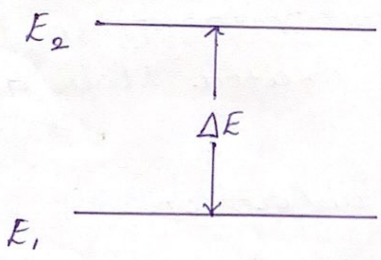
# U-5 LASERS, OPTICAL FIBERS, HOLOGRAPHY

## LASERS

LASER is the acronym of Light amplification by the stimulated emission of radiation. A laser beam is a highly parallel coherent beam of light of very high intensity. Laser action is achieved by creating population inversion which can be achieved by different means, such as optical pumping, electrical discharge, Solar energy etc.

## principle and production of Laser

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




$$\Delta E = E_2 - E_1$$

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

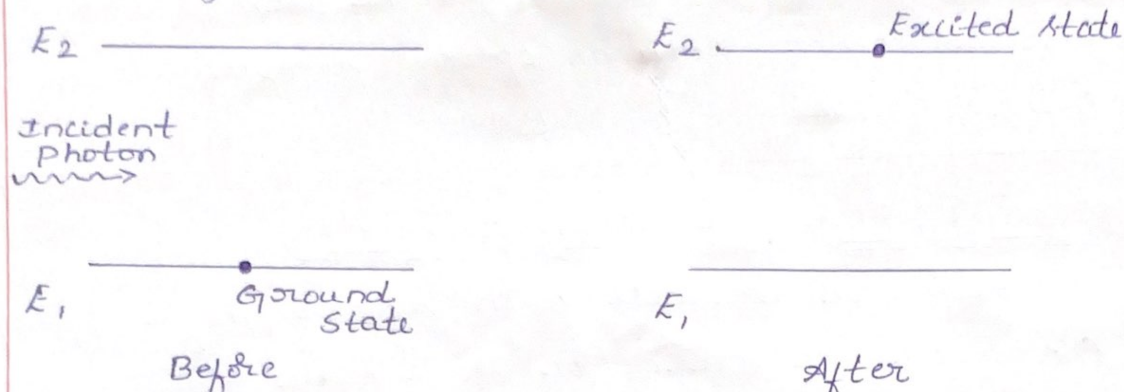
a) Induced absorption

b) Spontaneous emission

c) Stimulated emission

## a] Induced absorption

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




Induced absorption

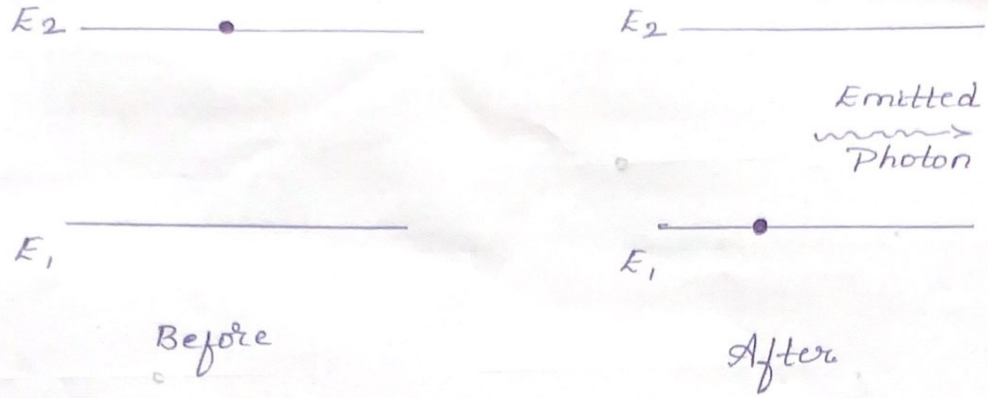
Let $E_1$ and $E_2$ be two energy levels in the energy level diagram. $E_1$ corresponds to lower energy and $E_2$ corresponds to upper energy. Let us assume that the atom is in the lower energy level. Let a photon having an engy $\Delta E$ be incident on the atom, the atom absorbs the energy from the photon. Then the atom makes a transition to the excited state and is indi- -cated as atom*.

This is called induced absorption.

atom + photon $\rightarrow$ atom*

## b] Spontaneous Emission

Spontaneous emission is the emission of a photo when a system transits from a higher energy state to a lower energy state without the aid of any external agency.




## Spontaneous Emission

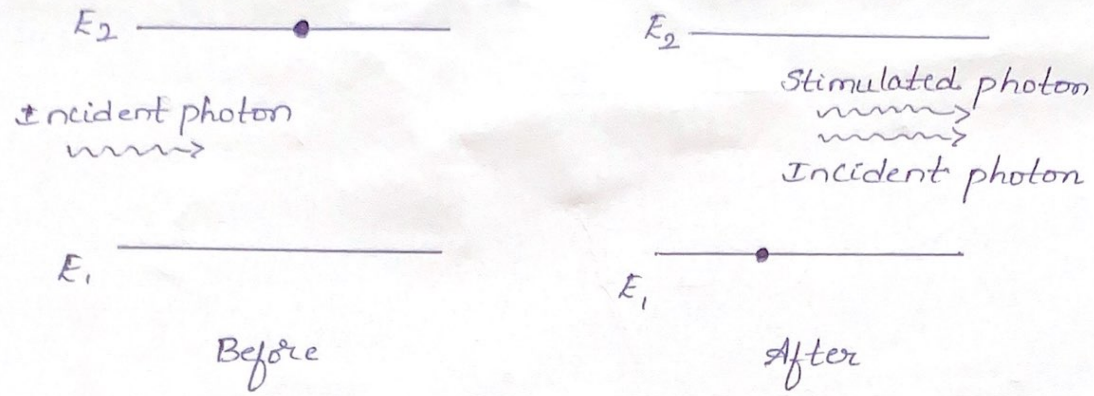
Consider an atom in excited state. To attain the least available energy state, the atom voluntarily emits a photon of energy equal to $\Delta E$. The atom is emitting a photon without being aided by any external means, it is called spontaneous emission.

$$atom^* \longrightarrow atom + photon$$

The photon may be emitted in any direction. Two such photons which are spontaneously emitted by two atoms under identical conditions, may not have any phase similarities & same direction. Hence they are incoherent.

## c] 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 transists from a higher energy state to a lower energy state. The photon thus emitted is called stimulated photon & will have same phase, energy & direction of movement as that of the passing photon called the stimulating photon.




consider an atom in the excited state. Let a photon having an energy $\Delta E$ interact with the atom. Then the atom emits a photon and transits to the lower energy state. The two photons travel in exactly the same direction & with exactly the same Energy. Thus they are coherent.

$$\text{atom}^* + \text{photon} \rightarrow \text{atom} + (\text{photon} + \text{photon})$$

This Kind of emission is responsible for laser action.

## Requisites of a Laser System

a) pumping action

b) Active medium

c) Laser cavity

## condition for laser action

a) population Inversion

b) Metastable state

## Pumping action

The process of supplying energy to the lasing system is Known as pumping action.

Two types of pumping action are:

a) optical pumping [Light Energy]

b) Electrical pumping [Electrical Energy]

## Active medium

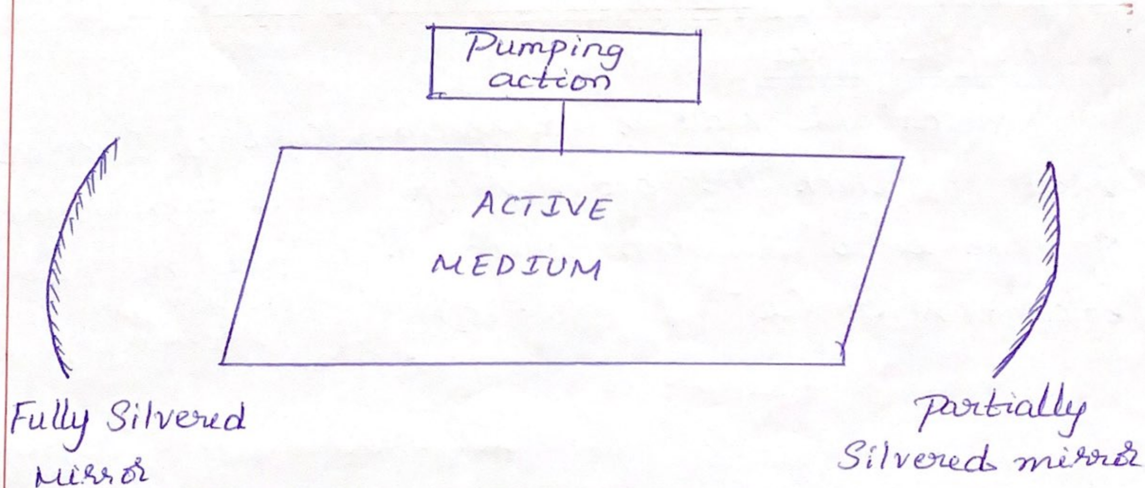
The medium in which lasing action takes place is Known as active medium.

or

The medium in which population inversion takes place is Known as active medium.

## Laser Cavity

The arrangement of active medium between a fully silvered mirror & a partially silvered mirror is Known as laser cavity.




LASER CAVITY

## Population Inversion

Consider three energy levels $E_1$, $E_2$ and $E_3$ of a quantum system which are such that $E_3 > E_2 > E_1$. Let $E_2$ be a metastable state. Let the atoms be excited from $E_1$ to $E_3$ state by the supply of appropriate energy from an external source. From the $E_3$ state, the atoms undergo spontaneous downward transitions to $E_1$ and $E_2$ states rapidly. Inspite of new arrival of atoms, the population of $E_1$ level cannot increase because of ongoing excitation of atoms to higher energy level. Since $E_2$ is a metastable state, atoms which get into that state stay over a long duration, due to which population of $E_2$ state increases steadily. At this condition $E_2 > E_1$ which is known as population inversion.

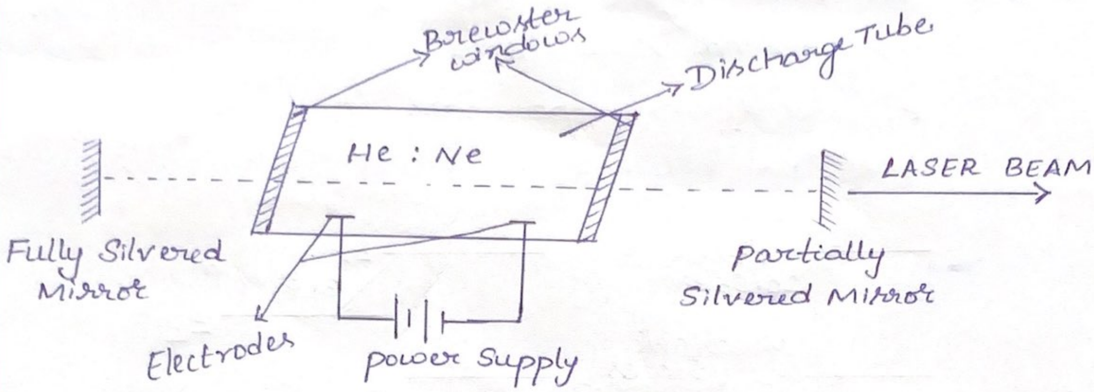
Thus population inversion may be defined as the state of a system at which the population of a particular higher energy state is more than that of a specified lower energy state.

## Metastable State

Metastable state is a special kind of excited state in which the atom stays for a long duration of time of $10^{-8}$ s when compared to the normal excited state ($10^{-3}$ to $10^{-2}$ s)

## Construction and working of He-Ne laser

### Construction




A helium-neon laser consists of a discharge tube, inside which the mixture of helium and neon gas is taken in the ratio 10 : 1. On the either sides of the discharge tube, is finely polished known as Brewster windows. It is arranged to obtain plane polarized laser beam. The discharge tube is placed between two mirrors, among which one is fully silvered mirror and another one is partially silvered mirror. Further the electrodes are connected to the power supply.

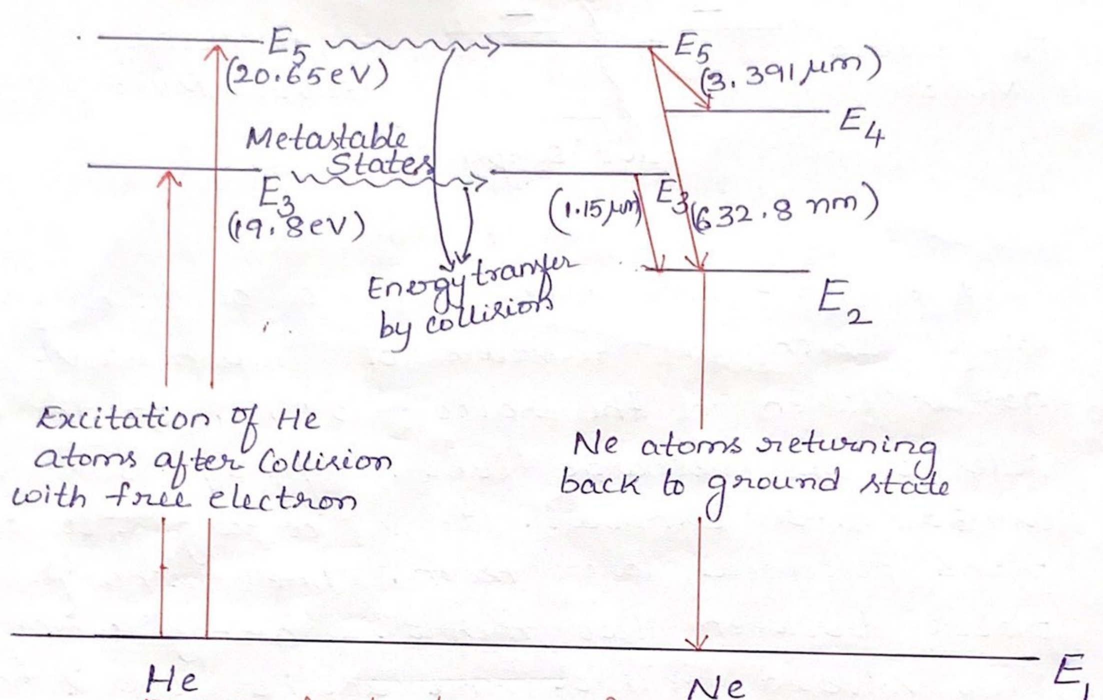
### Working

When a suitable voltage is applied across the two electrodes, a glow discharge of the gases is initiated in the tube. During discharge many electrons are rendered free from the gas atoms. These free electrons accelerate towards the positive electrode. During this movement, the electrons collide with the atoms of He, Since He is the majority gas present. Due to this collision, He atom jumps to the excited state. This collision is known as collision of I kind.

The process can be represented as,

$$\boxed{He + e_1 \longrightarrow He^* + e_2}$$

where He and $He^*$ → represents the Helium atom in ground state and excited state respectively.
$e_1$ and $e_2$ → represents the energy of free electron before and after collision respectively.




Energy level diagram for He-Ne laser

Since the He-atoms jumps to a special kind of excited state known as metastable state, the He-atoms stays there for a longer duration. Further it has been observed that the energy values of the metastable states of helium is almost equal to the energy values of the excited states of neon.

ie $E_3$ of helium ≃ $E_3$ of neon
$E_4$ of helium ≃ $E_4$ of neon

Due to this the transfer of energy takes place between the He and Ne atoms by colliding to each other. The He-atom in the metastable state collides with the Ne-atom in the ground state. Then the Ne-atom jumps to the excited state & the He-atom comes back to the ground state. This kind of collision is known as collision of II - kind.

The process can be represented as,

$$\boxed{He^* + Ne \longrightarrow Ne^* + He}$$

where, $He^*$ and He → represents the helium atom in excited state & ground state respectively.

Ne and $Ne^*$ → represents the neon atom in ground state and excited state respectively.

Since Ne-atom jumped to a normal excited state, it stays for a short duration and comes back to ground state to attain stability. while coming back to ground state, 3 types of transitions occured. They are,

$E_5$ to $E_4$ ⟶ 3.391 μm

$E_5$ to $E_2$ ⟶ 632.8 nm

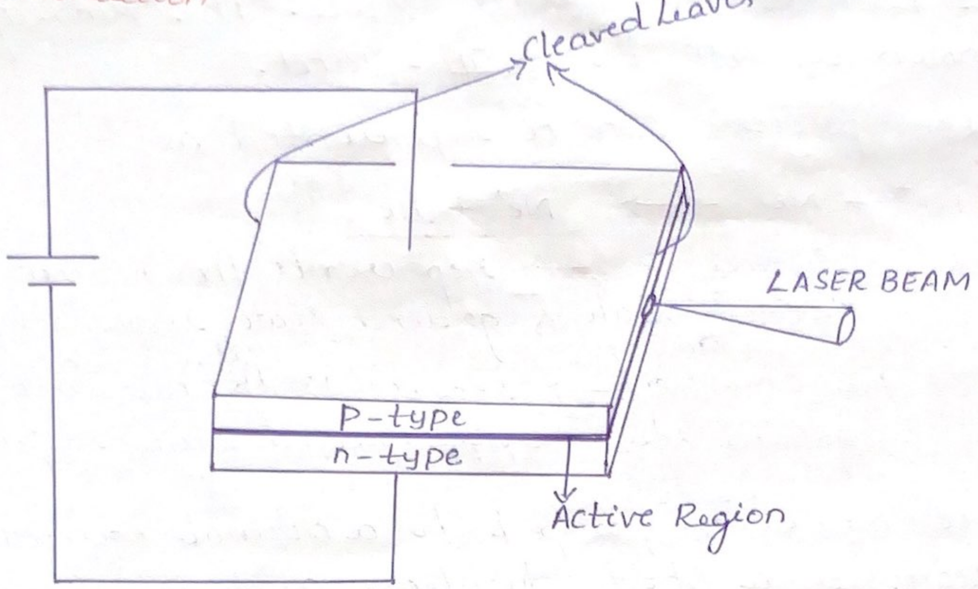
$E_3$ to $E_2$ ⟶ 1.152 μm

The transition occured from $E_5$ to $E_2$ comes in the visible region and gives the laser light of wavelength 632.8nm.

The He-atoms which returned back to the ground state, once again collides with free electrons & jumps to the Excited state and further collides with the Ne-atoms. The process goes continiously and hence it is known as a continious gas laser.

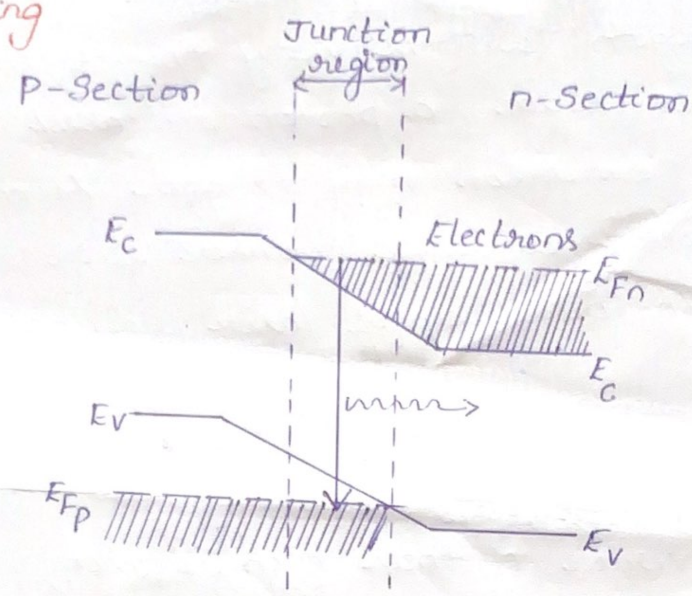
## Construction and working of Semiconductor Laser

### construction




Semiconductor laser is one in which the active medium is formulated by semiconducting materials. Gallium Arsenide laser is a semiconductor laser. The Gallium Arsenide laser diode is a single crystal of GaAS, and consists of heavily doped n and p sections. The n-section is formed by doping with tellurium whereas the p-section is obtained by doping with Zinc. The p-n junction layer has a width varying from 1μm to 100μm. A pair of parallel planes of the crystal are cleaved or polished at right angles to the p-n layer. These planes play the role of reflecting mirrors. The end surfaces of the p and n sections parallel to the plane of the junction are provided with electrodes in order to facilitate application of a forward bias voltage with the help of a voltage source.

Working




Energy band diagram for a Laser diode under forward bias

A suitable forward bias voltage is applied to the diode so as to overcome the potential barrier. As a result the electrons from n-type and holes from p-type region are injected into the junction. A current begins to flow following which there will be region near the interface in which population inversion Conditions are attained.

The energy band diagram for the diode under forward bias is as shown in the diagram. Initially the Concentration in the energy levels at the bottom of the Conduction band will be lesser than that in the energy levels at the top of the Valence band and the recombination results in spontaneous emission. But as the current is increased, a threshold for lasing will be attained beyond which the population gets inverted and an active region is formulated in the junction. The active region will be very thin of the order 1 $\mu m$. At this stage, a photon released by a spontaneous emission may trigger stimulated emissions over a large number of recombinations leading to the build up of laser radiation of high power.

## Applications of Lasers

By the virtue of their high intensity, high degree of monochromaticity and coherence, lasers find remarkable applications in a diversity of fields. Such as,

a) Medicine

b) Material processing

c) Communications

d) 3-D photography

e) Defence

f) Holography

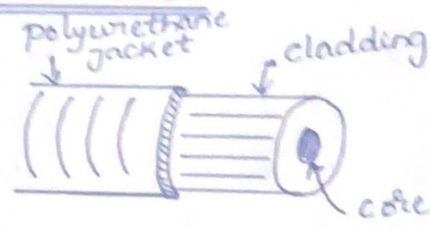
g) Laser welding, cutting, drilling

h) Measurement of pollutants in atmosphere.

# OPTICAL FIBERS

optical fibers are essential light guides used in optical communication as waveguides. They are transparent dielectrics and able to guide visible and infrared light over long distances.

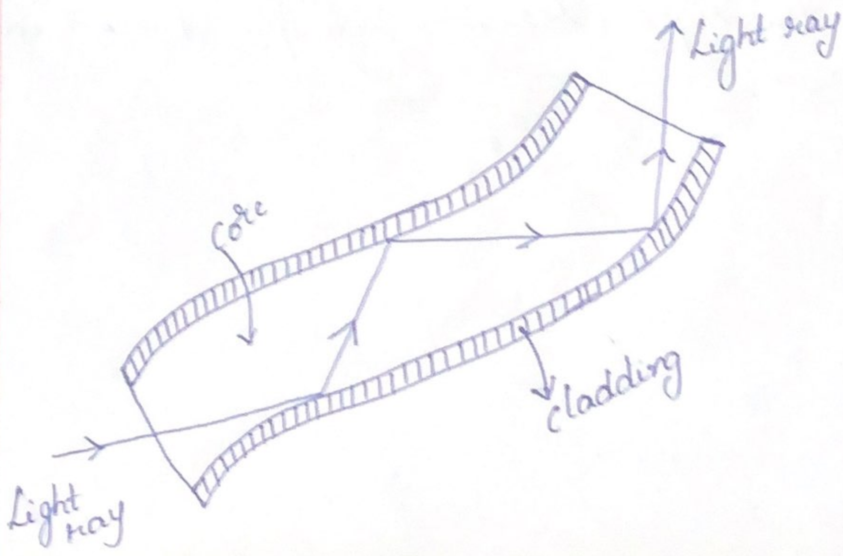
## Construction




An optical fiber is cylindrical in shape and it has just two parts. The inner part is made of glass or plastic known as core. The outer part which is a concentric cylinder surrounding the core, is called cladding. The cladding is also made of similar material but of lesser refractive index. The cladding is enclosed in a polyurethane jacket.

## Mechanism of light transmission in optical fiber

The physical principle based on which the optical fiber works is total internal reflection which is a well known optical phenomenon in physics.

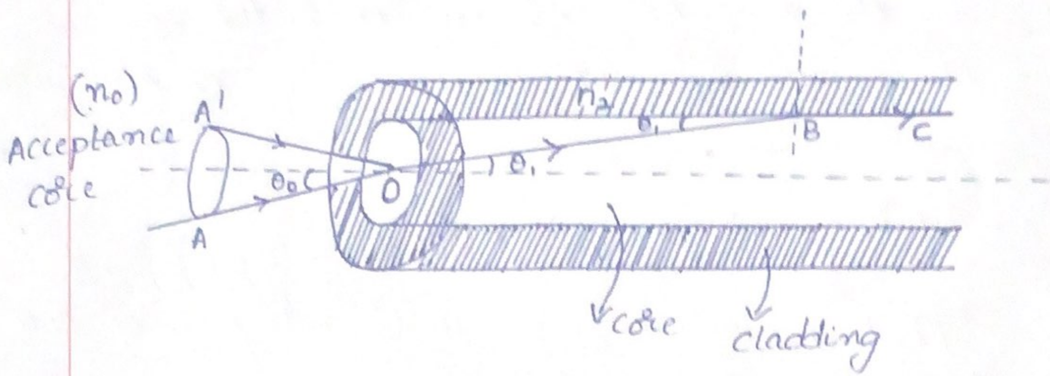


An optical fiber is Considered as a wave guide which is a tubular structure through which energy of some sort could be guided in the form of waves. Since light waves can be guided through a fiber, it is called light guide.

In any optical fiber, the refractive index of cladding is always lesser than that for its core. The light signal which enters into the core can strike the interface of the core and cladding only at large angles of incidence because of the ray geometry as shown in the diagram. The signal undergoes reflection after reflection at the points wherever it is incident on the interface. Since each reflection is a total internal reflection, the signal sustains strength and also confines itself completely within the core during propogation. Thus, the optical fiber functions as a waveguide.

The propagation of light Continues as long as the fiber is not bent too sharply, Since for sharp bends, the light fails to undergo total internal reflection & the signal strength drops drarastically.

## Derivation of expression for Numerical aperture and Angle of acceptance




Let us consider an optical fiber, through which a ray suffers critical incidence at the core cladding interface.

The ray travels along AO entering into the core at the angle $\theta_0$ to the fiber axis. Then it is refracted along OB at an angle $\theta_1$ in the core and further proceeds to fall at critical angle of incidence (equal to $90 - \theta_1$) at B on the interface between core and cladding, and further it grazes along BC.

Any ray that enters at anagle of incidence greater than $\theta_0$ at O, will have to be incident at the interface at an angle less than the critical angle., because of which it gets refracted into the cladding region.

The angle $\theta_0$ is called the waveguide acceptance angle and $\sin\theta_0$ is called the numerical aperture.

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

Consider the ray AO entering into the core, applying the snell's law at the interface of surrounding medium and core,

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

Then applying Snell's law at the interface of core and cladding,

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

$$n_1 \cos\theta_1 = n_2$$

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

eqn (1) can be written as,

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

$$\sin\theta_0 = \frac{n_1}{n_0} \sqrt{(1-\cos^2\theta_1)} \longrightarrow (3)$$

Sub eqn (2) in (1). we get

$$\sin\theta_0 = \frac{n_1}{n_0} \sqrt{1-\left(\frac{n_2}{n_1}\right)^2}$$

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

$$= \frac{\cancel{n_1}}{n_0}\left(\frac{1}{\cancel{n_1}}\right)\sqrt{n_1^2 - n_2^2}$$

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

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

If $n_0 = 1$ for air

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

$$\therefore \boxed{\theta_0 = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)}$$

## Condition for propogation

If $\theta_i$ is the angle of incidence of an incident ray, then the ray will be able to propogate,

if $\theta_i < \theta_0$

$$\sin\theta_i < \sin\theta_0$$

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

$$\boxed{\sin\theta_i < NA}$$

This is the condition for propogation.

## Types of optical fibers

In any optical fiber, the whole material of the cladding has a uniform refractive index value. But the refractive index of the core material may either remain constant or subjected to variation in a particular way. The curve which represents the variation of refractive index with respect to the radial distance from the axis of the fiber is called the refractive index profile.

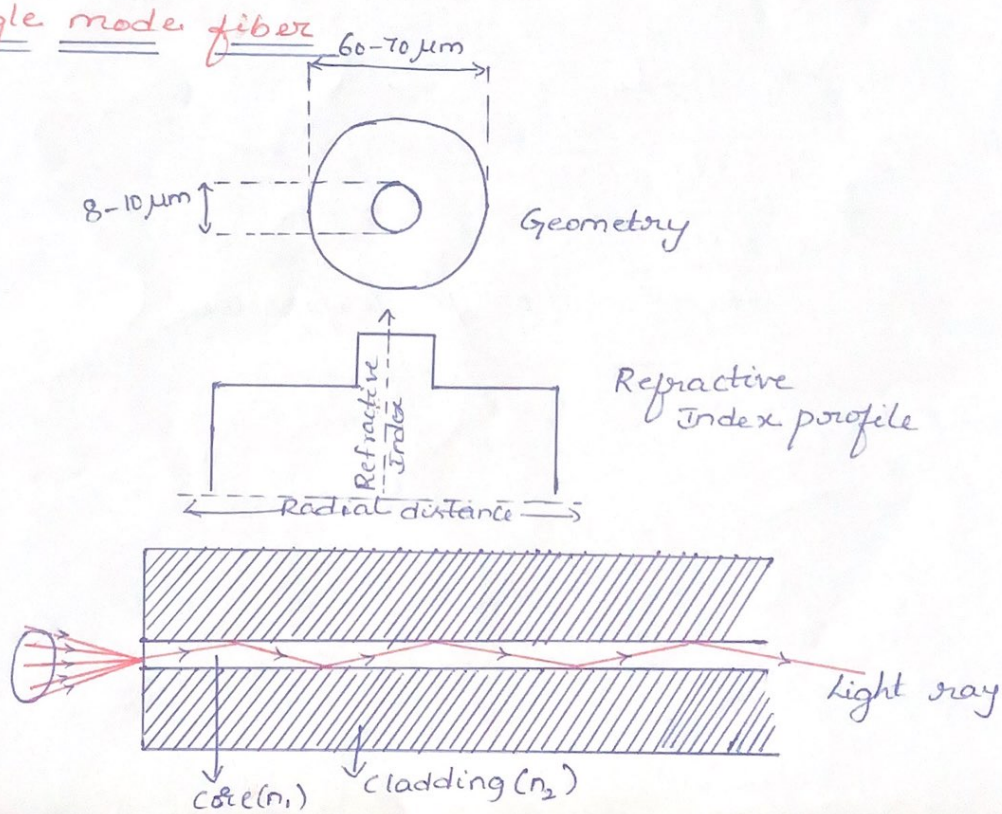
The optical fibers are classified under 3 categories,

a) Single mode fiber

b) Step index multimode fiber

c) Graded index multimode fiber

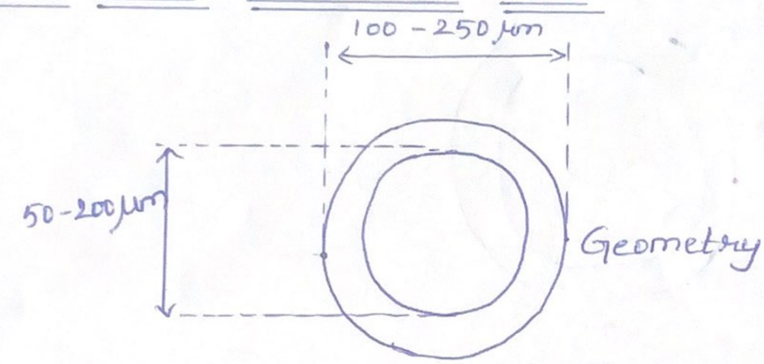
## Single mode fiber

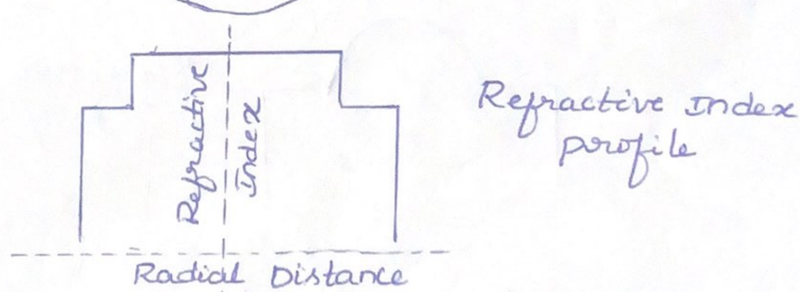


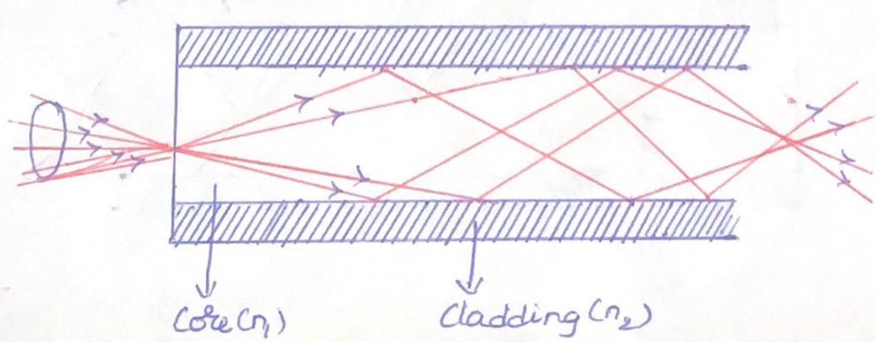
A single mode fiber has a core material of uniform refractive index value. Similarly cladding also have a material of uniform refractive index but of lesser value. This results in a sudden increase in the value of refractive index from cladding to core. Thus its refractive index profile takes the shape of a step. The diameter value of the core is about 8 - 10 $\mu m$ and external diameter of cladding is 60 - 70 $\mu m$.

Because of its narrow core, it can guide just a single mode as shown in the figure. Hence it is called single mode fiber. Single mode fiber is used in submarine cable system.

## Step Index multimode fiber



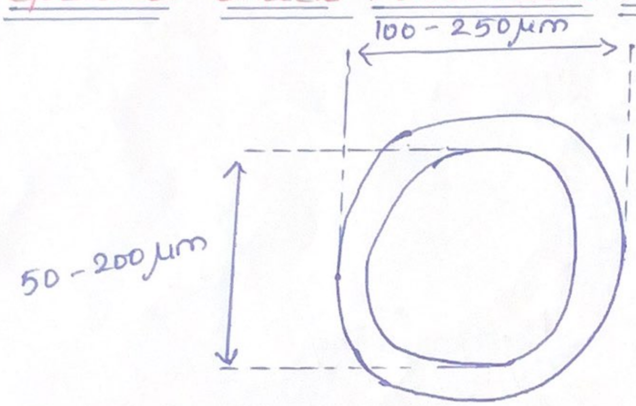



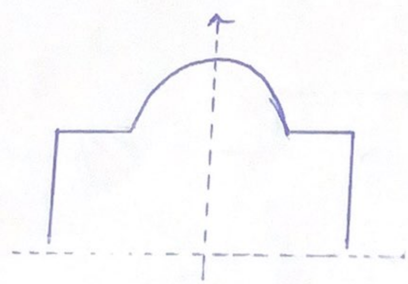
The geometry of a step-index multimode fiber is as shown in figure. Its construction is similar to that of a single mode fiber but its core has a much larger diameter by the virtue of which it will be able to support propogation of large number of modes as shown in figure. Its refractive index profile is also similar to that of a single mode fiber but with a larger plane region for the core.

Its typical application is in data links which has lower bandwidth requirements.

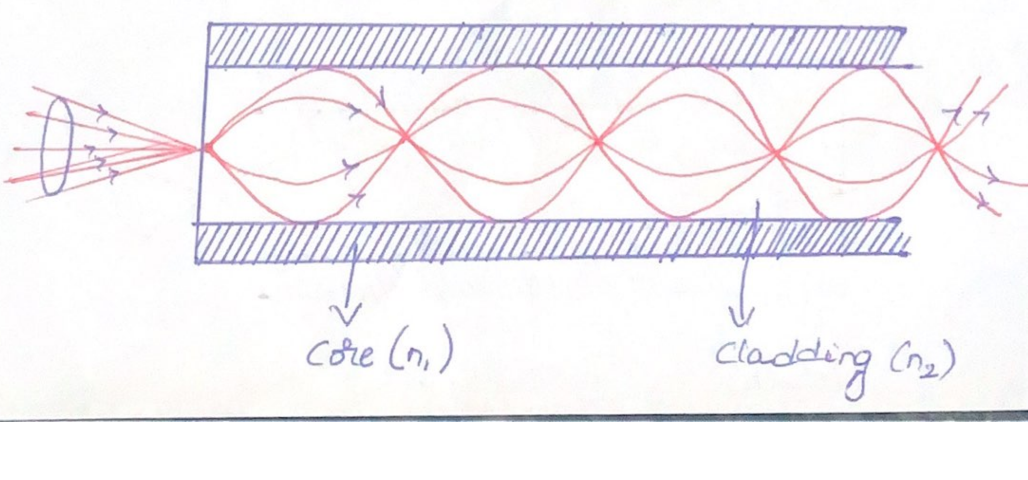
## Graded Index Multimode Fiber




Geometry



Refractive Index profile



Graded index multimode fiber is also denoted as GRIN. The geometry of the GRIN multimode fiber is same as that of step-index multimode fiber. Its core material has a special feature that its refractive index value decreases in the radially outward direction from the axis and becomes equal to that of the cladding at the interface. But the refractive index of cladding remains uniform. Its refractive index profile is as shown in the diagram.

Either a laser or LED can be the source for the GRIN multimode fiber. It is the most expen- -sive of all. Its typical application is in the telephone trunk between central offices.

## Critical Angle

Critical angle is the angle of incidence at which the incident light ray just grazes the axis between the two medium.

Critical angle is given by,

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

## Fractional Index Change ($\Delta$)

The fractional index Change is the ratio of the refractive index difference b/n the core & Cladding to the refractive index of core of an optical fiber.

$$\boxed{\Delta = \left(\frac{n_1 - n_2}{n_1}\right)}$$

Above eqn can be written as,

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

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

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

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

$$n_1 \approx n_2 \quad , \quad n_1 + n_2 = 2n_1$$

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

$$= \sqrt{2n_1^2 \Delta}$$

$$\boxed{NA = n_1 \sqrt{2\Delta}}$$

Above eqn shows the relation b/n numerical aperture, refractive index of core & fractional index change.

## V - Number

The number of modes supported for propogation in the fiber is determine by a parameter called V-number

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

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

$d \rightarrow$ diameter of core

$n_1 \rightarrow$ refractive index of core

$n_2 \rightarrow$ refractive index of cladding

$\lambda \rightarrow$ wavelength of light propogating in the fiber.

$$\boxed{V = \frac{\pi d}{\lambda} NA}$$

If the fiber is surrounded by a medium of refractive index no, then the expression is,

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

For $V >> 1$, the number of modes supported by the fiber (approximately) is given by,

$$\boxed{\text{number of modes} \simeq \frac{V^2}{2}}$$

## Loss mechanism in optical Fibers

Attenuation is the loss of power suffered by the optical signal as it propogates through the fiber. It is also called the fiber loss.

The three mechanisims through which attenuation takes place are.

a) Absorption Loss
b) Scattering Loss
c) Radiation Loss

## Absorption Loss

In case of absorption loss, the loss of signal power occurs due to absorption of photons associated with the signal. photons are absorbed by,

a) **Extrinsic absorption** :- Extrinsic absorption is the absorption ~~is the absorption~~ of photons by the impurities present in the fiber itself. The type of impurities that are generally present in fiber are the transition metal ions such as iron, chromium, Cobalt and copper.

b) **Intrinsic absorption** :- Intrinsic absorption is the absorption of photons by the fiber material itself.

## Scattering Losses

While the signal travels in the fiber, the photons may be scattered because of sharp changes in refractive index values inside the glass over distances that are small Compared to wavelength of light.

The sharp variation in refractive index value inside the fiber glass is induced by the localized structural inhomogeneity. This type of scattering is same as Rayleigh scattering.

## Others

There are defects in the fiber in the form of trapped gas bubbles, unreacted materials and some crystallized region in the glass. But the latest manufacturing methods make these losses negligible compared to the Rayleigh scattering.

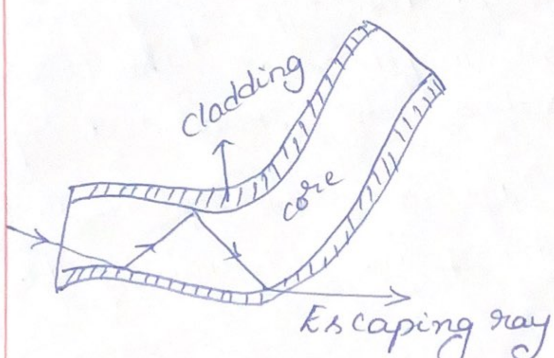
## Radiation losses

Radiative losses occur due to

a) macroscipic bends

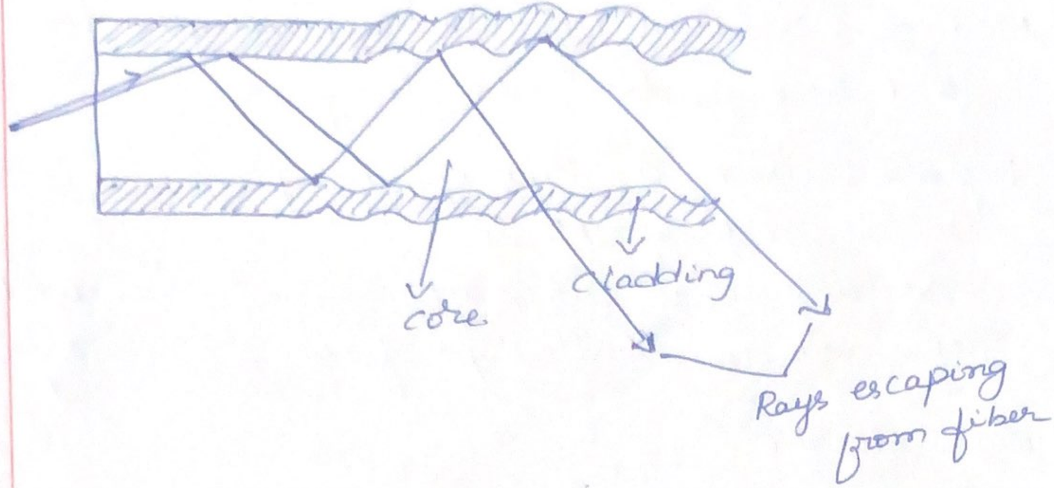
b) microscopic bends

**Macroscopic bends** :- They are the bends with radii much larger compared to the fiber diameter. These bends occur while wrapping the fiber on a spool or turning it around a corner.




The loss will be negligible for small bends but increases rapidly until the bending reaches a certain critical radius of curvature. Any bend of radius less than this threshold, makes the losses suddenly become extremely large which indicates the absence of total internal reflection.

## Microscopic bends




This type of bends are repetitive small scale fluctuations in the linearity of the fiber axis. They occur due to non-uniformities in the manufacturing of the fiber or by non uniform lateral pressures created during the cabling of the fiber. The microbends cause irregular reflections and some of them them leak through the fiber.

## Attenuation Coefficient

The loss suffered by the fiber is Expressed in terms of a coefficient, called attenuation coefficient. It is also called as attenuation or fiber loss.

Expression for attenuation Coefficient is given by,

$$\boxed{\alpha = -\frac{1}{L}\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \times 10 \ \text{dB/Km}}$$

$\alpha$ -> Attenuation Coefficient

$L$ -> Length of optical fiber

$P_{out}$ -> output power

$P_{in}$ -> Input Power

## Applications

a) Medical : used as light guides, imaging tools and also as lasers for surgeries.

b) Defence : used as hydrophones for Seismic waves and SONAR,
as wiring in aircraft, Submarines and other vehicles & also for field networking

c) Data storage

d) Telecommunications

e) Networking

f) Industrial / Commercial purpose

# HOLOGRAPHY

Holography is the technique of capturing pictorial details of 3-dimensions on a 2-dimensional recording aid, by using the phenomenon of interference.

Holographic technique was first suggested in the year 1948 by Dennis Gabor, a British scientist.

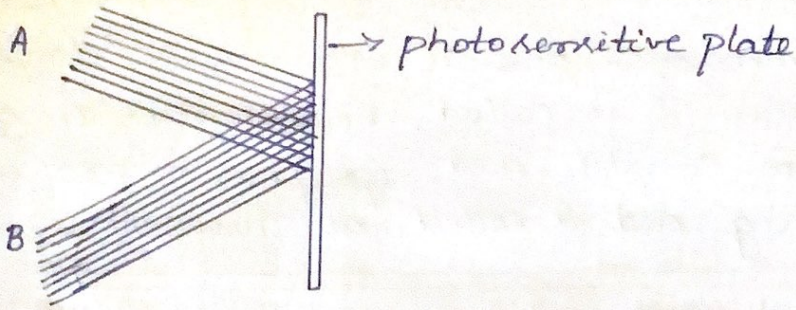
In this method, the pictorial details are recorded for a 3-dimensional object in a fashion nothing less than 3-dimensional one, it amounts to complete recording & hence it is called holography. In greek, Holos means complete and Graphos means writing. The recording aid is called as HOLOGRAM.

## Difference between Photography and Holography

| Photography | Holography |
| --- | --- |
| a) photography is a technique to generate 2-dimensional images. | Holography is a technique to generate 3-dimensional image |
| b) Reflection of light is used in Photography. | Interference & diffraction of light is used in holography. |
| c) No specific light need. | A coherent & monochromatic light is needed. |
| d) Lens is required to focus an object on the plate. | No lens is needed. |
| e) Information capacity is less as compared to holography. | Information capacity is high. |
| f) Multiple images can't be superimposed. | Multiple images can be superimposed onto each other. |

## Construction of a Hologram

Consider two ideally coherent beams A and B incident at different angles on a photographic plate over same place. The interference effect of the two beams on the photosensitive surface results in the recording of interference fringes on it.




Interference of beams

Let the photographic plate is developed, ie the interference fringes are recorded on the photographic. Such a photographic plate on which the interference fringes are recorded is called hologram.

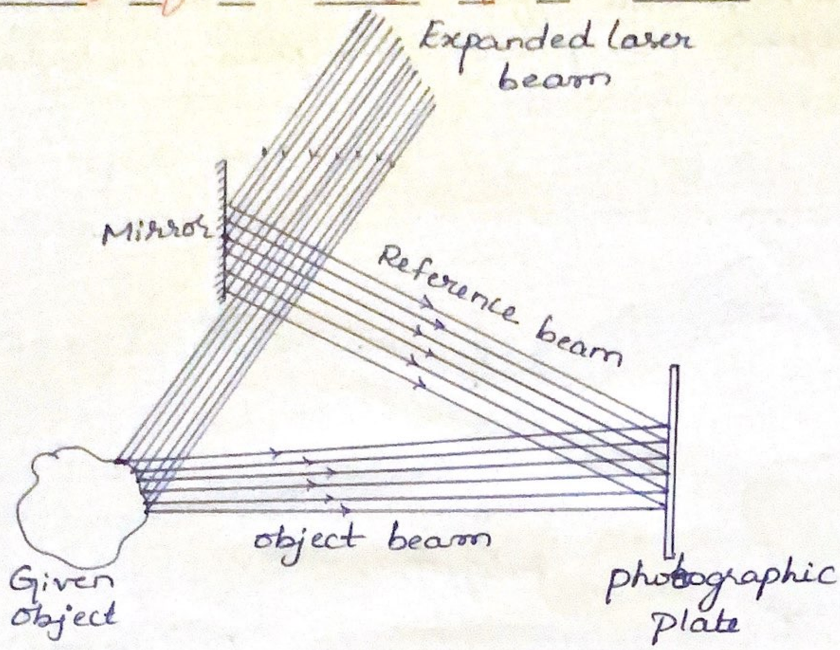
## Recording and Reconstruction of three dimensional Image

Recording and reconstruction of three dimensional image consists of two process.

a) Recording of the image of an object

b) Reconstruction of the image

## Recording of the Image of an Object

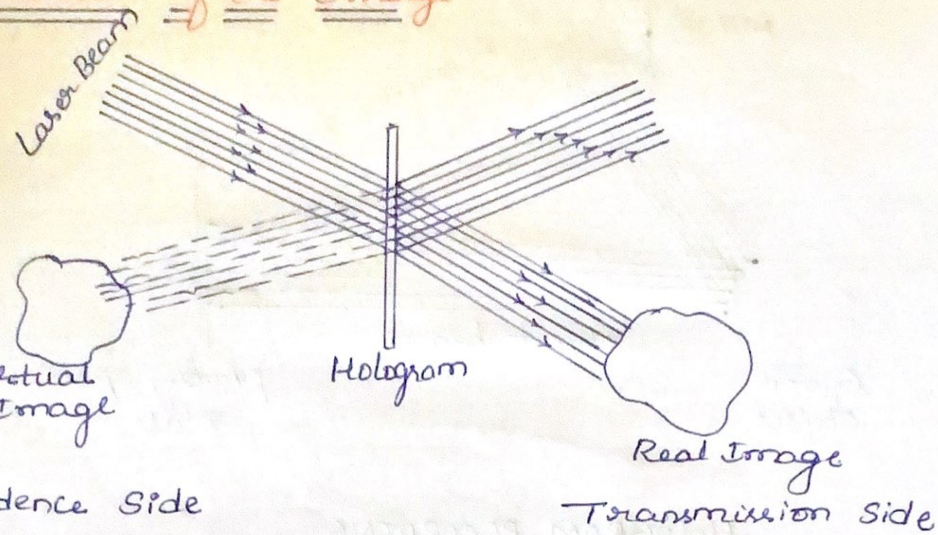



HOLOGRAM RECORDING

The given object and the mirror are placed one next to the other as shown in the figure. The expanded laser beam is then directed on this arrangement in which a part of the beam is incident on the mirror. The rest passes past the mirror & is incident on the object. A photographic plate is placed in such a position that it receives the light reflected from both mirror & the object. as shown. The part of the light reflected from the mirror & is incident on the photographic plate will be in the form of plane wavefronts. This is called reference beam.

Let us consider the part of the light reflected from the object & will be incident on the photographic plate as spherical wavefronts. This part is called object beam. The photosensitive surface responds to the resultant effect of interference between the spherical wavelets of the object beam & the plane waves of the reference beam. Thus the interference effects are recorded on the plate. on developing the photographic plate, hologram is Obtained.

## Reconstruction of the Image




For the reconstruction of the image, the original laser beam is directed at the hologram in the same direction as the reference beam was incident on it at the stage of recording. upon incidence, the reference beam undergoes diffraction in the hologram. Because of diffraction, secondary wavelets originate from each zone plate which interfere constructively in certain directions & generate both real & virtual image of the corresponding point of the object on the transmission side of the hologram.

## Applications

### 1) Holographic Interferometry

This method is used to study minute distortions of an object that take place such as due to stress or vibration etc.

### 2) Holographic Diffraction Gratings

The holographic gratings are obtained by interference of two laser beams each one with plane wavefronts on the hologram. This method produces the rulings much more uniformly than the ones made by a ruling engine on a conventional grating.

### 3) Acoustical Holography

This technique can provide three dimensional view of internal structures of the human body.

### 4) Thick Holograms

Thick holograms are the ones in which the interference pattern is recorded in 3-dimension. Such holograms are in use on credit cards in which improvement of security is the criteria.

### 5) Information Coding

For information coding holography technique was used.