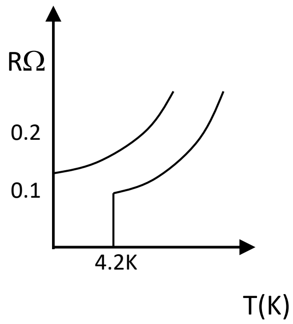
Superconductivity

The phenomenon by which the resistivity of some metals suddenly falls to zero below certain temperature is called transition temperature or critical temperature (T_c) is called superconductivity.



The phenomenon of superconductivity was discovered by Kannerlingh Onnes in 1911. Eg: For mercury (T_c = 4.2K) ; for aluminium(T_c = 1.175K)

Properties of superconductors

(i) Effect of temperature: Transition temperature (T_c)

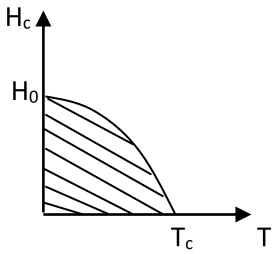
Transition temperature (T_c) is that temperature, below which the resistivity of superconductor falls to zero and above which it acts as a normal conductor.

(ii) Effect of magnetic field: Critical field (H_c)

The minimum strength of magnetic field required to destroy the superconducting nature of a metal at transition temperature is called critical field H_c.

The metal acts as a superconductor, when temperature is less than transition temperature and field is less than critical field. When $H < H_c$ and $T < T_c$, metals acts as a superconductor

- Variation of critical field H_c and temperature is shown below.



$H_c = H_0 \left[1 - \frac{T^2}{{T_c}^2}\right]$ where H_c - critical field at TK;

H_0 - critical field at 0K; T_c - transition temperature

(iii) Effect of current density: critical current- Silsbee effect

- The minimum current that can be passed through a superconducting material without destroying the superconducting property is called critical current I_c. $\mathbf{I_c = 2\pi r H_c}$

where H_c is critical magnetic field and r is radius of superconducting rod (wire)

- The minimum current that can be passed through a superconductor per unit area of cross section, without destroying the superconducting property is called critical current density J_c. $J_c = \frac{I_c}{A} = \frac{2\pi r Hc}{\pi r^2} = \frac{2Hc}{r}$

(iv) Isotope effect:

- Discovered by Maxwell and Reynold in 1950.
- Variation of transition temperature with isotopic mass is called isotope effect.
- Transition temperature and isotopic mass are inversely proportional. $\mathbf{T_c \propto \frac{1}{M^{\alpha}}}$

where M is isotopic mass and $\alpha = \frac{1}{2}$ (a constant)

$T_c \times M^{1/2}$ = a constant

$\mathbf{T_c\sqrt{M}}$ **= a constant**

Meissner Effect

It was discovered by Meissner and Ochenfeld in 1933.

* When a superconductor is cooled below the critical temperature (T_c) in an external magnetic field ($H < H_c$), then the magnetic field lines are expelled out of the superconductor, so the field inside the superconductor is zero. This phenomenon is called Meissner effect.

Flux density , B = $\mu_0(M + H)$ where μ_0 is permeabiltity of free space; M – magnetization

From Meissner effect, **B = 0**

Then $\mu_0(M + H) = 0$ or $M = -H$

Magnetic susceptibility $\chi = \frac{M}{H} = -1$

For diamagnets, magnetic susceptibility $\chi = -1$

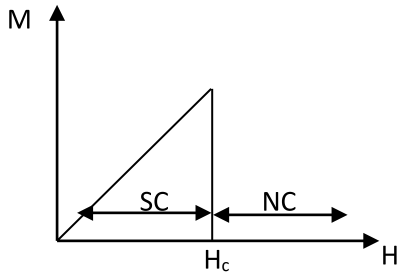
Thus super conductor is a perfect diamagnet.

Types of superconductor

Depending upon on the magnetic properties, superconductors are divided into two types.

Type I superconductors: (Soft superconductor)

* Variation of magnetic field and magnetization for type I superconductor is shown below.



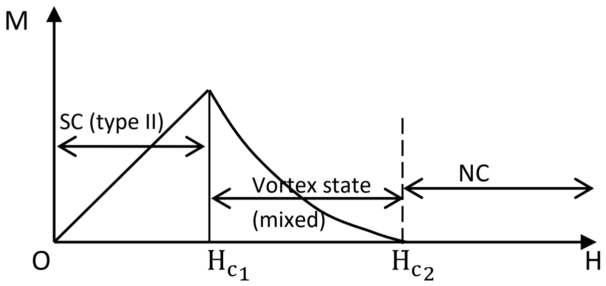
* When field H increases, magnetization M also increases linearly up to H_c .
* At critical field H_c , M suddenly decreases to zero and material changed to normal conductor.
* Transition from superconducting state to normal state is a sudden process.
* H_c is very small. i.e., $H_c \approx 0.1T$ to $0.2T$.

So a small magnetic field is only required to destroy the superconducting nature of the material.

* Eg: Lead, Tin, Aluminium, Mercury.

Type II superconductors: (Hard superconductor)

* Variation of magnetic field and magnetization for type II superconductor is shown below.



* When external field H increases, magnetization M also increases linearly up to H_{c_1} (lower critical field).
* Beyond H_{c_1} magnetic field lines slowly penetrate through the specimen, so magnetization M gradually decreases and is equal to zero at H_{c_2} (upper critical field).
* So from O to H_{c_2}, the material acts as a superconductor.
* The value of H_{c_2} is high . i.e., $H_{c_2} \approx$ 10T to 20T.

    So high magnetic field is required to destroy superconducting nature. So type II superconductor is called hard superconductor.
* Beyond H_{c_2} , the material changes to normal conductor.
* The state in between H_{c_1} and H_{c_2} is called vortex state (mixed state).
* Eg: Niobium, Niobium - tin, Niobium – titanium, Germanium

Uses

* Type II superconductors are used in power generators.
* Because type II superconductors can carry very high current densities, they have great technological importance.
* The high magnetic fields produced by type II superconductors are used in particle accelerators, plasma production, fusion reaction etc.
* This strong magnetic field is used for magnetic levitation.

BCS theory

In 1957, Bardeen, Cooper and Schriffer developed a new theory to explain superconductivity called BCS theory. It is based on the formation of Cooper pair of electrons.

During the flow of current in a superconductor, when an electron approaches a positive ion of the metal lattice, there is a coulomb attraction between the electron and the lattice ion. This produces a distortion in the lattice. This interaction is called the electron-phonon interaction.

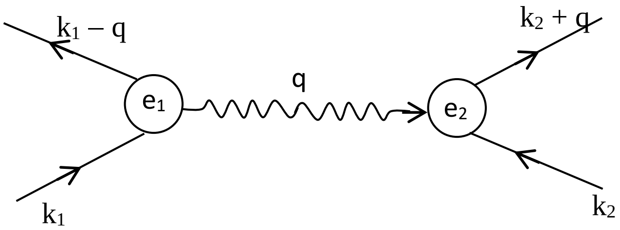
Now a second electron which approaches the distorted positive ion also experiences Coulomb attractive force. Thus there is an interaction of two electrons via the lattice. Because of this interaction, an apparent force of attraction develops between the electrons and they tend to move in pairs.

At normal temperature, the attractive force is too small and pairing of electrons does not take place. Below the transition temperature T_c , the apparent force of attraction reaches a maximum value for any two electrons of equal and opposite spin. This force of attraction exceeds the Coulomb force of repulsion between two electrons and the electrons moves as pairs.

These pairs of electrons formed by the interaction between the electrons with opposite spin and momenta in a phonon field are called **Cooper pair**.

The two electrons in a Cooper pair are exchanging phonons through lattice ions and shown in figure.

Here, an electron $\bar{e}_1$, with a wave vector k_1, emits a phonon and change its state to $(k_1 - q)$. A second electron $\bar{e}_2$ with a wave vector k_2 absorbs that a phonon and change its state to $(k_2 + q)$.



Characteristics of cooper Pairs

* Two electrons in a Cooper pair have opposite momenta and opposite spin.
* The mass of a Cooper pair is 2m where m is the effective mass of the electron. The charge on Cooper pair is -2e.
* As the spin of Cooper pair is zero, the Cooper pair behaves like a Boson, and it does not obey Pauli's exclusion principle.
* At a temperature less than T_c, almost all free electrons are paired as Cooper pair. Above T_c , this pairing is broken.
* The binding energy of Cooper pair is of the order of 10^{-3} - 10^{-4}eV. It is slightly less than twice the energy of free electron.

Coherence length (∈)

The maximum length up to which the states of paired electrons are correlated to produce superconductivity is called coherence length. $\in_0 = \frac{hv_f}{4\pi\Delta}$ where v_f is fermi velocity and 2Δ is energy gap.

Josephson Effect

Josephson suggested that a super current consisting of Cooper pairs can be made to flow across an insulating gap between two superconductors provided the gap is small enough. Such a junction is called Josephson junction. This tunneling of Cooper pairs across the Josphson junction is called Jospehson effect.

DC Josephson Effect:

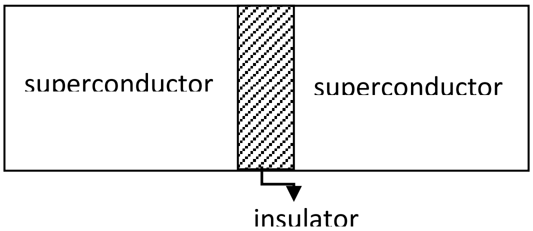
This effect was discovered by Josephson in 1962.

Consider two superconductors separated by a thin layer of (1 - 10nm thickness) insulating material. According to Josephson effect, Cooper pairs could tunnel from one superconductor to the other with no resistance, giving rise to dc current without any voltage across the junction. This is called DC Josephson effect.

Superconductor-insulator-superconductor junction is called Josephson junction.

Current across the junction is $\mathbf{I_s = I_{max} \sin \phi_0}$

where I_{max} - maximum current at zero voltage.



AC Josephson Effect:

When a dc voltage is applied across the Josephson junction, high frequency electromagnetic radiations are produced from the insulating gap and the current produced through the junction is alternating current. This is called AC Josephson effect.

Frequency of emitted radiation $\upsilon = \frac{2eV}{h}$ where 2e - charge of a Cooper pair and V is the applied dc voltage. Josephson current, $I_s = I_{max} \sin(\phi_0 + \delta)$. Here $\delta = \omega t = \frac{2\pi \times 2eV}{h} t = \frac{4\pi eVt}{h}$

Hence $\mathbf{I_s = I_{max} \sin\left(\phi_0 + \frac{4\pi eVt}{h}\right) t}$. This is ac current.

Applications of Superconductors

(i) Superconductors are used to produce a very strong and powerful magnetic field in the order of 20T. This high magnetic field is used in particle accelerators, cyclotrons, controlled nuclear fusion etc.

(ii) Medical application:

* They are used in MRI.
* Superconducting magnetic field is used to remove tumour cell from the healthy cells.
* Group of squids are used for the diagnosis of epilepsy.

(iii) Electronic and small devices:

* Squid
* Frictionless bearing, magnetically controlled superconducting switches, superconductor fuses, breakers, superconducting transformers.

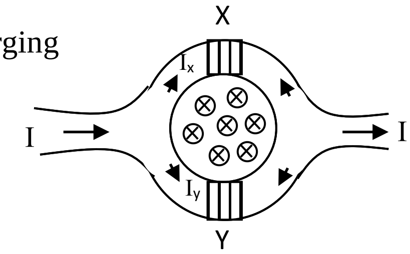
(iv) Computers:

* High capacity and high speed computer chips can be developed with superconductors.
* Used to perform logic and store functions in computers.

(v) Low loss transmission lines can be made with superconductors.

SQUID (Superconducting Quantum Interference Device)

* Squid is a very sensitive instrument used for measuring small changes in magnetic flux.
* It is working on the principle of Josephson effect.
* It consists of superconducting ring with two Josephson junctions in parallel. They are capable of measuring magnetic fluctuations of the order of 10^{-18} T.
* Super current is branched and passing through the insulating junction X and Y . Cooper pairs are tunneling through the junction. The super current emerging from the junction are coherent and they interfere. The net super current changes periodically with the changes in magnetic flux. Even a small change in magnetic flux can be detected accurately.



Applications of SQUID

* SQUIDs are used as very sensitive magnetometer to measure a minute change in magnetic field in the order of 10^{-21}T.
* used to detect the presence of ships, submarines, by detecting a small disturbances in the earth magnetic field.
* It is used to measure the weak magnetic pulse generated by heart, brain in their pathological analysis.
* Principle of SQUID is applied in MRI for the investigation and diagnosis of various diseases.
* Used to explore the oil deposits and other mineral deposits in different parts of the world.

High Temperature Superconductors: HTC superconductor

* Substance having T_c around or below 24K are low T_c superconductors.
* Substance having T_c above 24K are high T_c superconductors.
* All known high temperature superconductors are type II.

  Eg: Yittrium barium Copper oxide (Y-Ba-Cu-O) – T_c = 93K

  Mercury thallium barium calcium copper oxide (Hg-Tl-Ba-Ca-Cu-O) – T_c > 138K

Applications:

* used to produce powerful magnets
* used to detect infrared radiations
* used for diagnosis with the help of MRI.

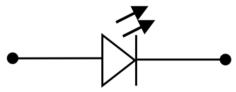
Photonics

Photonics is that branch of Science which deals with the production, control and detection of photons. In Photonics, photons have more or less the same roles as electrons in Electronics. Photonic devices have a number of advantages over electronic devices because of the very high speed of light. So the information transmitted photonically can travel very long distances within a very short time.

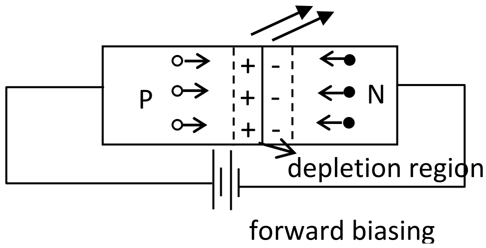
Solid State Lighting (SSL): It is a type of lighting that uses mainly LEDs. This type of lighting has higher efficiency, reliability and environmentally friendly technology compared to the conventional incandescent lighting.

Light Emitting Diode (LED)

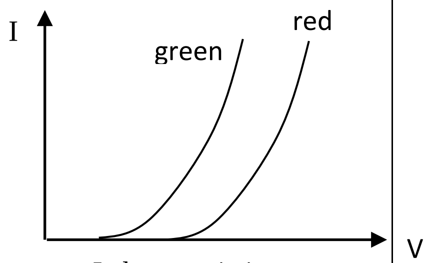
- LED is a heavily doped pn junction diode of suitable materials that emit light when it is forward biased.



symbol



Block diagram of LED



V- I characteristics

Working

- During forward bias, free electrons from conduction band of n region, and holes from valence band of p region moves towards depletion region and recombine together.
- During recombination, electromagnetic radiation is emitted with energy equal to band gap energy.

  $E_g = h\nu = \frac{hc}{\lambda}$ where ν is frequency; c is the velocity of light and λ is the wavelength.
- The band gap energy determines the colour or wavelength of the emitted light.

Applications

- used as indicator light.
- used in remote sensor.
- used for fancy light and decoration.
- used in optical communication.

Advantages

- low power consumption.
- has lower life.
- smaller size.

Disadvantages

- Output is low.
- Intensity of light is small.

* Incoherent light is produced.

Photodetectors

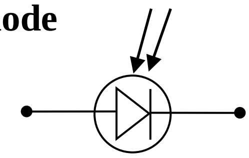
A photodetector has a pn junction which converts light into electrical current. These devices are widely used in optical communication systems.

It is operated in photovoltaic mode or photoconductive mode.

In **photovoltaic mode,** photovoltaic effect is used. i.e., Photovoltaic effect is the production of an emf across the junction of two semiconductors when light is incident at that junction. They are suitable for fibre optic communication systems.

In **photoconductive mode,** when light is incident on a semiconducting material, electron – hole pairs are formed and as a result photocurrent is produced. They are used in devices like remote control devices etc.

Junction Photodiode



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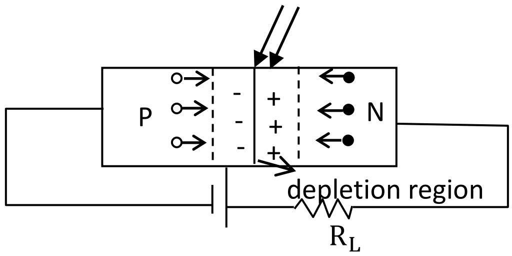
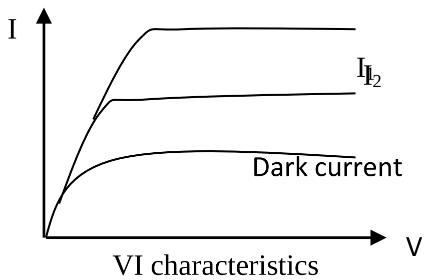


Block diagram

* This is a semiconductor device which converts light into current
* It is operated in the reverse bias

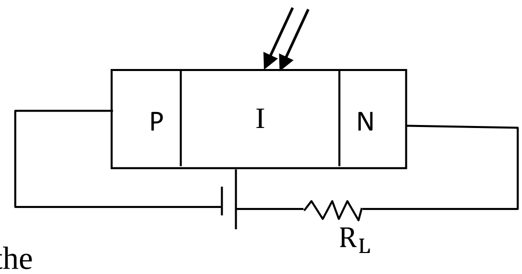
Working:

* In reverse bias condition, a small current is produced due to the flow of minority carriers from P and N sides. This current is called **dark current**.
* If light is incident at the junction (depletion region), large number of free electrons and holes are created.
* Due to the flow of these free electrons and holes, a current is created called photocurrent.
* Magnitude of current depends on the intensity of light incident on it.
* **Uses:** Used in CD players, smoke detectors, remote control devices.
*



VI characteristics

P-I-N Photodiode (P-type – intrinsic – N-type)

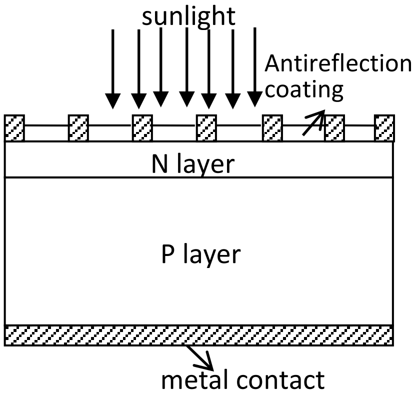


* In PIN photodiode, a thick intrinsic semiconducting layer is inserted between heavily doped P and N region. This is to improve the sensitivity of the photodiode.
* When light is incident on the diode, electrons are excited from the

valence band to the conduction band producing a large number of electron – hole pairs.

* Because of its large width, the intrinsic layer absorbs very large number of incoming photons compared to the P and N regions.
* This increases the photocurrent and improves the efficiency, speed and sensitivity compared to that in photodiode.

Solar cell (Photovoltaic cell)

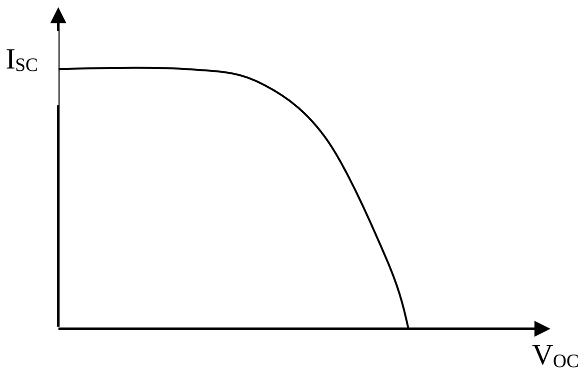


* Solar cells are PN junction diode, it absorbs radiant energy or sunlight and converts it into electrical energy.
* It works on the principle of photovoltaic cell.
* Solar cell consists of a heavily doped p-n junction.
* It has a large surface area to receive large amount of sunlight.
* Top N-layer is very thin, to allow solar radiations to reach the p-n junction.
* Connections are made from bottom P-layer and top N-layer using metal contacts. An antireflection coating is provided on the top layer to prevent loss of light by reflection.

Working

* Solar cell is a p-n junction diode under zero bias. At zero bias, free electrons flow from n-region to p- region. These free electrons will recombine with holes in the p-region and become bound electrons.
* When solar radiation are incident at pn junction, more electron-hole pairs are formed producing an electric current in the external circuit. Thus solar energy is converted into electrical energy.
* Total output voltage can be increased by connecting a number of solar cells in series. A solar panel is an array of a number of solar cells connected together.

VI characteristics of a solar cell



* At open circuit voltage V_{OC} (external resistance R_L is very high), current is zero.
* At short circuit current I_{SC}, current is maximum and terminal voltage will be zero.
* As R_L increases, the current remains constant up to a certain load. Only beyond that load, current decreases. Hence solar cell is called a constant current source.

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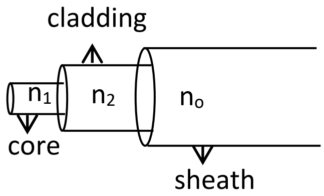
Fibre Optics

* 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.

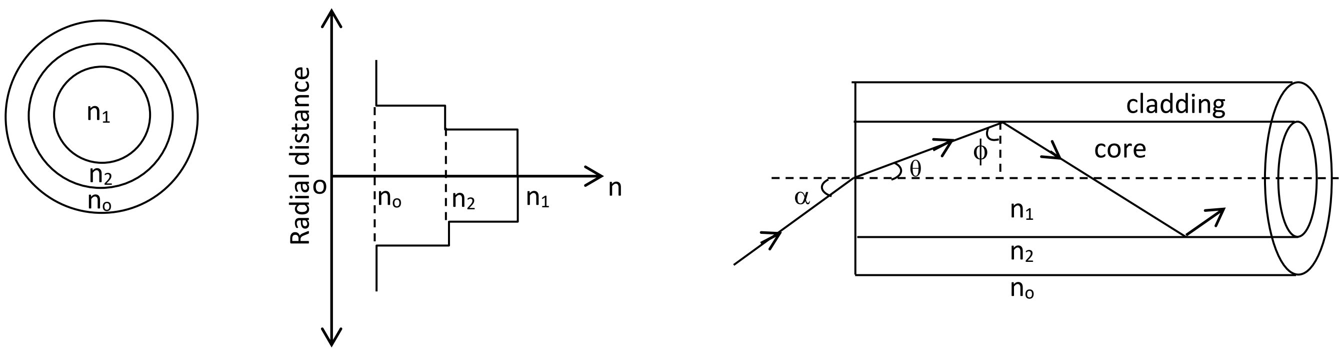
* **Working principle of propagation of light through optic fibre – Total internal reflection**

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.

Types of optic fibre

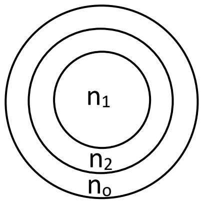
Step - index fibre

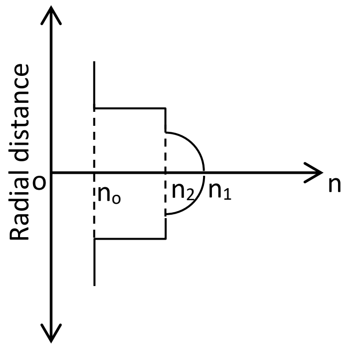
* This type of optical fibre consists of core and cladding of constant refractive index. i.e., n_1 and n_2 are constant and $n_1 > n_2$.
* Shape of index profile (graph with refractive index in x-axis and distance from the axis of fibre in y-axis) is like a step. Hence it got the name step-index fibre.
* Light entering through one face of fibre undergoes repeated total internal reflections at core-cladding.

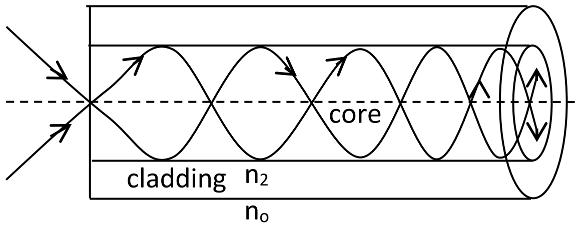


Graded index fibre

- 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.





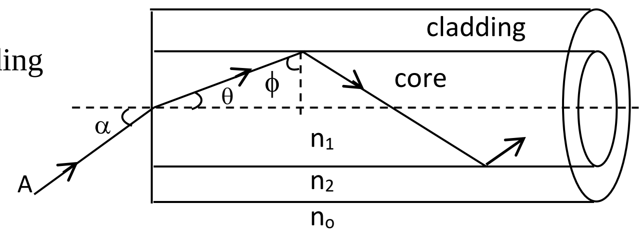


Acceptance Angle (α): It is the angle made by the incident light at one end of the core with its axis.

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** $\boldsymbol{\alpha_m} = \sqrt{\boldsymbol{n_1^2 - n_2^2}}$

  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

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

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

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

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 ${}^2n_1$. or ${}^2n_1 = \frac{n_1}{n_2}$

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

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

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

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

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)

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

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

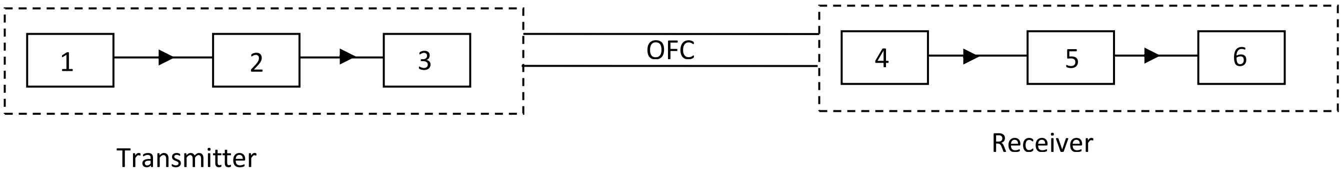
Since $n_1 \approx n_2$, $n_1 + n_2 = 2n_1$

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

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

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.

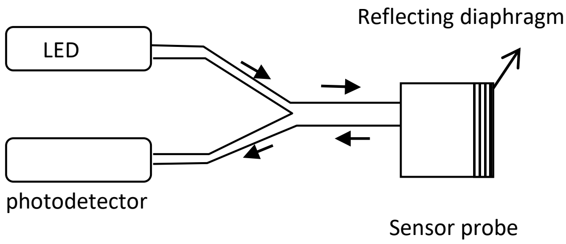
Optical fibre Sensors:

- 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.



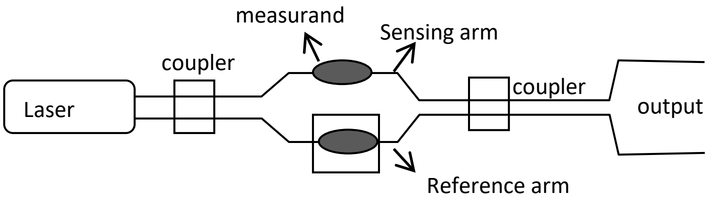
The light from the LED gets reflected from the diaphragm and it is detected by the photdector. Changes in external pressure causes the diaphragm to bend leading to changes in numerical aperture of the fibre.

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.