BPHYS102/202

MODULE - 01

LASERS AND OPTICAL FIBERS

LASERS

The word Laser stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. It is a device which amplifies light. It has properties like Coherence, Unidirectional, Monochromatic, Focus ability, etc.

Interaction of an electromagnetic wave with matter leads to transition of an atom or a molecule from one energy state to another. If the transition is from lower state to higher state it absorbs the incident energy. If the transition is from higher state to lower state it emits a part of its energy.

Emission or Absorption takes through quantum of energy called photons. $h\nu$ is called quantum energy or photon energy.

$h = 6.626\times10^{-34}$ Joules Second is Planck's constant and 'ν' is the frequency.

If ΔE is the difference between the two energy levels,

Then $\Delta E = (E_2 - E_1)$ Joule

According to Max Planck, $\Delta E = h\nu = (E_2-E_1)$

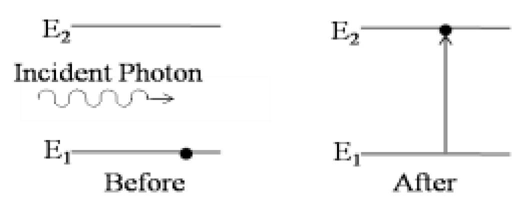
$\nu = (E_2 - E_1)/h$ Hz.

Three types of interactions, which are possible, are as follows:

1) Induced Absorption:

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

Consider the system having two energy states E_1 and E_2, $E_2 > E_1$. When a photon of energy $h\nu$ is incident on an atom at level E_1, the atom goes to a higher energy level by absorbing the energy.



When an atom is at ground level (E_1), if an electromagnetic wave of frequency ν is applied to the atom, there is possibility of getting excited to higher level (E_2). The incident photon is absorbed.

It is represented as

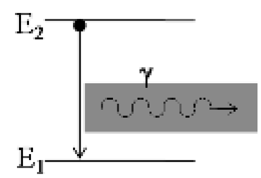
Atom + Photon → Atom*

2) Spontaneous Emission: The emission of a photon by the transition of a system from a higher energy state to a lower energy state without the aid of an external energy is called spontaneous emission.

Let 'E_1' and 'E_2' be two energy levels in a material, such that $E_2 > E_1$. E_1 is ground level and E_2 is the higher level. $h\nu = E_2 - E_1$ is the difference in the energy. The atom at higher level (E_2) is more unstable as compared to that at lower level (E_1).

The life time of an atom is less in the excited state, In spontaneous emission atom emits the photon without the aid of any external energy. It is called spontaneous emission. The process is represented as

Atom* → Atom + Photon



The photons emitted in spontaneous emission may not have same direction and phase similarities. It is incoherent.

Ex: Glowing electric bulbs, Candle flame etc.

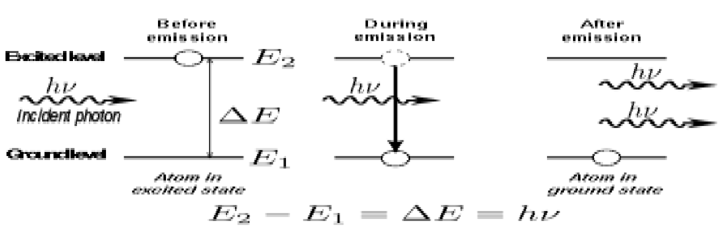
3) Stimulated Emission:

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

The photon thus emitted is called stimulated photon and will have the same phase, energy and direction of movement as that of the passing photon called the stimulation photon.

Initially the atom is at higher level E_2. The incident photon of energy $h\nu$ forces the atom to get de-excited from higher level E_2 to lower level E_1.

i.e., $h\nu = E_2 - E_1$ is the change in energy.



The incident photon stimulates the excited atom to emit a photon of exactly the same energy as that of the incident photons. The emitted two photons have same phase, frequency, direction and polarization with the incident photon and results in coherent beam of radiation. This kind of action is responsible for lasing action.

Atom* + Photon → Atom + (Photon + Photon)

Expression for energy density in terms of Einstein's Coefficients

Consider two energy levels E_1 and E_2 of a system of atoms with N_1 and N_2 are population of energy levels respectively.

Let U_ν be the energy density of incident beam of radiation of frequency γ. Let us consider the absorption and two emission process

1) Induced absorption:

Induced absorption is the absorption of an incident photon by system as a result of which the system is elevated from a lower energy state to a higher state.

The rate of absorption is proportional to N_1U_ν

Rate of absorption = $B_{12}N_1U_\nu$ …………….. (1)

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

2) Spontaneous emission:

The emission of a photon by the transition of a system from a higher energy state to a lower energy state without the aid of an external energy is called spontaneous emission.

Spontaneous emission depends on N_2 and independent of energy density.

The rate of spontaneous emission = $A_{21}N_2$ ……………(2)

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

3) Stimulated emission:

Stimulated emission is the emission of a photon by a system under the influence of a passing photon of just the right energy due to which the system transits from a higher energy state to a lower energy state

BPHYS102/202

The rate of stimulated emission is directly proportional to N_2U_γ.

The rate of stimulated emission = $B_{21}N_2U_\nu$ …………….. (3)

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

At thermal equilibrium,

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

$B_{12}N_1U_\nu = A_{21}N_2 + B_{21}N_2U_\nu$

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

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

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

$$U_\nu = \frac{A_{21}}{B_{21}}\left[\frac{1}{\left(\frac{B_{12}N_1}{B_{21}N_2}\right) - 1}\right] \quad \to (4)$$

By Boltzmann's law, $N_2 = N_1 e^{-\left(\frac{E_2 - E_1}{KT}\right)} = N_1 e^{-h\nu/KT}$

$$\text{i.e. } \frac{N_1}{N_2} = e^{\frac{h\vartheta}{KT}}$$

Eqn. (4) becomes
$$U_\upsilon = \frac{A_{21}}{B_{21}}\left[\frac{1}{\left(\frac{B_{12}}{B_{21}} e^{\left(\frac{h\upsilon}{kT}\right)} - 1\right)}\right] \quad \to (5)$$

By Planck's law,
$$U_\upsilon = \frac{8\pi h\upsilon^3}{c^3}\left[\frac{1}{\left(e^{\left(\frac{h\upsilon}{kT}\right)} - 1\right)}\right] \quad \to (6)$$

BPHYS102/202

Comparing equation (5) & (6)

$\frac{A_{21}}{B_{21}} = 8\pi h\nu^3/c^3$ & $\frac{B_{12}}{B_{21}} = 1$ i.e. $B_{12} = B_{21}$

The probability of induced absorption is equal to the stimulated emission.

Therefore A_{12} is written as A and B_{12}, B_{21} written as B.

Equation (5) becomes

$$\boxed{U_\upsilon = \frac{A}{B}\left[\frac{1}{\left(e^{\left(\frac{h\upsilon}{kT}\right)} - 1\right)}\right]}$$

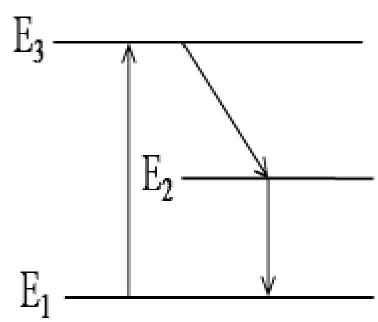
Above equation is the expression for energy density

<u>Condition for laser action:</u>

1) <u>Meta Stable State:</u>

It is the special type of excited state where in the life time of atom is more than the normal excited state.

This state plays an important role in lasing action. In metastable state, atoms stay of the order of 10^{-3} to 10^{-2} second. In normal excited state other than metastable atom stay of order of 10^{-8} to10^{-9} seconds. It is possible to achieve population inversion condition in certain system which possesses a metastable state.



2) <u>Population Inversion:</u>

It is the state of the system at which the population of a higher energy level is greater than that of the lower energy level.

Let E_1, E_2, E_3 be the energy levels of the system $E_3>E_2>E_1$. E_2 is the metastable state of the system. Atoms get excited from the state E_1 to E_3 by means of external source and stay there for short time. These atoms undergo spontaneous transitions to E_2 and E_1. The atoms at the state E_2 stay for longer time. A stage is reached in which the number of atoms at state E_2 is more than the number of atoms at E_1 which is known as population inversion.

BPHYS102/202

Requisites of a Laser System:

1) The pumping process:

It is the process of supplying energy to the medium in order to transfer it to the state of population inversion is known as pumping process

Optical Pumping: It is the process of exciting atoms from lower energy level to higher energy level by using high intensity light or by operating flash tube as an external source called optical pumping.

Electrical pumping: It is the process of exciting atoms from lower energy level to higher energy level by using dc power supply as an external source called electrical pumping.

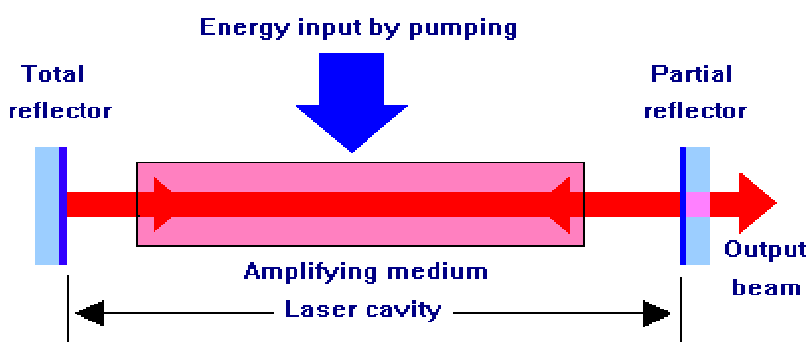
2) Active medium:

It is a medium which supports population inversion and promotes stimulated emission leading to light amplification

Active centers: In a medium consisting of different species of atoms only small fraction of the atoms of a particular type are responsible for stimulated emission and consequent light amplification they are known as Active centers

3) Laser cavity.

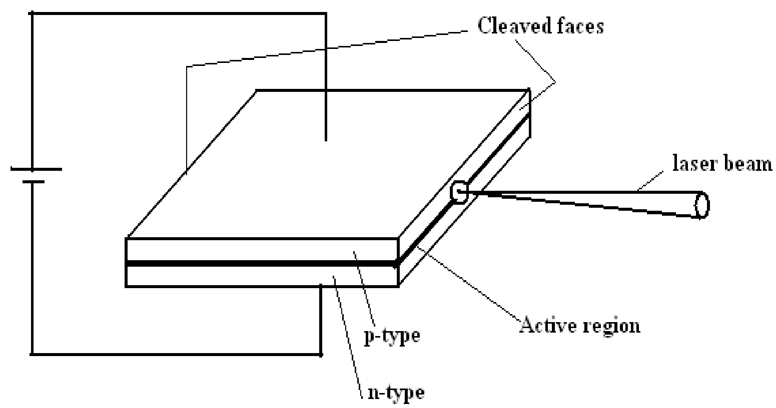
An active medium bounded between two mirrors is called as a laser cavity.



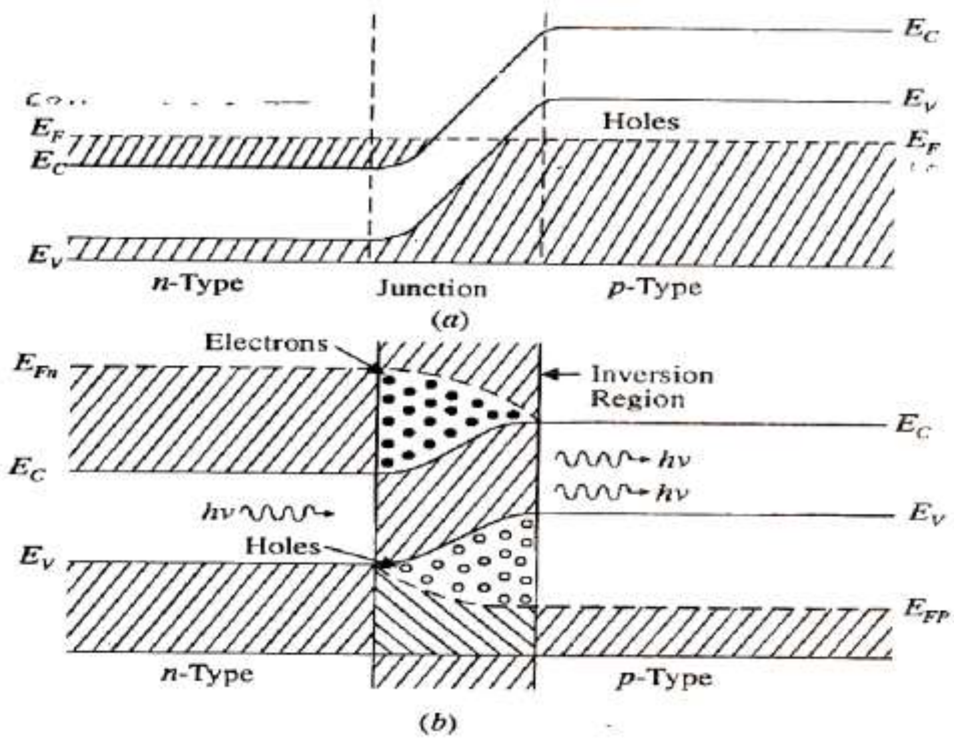
Semiconductor laser - Gallium-Arsenide Laser:

A Semiconductor diode laser is one in which the active medium is formulated by semiconducting materials.

Construction: Gallium-Arsenide Laser is a single crystal of GaAs consists of heavily doped n-type and p-type. The diode is very small size with sides of the order of 1mm. The width of the junction varies from 1-100μm. The top and bottom surfaces are metalized and Ohmic contacts are provided for external connection. The front and rear faces are polished. The polished faces functions as the resonant cavity. The other two faces are roughened to prevent lasing action in that direction.



Working:



Energy level diagram of p-n junction Ga-As semiconductor diode laser
(a) Before biasing (b) After biasing

- The energy band diagram of heavily doped p-n junction is as shown. At thermal equilibrium the Fermi level is uniform.
- Because of very high doping on **n- side**, the Fermi level is pushed in to the conduction band and electrons occupy the portions of the conduction band that lies below the Fermi level and on **p-side**, the Fermi level lies within the valence band and holes occupy the portions of the valence band that lies above the Fermi level.
- A suitable forward bias is applied to overcome the potential barrier. As a result electrons from n-region and holes from p-region injected into the junction.
- The current begins to flow following which there will be a region in junction in which the population inversion can be achieved.
- Initially concentration of electrons in the energy levels at the bottom of the conduction band will be less than that of energy levels at top of valence band. So that the recombination of electrons and holes result only in spontaneous emission.
- When the current exceeds the threshold value, population inversion is achieved in the active region which is formulated in the junction.
- At this stage the photons emitted by spontaneous emission triggers stimulated emission, over a large number of recombination leading to build up laser.
- Since the energy gap of GaAs is 1.4eV, the wavelength of emitted light is 8400 Å.

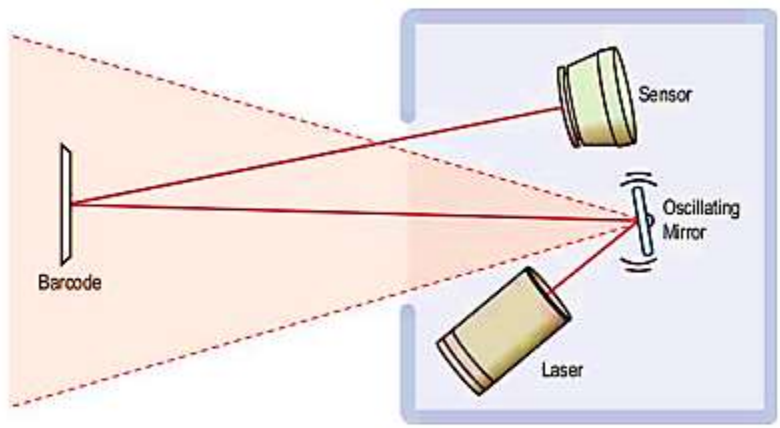
Properties of laser:

1. **Coherence:** The emitted radiation after getting triggered is in phase with the incident radiation.
2. **Monochromaticity:** The laser beam is highly monochromatic than any other radiations.
3. **Unidirectionality:** Laser beam travels in only one direction. It can travel long distance without spreading.
4. **Focusability:** A laser beam can be focused to an extremely fine spot.

Applications of Laser:

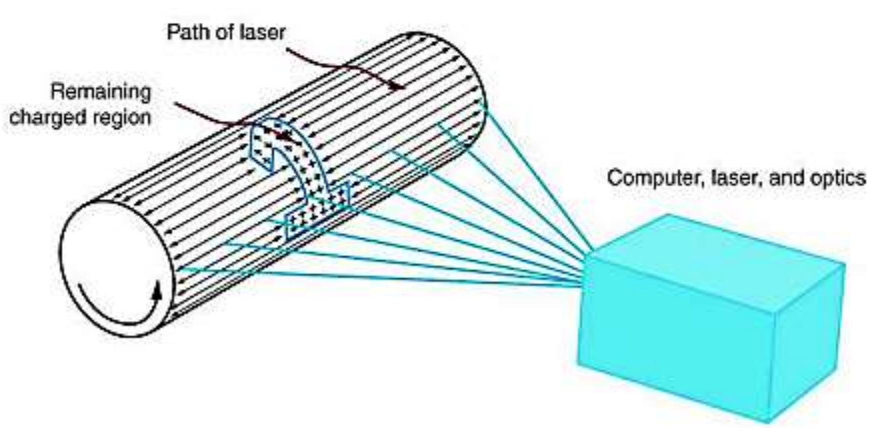
1. Barcode Scanner

A barcode is a method of representing data in a visual and machine-readable form. Barcodes represent data by varying the widths, spacing and sizes of parallel lines. These barcodes, now commonly referred to as linear can be scanned by special optical scanners, called barcode readers. A barcode reader is an optical scanner that can read printed barcodes, decode the data contained in the barcode to a computer. Laser scanners use a laser beam as a light source and typically employ oscillating mirrors to scan the laser beam back and forth across the barcode. A photo-diode is used to measure the intensity of the light reflected back from the barcode. An analog signal is created from the photodiode, and is then converted into a digital signal. The digital data from the scanner is sent to a computer program, which figures out the final barcode.



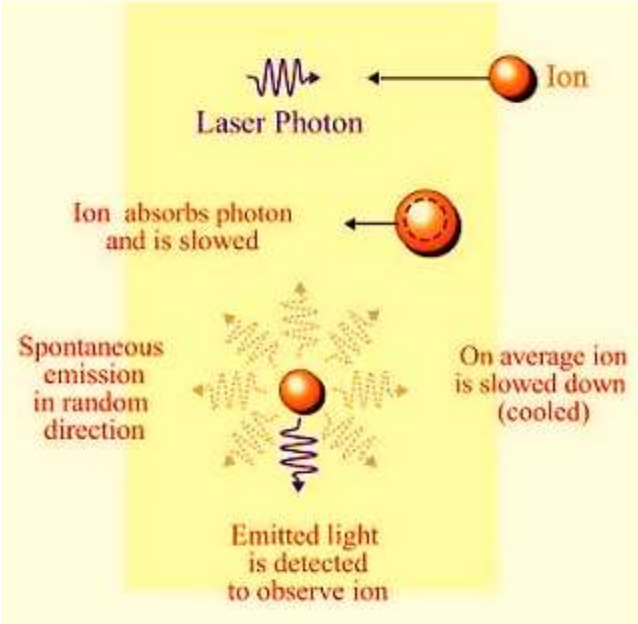
2. Laser Printer

Laser beam is used in laser printers to get printouts with better quality. Laser printers read the electronic data from computer and beam this information onto a drum inside the printer, which builds up a pattern of static electricity. This attracts a dry powder called toner onto the paper. A fuser roller generates heat and pressure to permanently fix the image onto the paper.



3. Laser Cooling

In this technique, heat can be removed optically with the help of laser. Atoms can be cooled using lasers because light particles from the laser beam are absorbed and re-emitted by the atoms, causing them to lose some of their kinetic energy. Reduction in the momentum results in the reduction in temperature of atom. After thousands of such impacts, the atoms will be chilled near to zero Kelvin.



OPTICAL FIBERS

An optical fibre is a cylindrical wave guide made of transparent dielectric material (glass or plastic) which guides light waves along its length by total internal reflection.

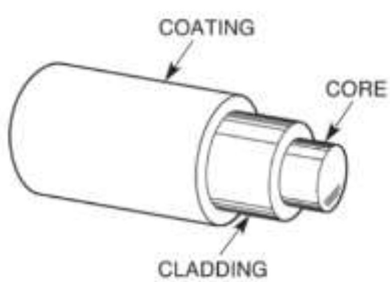
Principle

The propagation of light in an optical fibre from one end to the other end is based on the principle of Total internal reflection (TIR). They are used in optical communication.

When a light enters one end of the fibre, it undergoes successive total internal reflections from side walls and travels down the length of the fibre along zigzag path.

Construction

- A practical optical fibre is cylindrical in shape and has three regions.
- The innermost cylindrical region is the light guiding region called as core which is usually made up of glass or plastic.
- The outer part which is a concentric cylinder surrounding the core is called as cladding and is also made up of similar material but of lesser refractive index.
- The outermost region is called a Sheath or Protective buffer coating, nothing but the plastic coating providing a physical and environmental protection for the fibre. Number of such fibers is grouped to form a cable.

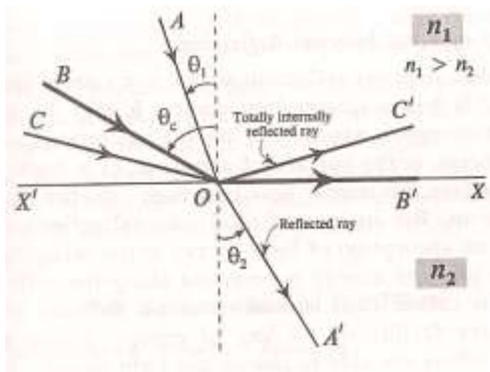


Total Internal Reflection

- When a ray of light travels from denser to rarer medium it bends away from the normal.
- As the angle of incidence increases in the denser medium, the angle of refraction also increases. For a particular angle of incidence called the "*critical angle*" (θ_c), the refracted ray grazes the surface separating the media or the angle of refraction is equal to 90°.
- If the angle of incidence is further increased beyond the critical angle, the light ray is reflected back to the same medium. This is called *"Total Internal Reflection".*

- In total internal reflection, there is no loss of energy. The entire incident ray is reflected back.

Let XX^l is the surface separating medium of refractive index n_1 and medium of refractive index n_2, $n_1 > n_2$. AO and OA^l are incident and refracted rays. θ_1 and θ_2 are angle of incidence and angle of refraction, $\theta_2 > \theta_1$. For the ray BO, θ_c is the critical angle. OB^l is the refracted ray which grazes the interface. The ray CO incident with an angle greater than θ_C is totally reflected back along OC^l.



TOTAL INTERNAL REFLECTION

From Snell's law,

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

For total internal reflection, $\theta_1=\theta_c$ and $\theta_2=90°$

$$n_1\sin\theta_c = n_2 \quad \text{(because } \sin 90°=1)$$

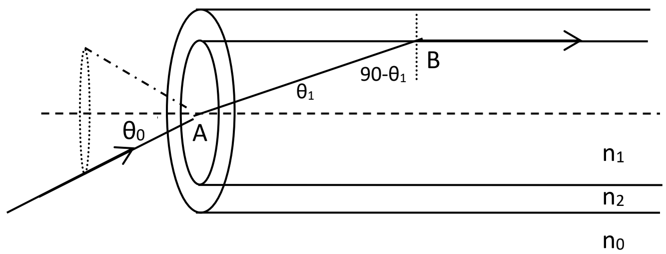
$$\therefore \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

In total internal reflection there is no loss or absorption of light energy. The entire energy is returned along the reflected light. Thus is called Total internal reflection.

Acceptance angle and numerical aperture

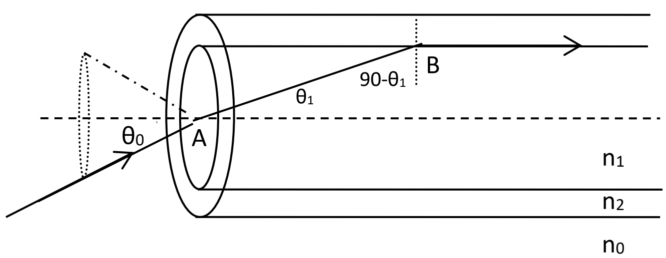
- Consider a light ray entering into the core of an optical fiber with an angle of incidence (θ_0), such that after entering, the ray incidents on the core-cladding interface with an angle of incidence equal to the critical angle.
- From figure it is clear that any ray which enters into the core with an angle more than θ_0, will

have to be incident at an angle less than the critical angle at the core-cladding interface.



- Therefore the ray does not undergo total internal reflection and the ray will be lost. Thus for any ray to propagate through the fiber it must enter with an angle less than θ_0. This maximum angle is called as '<u>Acceptance angle</u>' and the conical surface described by the ray when rotated about the axis of the fiber is called '<u>Acceptance cone</u>'.
- Thus acceptance angle is defined as "The maximum angle that a light ray can take relative to the axis of the fiber to propagate through the fiber".
- Sine of the acceptance angle of an optical fiber is called as "Numerical aperture".

Expression for Numerical aperture and condition for propagation



Consider a light ray entering into the core of an optical fiber with an angle of incidence (θ_0), such that after entering, the ray incidents on the core-cladding interface with an angle of incidence equal to the critical angle. Let n_0, n_1 and n_2 are the refractive indices of the surrounding medium, core and cladding respectively. Now, applying Snell's law at the point of entry of the ray i.e., at A,

$$\frac{\sin\theta_0}{\sin\theta_1} = \frac{n_1}{n_0}$$

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

Applying Snell's law at B,

$$\frac{sin(90° - \theta_1)}{sin\,90°} = \frac{n_2}{n_1}$$

$$\Rightarrow cos\,\theta_1 = \frac{n_2}{n_1} \dots\dots\dots\dots\dots\dots\dots\dots (2)$$

From expression (1) $sin\,\theta_0 = \frac{n_1}{n_0}\sqrt{1 - cos^2\,\theta_1}$

Substituting for cos θ_1 from (2)

$$sin\,\theta_0 = \frac{n_1}{n_0}\sqrt{1 - \frac{n_2^2}{n_1^2}}$$

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

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

If n_0=1 i.e., surrounding medium if it is air

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

i.e., $N.A. = \sqrt{n_1^2 - n_2^2}$

Condition for propagation:

If θ_i is the angle of incidence of the incident ray, then the ray will be able to propagate,

if $\theta_i < \theta_0$

$$\Rightarrow if\ sin\,\theta_i < sin\,\theta_0$$

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

$$i.e., sin\,\theta_i < N.A.$$

Fractional index change (Δ)

The ratio of the difference in refractive index of core and cladding to the refractive index of core of an optical fiber. $i.e., \Delta = \frac{n_1 - n_2}{n_1}$

Relation between N.A. and Δ

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

Increase in the value of Δ enhances the light gathering capacity of the fiber. Δ value cannot be increased very much because it leads to intermodal dispersion intern signal distortion.

V- Number

The number of modes supported for propagation in the fiber is determined by a parameter called V-number.

If the surrounding medium is air, then V-number is given by,

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

Where, d is the core diameter,

n_1 and n_2 are refractive indices of core and cladding respectively,

λ is the wavelength of light propagating in the fiber.

or $$V = \frac{\pi d}{\lambda}(NA)$$

If the fiber is surrounded by a medium of refractive index n_0, then,

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

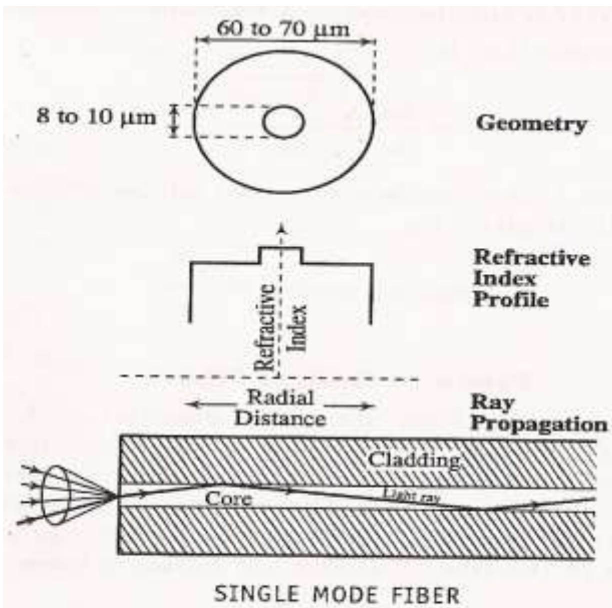
For V ≫1, the number of modes supported by the fiber is given by, number of modes $\cong \frac{V^2}{2}$

Types of optical fibers

Based on the refractive index profile and mode of propagation, There are three types of optical fibers,

1. Single mode fiber
2. Step index multimode fiber
3. Graded index multimode fiber

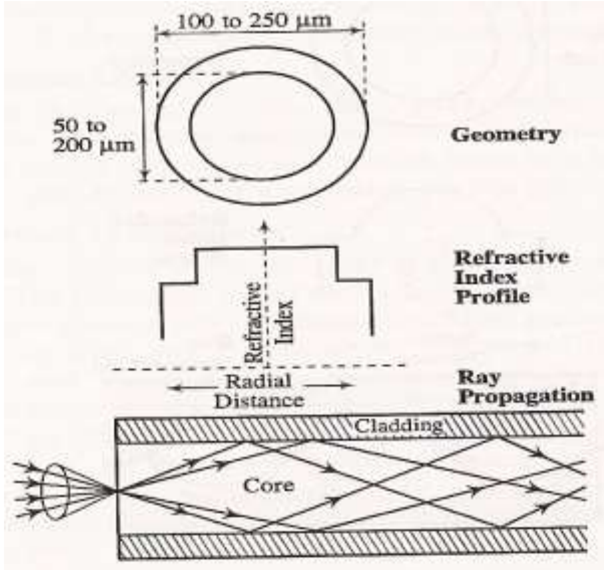
(i) Single mode fiber



- Single mode fibers have a core material of uniform refractive index value.
- Cladding material also has a uniform refractive index but of lesser value than that of core.
- Thus its refractive index profile takes a shape of a step. The diameter of the core is about 8-10 μm and the diameter of the cladding is about 60-70 μm.
- Because of its narrow core, it can guide just a single mode as shown in above figure.
- Single mode fibers are the extensively used ones ant they are less expensive. They need LASERs as the source of light.

(ii) Step index multimode fiber

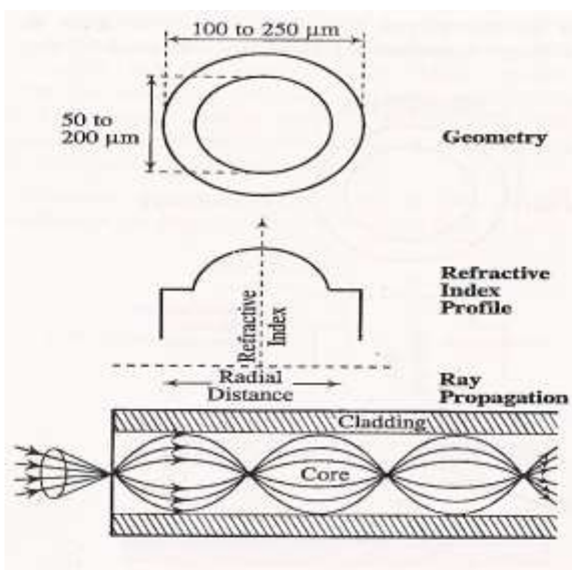
- A step index multimode fiber is very much similar to the single mode fiber except that its core is of large diameter. A typical fiber has a core diameter 50 to 200 μm and a cladding about 100 to 250μm outer diameter.



STEP - INDEX MULTIMODE FIBER

- Its refractive index profile is also similar to that of a single mode fiber but with a larger plane region for the core.
- Due to the large core diameter it can transmit a number of modes of wave propagation.
- The step index multimode fiber can accept either a LASER or an LED as source of light.
- It is the least expensive of all and its typical application is in data links which has lower bandwidth requirements.

(iii) <u>Graded index multimode fiber</u>



GRADED - INDEX MULTIMODE FIBER

- It is also called GRIN.
- The refractive index of core decreases in the radially outward direction from the axis of the fibre and becomes equal to that of cladding at the interface but the refractive index of the cladding remains uniform.
- Laser or LED is used as a source of light.
- It is the expensive of all. It is used in telephone trunk between central offices.

Signal attenuation in optical fibers

- Attenuation is the loss of optical power suffered by the optical signal as it propagates through a fiber also called as the fibre loss.
- There are three mechanisms through which attenuation takes place.

Attenuation can be caused by three mechanisms.

(i) Absorption losses

- Absorption of photons by impurities like metal ions such as iron, chromium, cobalt and copper in the silica glass of which the fiber is made of.
- During signal propagation photons interact with electrons of impurity atoms and the electrons are excited to higher energy levels.
- Then the electrons give up their absorbed energy either in the form of heat or light energy.
- The re-emission of light energy will usually be in a different wavelength; hence it is referred as loss of energy.
- The other impurity such as hydroxyl (OH) ions which enters into the fiber at the time of fabrication causes significant absorption loss.
- The absorption of photons by fiber itself assuming that there are no impurities and in-homogeneities in it is called as *intrinsic absorption*.

(ii) Scattering losses

- Scattering of light waves occurs whenever a light wave travels through a medium having scattering objects whose dimensions are smaller than the wavelength of light.
- Similarly when a light signal travels in the fibre, the photons may be scattered due to the sharp changes in refractive index values inside the core over distances and also due to the structural impurities present in the fibre material.
- This type of scattering is called as Rayleigh scattering. Scattering of photons also takes place due to trapped gas bubbles which are not dissolved at the time of manufacturing.
- A scattered photon moves in random direction and leaves the fibre.

(iii) Radiation losses

Radiation losses occur due to macroscopic bends and microscopic bends.

- **Macroscopic bending:** All optical fibers are having critical radius of curvature provided by the manufacturer. If the fiber is bent below that specification of radius of curvature, the light ray incident on the core cladding interface will not satisfy the condition of total internal reflection. This causes loss of optical power.
- **Microscopic bending:** Microscopic bends are repetitive small scale fluctuations in the linearity of the fibre axis. They occur due to non-uniformities in the manufacturing and also lateral pressure built up on the fiber. They cause irregular reflections and some of them leak through the fibre. The defect due to non-uniformity (micro-bending) can be overcome by introducing optical fiber inside a good strengthen polyurethane jacket.

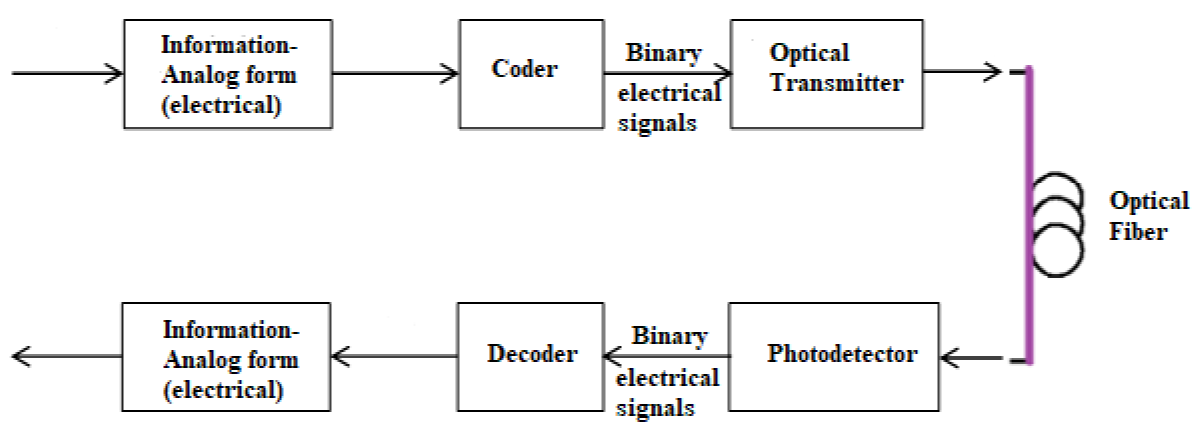
Attenuation co-efficient

- The attenuation of a fiber optic cable is expressed in decibels.

  i.e., $\alpha = -\frac{10}{L} log\left[\frac{P_{out}}{P_{in}}\right] \quad \frac{dB}{km}$

- The main reasons for the loss in light intensity over the length of the cable is due to light absorption, scattering and due to bending losses.

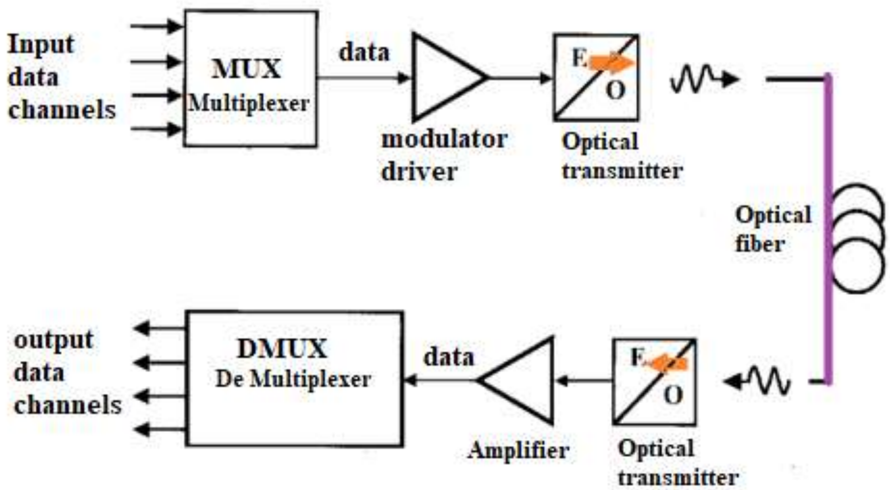
Applications: Point to point optical fibre communication System



- In point to point communication analog information are fed into the coder.
- Coder- converts analog information into binary data which comes out as electrical pulses.
- The electrical pulses from the coder are fed to optical transmitter which converts electrical pulses into pulses of optical power which are further fed into the optical fiber.
- The incident light which is funneled into the core within the acceptance angle propogates within the fiber by means of total internal reflection.

- The photodetector converts optical signals into electrical pulses in binary form and the decoder converts the binary data into analogue signal.

Applications: Fiber Optic Networking



- Information from the input data channels are fed into a Multiplexer.
- Multiplexer- Receives multiple signal and combine them.
- Modulator- Superimposes a low frequency (information) signal onto a high frequency (carrier) signal. Modulation is a process of influencing data information on to the carrier.
- Optical transmitter (Laser or LED)– converts electrical signals into optical pulses.
- Optical signals are further carried through a Multi-mode or single-mode optical fiber.
- From the optical fiber, the optical signals carrying information will be passed through an optical transmitter that converts optical pulses into electrical signals.
- Optical amplifier- enhances the signal strength.
- Demultiplexer –receives single signal (input) and generate multiple signals (outputs).

****

LASERS AND OPTICAL FIBERS

1. **Explain the requisites of laser action. Obtain an expression for energy density in terms of Einstein's coefficients.**
2. **Define the terms population inversion and metastable state. Explain the construction and working of a semiconductor laser.**
3. **Explain the applications of lasers in (a) Bar Code Scanner (b) Laser Printer (c) Laser Cooling.**
4. **What is numerical aperture? Derive an expression for numerical aperture of an optical fiber and mention the condition for ray propagation.**
5. **Explain different types of optical fibers with neat diagram.**
6. **Discuss the attenuation and various losses in an optical fibers.**
7. **Briefly explain the application of optical fibers in (a) Fiber optic networking (b) point to point communication system.**