kT}} - 1}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

According to Planck's law, the equation for $U\gamma$

$$U\gamma = \frac{8\pi h\nu^3}{c^3}\left[\frac{1}{e^{h\nu/kT}-1}\right] \qquad \ldots\ldots(7)$$

By comparing the equations (6) and (7), we have

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

And $\frac{B_{12}}{B_{21}} = 1$ or $B_{21} = B_{12}$

It implies that the probability of induced absorption is equal to the probability of stimulated emission. Because of the above identity, the subscripts could be dropped, and A_{21} and B_{21} can be represented as A and B and equation (6) can be rewritten as

$$U\gamma = \frac{A}{B}\left[\frac{1}{e^{\frac{h\nu}{kT}}-1}\right]$$

Condition for Light Amplification:

At thermal equilibrium, the ratio of the stimulated to spontaneous transition is generally small and the stimulated emission is negligible. The ration is given by

$$\frac{Stimulated\ transitions}{Spontaneous\ transitions} = \frac{B_{21}N_2U_\gamma}{A_{21}N_2} = \frac{B_{21}}{A_{21}}U_\gamma \qquad (8)$$

The ration of stimulated to absorptions is given by

$$\frac{Stimulated\ transitions}{Absorption\ transitions} = \frac{B_{21}N_2U_\gamma}{B_{21}N_1U_\gamma} = \frac{N_2}{N_1} \quad (\because B_{21} = B_{12}) \qquad (9)$$

(i) The equation (8) suggests that in order to enhance the number of stimulated transitions the radiation density $U\gamma$ is to be made large.

(ii) The relation (9) indicates that stimulated emission will be larger than absorption only when $N_2 > N_1$.

When these conditions are fulfilled, the medium amplifies light passing through it.

[Note: $\frac{A_{21}}{B_{21}} = \frac{Rate\ of\ spontaneous\ emission}{Rate\ of\ stimulated\ emission} = \frac{8\pi h\nu^3}{c^3}$ It implies that Spontaneous emission/Stimulated emission α (frequency)^3. This is why it is difficult to achieve laser action at higher frequency ranges such as X-rays.

The equation (8) suggests that in order to enhance the number of stimulated transitions the radiation density $U\gamma$ is to be made large. However, it will lead to more absorption transitions. Hence, large photon density alone will not assure more stimulated emissions.

However, stimulated emission probability can be increase, if the lifetime of atoms at the excited should be larger.]

Requisites of a Laser System:

1) An excitation source for pumping action. (The excitation source provides the appropriate amount of energy for pumping the atoms to higher energy levels. The energy input may be in the form of light energy, electrical energy, etc.)
2) An active medium which supports population inversion.
3) A laser cavity.

P**umping:** The process of exciting the atoms from lower energy level to higher energy level by supplying external source energy is called pumping or the process of producing population inversion is known as pumping.

Optical pumping: Here the external source is Light – solid state laser. Ex: ruby laser

Electrical pumping: Here the external source is Electric field – Gas laser. Ex: He-Ne laser.

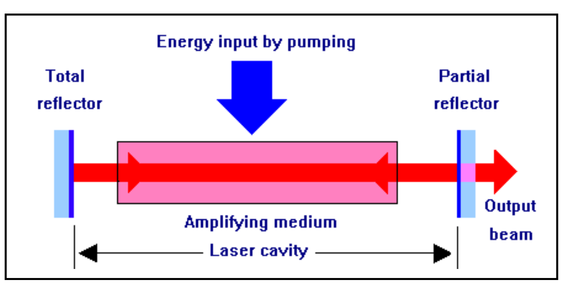
Lasing: The process which leads to emission of stimulated photons after establishing the population inversion is called lasing.

Active system: The system, in which the pumping and lasing actions occur, is called an active system. The medium may be solid, liquid or a gas.

The efficiency of laser emission depends on the nature of the active medium and the energy levels between which the laser action takes place.

Laser Cavity (Optical Resonator):

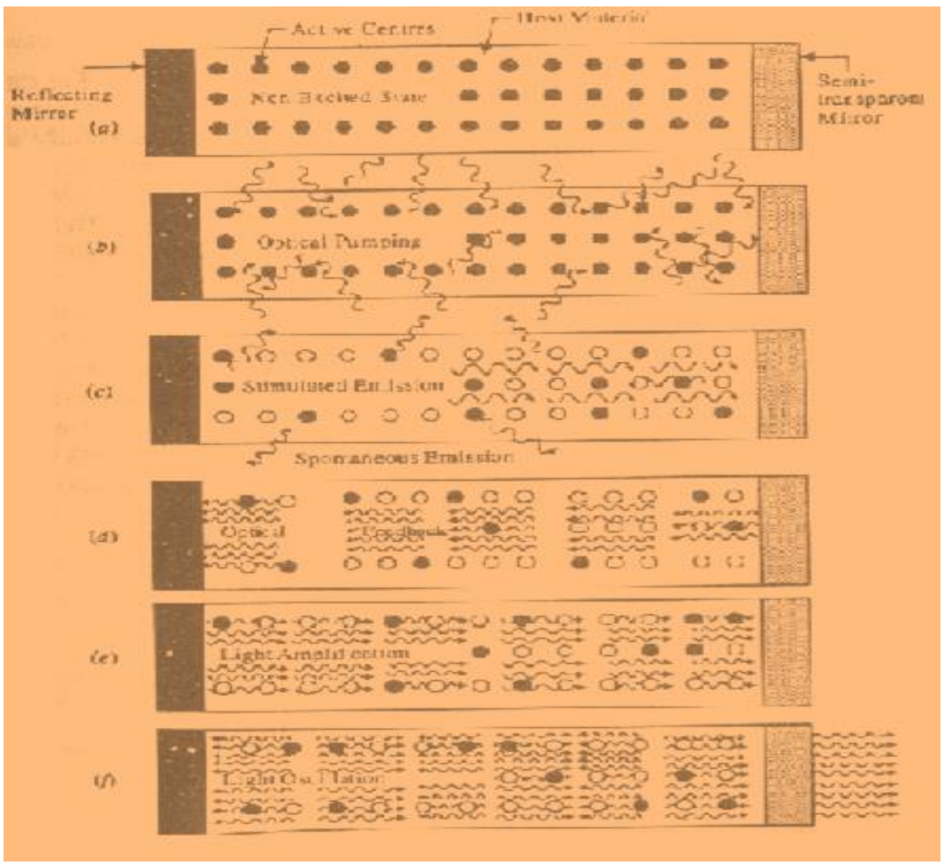
A laser device consists of an active medium bound between two reflecting mirrors called laser cavity. The mirrors reflect the photons to and fro through the active medium. A photon moving represents a light wave moving in the same direction.



The two mirrors along with the active medium form a cavity inside which two types of waves exist; one type of waves moving to the right, and the other one to the left.

The two waves interfere constructively, if there is no phase difference between the two waves. But, if the waves are out of phase, their interference becomes destructive.

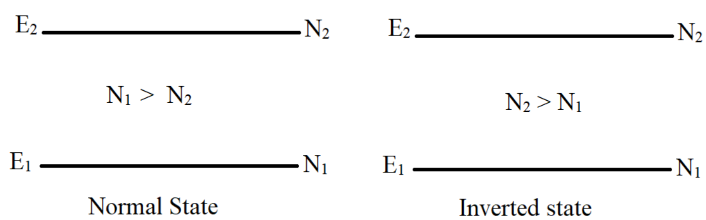
To get the constructive interference, the distance between mirrors 'L' should be $L = m\,\frac{\lambda}{2}$, where m is an integer > 0 and λ - wavelength of the laser light inside the medium. In such cases, a standing wave pattern is established within the cavity and the cavity is said to be resonant at wavelengths $\lambda = 2L/m$.



Condition for Laser Action:

Population inversion:
In a normal condition, (the condition stipulated in the Boltzmann factor) there are more number of atoms in the ground state than in the excited high energy states i.e. $N_1 > N_2$ (hence the probability of the absorption of photons is more than the stimulated emission). However, by pumping technique, we can make that $N_2 > N_1$ i.e. number of atoms in the excited state is more than that of a specified lower energy state. This is called population inversion.

"The condition where the number of atoms in the excited state exceeds that in the lower state is called population inversion."



Metastable State: It is one of the excited states in the system, in which, the atoms remain there for a long period of about 10^{-3}s (where as in the normal excited state, they remain for an interval of 10^{-8}s).

- This state helps in achieving the population inversion in the system. Once the population inversion is achieved, the probability of stimulated emission becomes predominant. In this case, the photons emitted are all identical in respect of phase, wavelength and direction; grow to a large number which is the laser light.

Principle of producing Laser Light:

The stimulated emission produced by the active laser medium is repeatedly made to pass through it using the external parallel mirrors of high reflectivity. The system containing the laser medium between the mirrors is called laser cavity. Thus the radiation inside the laser cavity builds up resulting in amplification of stimulated emission of radiation and the laser light is coming out through partial reflecting mirror.

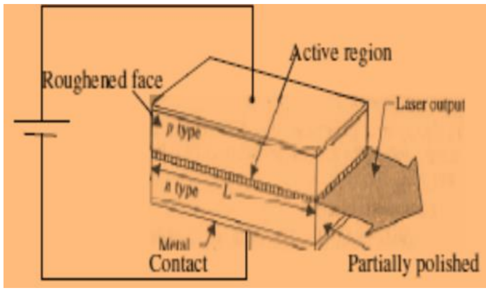
Characteristics of Laser: - Directionality
Monochromaticity
Coherence
High Intensity
High focussability

Semiconductor Laser

***Principle* –** It is based on the principle of electron hole recombination in a direct band gap semiconductor which results in emission of photons. Here, the required active medium is formulated by semiconducting material itself. Hence population of lowest energy of the conduction band is obtained by driving current through the diode. When the current exceeds the threshold value population inversion will be attained between highest level of valence band and lowest level of conduction band leading to stimulated emissions followed by LASER light.

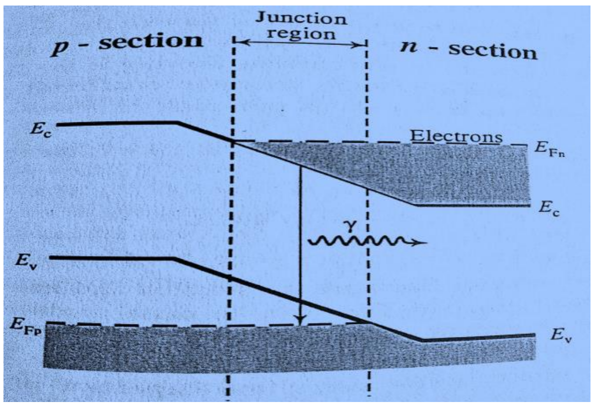
Construction:

1. **Gallium Arsenide (GaAs)** laser is one of the primitive diode laser consists of p-n junction in forward bias condition.
2. The p and n sections are obtained by doping with zinc and tellurium respectively with the substantial doping concentration$\approx 10^{19}$ dopant atoms/cm^3.
3. The top and bottom surfaces are metalized and two electrodes are provided to pass the current through the diode.
4. The front and rear surfaces perpendicular to the Junction are polished so that they act as optical resonators and the other two surfaces roughened to prevent lasing in that direction.
5. Each side of the laser is of the order of 1 mm whereas the p-n junction layer width is $\approx$ 1μm.



Working:

1. When GaAs diode is forward biased electrons move to p-region and holes move to n-region.
2. These electrons and holes recombine in the junction region and photons are emitted.
3. At low forward current only spontaneous emission takes place.
4. As the current increases and reaches a threshold value the depletion region contains high concentration of electrons within the conduction band and a large concentration of holes within the valence band.
5. As the voltage is gradually increased due to forward biasing population inversion is achieved between the valence band and conduction band which in turn result in stimulated emission.
6. Photons produced are amplified between polished optical resonator surfaces producing laser beam.
7. The emission of output wavelength depends on doping and threshold current and the condition of lasing in a semiconductor laser is $E_g < h\nu < E_{Fn} - E_{Fp}$ (Shown in below figure)
8. GaAs laser produce laser beam of wavelength 8400Å with the band gap of 1.4 eV.



Energy level diagram of diode laser

Applications of Laser

Because of high intensity, high degree of monochromaticity, and coherence, lasers are using in different fields such as bar code scanner, laser printer, laser cooling, medicine, material processing, communications, holography, etc.

Applications laser in bar code scanner:

A **barcode reader** is an optical scanner that can read printed barcodes, decode the data contained in the barcode to a computer.

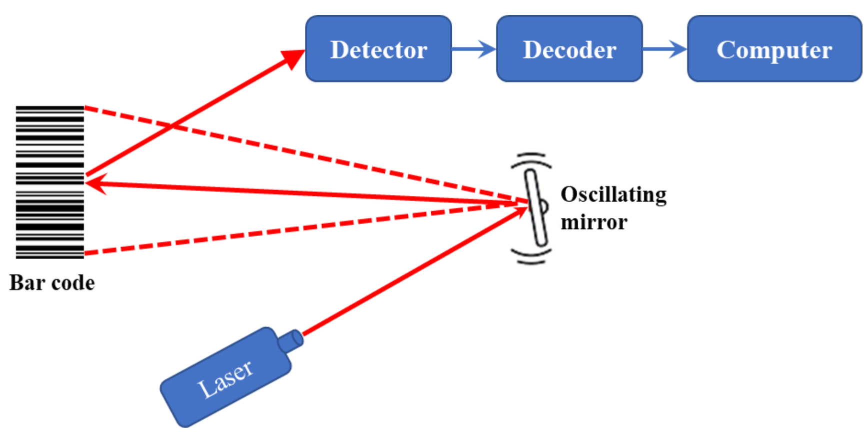
The Universal Product Code (UPC), a line of vertical stripes with a set of numbers printed underneath is widely used for identifying the product.

A bar code consists of a series of strips of dark and white bands.

These white and dark bands are of different widths separated from each other by specific distances that contain all the information about the product.

Bar code scanner consists of a laser source, a lens and a light sensor for translating optical impulses into electrical signals.

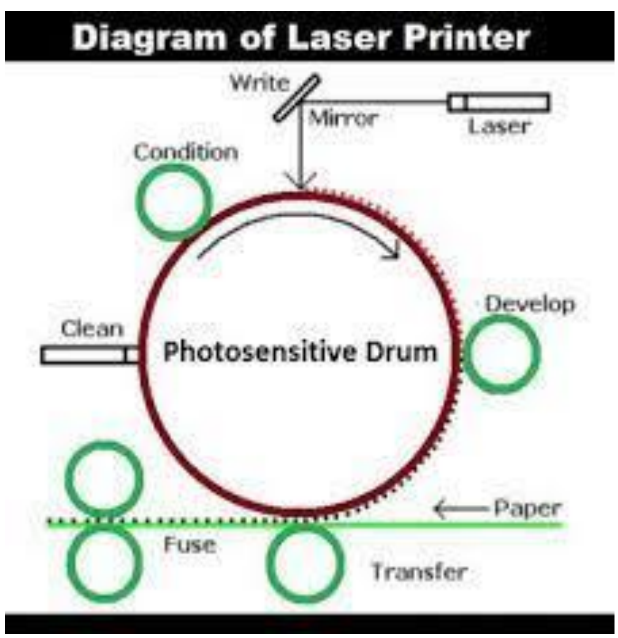
A laser is used to scan the bar code with the help of a rotating mirror (speed is about 200 m/s). When the laser beam is incident on the bar code, the amount of light scattered depends on whether the strip is black or white. Since, the bars are separate by variable distances; light intensity varies with time and is recorded by the photo detector. The signal is fed into an amplifier and later to a decoded which displays the information on the screen and also sends it to product inventory system.

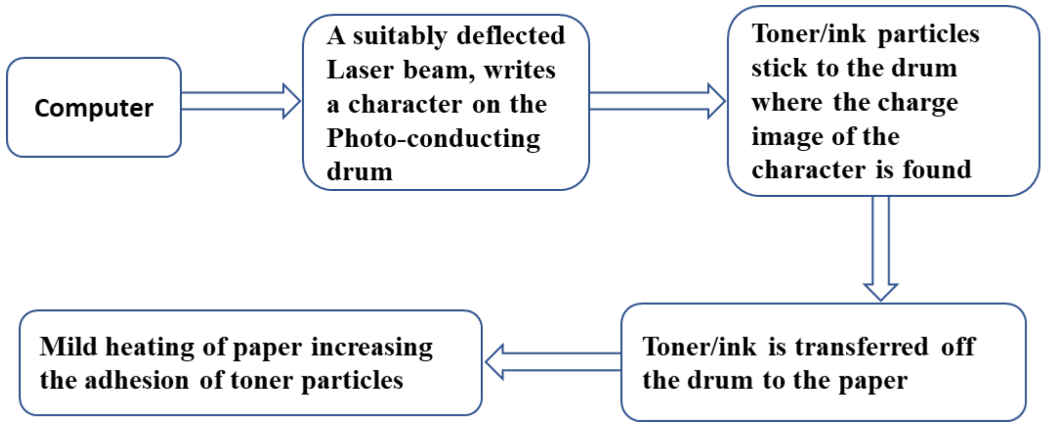


{While cell phone cameras without auto-focus are not ideal for reading some common barcode formats. there are 2D barcodes which are optimized for cell phones, as well as QR Codes (Quick Response) codes and Data Matrix codes which can be read quickly and accurately with or without auto-focus. Recent versions of the Android, iOS, and Windows Phone mobile phone operating systems feature QR or barcode scanners built in, usually accessible from their respective camera application.}

Laser Printer:

A laser printer acts as photocopier machine that uses laser light and toner to print a document. The primary working principle is static electricity. In a laser printer, laser beam is used to write a charge image directly onto the photoconductor drum. This rotating drum is charged initially and then a spinning mirror scans laser light across the surface. Whenever laser light fall on the drum, charge flows through photoconductor and it constructs the charge image. With the help of static electricity, drum gets to attract with powdered toner from its cartridge. The drum gets to spin the toner on the paper as a format of your sending print commands. Then, toner gets to start melt on the paper by heat from fuser that is passed underneath. The fuser rolls the paper to the output tray.

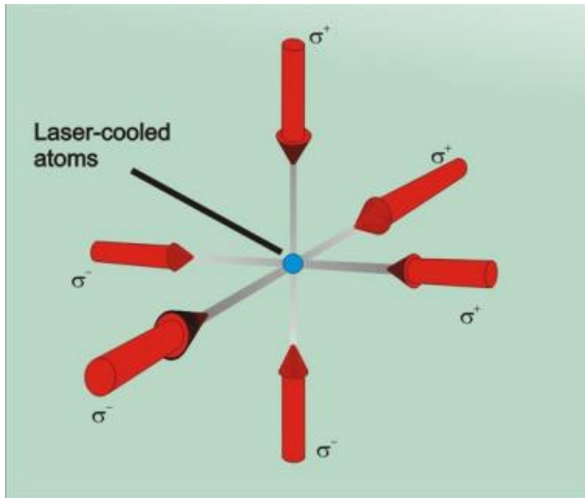




Laser Cooling:

Laser cooling is a set of methods for cooling atoms, molecules, and small mechanical systems to temperatures that are often close to absolute zero. This cooling changes the momentum of an object-typically an atom since the system absorbs and re-emits a photon. It includes light interaction and atomic spectroscopy as a combined process. Doppler cooling is the basic type of laser cooling and is also the most popular technique and it is frequently referred to as simply "laser cooling".

When the atom absorbs the photon, the atom will experience a change in momentum; the momentum of the atom will increase in the direction of the laser beam. When the atom emits a photon, it will again experience a change in momentum; the atom will recoil in a direction opposite the direction of the emitted photon. If an atom repeatedly absorbs photons from a laser beam, emitting a photon in a random direction after each absorption, the atom will experience a net change in momentum in the direction of the laser beam due to the absorption of photons. Since the emitted photons come out in all directions, the average change in momentum due to the emitted photons will be zero. Thus the atom slows down and thus the kinetic energy of the system and hence the temperature goes down leading to cooling of Atoms. This process makes the temperature down to few milli kelvins.



Uses of Laser cooling:

- Construction of atomic clocks
- In the construction of scientific instruments for atom optics and atomic lithography
- In atomic interferometers
- Used to study ultra-cold gases
- Navigation applications

List of formulae

Ratio of population ----- $\frac{N_1}{N_2} = e^{\frac{h\nu}{kT}}$

Number of Photons ----- $N = \frac{Energy\ of\ each\ photon\ (\Delta E)}{Energy\ of\ the\ laser\ (E)}$

Power of the Laser ------$P = \frac{Energy}{Time}$

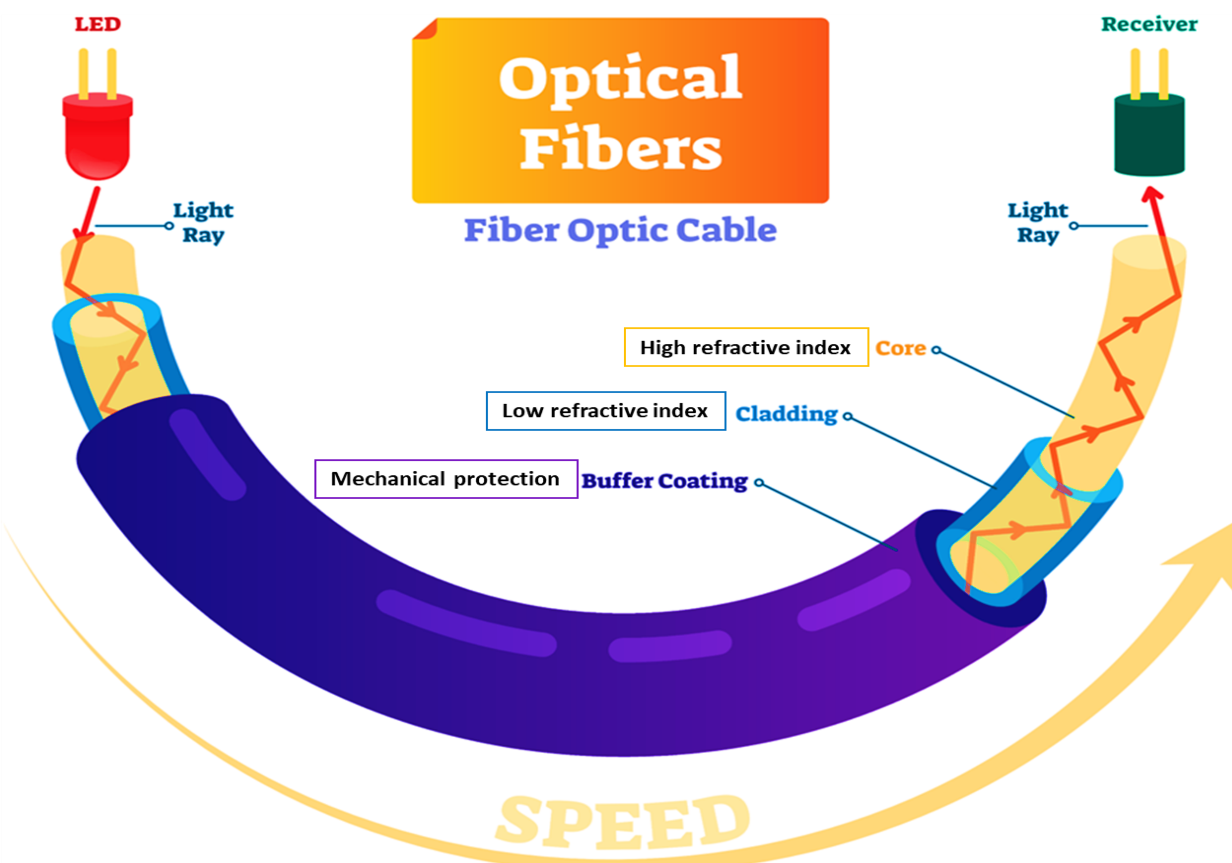
Sample Numerical Problems

1. A medium in thermal equilibrium at temperature 300 K has two energy levels with a wavelength separation of 1 μm. Find the ratio of population densities of the upper and lower levels.
2. The average output power of laser source emitting a laser beam of wavelength 6328Å is 5 mW. Find the number of photons emitted per second by the laser source.
3. A laser operating at 632.8 nm emits 3.182×10^{16} photons per second. Calculate the output power of the laser if the input power is 100 Watt.

MODULE-1: OPTICAL FIBERS

Optical Fiber: Principle and structure, Acceptance angle and Numerical Aperture (NA) and derivation of Expression for NA, Classification of Optical Fibers, Attenuation and Fiber Losses, Applications: Fiber Optic Communication, advantages and disadvantages, Numerical problems.

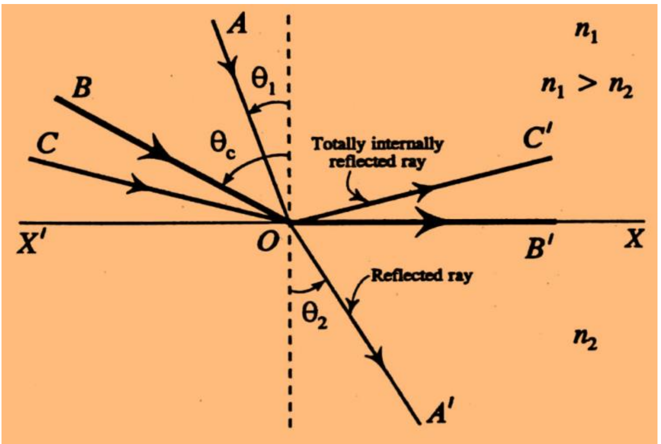
Pre requisite: Properties of light: Total Internal Reflection & Propagation Mechanism



OPTICAL FIBERS (WAVE GUIDES)

Def: Optical fiber is a device used to transmit light signals through the transparent medium made up of dielectric materials like glass from one end to other end over a long distance.

Principle: It works on the principle of **"Total Internal Reflection (TIR)".**



If the angle of incidence is greater than the critical angle i.e. $\theta_i > \theta_c$ then the total internal reflection occurs. TIR is not just one kind of reflections. The significance of TIR is that there is no loss of light energy at the reflecting surface. The entire incident energy is returned along the reflected light. Hence, it is called **T**otal **I**nternal **R**eflection (TIR). Because of no loss of energy during reflection, the optical fibers are able to sustain the light signal transmission over long distance inspite of multiple number of reflections that occur within the optical fiber.

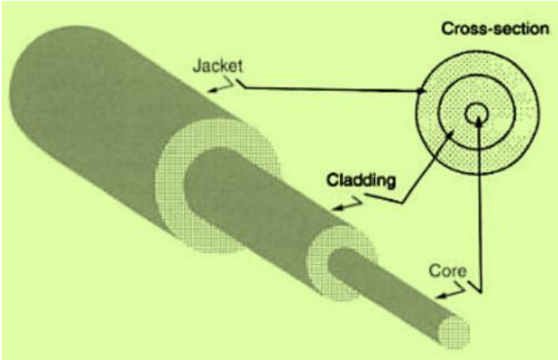
Construction: An optical fiber is a thin strand of dielectric material which can conduct light. It is made of two parts. One is the inner cylindrical material made up of glass or plastic of refractive index (n_1) called core. The core is surrounded by the same material of low refractive index (n_2) known as cladding. The cladding is enclosed in polyurethane jacket to prevent the chemical reaction with surroundings and against crushing.

Here the cladding is not only required for the propagation of light along the core of the fiber, but it serves for other purposes also:

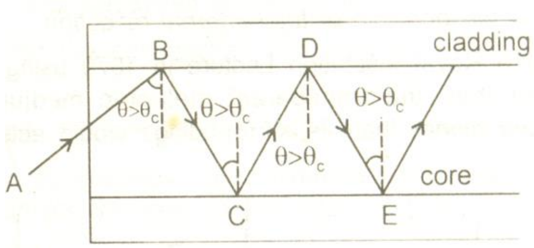
(a) cladding reduces the scattering loss resulting from dielectric discontinuities at the core surface.

(b) It adds mechanical strength to the fiber

(c) It protects the core from absorbing surface contaminants with which it could come in contact.



Working:



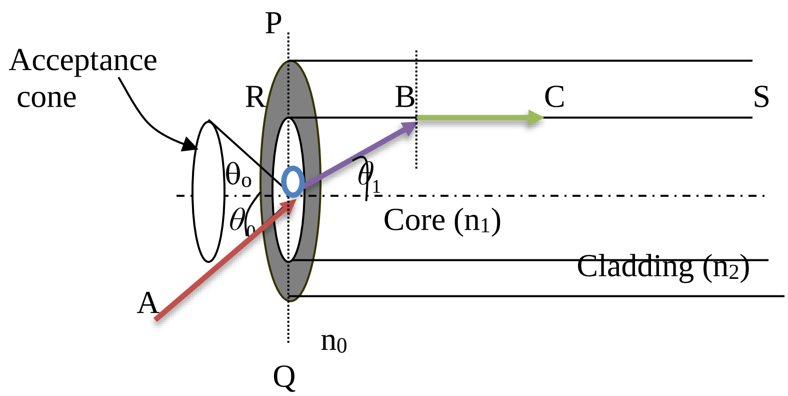
Suppose a ray of light A entering the fiber through one end and strikes the core-cladding surface at B at an angle of incidence θ greater than the critical angle θ_c , it undergo TIR at the point B and then it strikes the point C. At this point also $\theta_i > \theta_C$ and again gets TIR at C. Like this, the ray undergoes such multiple reflections in the medium of fiber and finally emerges out at the other end. The propagation of light continues as long as the fiber is not bending too sharply, since for sharp bends, the light fails to undergo TIR. Hence the signal strength decreases drastically.

Numerical Aperture:

Consider an optical fiber consisting of inner cylindrical core made of glass of refractive index n_1 and is surrounded by cladding of refractive index n_2 such that $n_2 < n_1$.

Consider a ray of light AO incident on the core at 'O' at an angle $\theta_0$with the fiber axis. Then it refracts along OB at an angle of θ_1 in the core.

The refracted ray is incident on the interface between core and cladding at B an angle of incidence (90 -θ_1). Assuming this angle (90 –θ_1) is equal to critical angle, then the ray is refracted at 90^0 to the normal drawn to the interface. i.e. it grazes along BC.



Now, it is clear from the figure that any ray that enters into the core at angle $\theta_i < \theta_0$ will have refractive angle less than θ_1 because of which its angle of incidence at the interface (=90 - θ_1) will become greater than critical angle of incidence and thus undergoes total internal reflection.
If the angle of incidence at 'O' is greater than θ_0 , then the refracted ray pass through the cladding and it will be lost. If AO is rotated around the fiber axis keeping θ_0 as constant, then it forms a conical surface called acceptance cone. All the light rays which enter within this acceptance cone will undergo total internal reflection and propagates through the fiber.

"The angle θ_0 is called waveguide acceptance angle or acceptance cone half angle and **Sin**θ_0 is called "**Numerical Aperture" of the fiber**". The N.A. represents the number of light rays that can be transmitted along the optical fiber i.e. light gathering ability of the fiber.

<u>Expression for N.A.:</u>

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

Apply Snell's law to the surface PQ, which separates surrounding medium and core:

$$n_0 \, Sin\theta_0 = n_1 \, Sin\theta_1$$

$$Sin\theta_0 = \frac{n_1}{n_0} Sin\theta_1 \qquad \ldots(1)$$

Apply the Snell's law to surface RS which separates core and cladding:

$$n_1 \, Sin(90 - \theta_1) \; = \; n_2 \, Sin 90^0$$

$$n_1 \, Cos\theta_1 \; = \; n_2$$

$$Cos\theta_1 \; = \; \frac{n_2}{n_1} \qquad \ldots(2)$$

Rewrite the equation (1) => $Sin\theta_0 \; = \; \frac{n_1}{n_0} \sqrt{1 - \cos^2 \theta_1}$

$$= \; \frac{n_1}{n_0} \sqrt{1 - \frac{n_2^2}{n_1^2}}$$

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

If the surrounding medium is air then $n_0 = 1$, Therefore

$$Sin\theta_0 \; = \text{N.A.} = \; \sqrt{n_1^2 - n_2^2}$$

<u>The condition for propagation</u> is that

The angle of incidence θ_i should be less than acceptance angle θ_0 (i.e. $\theta_i < \theta_0$)

i.e. $Sin\theta_i < Sin\theta_0$

$$Sin\theta_i < \text{N.A.} < \sqrt{n_1^2 - n_2^2}$$

Fractional Refractive index change (Δ): It is the ratio of change in Refractive Indices of core and cladding to the Refractive Index of the core.

$$\Delta = \frac{n_1 - n_2}{n_1}$$

Modes of Propagation

Light propagates as an electromagnetic wave through an optical fiber. It is true that all waves, having directions above the critical angle, will be trapped within the fiber due to TIR. But is not true that all such waves propagate along the fiber and only certain ray directions are allowed to propagate. The allowed directions correspond to the modes of the fiber i.e. **Mode refers to the number of paths for the light rays to propagate in the fiber.** The number of modes that a fiber will support depends on d/λ. Where d – diameter of the core and λ is the wavelength of the wave transmitted.

[**Note:** As a ray gets repeatedly reflected at the walls of the fiber, phase shift occurs. Consequently, the waves traveling along certain zigzag paths will be in phase and intensified, however, some other paths will be out of phase and hence the signal strength diminishes due to destructive interference. The light ray paths along which the waves are in phase inside the fiber are known as modes.]

V- Number: The number of modes supported for propagation in the fiber is determined by a parameter called V-number and is given by

$$V = \frac{\pi d}{\lambda} \frac{\sqrt{n_1^2 \quad n_2^2}}{n_o}$$ d – diameter of the core, λ - wavelength of the light,

n_0 – R.I. of the surrounding medium, n_1 – R.I. of the core, n_2 – R.I. of the cladding

Number of modes= $\frac{V^2}{2}$

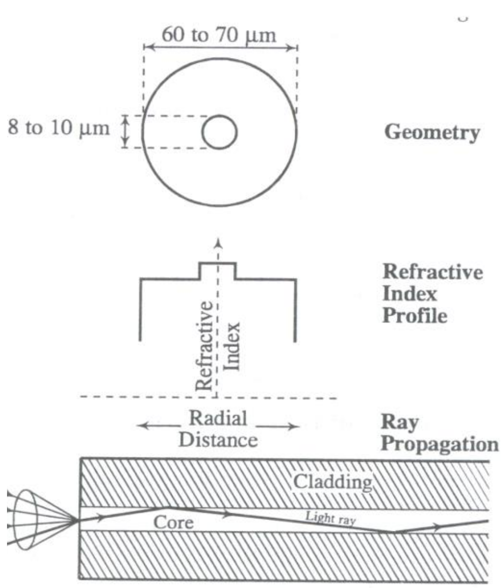
Refractive index Profile: It refers to the variation of refractive index of the core along the radial distance.

Types of Optical Fiber:

Optical fibers are classified into 3-types based on their R.I. of core and cladding and number of modes of propagation in the fiber.

(1) Step index single mode fiber
(2) Step index multi mode fiber
(3) Graded Index multi mode fiber.

(1) Step Index Single Mode optical fiber:



SINGLE MODE FIBER

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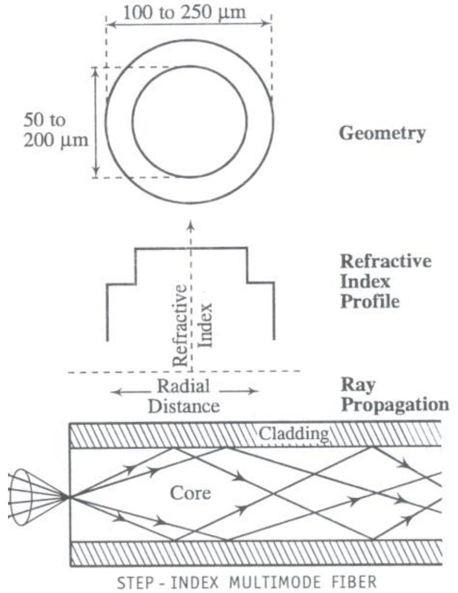
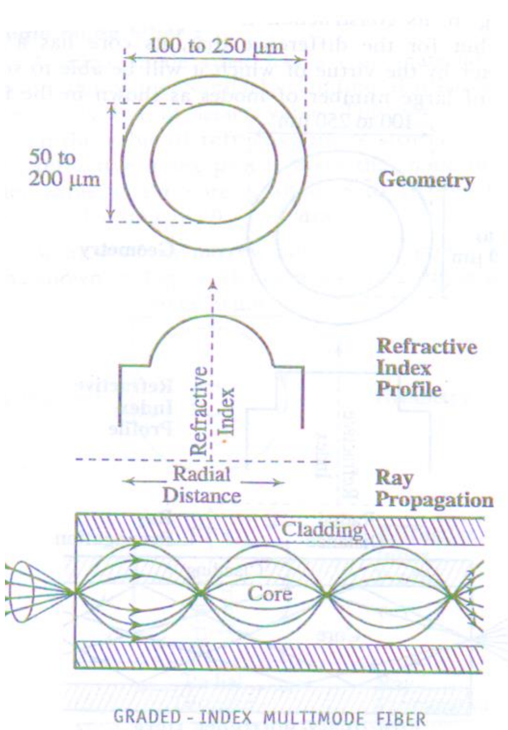
- It consists of a core of uniform refractive index n_1
- The diameter of the core is about 8-10 μm
- The core is surrounded by a material of uniform R.I. n_2 called cladding such that $n_2<n_1$. The external diameter of the cladding is 60 – 70 μm
- The variation of R.I.s of core and cladding takes the shape of step as shown in fig.
- Since the core diameter is very small, therefore, it can guide a single mode as shown in figure.
- Laser can be used as a source.
- They are used for long distance communications and submarine cable system.

(2) Step index multi mode fiber



- It consists of a core of uniform refractive index n_1
- The diameter of the core is about 50 - 200 μm
- The core is surrounded by a material of uniform R.I. n_2 called cladding such that $n_2 < n_1$. The external diameter of the cladding is 100 – 250 μm
- The variation of R.I.s of core and cladding takes the shape of step as shown in fig.
- Since the core diameter is very large, therefore, it will be able to support propagation of large number of modes.
- LED or Laser can be used as a source.
- Applications: It can be used in data links which has lower band width requirements.

(3) Graded Index multi mode fiber



- It is also called as GRIN.
- The core material has a special feature 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.
- The diameter of the core is about 50 - 200 μm
- The core is surrounded by a material of uniform R.I. n_2 called cladding such that $n_2 < n_1$. The external diameter of the cladding is 100 – 250 μm
- The variation of R.I.s of core and cladding is as shown in fig.
- Since the core diameter is very large, therefore, it will be able to support propagation of large number of modes.
- LED or Laser can be used as a source.
- Applications: It can be used in telephone trunk between central offices and it is most expensive compared to other two types.

Attenuation (Fiber Loss)

"The loss of light energy of the optical signal as it propagates through the fiber is called **attenuation** or fiber loss."

The main reasons for the loss of light intensity over the length of the cable is due to

i) absorption (ii) Scattering (iii) Radiation loss

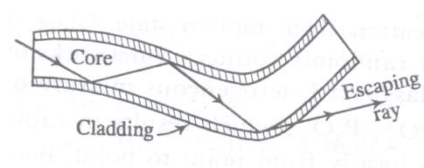
(i) **Absorption Losses**: In this case, the loss of signal power occurs due to absorption of photons associated with the signal. Photons are absorbed by (a) impurities in the silica glass (b) Intrinsic absorption by the glass material.

ii) **Scattering Loss: Rayleigh scattering-** As glass has disordered structure having local microscopic variation in density which may also cause variation in RI. Therefore, when the light travels in the fiber, the photons may be scattered. Due to the scattering, photons move in random direction and fails to undergo total internal reflection and escapes from the fiber through cladding and it becomes loss. So light traveling through these structures may suffer scattering losses due to Rayleigh

iii) **Radiation loss:** Radiation losses occur due to bending of fiber.

(a) Macroscopic bends: When optical fiber is curved extensively such that incident angle of the ray falls below the critical angle, then **no** total internal reflection occurs.

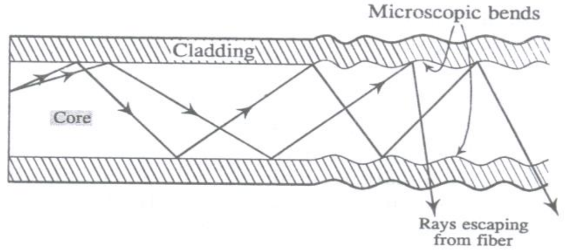
Hence, some of the light rays escape through the Cladding and leads to loss in intensity of light



RADIATION LEAKS

(b) Microscopic bends:

The microscopic bendings are occur due to non-uniformities in the manufacturing of the fiber or by non-uniform lateral pressures created during the cabling of the fiber. At these bends some of the radiations leak through the fiber due to the absence of total internal reflection and leads to loss in intensity.



The net attenuation can be determined by a factor called **attenuation co-efficient (α).**

Or $\alpha = -\frac{1}{L}\log_{10}\left[\frac{P_{out}}{P_{in}}\right]$ Bel / unit length

The unit of attenuation for light in optical fiber is Bel. In optical fiber technology, it is customary to express α in terms of decibel/kilometer. P is in watt and 1B = 10decibel

Therefore, $\alpha = -\frac{10}{L}\log_{10}\frac{P_{out}}{P_{in}}$ dB / km

Application of optical fibers

Communication applications

The various applications of optical fibers in the telecommunication area in general could be telephones, video phones, telegraph services and data networks can be transmitted over common carrier links.

Optical Fiber Communications systems can be broadly classified into two groups

i) local and intermediate range systems where the distance involved or small and

ii) long haul systems where cables span large distances

Local and intermediate range systems cover communication networks in small community, an industry, a bank, an education institution etc., In many organizations a LAN distributes information to several stations within the organization. A network is a group of computers connected mutually for exchanging information and sharing equipment. A number of computer terminals are interconnected or a common channel to keep track of the flow of data and to process the data.

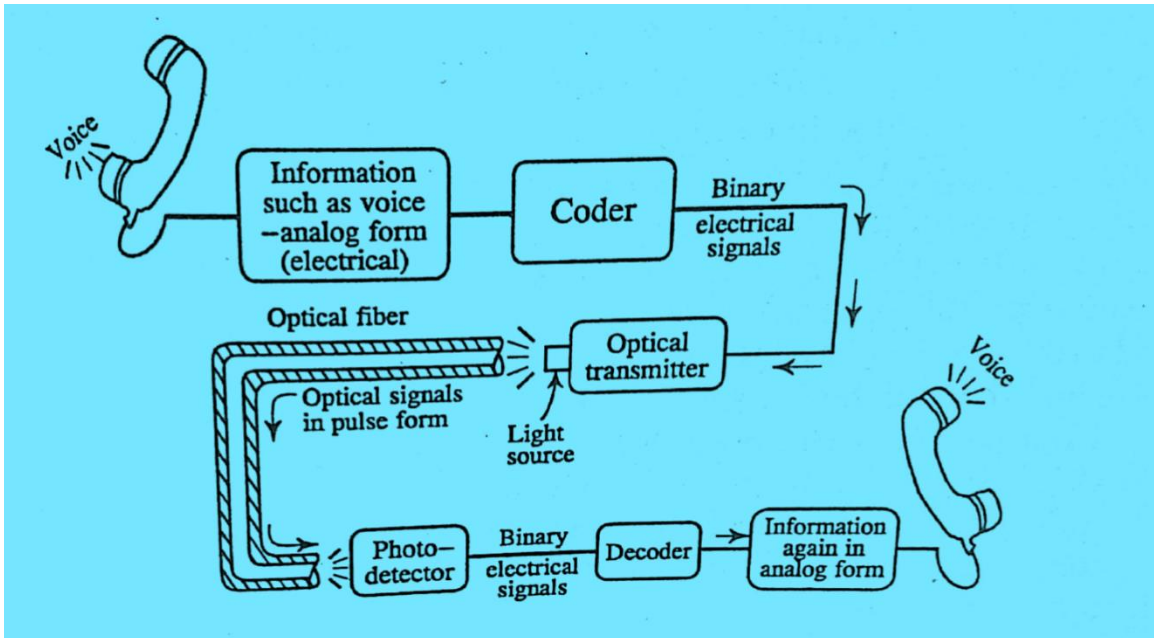
An optical fiber data bus offers a great reduction in cost and enormously increases information handling capacity compared to a parallel multiwire database

Telephone cables connecting various countries come under the category of long-haul system

Point-to-point communication

The block diagram of optical point-to-point optical fiber communication is shown figure.

The information / voice converted into electrical signal in an analog form is coming out from the telephone. The analog electrical signal is converted into binary data with the help of coder.



These electrical pulses are converted into binary optical signals using optical source (ex. LED). This unit is called an optical transmitter from which the optical signals are fed into the fiber. The incident light pulses which are funneled into the core within the half angle acceptance cone, will be sustained for propagation within the fiber by means of total internal reflection.

At the other end of the fiber, the optical signal is fed into a photo detector where it is converted into electrical pulses. These electrical pulses are fed to decoder which converts the sequence of binary data stream into an analog signal which will be the same information such as voice, which was there at the transmitting end.

Along with these components, repeater needs to be used. Since, as the optical signal propagating through the fiber, the signal is subjected to both attenuation and delay distortion.

These effects cause degradation of the signal as the light propagates and may reach a stage beyond which it may not be possible to retrieve the information from the light signal. At this stage a repeater is needed in the transmission path. The repeater consists of receiver and transmitter. The receiver section converts the optical signal into corresponding electrical signal and these electrical signals amplified and recast in the original form. This reshaped electrical signal which is in the form of binary form is sent into an optical transmitter which is converted into optical signal and feedback into the optical fiber.

Applications of Optical Fiber:

Optical fibers find their applications in many fields.

- Optical fibers can be used in point-to-point communications
- They can be used in local area network (LAN) communication system
- Medical applications: Endoscope
- Industrial applications: They are used in the design of Boroscopes, which are used to inspect the inaccessible machinery parts.
- Domestic applications: They can be used to illuminate the interior places where the sunlight has no access to reach.
- Sensing applications of optical fibers are: Displacement sensor Liquid level sensor, Temperature and pressure sensor Chemical sensors

Advantages of Optical Fiber:

2. Optical fibers can carry very large amounts information.
3. The materials used for making optical fibers are silicon oxide and plastic, both are available at low cost.
4. Because of the greater information carrying capacity by the fibers, the cost, length, channel for the fiber would be lesser than that for the metallic cable.
5. Because of their compactness, and light weight, fibers are much easier to transport.
6. There is a possibility of interference between one communication channel and the other in case of metallic cables. However, the optical fiber is totally protected from interference between different communication signals, since, no light can enter a fiber from its sides. Because of which no cross talk takes place.

7. The radiation from lightning or sparking causes the disturbance in the signals which are transmitting in the metallic cable but cannot do for the fiber cable.
8. The information cannot be tapped from the optical fiber.
9. Since signal is optical, no sparks are generated as it could in case of electrical signal.
10. Because of its superior attenuation characteristics, optical fibers support signal transmission over long distances.'

Limitations of Optical fiber communications system:

1. Splicing is skillful task, which if not done precisely, the signal loss will be so much. The optic connectors, which are used to connect (splicing) two fibers are highly expensive.
2. While system modifications or because of accidents, a fiber may suffer line break. To establish the connections, it requires highly skillful and time consuming. Hence, maintenance cost is high.
3. Though fibers could be bent to circles of few centimeters' radius, they may break when bent to still smaller curvatures. Also, for small curvature bends, the loss becomes considerable.
4. Fibers undergo expansion and contraction with temperature that upset some critical alignments which lead to loss in signal power.

List of Equations:

1.Numerical Aperture:

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

2. Acceptance Angle:

$$\theta_0 = Sin^{-1}(\sqrt{n_1^2 - n_2^2})$$

3. Attenuation Co-efficient:

$$\alpha = -\frac{10}{L}\log_{10}\frac{P_{out}}{P_{in}} \text{ dB / km}$$