Chapter 5

Laser and Fiber Optics

Laser

Ordinary Light

In an ordinary source of light the billions and billions of atoms or molecules produce light of all possible wave length in all possible direction. So due to superposition of different types of wave (different in phase, plane of polarization etc), the intensity decreases with distance. The light produced by ordinary source of light is not unidirectional, not monochromatic and in out of phase.

Laser Source

The light from a source come as the sum of total radiations produced by all individual atoms or molecules in the source. In laser, the radiations given out by all the emitters in the source are in mutual agreement not only in phase but also in the direction of emission and plane of polarization. Such monochromatic and highly coherent sources are the laser sources. The word LASER stands for Light Amplification by Stimulated Emission of Radiations.

Principles of Generation of Laser Light

Induced Absorption

If the atom is initially in the lower state E_1, it can be raised to higher energy state E_2 by imparting it with a photon of energy $E_2 - E_1 = hf$, f = frequency of incident photon. The photon is absorbed by the atom and reached to higher energy state E_2. This phenomenon of absorption of photon by atom is called induced absorption.

The rate of induced absorption is given by,

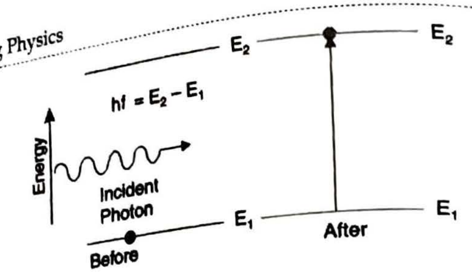
$$R_{abs} = B_{12}\,\rho\,N_1$$

Where

N_1 = Population of atoms at E_1

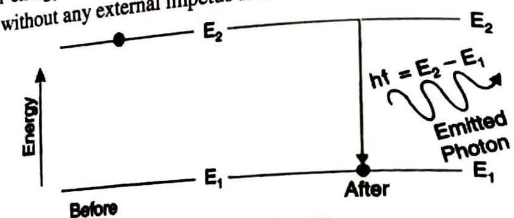
ρ = Energy density of incident beam

B_{12} = Einstein's coefficient for induced absorption.



Spontaneous Emission

An atom cannot stay in the excited state for a longer time. In a time of about 10^{-8} second the atom returns to the lower energy state by releasing a photon of energy $E_2 - E_1 = hf$. The emission of a photon by an atom without any external impetus is called spontaneous emission.



The rate of spontaneous emission is given by, $R_{sp} = A_{21} N_2$

Where N_2 = Number of atoms at excited state.

A_{21} = Einstein's coefficient for spontaneous emission.

Characteristic of Spontaneous Emission

1. The process of spontaneous emission is probabilistic.
2. The process of spontaneous emission is not controllable from out side.
3. The instant of emission, direction of propagation, the phase and the plane of polarization of each photon are all random.
4. The light resulting from this process is not monochromatic.
5. The intensity goes on decreasing rapidly with distance from source.
6. Light emitting from this process is incoherent.
7. The net intensity is proportional to the number of radiating atoms.

   i.e. $I_{total} = NI$, where N = Number of atoms and

   I = Intensity of light emitted by one atom.

Stimulated Emission

The atoms in the excited state can be returned to original state before spontaneous emission by the incident of an external photon with the emission of both incident and stimulated (induced) photon. This type of emission of radiation is called the stimulated emission or induced emission. The rate of stimulated emission of photon is given by

$$R_{st} = B_{21}\,\rho N_2$$

Where B_{21} = Einstein's coefficient for stimulated emission.

N_2 = Number of atoms at excited state.

ρ = Energy density of incident photon

Characteristic of Stimulated Emission

1. The process of stimulated emission is controllable from outside.
2. The photon induced propagates in the same direction as that of incident photon and has same frequency, phase and plane of polarization as that of incident photon.
3. In this process, two photon emerges with the incidence of one photon. These two photons traveling in the same direction interact with two more excited atom and generate two more photon and so on.
4. All the light waves generated in the medium are due to one initial wave and all of the waves are in phase. So the waves are coherent and interfere constructively to produce larger intensity.
5. The net intensity is proportional to the square of number of radiating atoms.

   $I_{total} = N^2 I$, I = intensity of light radiation emitted by one photon.
6. The resulting light is of high intensity and said to be amplified.

Pumping and Population Inversion

To achieve a high percentage of stimulated emission, a majority of atoms should be at the higher energy level than at the lower level. The establishment of situation in which the number of atoms in the higher energy level is greater than that of lower energy level is called population inversion. The process carried out to achieve population inversion by supplying energy to laser medium is called pumping. When the pumping is done by light energy it is called optical pumping.

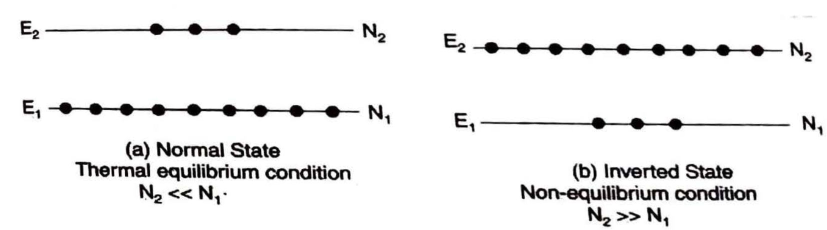


Figure: Population inversion

Active Medium

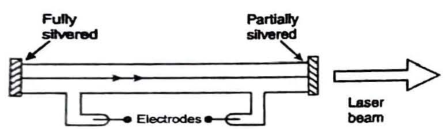
Atoms are generally characterized by a large number of energy levels. How ever all types of atom are not suitable for laser operation. Even in a medium consisting of different species of atoms, only a small fraction of atoms of a particular type have energy level suitable for achieving population inversion such atoms can produce more stimulated emission than spontaneous emission and causes amplification of light. These atoms are called active centers. The rest of the medium acts as host and supports active center. The medium hosting the active center is called active medium.

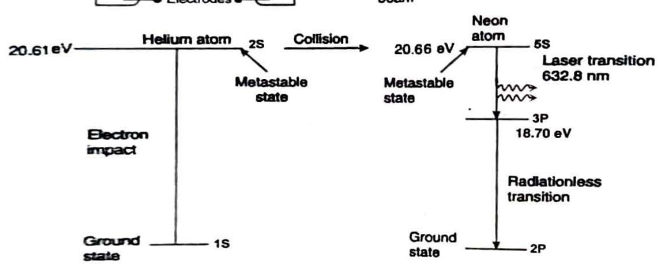
Metastable State

Normally the life time of an atom in excited state is very short (10^{-8} sec). How ever the atoms of special elements can stay for longer time in the higher energy state where the life time is greater than 10^{-4} sec. Such higher state is called meta stable state. There is no radiative transitions when the electron jumps to the metastable state from the excited state. The emission of radiation occurs when it goes from metastable state to the ground state.

Helium-Neon Laser

The schematic diagram for He-Ne laser is as shown in figure. It consist of a long discharge tube filled with a mixture of Helium and Neon gas in the ratio 10:1. Neon atoms are the active center and have energy level suitable for laser transition while helium atoms help in exciting Neon atom. Electrodes are provided in the discharge tube to produce discharge in the gas. When the power is switched on, a high voltage of about 10 KV is applied across the gas. It is sufficient to ionize the gas. The electrons and ions produced in the process of discharge are accelerated towards the anode and cathode respectively. The energetic electrons excite helium atoms through collisions.





One of the excited level of He is 2S at 20.61 ev above the ground level. It is metastable state and excited helium cannot return to ground level through spontaneous emission. How ever it can return to ground level by transferring its excess energy to a Neon atom through collision. Such an energy transfer can take place when two colliding atom have identical energy levels. One of the excited level 5S of Neon is at 20.66ev, which is nearly at the same level as 2S of Helium atom. The kinetic energy of Helium atoms provides the additional 0.05 eV required for excitation of the Neon atoms. Helium atoms drop to the ground state after exciting the Neon atoms. This is pumping mechanism in He - Ne laser.

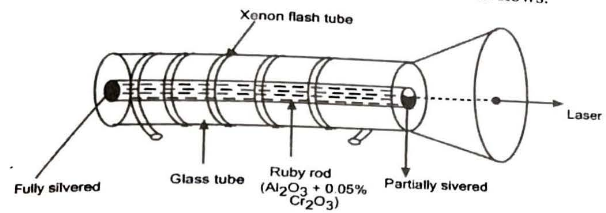
The upper state (5S) of Neon atoms is a meta stable state. Therefore Neon atoms accumulate in this upper state. A state of population inversion is established between 5S and 3P levels. Random photons emitted causes stimulated emission. The transition from 5S to 3P of Neon generate a laser beam of wave length 6328A°.

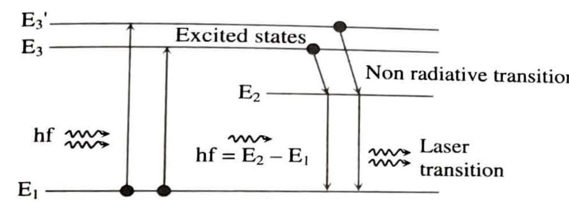
After the intensity has reached optimum value, a highly monochromatic and intense beam of laser light emerges through half silvered mirror.

Ruby Laser

It's main part is a ruby rod called the laser rod. Ruby is a crystal of aluminum oxide (Al_2O_3), with an addition of 0.03% to 0.05% of chromium oxide (Cr_2O_3) in which Cr^{3+} ions replace some of the atoms in crystal lattice. Flat end faces of the rod are made strictly parallel, grounded and silvered so that left face becomes fully reflecting and right face partially reflecting.

The ruby rod is surrounded by xenon flash tube through which current flows.





The energy level diagram is as shown in figure. When the flash lamp is activated the Cr^{3+} ions are excited to the energy bands E_3 and E_3' by the green and blue components of white light. The energy levels in these bands have a very small life time (10^{-9} sec). Hence the excited cr^{3+} ions rapidly undergo non radiative transitions and quickly drop to level E_2. The levels at E_2 are metastable state. Hence the state of population inversion is established between E_2 and E_1 level. Some photons emitted spontaneously initiate a chain of stimulated emission in excited Cr^{3+} ions at metastable state. The emitted photons are repeatedly reflected at the ends of mirror and light amplification takes place. A strong intense beam of red light of wave length 6943A° emerge out from half silvered mirror.

Once all the Cr^{3+} ions in the metastable state E_2 gets depopulated, the lasing action ceases and laser becomes in active. The process repeat if an extra flash is sent from flash tube.

Uses of Laser

1. Since the intensity of laser light is high, they have been used in drilling holes in hard metals and diamond. Laser light can also be used to cut, hard material such as glass. (cutting and drilling).
2. Laser light is highly coherent, so it is used in radios and television. These can be modulated to send large number of message simultaneously (modulation.)
3. They are used for 'blood less surgery' in hospitals. Many medical equipment are made in the principle of laser. (Medical)
4. They are used in scientific research. Such as in the study of chemical and crystalline structure of various molecule, in Raman spectroscopy, in astronomy. (to find distance between the stars) (Scientific Research).
5. They are even used in wars to target missiles. (war)
6. Many modern electronic devices such as CD players, laser printers, memory cards etc are made in the principle of laser (Modern equipments)
7. Holography and fiber optics are also the result of laser (holography, fiber)
8. High power lasers are used to carry thermo-nuclear reactions.
9. Lasers are used for separating isotopes of an element (to separate isotopes)

Characteristics of Laser Light

1. Laser light is highly mono chromatic.
2. Laser light is highly coherent (Two independent source can act as coherent sources)
3. Laser light is highly directional.
4. It is highly intense.

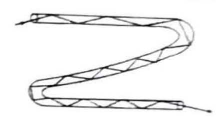
Exercise

1. What are the principles of generation of Laser light?
2. Explain the basic principles of production of laser light and its application.
3. Write down the characteristics of a laser beam.
4. Discuss briefly working principles of Laser. How laser beam can be obtained by using Ruby Laser.
5. What is meant by LASER? Explain the terms induced absorption, Spontaneous emission, Stimulated emission, population inversion, metastable state and pumping.
6. Explain why laser action cannot occur without population inversion.
7. How laser is Superior to the normal light? Explain, what are requirement for producing laser action? How are they achieved?
8. Differentiate between active center and active medium.
9. Explain the construction and working of He-Ne laser with a suitable energy level diagram.
10. Explain the lasing action of a gas laser with necessary energy level diagram.
11. Differentiate between LASER and ordinary light.
12. What is the role of He and Ne atoms in He-Ne laser.
13. What is the importance of laser?
14. Write down the principles of laser action and explain the construction and working principle of He-Ne laser.

Optical Fibre

Definition

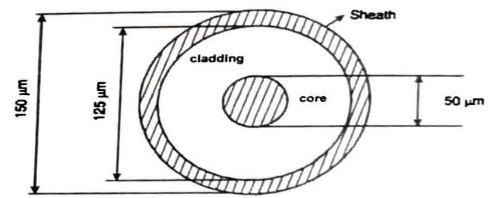
An optical fiber is a transparent conduit, as thin as human hair, made up of glass or clear plastic, designed to guide light waves along its length.



An optical fiber works on principle of total internal reflection. The movement of light is in a zig–zag path and some fraction of light may escape through side walls but major fraction comes out from the other end of the fiber.

An optical fiber consists of following three regions

1. ***Core:*** It is innermost light guiding region.
2. ***Cladding:*** Core is surrounded by a co-axial middle region known as the cladding. The refractive index of cladding is always lower than that of the core.
3. ***Sheath:*** The outermost region is called sheath. The sheath protects the core and cladding from moisture, abrasion contamination and give mechanical strength to fiber.



In optical fiber light travels through core and basic purpose of cladding is to confine the light to the core. The function of sheath is to protect core and cladding from external factor.

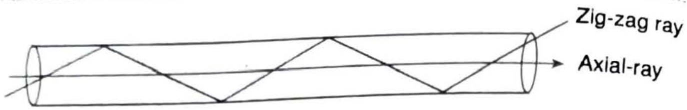
The core is made of silica doped with some impurities to increases its refractive index. The cladding is made by pure silica.

Modes of Propagation

In optical fiber, only certain directions (or path) are allowed for the propagation of light wave. These allowed paths are called modes of propagation.

The light rays traveling through a fiber may be classified as 1) zig–zag rays 2) axial rays.

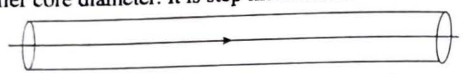
1) *Zig–zag rays:* The rays traveling inside the fiber get repeatedly reflected at the interface of core and cladding. Some of them may be in phase and get intensified while some other be in out of phase and fade out due to destructive interference. The light ray paths along which the waves are in phase are the allowed modes of propagation.
2) *Axial rays:* The light ray path along the axis of fiber is also a allowed modes of propagation. The rays traveling along the axis of fibre are axial rays.



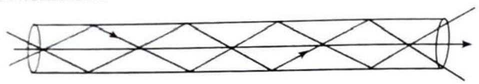
Types of Optical Fiber

A. On the basis of modes of propagation there are two types of optical fibers

1. **Single mode fiber:** In single mode fiber there is only one mode of propagation (only axial mode). It has smaller core diameter. It is step index fibre.



2. **Multimode fibre:** In multimode fibre there are two or more than two modes of propagation, so it has large core diameter.



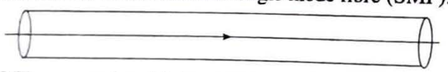
B. on the basis of index profile optical fibres are further classified into two groups, (a) Step index fibre and (b) graded index fibre.

The single mode fibre is usually of step index type but the multimode optical fibre is of both step index and graded index type.

An index profile is the plot of refractive index along y-axis and distance from core along x-axis. It gives the variation of refractive index with distance as we move outward from core.

1. Single mode step index fibre

i. In single mode fibre, there is only one mode of propagation i.e. along the axis only, called zero order mode. So it is named single mode fibre (SMF).



ii. In this type of fibre, core has higher constant refractive index (n_1 = 1.52) and cladding has lower constant refractive index (n_2 = 1.48). So refractive index changes abruptly at core cladding interface. Therefore it is called step index fibre.

iii. It has smaller core diameter of 4μm which corresponds to some of the wave lengths of light waves.

iv. Normalized frequency (V-number) is less than 2.405.

v. It has low value of fractional refractive index change (Δ).

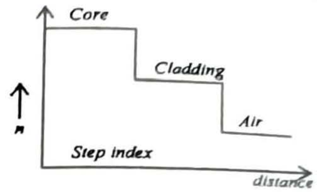
vi. Numerical aperture (N.A.) is small.

vii. The value of acceptance angle (θ_o) is small.

viii. Since there is only one mode of propagation, so there is no (or less) intermodal dispersion and hence the data rate is high.

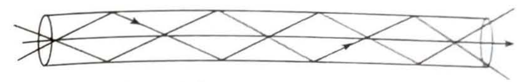
ix. It has high transmission loss (because of abrupt change in refraction index)

x. It is difficult to manufacture and handle and therefore is costly.



2. Multimode step index fibre

i. In this type of fibre there are multiple modes of propagation.



ii. In this type of fiber, core has higher constant refractive index (n_1 = 1.52) and cladding has lower constant refractive index (n_2 = 1.42). So refractive index changes abruptly at core - cladding interface. Therefore it is called step index fiber.

iii. It has larger core diameter of 100 μm, which is very large as compared to the wave length of light.

iv. Normalized frequency (v-number) is greater than 2.405.

v. It has higher value of fractional refractive index change (Δ)

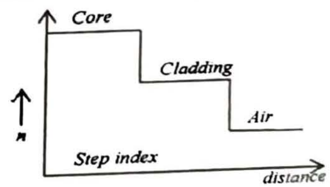
vi. Numerical aperture is high (0.3)

vii. The value of acceptance angle is larger.

viii. Since there is multiple mode of propagation, (and NA is more) so there is high intermodal dispersion and hence the data rate is low.

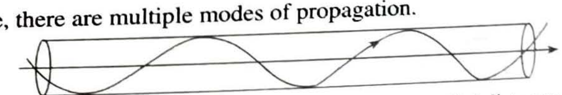
ix. It has high transmission loss (because of abrupt change in refractive index).

x. It is easy to manufacture and is less costly.



3. Multimode Graded Index Fibre

i. In this fibre, there are multiple modes of propagation.



ii. The refractive index of core decreases with increasing radial distance from the axis.

iii. It has larger core diameter of 100 μm, which is very large as compared to the wave length of light.

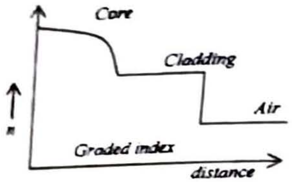
iv. Numerical aperture decreases with increasing radial distance from the axis.

v. The acceptance angle also deceases with radial distance from the axis.

vi. The number of modes in graded index fibre is about half of that in multimode index fibre. So it has lower dispersion than in multimode step index fibre.

vii. It has low transmission loss because the continuous decrease in the refractive causes bending of light towards the center of the core.

viii. It's manufacture is more complex than step index Multimode Fibre (MMF).



Fractional Refractive Index Change

The ratio of difference in refractive indices of the core and the cladding to the refractive index of core is called fractional refractive index change. Fractional refractive index change, $\Delta = \frac{n_1 - n_2}{n_1}$

Since, $n_1 > n_2$ so Δ is always +ve.

Acceptance Angle

Consider an optical fibre through which light is launched at one end. Let n_1, n_2 and n_0 be the refractive indices of core, cladding, and the medium from which light is launched into the fibre.

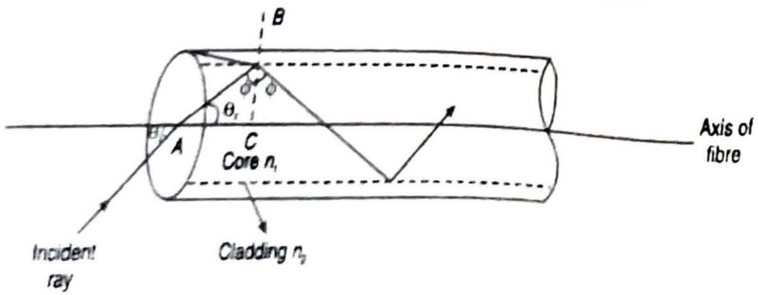
Assume a light ray enters the fibre at an angle θ_i to the axis of the fibre. The ray refracts at an angle θ_r and strikes the core-cladding interface at an angle ϕ. The angle ϕ is greater than critical angle ϕ_c, and total internal reflection occurs. So the light will stay with in the fibre.

Applying Snell's law at the incident edge, we get,

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0} \quad \text{......... (1)}$$

If θ_i is increased beyond a limit, ϕ will drop below the critical value ϕ_c and the ray escapes from the sidewall of the fibre. The largest value of θ_i occurs when $\phi = \phi_c$.

Acceptance angle is the maximum value of angle of incidence θ_i for which a light ray can propagate through fibre. It is the angle made by incident ray with fibre axis.



From figure in Δ ABC, $\theta_r = 180 - 90 - \phi = 90 - \phi$

$$\sin\theta_r = \sin(90-\phi) = \cos\phi \quad \text{......(2)}$$

From equation (1) and equation (2)

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0} \Rightarrow \frac{\sin\theta_i}{\cos\phi} = \frac{n_1}{n_0}$$

$$\sin\theta_i = \frac{n_1}{n_0}\cos\phi$$

For $\phi = \phi_c$, $\theta_i = \theta_{i\,max}$ [Here, $\theta_{i\,max}$ is the acceptance angle]

Therefore, $\sin\theta_{i\,max} = \frac{n_1}{n_0}\cos\phi_c$ .... (3)

But at critical angle, total internal reflection just occurs

Applying Snell's law at core to cladding interface.

$$\frac{\sin\phi_c}{\sin 90} = \frac{n_2}{n_1}$$

$$\sin\phi_c = \frac{n_2}{n_1} \text{ and } \cos\phi_c = \sqrt{1-\sin^2\phi_c} = \sqrt{1-\frac{n_2^2}{n_1^2}} = \sqrt{\frac{n_1^2-n_2^2}{n_1^2}}$$

Substituting $\cos\phi_c$ for equation (3),

$$\sin\theta_{i\,max} = \frac{n_1}{n_0}\sqrt{\frac{n_1^2-n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2-n_2^2}}{n_0} \quad \text{...... (4)}$$

$$\theta_{i\,max} = \sin^{-1}\frac{\sqrt{n_1^2-n_2^2}}{n_0} \quad \text{....... (5)}$$

which is the expression for acceptance angle.

If the incident ray is launched from air medium,

$$\theta_0 = \theta_{i\,max} = \sin^{-1}\sqrt{n_1^2-n_2^2}.$$

The light ray incident at an angle less than $\theta_{i\,max}$ will propagate along the fibre and the light ray incident at an angle larger than $\theta_{i\,max}$ will escape out.

Numerical Aperture (N.A.)

Numerical aperture is the measure of the amount of light that can be accepted by a fibre. Mathematically it is defined as the sine of the acceptance angle i.e.

$$\text{N.A.} = \sin\theta_0$$

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

$$= \{(n_1-n_2)(n_1+n_2)\}^{1/2} = \left(\frac{n_1-n_2}{n_1}\cdot\frac{n_1+n_2}{2}\cdot 2n_1\right)^{1/2}$$

Since fractional refractive index change $\Delta = \frac{n_1-n_2}{n_1}$

$$\text{N.A.} = \left(\Delta.\frac{n_1+n_2}{2}.2n_1\right)^{1/2}$$

Approximating $\frac{n_1+n_2}{2} \approx n_1$ as $n_1>n_2$

$$N.A. = (\Delta.n_1.2n_1)^{1/2} = \sqrt{2n_1^2\Delta}$$

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

It is seen that N.A. only dependent on the refractive indices of core and cladding. The value N.A. ranges from 0.13 to 0.50. Larger value of N.A. means the fibre can accept more light fro the source.

Normalized Frequency: (V-number)

The V-number determines the number of modes that can propagate through a fibre. It is an important parameter that characterize an optical fibre. Mathematically it is give by.

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

Where a = radius of the core, λ = free space wave length, n_1 and n_2 are refractive indices for c and cladding.

- For V < 2.405, fibre can support only one mode and is called single mode fibre (SMF)
- For V> 2.405, fibre can support number of modes simultaneously and is called multim fibre (MMF).

Application

Optical fibre has a wide variety of applications. Some of them are discussed below.

1. **Medical application**
   - The optical fibre technique is employed for endoscopy, which helps in the study inaccessible part of human body.
   - This can be employed to join a detached retina or rectify other eye defects using lase
   - In cardiology, optical energy transmitted through a optical fibre is used to evapora built-up plaque that is blocking an artery.
   - The optical fibre technology is used in the treatment of cancer.
2. **In Communications**

   An optical fibre communication system is similar to traditional communication system, w the exception that this system is highly efficient.

   A traditional communication system consist of a transmitter, a receiver and an informat path way. Generally the information to be communicated is non electrical message which first converted into electrical message by transducer. These are modulated with a wave very high frequency called carrier wave [In fibre communication, laser light plays the role carrier wave and can carry large number of messages].

   The message travels along transmission channel and is received at the receiver. The receive demodulates the modulated wave and message is fed to transducer to transform it in original form.

Higher the band width of carrier signal larger will be the number of message that it can transmit. The band width of light wave used in optical fibre communication is appreciably high than that of micro waves used in traditional communication system. So the optical fibre communication system is highly efficient than traditional one.

Advantages of optical fiber communication

1. Because the light waves plays the role of carrier waves, the rate of data transmission is very high.
2. Band width of light wave is greater than that of electrical wave so greater amount of information carried over in optical fiber.
3. Optical fiber are light in weight and flexible.
4. There is less interference of waves so the cross talk is negligible in fiber communication.
5. Optical fiber have longer life time.
6. There is no corrosion and tolerability over high temperature.
7. Easy to maintain and more reliable.
8. Optical fiber transmit light wave not electrical so they are safer than copper cables.

3. **Optical fibre sensors**

   The property of variation of refractive index under the action of external force in optical fibre is of crucial importance. In optical fibre sensor, LED act as a source of light, photo detector measures the output intensity.

   a) ***Thermometer (Heat sensor)***: If the optical fibre is subjected to heating, it causes a change in refractive index. As temperature increses, the refractive index of cladding increases. Thus the difference in refractive indices of core and cladding reduces and light gets leak away from the cladding. Due to this effect the output intensity decreases. The reverse effect occurs when the temperature is decreased. By observing the variation in emergent intensity, the temperature at different place can be notified.

   b) ***Smoke and pollution detector***: If foreign particle (due to smoke and pollution) are present in a region between two optical fibre the variation in emergent intensity determines the extent of foreign particle between the two fibre.

   c) A loop of optical fibre can used to determine the level of liquid inside an unreachable place. A part of cladding at which optical fibre is going to touch liquid level is scraped. A bare (naked) core losses more light when it is immerged in liquid than when it is in air. Therefore sudden change of out coming intensity indicates liquid level.

   d) The other sensors such as pressure sensor, current sensor, voltage sensor, magnetic field sensor are made on the basis of optical properties of optical fibre.

4. **Military Application:**

   Optical fibres have a lot of application in various warfare's and military operations. For control mechanism or communication, a lot of copper cables are to be transported by an aircraft, a ship or tank. How ever with fibre optics, the weight is enormously reduced and communication network is greatly improved. With fibre communication secrecy is also maintained.

   Fibre guided missiles are used in recent wars. Sensors mounted on the missile transmit video information through the optical fibre to a ground control van and receives commands