LASERS

Laser is an acronym for Light Amplification by Stimulated Emission of Radiation. The first successful laser was made by TH Maimann in 1960 using a ruby crystal.

Properties of Laser beam

(i) Directionality: Laser emit light only in one direction. Because of high directionality, it is possible to focus laser beam to a fine spot.

(ii) Intensity: As laser beam is highly directional, its entire energy is concentrated in a narrow region. So intensity of laser beam is very high compared to ordinary beam of light.

(iii) Monochromaticity and Coherence: A highly monochromatic radiation has very small frequency range. Laser beam is spatially, temporally and directionally coherent.

Characteristics of laser beam

(ii) Highly monochromatic beam

(iii) Laser beam is highly coherent.

(iv) High brightness and intensity.

(v) Focussing and collimating property. Laser beam can be focused to a very small area. So density and power can be increased. This is used in microwelding, blood less surgery, diamond cutting etc.

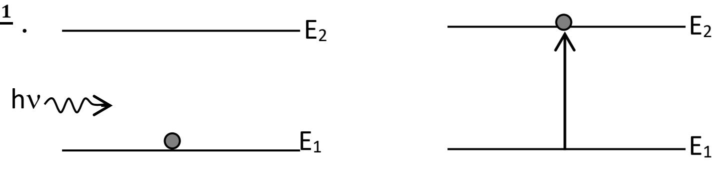
Absorption and Emission of Radiation

A material medium is composed of identical atoms or molecules having a set of discrete allowed energy levels. An atom can move from one energy state to another when it receives or release an amount of energy equal to the difference in energy between the two states. $\mathbf{h\nu = E_2 - E_1}$

If $h\nu = E_2 - E_1$, the interaction of radiation with atom leads to three distinct processes. They are (i) absorption (ii) spontaneous emission (iii) stimulated emission

Absorption (Stimulated absorption)

The phenomenon of reception of radiation by atoms or molecules for excitation is called **absorption**. If an atom is initially in lower energy level E_1, it can rise to a higher energy level E_2 by absorbing a photon of energy $\mathbf{h\nu = E_2 - E_1}$ or frequency $\nu = \frac{E_2 - E_1}{h}$.



Initial state of atom final state of atom

This process of transition of atoms from lower energy level to higher energy level is called induced absorption.

Absorption depends on the energy density (energy per unit volume) of incident radiation and the number of atoms per unit volume in the lower level (N_1)

Rate of absorption $\frac{dN_1}{dt} \propto \rho\, N_1$

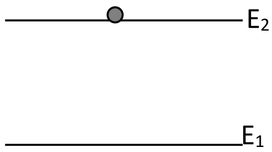
$\frac{dN_1}{dt} = B_{12}\, \rho\, N_1$ where B_{12} is Einstein's coefficient of induced absorption.

Spontaneous Emission

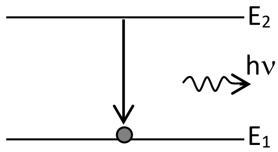
The process of emission of photon without the influence of any external agency is called spontaneous emission.

Consider an atom initially at excited state E_2. Since the life time of excited state is $\approx 10^{-8}$ sec, the excited atoms suddenly jumps back to the lower energy level E_1, by emitting a photon of energy $h\nu = E_2 - E_1$.

This is called spontaneous emission.



Initial state of atom



final state of atom

The rate of spontaneous emission to the lower level is proportional to the number of atoms per unit volume in the excited level

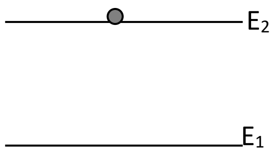
Rate of absorption $\frac{dN_2}{dt} \propto N_2$

$\frac{dN_2}{dt} = A_2\, N_2$ where A_{21} is Einstein's coefficient of spontaneous emission.

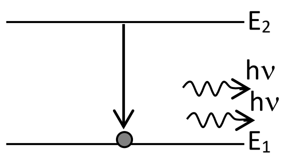
In the case of spontaneous emission, the atom emits an electromagnetic wave which has no definite phase relationship with that emitted by another atom.

Stimulated Emission

The process in which the emission is triggered by the external photon is called stimulated emission. Consider an atom in an excited energy level E_2. If a photon of energy hν is incident on it, as a result, it (atom) jumps back to lower energy state by emitting a photon of energy hν.



Initial state of atom



final state of atom

i.e., the emission is stimulated by an external photon and this is called stimulated emission.

Here, two photons (one original and the other which is emitted) are moving in the same direction with the same phase. The stimulated emission process amplifies the intensity of the radiations. i.e., all the stimulated radiations will have the same direction of propagation, will be coherent and polarization with the triggering pulse. This makes stimulated emission distinct from ordinary light.

Rate of stimulated emission $\frac{dN}{dt}$ is proportional to (i) energy density of incident photon (ρ),

(ii) number of atoms in higher energy level N_2

So, $\frac{dN}{dt} \propto \rho N_2$

$\frac{dN}{dt} = B_{21} \rho N_2$ where B_{21} is Einstein's coefficient of stimulated emission.

Relation between Einstein's coefficients OR

(Relation between Spontaneous and Stimulated probabilities)

* According to Einstein, at thermal equilibrium, the rate of upward transition will be equal to the rate of down ward transition.

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} + \frac{dN}{dt}$$

$$B_1 \rho N_1 = A_2 N_2 + B_2 \rho N_2$$

$$\rho(B_1 N_1 - B_2 N_2) = A_2 N_2$$

$$\rho = \frac{A_2 N_2}{B_1 N_1 - B_2 N_2}$$

Dividing the numerator and denominator of RHS by $B_2 N_2$,

$$\rho = \frac{A_2/B_2}{\frac{B_1 N_1}{B_2 N_2} - 1} \rightarrow (1)$$

* According to Boltzmann theorem, number of particles at a particular energy level E_1 is given by

$N = N_0 e^{-E/KT}$ where N_0 is the number of atoms at ground energy level

* So $N_1 = N_0 e^{-E_1/KT}$ and $N_2 = N_0 e^{-E_2/KT}$

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/KT} \text{ or } \frac{N_1}{N_2} = e^{h\nu/KT}$$

From eqn (1), $\rho = \frac{A_2/B_2}{\frac{B_1}{B_2} e^{(E_2-E_1)/KT} - 1}$ or $\rho = \frac{A_2/B_2}{\frac{B_1}{B_2} e^{h\nu/KT} - 1} \rightarrow (2)$

* From Planck's radiation formula, $\rho = \frac{8\pi h\nu^3/c^3}{e^{h\nu/KT} - 1} \rightarrow (3)$

Comparing (2) and (3), we get,

$\frac{\mathbf{A_2}}{\mathbf{B_2}} = \frac{\mathbf{8\pi h\nu^3}}{\mathbf{c^3}}$ and $\frac{\mathbf{B_1}}{\mathbf{B_2}} = \mathbf{1}$ These are the relations between Einstein's coefficient.

For laser production, stimulated emission rate must be greater than spontaneous emission rate.

* $$\frac{\text{spontaneous emission rate}}{\text{stimulated emission rate}} = \frac{A_2 N_2}{B_2 \rho N_2} = \frac{A_2}{B_2 \rho} = \frac{8\pi h\nu^3/c^3}{8\pi h\nu^3/c^3} e^{h\nu/KT} - 1$$

$$= e^{h\nu/KT} - 1$$

* When spontaneous emission is less than the stimulated emission, $e^{h\nu/KT} - 1 < 1$, then,

  $h\nu <<< KT$ or $\nu <<< \frac{KT}{h}$ (for lasing action to occur)

* In visible region, frequency $\nu > \frac{KT}{h}$

  At normal temperature, spontaneous emission is greater than stimulated emission and hence no lasing action

  occurs in visible region at normal temperature.

Difference between spontaneous and stimulated emission

Spontaneous Emission	Stimulated Emission
It is a natural transition in which an atom is deexcited after the end of its life time in the higher energy level	It is an artificial transition which occurs due to deexcitation of an atom before the end of its life time in the higher energy level.
Deexcitation of atoms takes place without any external help	Deexcitation of atoms takes place with the help of external photons of sufficient energy.
Uncontrolled random process.	Controlled from outside
Released radiation is incoherent and not monochromatic.	Released radiation is coherent and monochromatic.
Probability of spontaneous emission depends only on the properties of the two energy levels between which the transition occurs.	Probability of stimulated emission depends on the properties of the two energy levels involved in the transition and also on the photon density of incident radiation

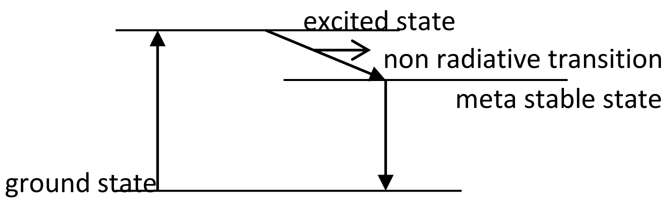
Population inversion

Population means the number of atoms per unit volume at a particular state. Normally population at a lower energy state is larger than that of higher energy state. i.e., $N_1 > N_2$. For laser action to occur, stimulated emission should be greater. For this, N_2 should be greater than N_1.

Population inversion is a state in which the number of atoms in the higher energy state(N_2) is made larger than that of lower energy state (N_1). i.e., $N_2 > N_1$

Meta stable state

The energy state which lies in between lower level and unstable excited energy level. Life time of meta stable state is 10^{-3}seconds. So the excited atoms can remain in a meta stable state for sufficiently long time and population inversion can be achieved.



So the presence of meta stable state is essential to achieve population inversion. Lasing transition by stimulated emission takes place between the metastable level and a lower level.

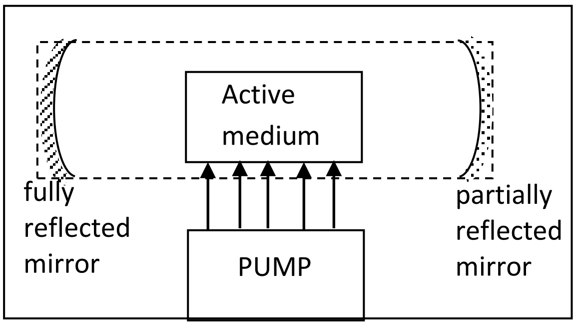
Basic Components of laser

A laser system generally requires three components for its generation. They are

(i) active medium

(ii) pumping source

(iii) an optical resonator



(i) Active medium: An active medium is one with energy levels having a population inversion between some levels and the laser action takes place here. It may be solid, liquid or gas. This medium determines the wavelength of the laser.

(ii) Pumping source: The pump is an external energy source that supplies energy needed to transfer the laser medium into the state of population inversion. There are different types of pumping methods such as optical, electrical, chemical etc.

(iii) Optical Resonator (Resonant cavity): It consists of a pair of parallel mirrors between which the active medium is kept. The mirrors could be either plane or curved. One of the mirrors is fully reflecting and the other is partially reflecting. Photons emitted during stimulated emission are shuttled between these two mirrors and as a result, more coherent laser beam is produced. Thus it provides the feedback necessary to produce coherent stimulated emission.

Pumping

It is the method by which population inversion is achieved by supplying energy from an external source is known as pumping. The commonly used pumping methods are:

(i) Optical pumping: The method of achieving population inversion using light energy. This method is used in solid state lasers like Ruby laser where the energy level of their active medium is broad. But this method is not suitable for gas lasers whose energy levels are sharp.

(ii) Electrical pumping: An extremely high electric field in an electrical discharge accelerates the electrons emitted by the cathode towards the anode. Collisions between these high energy electrons and the active medium produce atoms, molecules and ions of the medium in the excited states, producing the needed population inversion. This procedure is used in gas lasers. Eg: gases.

(iii) Direct conversion: In semiconductor lasers and in LEDs, electrical energy is converted into light energy takes place. Here the current carriers are excited and population inversion is achieved.

(iv) Inelastic atom-atom collision: This procedure is suitable when we have two types of atoms in the active medium. An electric discharge raises one type of atoms to their excited states. These excited atoms collide inelastically with the second type of atoms, energy exchange takes place and the required population inversion is created in the later atoms. Eg: He-Ne laser.

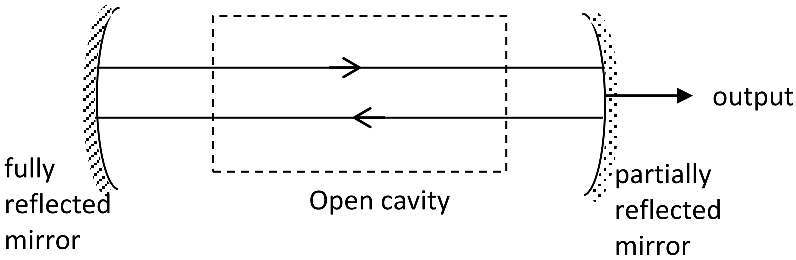
(v) Chemical conversion: Here pumping energy comes from chemical reactions. Eg: CO_2 laser.

Pumping Scheme

(i) Three level pumping scheme: An atomic system in the lowest energy state E_1 will be excited to the highest level E_3 by pumping. The level E_3 is not a stable state and its life time is of the order of 10^{-8}seconds. Some of the excited atoms make spontaneous transition to the ground state, but many of them undergo spontaneous nonradiative transition to the metastable state E_2 having life time of the order 10^{-3} s. So as the pumping continues the population of E_2 exceeds, the population E_1 and population inversion is attained. Thus a photons can induce stimulated and laser action occurs between E_2 and E_1.

(ii) Four level pumping scheme: Atoms in the level E_1 are excited by pumping to short lived uppermost level E_4. From E_4, they decay very rapidly to metastable state E_3 through nonradiative transition. Population inversion between levels E_3 and E_2 is quickly established. A spontaneous photon of energy $h\nu = E_2 - E_1$ can initiate a chain of stimulated emission results in laser action. The life time of atom in level E_2 is very short. From E_2, the atoms return to the ground level E_1, through nonradiative transition quickly. Again, these atoms are excited to E_4 through pumping.

Optical Resonator (Resonant Cavity)



In a laser, to generate high intensity outputs, the light is directed back and forth through the medium. For this the active medium is placed between two mirrors. Such an arrangement is called a resonator. Resonator cavity of different forms are in use. Its simplest form consists of a pair of parallel mirrors between which the active medium is kept. The mirrors could be either plane or curved. One of the mirrors is fully reflecting and the other is partially reflecting. This partially silvered mirror serves as the output element and let the laser out of the device.

Resonator action: Photons released spontaneously in a direction parallel to the optic axis of the resonator will travel within the active material again and again by multiple reflection by resonator mirrors. During this travel, the photon will trigger stimulated emission of radiation along the axis which will keep on multiplying.

The photons emitted spontaneously in other directions and their stimulated avalanches will traverse short distances and die out soon.

Thus optical resonator serves the important function of selecting the desired intensity of laser and can achieve directionality.

Thus both the stimulated emission process and the optical resonant cavity action give all the unique features of laser namely high degree of coherence, directionality, monochromaticity and high beam intensity.

Working Principle of Laser

Consider an active medium that has a metastable state. With suitable pumping mechanism, we can create population inversion between two states. Once it is achieved, a photon emitted due to spontaneous emission will produce stimulated emission. Photons due to these will again trigger stimulated emissions. Thus amplification takes place, i.e., lasing action occurs.

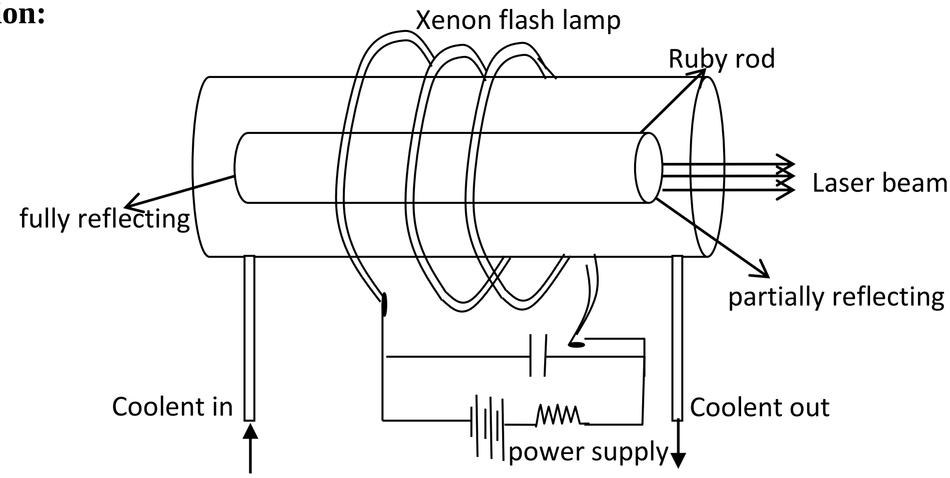
The beam thus produces passes through same medium many times due to reflections at that mirrors forming a resonant cavity. The laser of desired intensity is obtained as output through the partially silvered mirror. Lasers are devices that work on this principle of amplification by stimulated emission.

Different types of lasers

(i) Ruby Laser: (Three level laser)

It is a solid state laser. It was first fabricated by Maimann in 1960. It is a three level laser.

Construction:



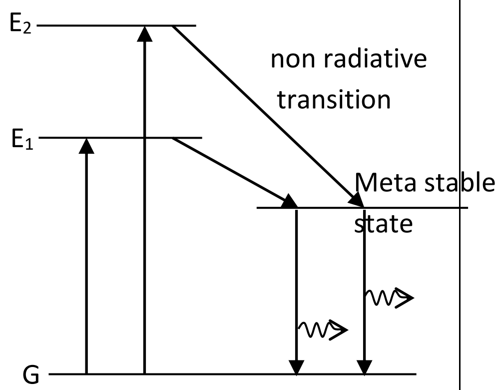
Active Medium: A ruby crystal in the form of a cylindrical rod is the active medium. Ruby is a aluminium oxide crystal (Al_2O_3) doped with 0.05% of chromium ions. The ruby rod is of length about 10cm and diameter about 1cm. Ruby rod is pink in colour.

Pumping Method: Optical pumping method is used here. The ruby rod is surrounded by helical Xenon flash lamp. Chromium ions possess suitable energy levels to produce laser. The flash of xenon tube produces optical pumping. Only a part of this energy is used in pumping the chromium ions. The remaining energy heats up the apparatus and hence a cooling arrangement is provided to keep the Ruby rod cool.

Optical resonator: The two end faces of the Ruby rod acts as optical resonator. One face is completely silvered and it act as a perfect reflector. The other face is partially silvered and it is a partial reflector.

Working:

* When Xenon flash tube is ON, the Cr^{3+} ions absorbs the energy and get excited to higher energy levels E_1 and E_2 . (**Induced absorption**)
* Since the life time of E_1 and E_2 is too small (10^{-8}s), they suddenly jump to meta stable state which is a non radiative transition.
* Since the life time of meta stable state is 10^{-3}s, number of chromium ion gets increased and population inversion is achieved.
* Once population inversion is achieved, spontaneous emission starts.
* The spontaneously emitted photons in the system, stimulate the laser action.

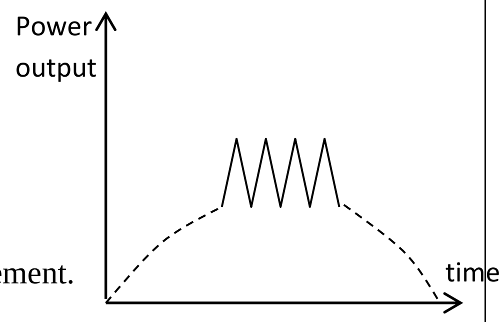


* Large numbers of photons are emitted by stimulated emission from metastable state to ground state.
* These photons are shuttled between two end faces of the rod and then highly coherent laser beam is produced.
* Now through the partially reflecting end, a highly coherent, intense, monochromatic and directional red beam of light emerges. This is Ruby laser. Its wavelength is 6943A°.
* The moment the Xenon flash tube is OFF, the lasing action stops. The operation starts again when flash tube is again ON.

In the graph, the bold line shows stimulated emission and the dotted line shows spontaneous emission.

Efficiency of Ruby laser is less because only 1% of the energy of the flash lamp is converted into laser output.

Remaining energy is released as heat and is removed by cooling arrangement.



Disadvantages:

* Large input energy is required for its function.
* Efficiency is less.
* Output is not continuous, but it is pulsated.

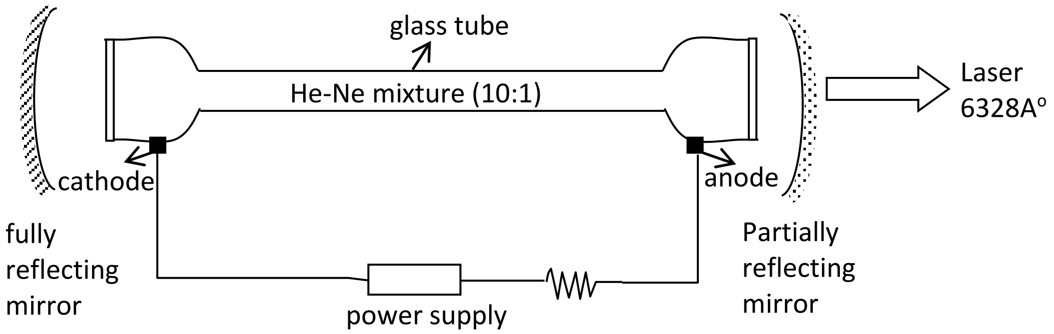
Application:

* Used for recording holograms.
* Used in industry for drilling and cutting materials.
* Used in spectroscopy.
* Used in laser weapons.
* Used for recording holograms.
* Used in ophthalmic surgeries and for diagnosis.

(ii) Helium - Neon Laser: (Four level laser)

He-Ne laser was the first gas laser fabricated by Ali Jawan and his coworkers. This is the most widely used laser with continuous power output. It is a four-level laser.

Construction:

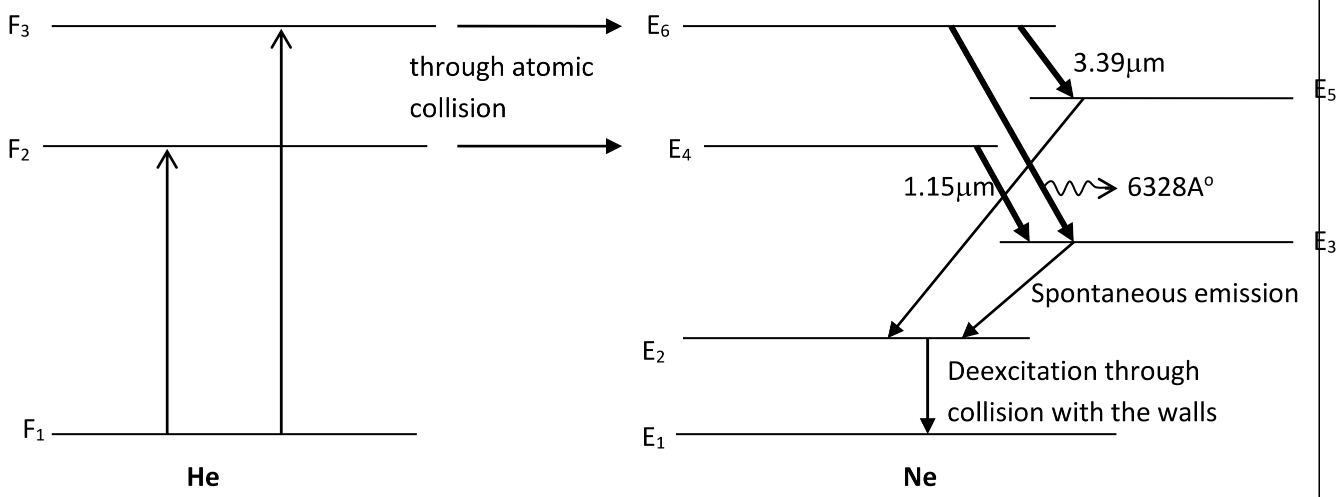


Active medium: The arrangement consists of a long and narrow discharge tube of length about 90cm and 1cm in diameter. The discharge tube is filled with a mixture of He and Ne gases in the ratio 10:1 at a pressure of 1torr (1torr = 1mm of Hg). This gas mixture is the active medium. Here He is a pumping agent and Ne atoms is the lasing agent. As He atoms are lighter and larger in number, they are easily excitable than Ne atoms.

Optical resonator: On the axis of the tube, two mirrors are fixed. One of the mirror is fully reflecting and the other is partially reflecting.

Pumping Method: Inelastic atom-atom collision method is used for pumping. Electrodes are provided to produce a discharge in the gas and they are connected to a high voltage power supply. As the electrons are accelerated from the cathode, they collide with the He atoms and thereby excite them. The excited helium atoms transfer their energy to neon atom to produce population inversion of neon atoms.

Working:



* When the power supply is switched ON, electrons are accelerated towards the anode. He atoms are excited to level $\mathbf{F_2}$ and $\mathbf{F_3}$. F_2 and F_3 are meta stable states.
* The excited He atoms in the level F_2 and F_3 returns to the ground state by transferring the energy to Ne atoms through collision.

* Ne atoms get excited to the energy levels $\mathbf{E_4}$ and $\mathbf{E_6}$ (are meta stable states) which coincides with F_2 and F_3 level of Helium atom.
* Population inversion is achieved at energy states $\mathbf{E_4}$ and $\mathbf{E_6}$.
* Spontaneously emitted photons in the system trigger the stimulated emission.
* Stimulated emission takes place
  - **from E_6 to E_3 producing laser beam of λ = 6328A° in the visible region.**
  - **from E_4 to E_3 producing laser beam of λ = 1.15μm in the IR region.**
  - **from E_6 to E_5 producing laser beam of λ = 3.39μm in the IR region.**
* The transition of Ne atoms from $\mathbf{E_5}$ and $\mathbf{E_3}$ to $\mathbf{E_2}$ (which is a meta stable state) is spontaneous emission.
* The Neon atoms at $\mathbf{E_2}$ are de excited to $\mathbf{E_1}$ by colliding with the walls of the discharge tube.
* The photons that are released during the stimulated emission are shuttled between the two mirrors and a highly coherent beam of laser is produced.
* The output beam of laser is released through the partially reflecting mirror.
* We get a continuous supply of plane polarised laser beam.
* The desired wavelength can be selected in the output by changing the reflectivity of the end mirrors.

Application

* Used for recording and reconstructing holograms.
* Used in communication systems
* Used in barcode reading and pattern recognition.
* Used for testing surface roughness.
* Used for producing interference and diffraction pattern.

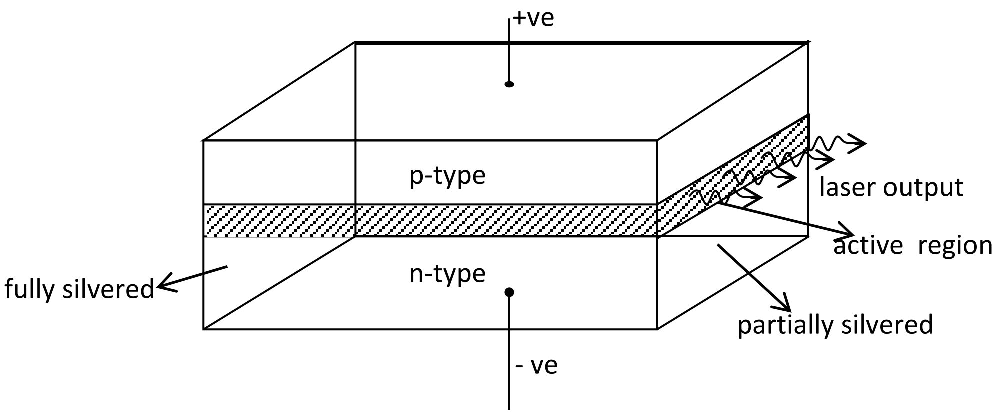
Advantages

* These have high monochromaticity, highly coherent, and highly collimated.
* These can be operated continuously without cooling mechanism.
* They are easily portable.
* They can be constructed easily and cheaply.

(iii) Semiconductor Laser

Semiconductor laser is a solid state laser. The first and widely used semiconductor lasers were the p-n junction diode lasers made of Gallium Arsenide (GaAs). Laser printers, CD players etc have semiconductor lasers. In a semiconductor laser, the transitions are associated with the electron states in the conduction and valence bands. The upper and lower energy states are continuous and hence the output is not sharp.

Construction



The semiconductor laser consists of a pn-junction formed by two heavily doped semiconductor.

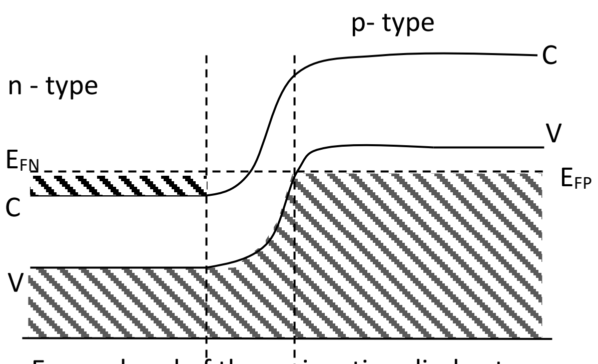
Active medium: The depletion region is the active medium in semiconductor laser. The thickness of depletion layer is very small about 1μm.

Pumping Source: Under the influence of forward biased electric field, conduction electrons will be injected from n-side into the junction area, while holes will enter junction area from p-side. Thus there will again be recombination of holes and electrons in depletion region and hence this region becomes thinner. The direct conversion method is used as pumping method.

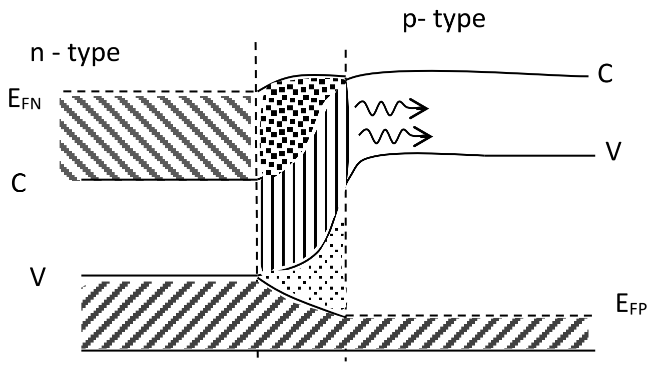
Optical resonator: The two faces of semiconductor which are perpendicular to junction make a resonant cavity.

The top and bottom faces of diode which are parallel to junction are metallised to make external connection. The front and back faces are roughened.

Working:



Energy band of the pn junction diode at absolute zero



Energy band of the pn junction diode when forward biased

When no voltage is applied, the Fermi levels of p-type semiconductor and n-type semiconductor lies in the same horizontal line.

When a forward bias voltage V is applied to the diode, the two Fermi levels become separated by an amount given by $\Delta E = eV$. The forward biasing has caused to inject electrons from the conduction band of the n-type semiconductor and holes from the valence band of the p-type semiconductor into active region (depletion region) of the diode.

The radiative emission occurs when an electron in the conduction band recombines with the hole in the valence band. The frequency of the emitted radiation has a frequency corresponding to the frequency of the band gap energy. In GaAs laser, the photons emitted have a wavelength 8200A^o to 9000A^o in IR region.

Advantages

* High efficiency.
* Simple, compact and small in size.
* This laser can be operated at low power compared to the other lasers.
* Laser output can be controlled by controlling the junction current.

Application

* Used in fibre optic communication.
* Used to produce laser diodes which are powerful than LED.
* Used to heal wounds.
* Used for laser printing.
* Used as a barcode reader.

Applications of Lasers

(i) In Industry:

* Laser is used for welding. Highly collimated and intense beam of laser can be used for cutting. When focussed to an appropriate spot size, the heat generated melts the metal, rapidly producing a narrow weld with joint efficiency and minimal distortion.
* Laser is used for cutting. Cutting with a laser is achieved by heating the metal to its melting point while, at the same time, applying a jet of gas through a nozzle located coaxially with the path of the laser beam. This gas removes the vapourised and molten metal from the bottom of the cut.
* Laser is used for drilling. To drill with a laser, a short pulse of a laser light energy is used. This pulse heats the surface so rapidly that vapourisation takes place. Resultant gases and vapour pressures generated blow away the vapourised and molten material. Hence holes with high precision, holes in hardest materials, and holes in difficult to reach areas and at different angles can be drilled using laser drilling.

(ii) In Medical field:

* Laser is used in eye surgery, used to treat patients suffering from myopia.
* Laser is used to breakup gallstone and kidney stone.
* Lasers can be used to destroy cancerous cells.
* Laser is used in surgery. The major advantages of laser surgery are (i) it is a non contact process (ii) it can be focused to micro-size spot, (iii) it is almost a bloodless surgery, (iv) there is an apparent reduction in post operative pain.
* Laser are used in endoscopy.

(iii) In communication field:

* Laser is used in fibre optic communication.
* Laser is used to transmit radio and television programmes.
* Lasers can be used for establishing underwater communication between submarines..
* Laser is used in satellite communication.

(iv) In computers:

* Laser is used in computer printer, compact discs, optical memory cards etc.

(v) In defence:

* Laser is used to find distance of targets.
* Laser is used to guide missiles.
* Lasers can be used to destroy war planes.

(vi) In holography:

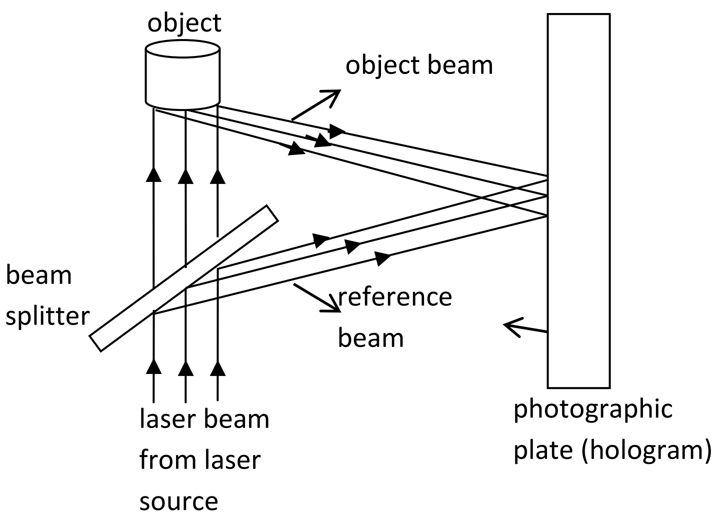
* Laser is used in 3D photography called holography.

Holography

* It is a method of recording 3 dimensional image of an object by using interference principle. It was invented by Dennis Gabour.
* In holography, intensity and phase of the light waves scattered from different points of an object is recorded on a photographic film. The phase recording helps to record the depth of the object.
* The recorded interference pattern is known as hologram.

Holography involves two processes, recording the hologram and reconstruction of the image.

Recording the hologram



* The basic principle of recording hologram is interference.
* The light from laser source is made to split into two components.

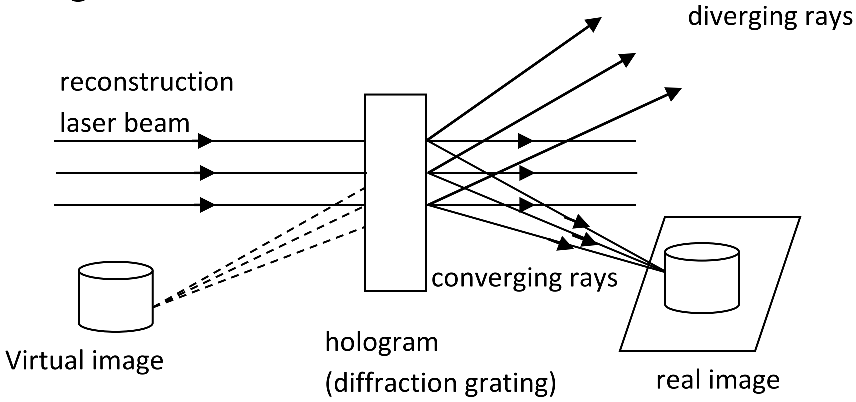
∗ One of the light component is incident on the object and is scattered by it. This wave is called **object wave** and it proceeds towards the recording medium (photographic plates).

∗ The other wave is directed towards recording medium (photographic plates) and this wave is called **reference wave**.

∗ These object waves and reference waves which are coherent interfere and produce a stable interference pattern on the photographic plate. The developed negative of the interference pattern is called a hologram.

∗ This interference pattern contains all information about the object.

Reconstruction (Reading) of the hologram



∗ Reading is the process of reconstructing the three dimensional image from the hologram.

∗ Hologram is illuminated by the same reference wave used in recording process. This beam is called readout wave and should incident on the hologram at the same angle as did the reference wave.

∗ The hologram acts as diffraction grating and it produces two diffracted beams when the read out wave is incident on it.

∗ One of these is a divergent beam which produces a virtual image. This is an exact replica of the original 3D object.

∗ The other beam which is a convergent beam produces a real image which can be recorded on a photographic plate.

Applications

∗ Holography is used in non destructing testing.

∗ It is used in data storage, character recognition etc.

∗ Fine diffraction grating can be made using holography.

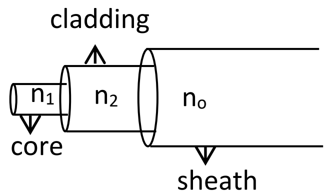
∗ It is used in interferometry.

Difference between Holography and Photography

Holography	Photography
Image recorded in 3D form	Image recorded in 2D form.
Both amplitude and phase variations are recorded.	Only amplitude variations recorded.
Each part of the hologram can reproduce entire image.	It is impossible to recover information corresponding to each point if damaged.
Several images can be recorded on a single hologram.	Only one image can be recorded.
Holography requires monochromatic and coherent light sources.	No need of monochromatic and coherent light sources.

FIBRE OPTICS

- Optical fibre is a thin long cylindrical fibre made of glass or plastic used for transmission of light.
- It consists of three parts.



(i) A **core** is the innermost cylindrical region. Refractive index of the core n_1 is made higher. It is made of germanium doped silica glass. Light wave can propagate through the core. The size of the core is about 10 - 50μm.

(ii) **Cladding:** A core is surrounded by another cylindrical shell called cladding. Its refractive index is made smaller compared to the core. It is made of purely silica glass. Purpose of cladding is to keep the light waves within the core itself by total internal reflection. The size of cladding is about 125μm.

(iii) **Sheath:** Outermost cylindrical layer is called sheath. It is an opaque layer used to provide protection to the fibre. It is made of plastic material. Its size is about 150μm.

- **Working principle of optic fibre – Total internal reflection**

When a ray of light travel from a denser medium of refractive index n_1 to a rarer medium of refractive index n_2 , and if the angle of incidence θ is greater than the critical angle θ_c , the ray is totally reflected back. This phenomenon is known as total internal reflection. By multiple total internal reflection, the light is transmitted through the fibre.

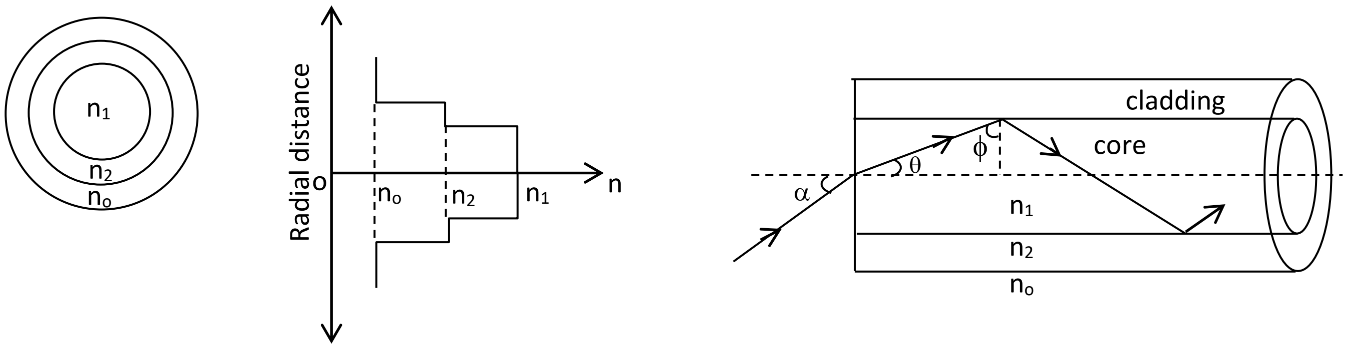
Classification of optic fibre

Step - index fibre

- This type of optical fibre consists of core and cladding of constant refractive index.

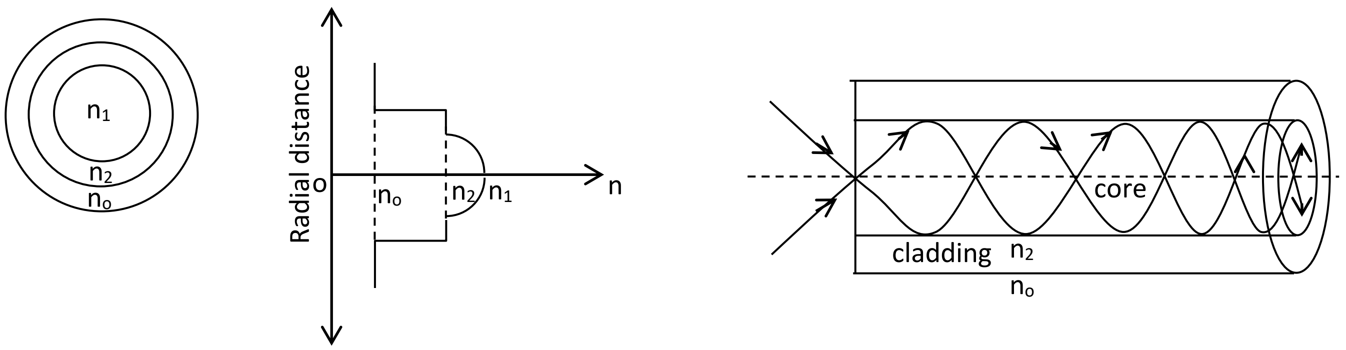
i.e., n_1 and n_2 are constant and $n_1 > n_2$.

- Shape of index profile (graph with refractive index in x-axis and distance from the axis of fibre in y-axis) is like a step. Hence it got the name step-index fibre.
- Light entering through one face of fibre undergoes repeated total internal reflections at core-cladding.



Graded index fibre

* This type of optical fibre consists of core with varying refractive index and cladding of constant refractive index and $n_1 > n_2$.
* n_1 is maximum at axis of the core and decreases radially outwards.
* Light entering through one face of fibre is travelling in a parabolic path by undergoing a number of gradual total internal reflection.



Acceptance Angle (α): It is the angle made by the incident light at one end of the core with its axis.

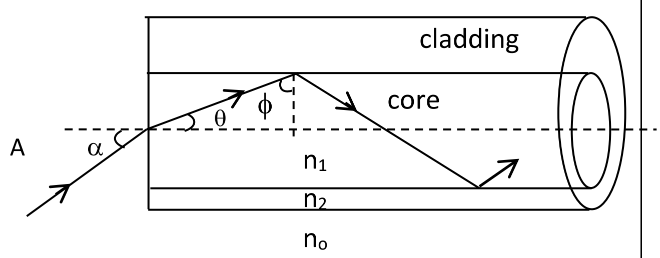
Numerical Aperture of an optical fibre

* It is the measure of its light gathering capacity of an optical fibre.
* It is the sine of the maximum value of acceptance angle.
* Numerical aperture **NA = $\sin\alpha_m$** = $\sqrt{n_1^2 - n_2^2}$

Consider a step index fibre made of core with refractive index n_1 and a cladding of refractive index n_2. Here $n_1 > n_2$.

* Let a light ray is incident at an acceptance angle α.
* It is refracted along BC at θ.
* After refraction, the ray is incident at the core-cladding interface at an angle ϕ which is greater than the critical angle ϕ_c.

  Hence it undergoes total internal reflection.



Refractive index of core w.r.t air is ${}^{0}n_1 = \frac{\sin\alpha}{\sin\theta}$ (by Snell's law)

$\frac{\sin\alpha}{\sin\theta} = \frac{n_1}{n_0} = {}^{0}n_1$(refractive index of core w.r.t air)

$n_0 \sin\alpha = n_1 \sin\theta \quad \rightarrow (1)$

From figure, $\theta = \frac{\pi}{2} - \phi$

So eqn (1) becomes, $n_0 \sin\alpha = n_1 \sin\left(\frac{\pi}{2} - \phi\right)$

$n_0 \sin\alpha = n_1 \cos\phi \quad \rightarrow (2)$ $\qquad \sin\left(\frac{\pi}{2} - \phi\right) = \cos\phi$

For critical rays, $\alpha = \alpha_m$; $\theta = \theta_m$; $\phi = \phi_c$

$\therefore \; n_0 \sin\alpha_m = n_1 \cos\phi_c \quad \rightarrow (3)$

Refractive of core w.r.t cladding is ${}^{2}n_1$. or ${}^{2}n_1 = \frac{n_1}{n_2}$

${}^{2}n_1 = \frac{1}{\sin\phi_c}$; $\sin\phi_c = \frac{n_2}{n_1}$

We know that, $\cos\phi_c = \sqrt{1 - \sin^2\phi_c} = \sqrt{1 - \frac{n_2^2}{n_1^2}}$

i.e., $\cos\phi_c = \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}$

or $\cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \quad \rightarrow (4)$

Substituting, (4) in (3), $n_0 \sin\alpha_m = n_1 \frac{\sqrt{n_1^2 - n_2^2}}{n_1} = \sqrt{n_1^2 - n_2^2}$

Or **NA =** $\mathbf{\sin\alpha_m = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}}$

The refractive index of air is unity, $n_0 = 1$, then **NA =** $\mathbf{\sin\alpha_m = \sqrt{n_1^2 - n_2^2}}$

Relative refractive index of a fibre or fractional refractive index (Δ)

It is the ratio of the difference between refractive indices of the core and cladding of a fibre to the refractive index of the core. $\mathbf{\Delta = \frac{n_1 - n_2}{n_1}}$

Relation between NA and relative refractive index of a fibre (Δ)

$NA = \sin\alpha = \sqrt{n_1^2 - n_2^2} = \sqrt{(n_1 - n_2)(n_1 + n_2)}$

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

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

Then $NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(n_1 - n_2)(n_1 + n_2)} = \sqrt{2n_1 \Delta n_1}$

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

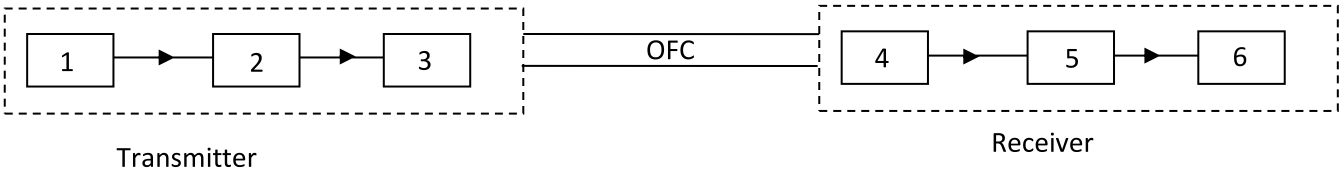
Signal attenuation (a)

Due to absorption and scattering, there will be a decrease in the strength of optical signal passing through the fibre. This is known as signal attenuation of the fibre.

Signal attenuation $\mathbf{a = \frac{10}{L}\log_{10}\frac{P_1}{P_2}}$ **dB/km** where P_1 is power of input signal at one end of an optical fibre and P_2 is power of output signal at the other end and L is the length of the fibre in kms.

Fibre optic Communication System

It consists of three sections (i) transmitter (ii) receiver (iii) information channel (fibre optic cable)



Block diagram of an optical communication system

(i) Transmitter: It converts electrical signal into optical signal.

It consists of

Unit 1: It is the subscriber's telephone where sound wave is converted to electrical energy.

Unit 2: It is an **encoder**. This converts continuous electric signal into coded digital pulse by means of an analogue to digital converter.

Unit 3: It is an **optical transmitter**. It consists of miniature semiconductor laser or LED. Light source from this source turns on and off according to the digital pulses received from the encoder.
i.e., Light beam is modulated by the digital pulses. This modulated light is transmitted through an optical fibre to the receiver section.

(ii) Optical fibre cable: Transmits information containing light by multiple total internal reflection.

(iii) Receiver: It consists of

Unit 4: It is a **photodetector** which demodulates the optical signal and send the digital signal to unit 5.

Unit 5: It is a **decoder** which converts digital pulses into analog signal with the help of a digital to analog converter and send the signal to unit 6.

Unit 6: It is a subscriber's telephone where the sound is reproduced from the analog signal.

Advantages of fibre optic communication

(i) High band width: Large amount of information can be transmitted through a single fibre.

(ii) Small size and weight.

(iii) Low transmission loss.

(iv) High security – taping is not possible.

(v) Long cost and long lasting.

Applications of optical fibre

Industrial uses:

* Optical fibres are used as sensors to measure or monitor displacement, pressure, temperature, flow rate, chemical composition etc.
* Used in security alarm system, industrial automation etc.
* Used to know the level of atmospheric pollution.

Technological uses:

* Used in cable TV, CCTV, LAN, WAN etc.
* Internet connections made through optical fibres.
* Used for transmission of digital data generated by computers.

Medical uses:

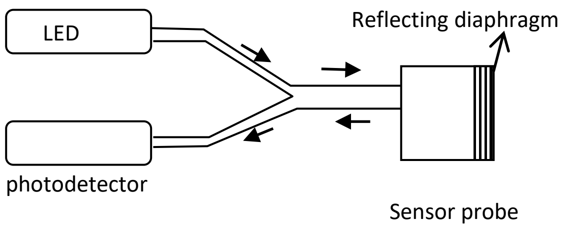
* Optical fibres used in endoscope.
* Used to test the tissues and blood vessels which are far below the skin.
* They are used to measure and monitor blood flow, oxygen saturation level etc.
* Used for bloodless surgery.
* Used in angioplasty.

Optical fibre Sensors:

* It is a device used to measure displacement, force, pressure, temperature etc by detecting the variation of light through fibre with respect to external parameters.
* There are different types of sensors.

Intensity Modulated Sensor

* Here a change in physical parameter produces a change in intensity of light through the optic fibre.
* By measuring this change in intensity of light, the change in physical parameter can be found out.
* Eg: Force or pressure sensor.



A typical pressure sensor is as shown in figure.

The light from the LED gets reflected from the diaphragm and it is detected by the photdector.

Changes in external pressure causes the diaphragm to bend leading to changes in numerical aperture of the fibre.

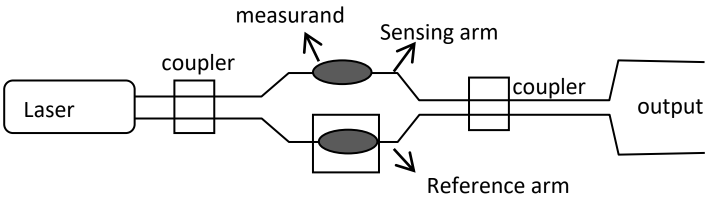
This produces the modulation in the intensity of light transmitted by the fibre. Pressure changes upto 6MPa can be measured accurately.

These types of fibre optic sensors are useful for monitoring pressure changes in arteries, bladder urethra etc. They are also useful for pressure monitoring of gaseous reactants and products in chemical industries.

Phase Modulated Sensor

∗ Here a change in physical parameter produces a change in phase of light through the optic fibre which can be detected and calculated for measuring the physical quantity.

∗ Eg: Temperature sensor.



Light from a highly monochromatic laser source is split equally by a coupler and sent through the sensing fibre arm and reference fibre arm. The output light from the two fibres are recombined at the second coupler. The sensing arm is in direct contact with the measurand while the reference arm is protected from external parameters. The measurand acts on the sensing arm and causes a change in its length, its refractive index or both. This produces a change in phase of light wave passing through the sensing arm. The light wave through the reference arm is not affected by the measurand. So there appears a phase difference between the two light waves reaching the second coupler. The intensity of light waves emerging as the output depends on this phase difference. The changes in phase can be detected accurately by interferometer.