Engineering Physics (PHT 100-A)

Lecture Notes - Module 5; SuperConductivity

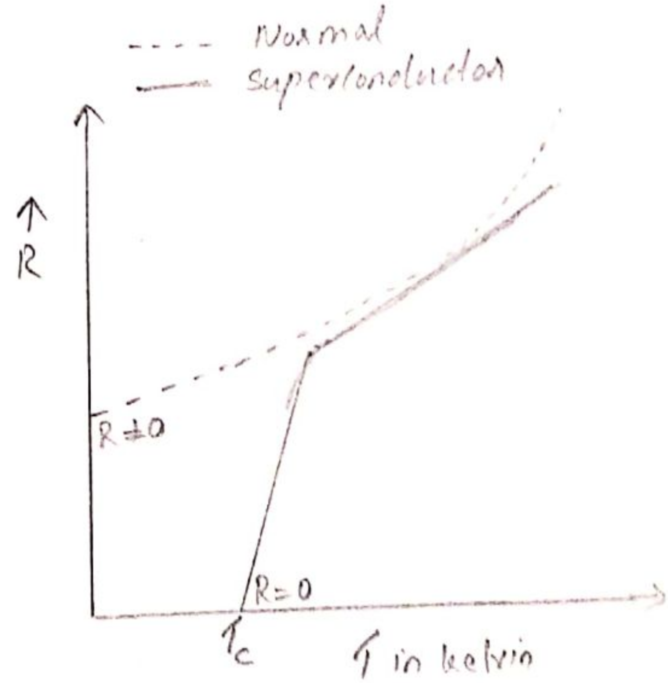
Qn: 1) Explain Superconductivity. Define Critical Temperature (T_c).

"It is the phenomenon of exactly zero electrical resistance in certain materials when they are cooled below a characteristic critical temperature".

For a normal conductor, resistance is a function of temperature. i.e; $R = f(T)$. As temperature decreases, resistance also decreases and at '0K' resistance has a minimum value (non-zero). But when we decrease the temperature, Some materials show zero resistance (infinite conductivity) at certain lower temperature. This phenomenon is called superconductivity and the materials are called superconductors.

The temperature below which resistance is zero is called transition temperature / critical temperature (T_c).

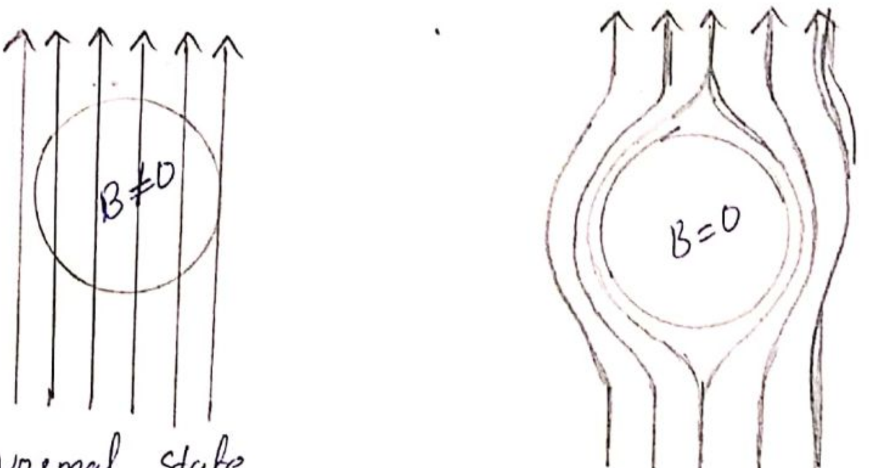
Above this critical temperature, the material will be in the normal state. Superconductivity is a reversible process. i.e; when we increase the temperature, at $T = T_c$ it changes to normal state.



Qu: 2) (a) Explain Meissner Effect. (b) Show that Superconductors are perfect diamagnets.

The Phenomenon of complete expulsion of magnetic lines from a superconductor is termed as Meissner effect.

In 1933, two German Physicists, Meissner and Ochsenfeld kept a specimen in a magnetic field (MF) at a temperature $T > T_c$. Then magnetic lines will enter in the specimen. Now reducing the temperature down to the critical temperature i.e; $T = T_c$, magnetic lines will be suddenly and completely expelled from the specimen. i.e; inside the specimen $B = 0$. This effect is reversible, because when we increase the temperature, at $T = T_c$ lines will again penetrate the specimen and it changes to normal state.



Normal state
$T > T_c$
or
$H > H_c$

Superconducting state
$T < T_c$ and
$H < H_c$

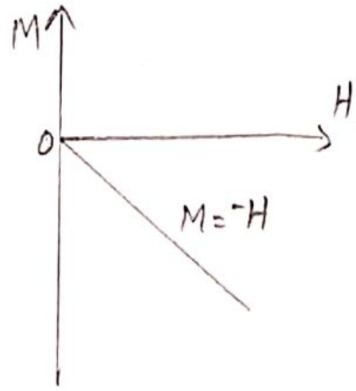
In the normal state, Total magnetic induction inside the specimen is given by

$$B = \mu_0 (H + M) = \mu_0 H (1 + M/H)$$

where $H \rightarrow$ Intensity of external M.F.
$M \rightarrow$ Magnetisation
(Magnetic moment /unit volume)

But $M/H = \chi$; Magnetic Susceptibility.

$\therefore B = \mu_0 H (1+\chi)$



In the superconducting state, $B = 0$

i.e; $\mu_0 H (1+\chi) = 0$

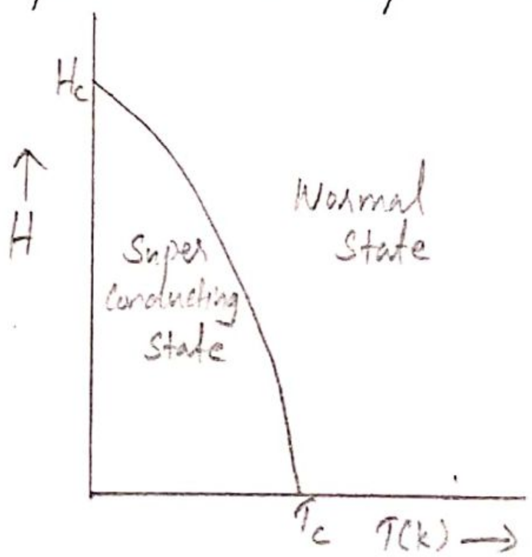
$\mu_0 \neq 0$; $H \neq 0$

$\therefore 1+\chi = 0 \Rightarrow \chi = -1$

This means that the superconductor get magnetised in a direction opposite to the applied field. Thus superconductor is a perfect diamagnet.

Qn:3) What is meant by critical magnetic field. write the equation connecting H_c and T_c.

Keeping the specimen at a temperature $T < T_c$, suppose one increase the strength of external M.F., then at a particular value of 'H' lines of magnetic force will enter the specimen and it changes to normal state. This field is called critical magnetic field (H_c). Value of H_c depends on the temperature of the specimen.



From the fig: it is clear that H_c has maximum value at $T = 0K$.

Critical magnetic field (H_c) at any temperature T can be calculated using the expression,

$$H_c(T) = H_c(0)\left[1 - T^2/T_c^2\right]$$ where $H_c(0)$ is the critical MF at 0K and T_c is the critical temp.

Qu: 4) Distinguish between Type I and Type II Super-Conductors(SC). Give examples.

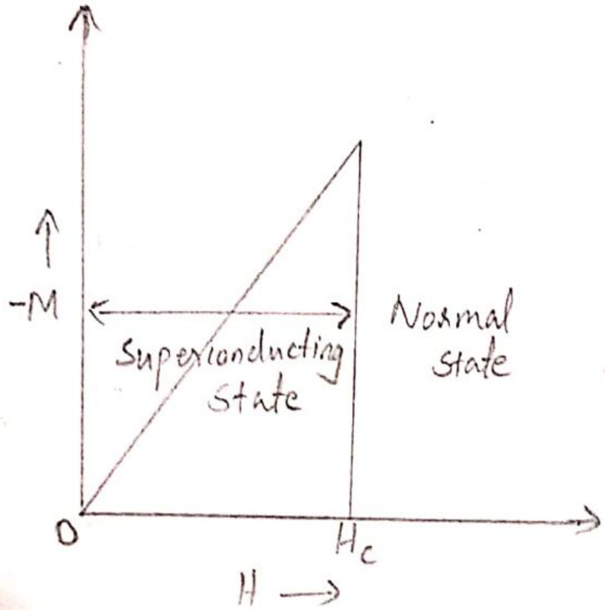
Depending on their magnetisation, superconductors are classified into two types; Type I and Type II superconductors.

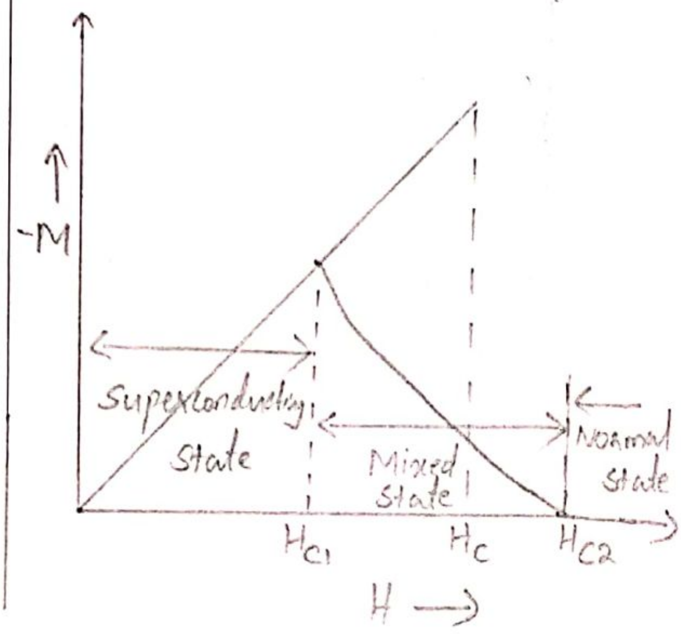
When we increase the strength of external M.F. of a superconductor, at a particular value H_c, the magnetic lines enter into the specimen completely. They are Type I Superconductor. They have a sharp value for 'H_c'. Below H_c they are sc's and above H_c they are normal conductors.

But Type II sc's have two critical fields. H_{c1} and H_{c2}. At H_{c1} lines start to enter and at H_{c2} the process is complete.

A comparison between Type I and Type II sc's are given below.

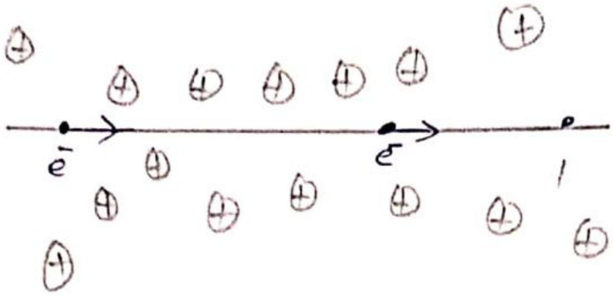
Type I	Type II
• The material loses its magnetisation abruptly	• The Material loses its magnetisation gradually
• Exhibit Complete Meissner effect.	• Do not exhibit complete Meissner effect
• There is only one critical magnetic field.	• There are two critical magnetic fields : lower critical and upper critical fields.
• No mixed state	• Mixed state is present
• They are called soft sc's.	• They are called hard s.c's.
eg: Al, In, Sn, Pb (Aluminium, Indium, Tin, Lead)	eg: Germanium, Niobium (Nb), Vanadium (V)





Qn :5) Write a note on BCS Theory. (What are Cooper pairs?)

To explain Superconductivity, BCS theory was developed by J. Bardeen, L.N. Cooper and J.R. Schrieffer. It is based on the formation of Cooper pair of electrons.



Consider an electron moving through the lattice. The positive ions are attracted to this electron due to coulomb attraction. As a result the positive ions get displaced from their mean position. This interaction is called 'electron - phonon interaction'. Now the region of increased charge density (+ve) attracts another electron and it also experiences a Coulomb attractive force. We can consider this process as interaction of two electrons through lattice. Because of this interaction an apparent force of attraction develops between the electrons and they tend to move in pairs called cooper pair.

Thus cooper pair is defined as a pair of electrons formed by the interaction between electrons with opposite spin and momenta in a phonon field.

At normal temperatures the attractive force is too small and pairing of electrons doesn't takes place. But, below the transition temperature (T_c) the force of attraction between electrons reaches maximum for any two electrons of equal and opposite spin.

- Spin of a cooper pair is zero. So it is a boson (single electron is a fermion).
- The dense cloud of cooper pairs move together in the same direction. As a result the substance possesses infinite electrical conductivity i.e; zero resistivity.
- Due to the very low pairing energy of the cooper pair, a small rise in temperature can destroy the cooper pair. As a result of this material changes to normal state since motion of normal electrons lead to resistance.

Qu: 6) What are high temperature SC's. Give examples. (HTSC)

To achieve superconductivity, we have to maintain very low temperature. It is very difficult and expensive. This marks the need for SC's with high T_c values. If we could achieve a T_c of about 300k then the need of cryogenic fluids can be eliminated.

The Superconductors with high value of T_c are called HTSC's. All known HTSC's are Type II.

In Yttrium compounds a critical temperature of 130 K is detected. The discovery of a SC. with transition temperature above 77K was a remarkable development. This is because we can use relatively inexpensive liquid nitrogen as a coolant to maintain the low temperature.

eg:

Bi-Sr-Ca-Cu-O (BSCCO Sc's) ; $T_c = 107K$

Tl-Ba-Ca-Cu-O (TBCCO ") ; $T_c = 125K$

Hg-Tl-Ba-Ca-Cu-O (HTBCCO ") ; $T_c = 138K$.

Qu: 7) Give some applications of Sc's.

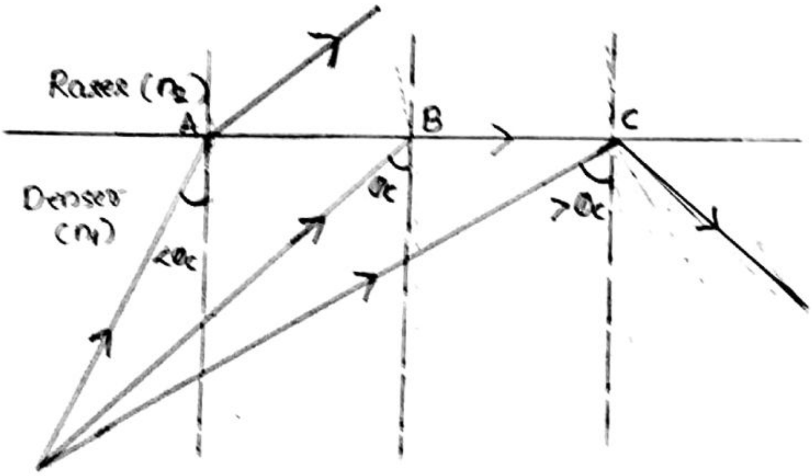
Superconductors possess wide ranging applications from large scale devices to small scale electronic devices.

- Large scale superconducting magnets are used in
  - → Magnetohydrodynamic (MHD) power plants.
  - → Controlled fusion and energy storage
  - → Levitated trains for a rapid transit system (Maglev)
- Low loss transmission lines and transformers can be made with sc's.
- Sc's are used to perform logic and store function in computers.
- Superconducting coils are used to develop small size electric generators.
- High capacity and high speed computer chips
- Cryotron, a fast electrical switching system, utilises superconductivity for its operation.
- SQUID - a superconducting device, that possess many applications in scientific, Industrial, medical and communication fields.

FIBRE OPTICS

① Explain propagation of light through optic fibre cable.

Ans: Transmission of light in an optical fibre is by the principle of total internal reflection. Consider a beam of light travelling from a denser medium to a rarer medium. If the angle of incidence is greater than critical angle (θ_c), the light ray gets reflected back to the same medium.



In figure,

At A, $i<\theta_c$ → normal refraction

At B, $i=\theta_c$ → ray just grazes along the surface of sepn.

At C, $i>\theta_c$ → Total internal reflection (TIR)

Applying Snell's law at B,

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

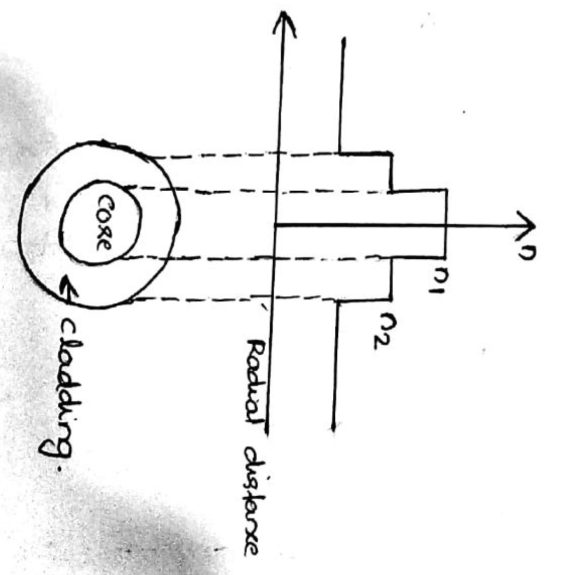
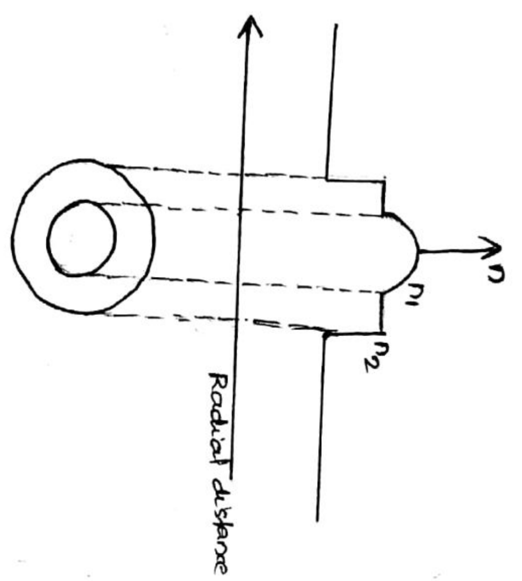
$$\sin \theta_c = \frac{n_2}{n_1}$$

$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$, is the critical angle.

An optic fibre is fabricated according to the principle of TIR. Light incident at the core-cladding boundary at an angle $> \theta_c$.

② Distinguish between step index and graded index fibres.

Ans :-

step index fibre	Graded index fibre.
① Core has a constant refractive index (n_1) throughout.	① Refractive index of core is gradually decreasing outwards.
② At the core-cladding boundary refractive index decreases from n_1 to n_2 suddenly	② At the core-cladding boundary, the difference of refractive indices is small
 	

③ Used to transmit single and multimode signals	③ Mainly used for transmitting multimode signals.
④ Used for long-distance transmission applications	④ Used for short distance transmission applications
⑤ Light rays are propagated into the core in a zigzag manner.	⑤ Light rays are propagated into the core either spherical or helical form.

③ Define acceptance angle and numerical aperture.

Ans:-

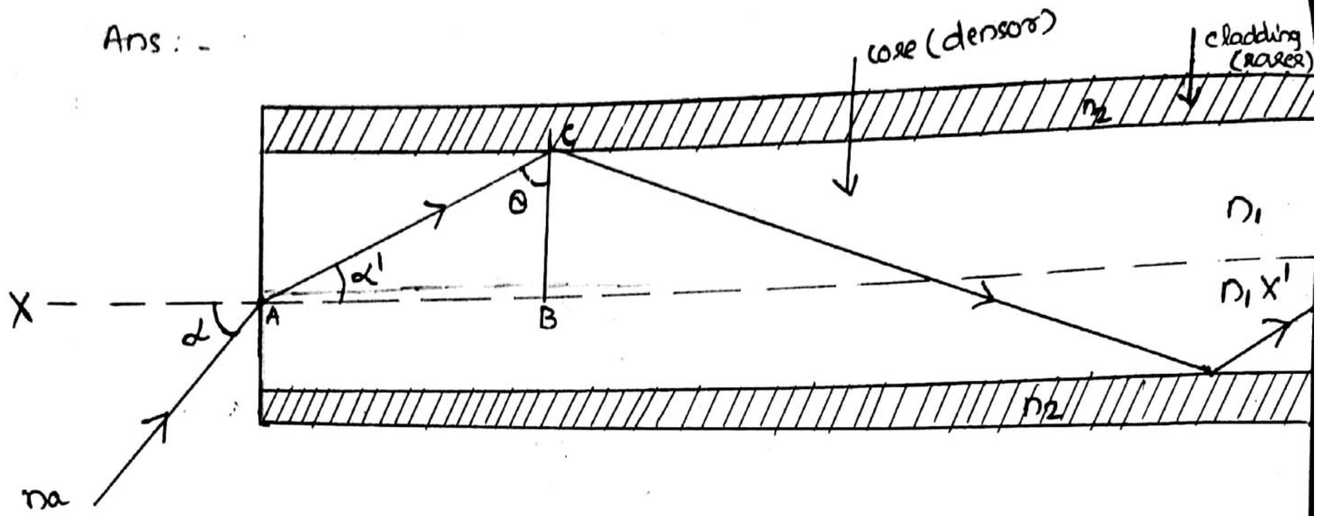
NA of an optical fibre is the measure of its lights gathering capacity. It is also defined as the sine of acceptance angle.

Numerical aperture = $\sin \alpha_m$

The maximum angle of incidence 'at or below' which the light rays undergo total internal reflection is known as acceptance angle (α). IF the angle of incidence is greater than this angle, the will be no TIR).

(4) Derive an expression for NA of a step index fibre.

Ans :-



Consider a step index fibre with core of refractive index n_1 and cladding of refractive index n_2 ($n_2 < n_1$). The end face is cut at right angles to the axis of the fibre (In fig XX' is the axis). Light enter through one end from air into the core at an angle 'α'. After refraction (angle of refraction is α') the ray incident at the core-cladding interface and an angle θ ($\theta > \theta_c$, critical angle). It undergoes TIR and returns to the core. After a number of reflections light reach at the other end of optic-fibre.

At the left end of the fibre (in figure), we can write Snell's law as

$$\frac{n_1}{n_a} = \frac{\sin \alpha}{\sin \alpha'}$$

$$n_a \sin \alpha = n_1 \sin \alpha' \quad \text{—— (1)}$$

For TIR to take place in the minimum value of $\theta = \theta_c$, the critical angle.

From fig, in ΔABC, $\alpha' + \theta = 90$

$\therefore \alpha' = 90 - \theta$

when $\theta = \theta_c$, $\alpha' = \alpha'_{max}$ and

$\alpha = \alpha_{max}$

ie, $\alpha'_{max} = 90 - \theta_c$ —— (2)

$n_1 \rightarrow$ Refractive index of core

$n_a \rightarrow$ refractive index of outer medium $= 1$ for air

$n_2 \rightarrow$ refractive index of cladding

$\alpha' \rightarrow$ angle of refraction

$\theta_c \rightarrow$ critical angle.

Now eqn. (1) becomes,

$n_a \sin\alpha_m = n_1 \sin\alpha'_m = n_1 \sin(90 - \theta_c)$

ie $n_a \sin\alpha_m = n_1 \cos\theta_c$ —— (3)

But from the principle of TIR, we know that

$\sin\theta_c = \frac{n_2}{n_1}$ ie, $\cos\theta_c = \sqrt{1 - \frac{n_2^2}{n_1^2}} = \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}$

Substituting this value of $\cos\theta_c$ in eqn. (3)

$n_a \sin\alpha_m = n_1 \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}} = \sqrt{n_1^2 - n_2^2}$

For air $n_a = 1$ ie $\boxed{\sin\alpha_m = \sqrt{n_1^2 - n_2^2} = NA}$ —— (4)

The acceptance angle $\alpha_m = \sin^{-1} NA$

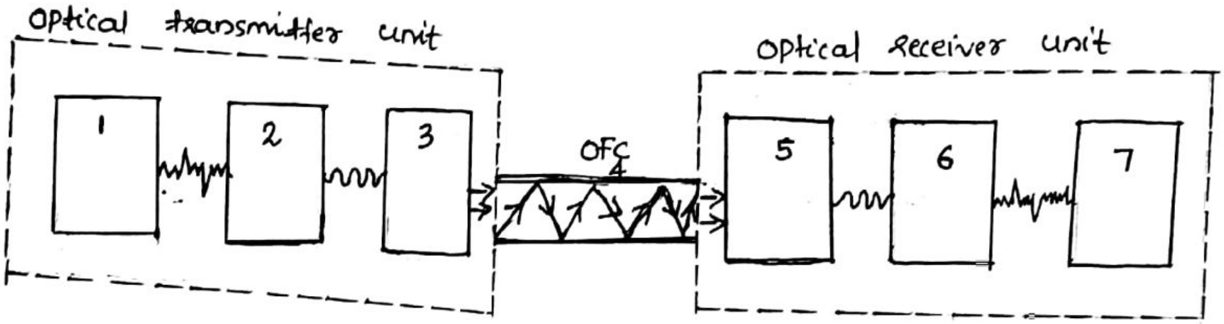
$= \sin^{-1}\sqrt{n_1^2 - n_2^2}$

⑤ With a block diagram explain the working optic fibre communication system.

Ans:-

The major components are.

1) optical transmitter 2) optical fibre transmission line and ③ optical receiver.



Components and functions.

1. Subscribers telephone : Sound is converted to electric signal.

2. Encoder : It converts electrical signals to coded digital pulse (analogue to digital converter)

3. Optical transmitter : Semiconductor laser or LED is used. Here according to the signals light source turns on and off. Hence light source is modulated with the signals to be transmitted.

4. OFC : The modulated optical signal is transmitted through OFC to the receiver unit.

5. photo detector : Converts optical signals back to electrical pulses (photodiodes can be used for this)

6. Decoder : Decodes digital pulse to analogue signal.

7. Receiver's telephone : Electric signal is converted to sound. ie sound is reproduced.

Like conventional cables, optic fibre cable also suffers dispersion and attenuation to some extent. But there are so many advantages when compared with conventional cables.

(6) What are the advantages of OFC system.

Ans:-

1. Small size and weight : Due to small size they occupy very little space.

2. Very high bandwidth and hence higher information carrying capacity.

3. Immunity from electrical interference caused by lightning, electric motors and other electric noise sources.

4. Immune to cross talk between cables. So we can use a number of cables together.

5. Easy and safe to install and maintain.

6. Signal security : It is difficult to tap information during transmission.

7. Flexible and mechanically strong.

8. They are cheaper. Made from silica (SiO_2) which is abundant on earth.

(7) What are fibre optic sensor? Explain identify and phase modulated sensors?

Ans:

Sensor can be defined as a device which has the role of converting a change in the magnitude of one physical parameter into a change in magnitude of a second different parameter which can be measured more conveniently and accurately.

Sensors are mainly used to measure pressure, Temperature, Refractive index of a liquid, PH value of liquid, electric current, displacement, acceleration, electric and magnetic field etc.

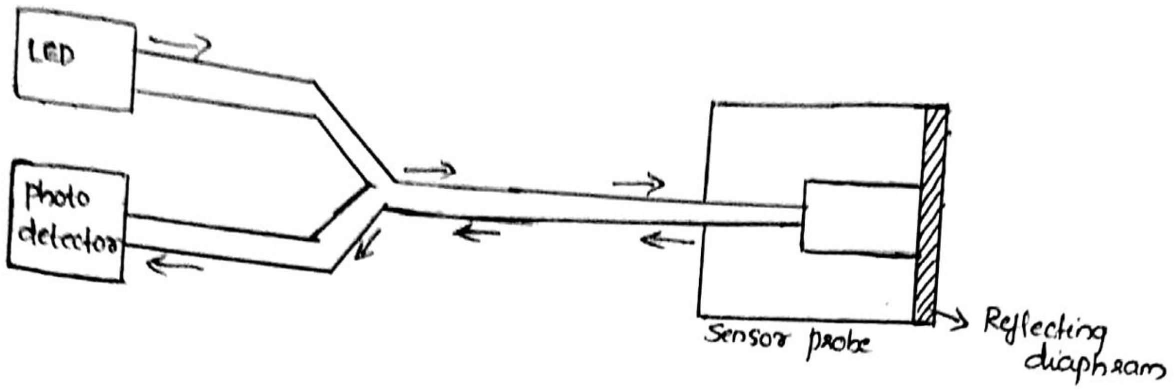
There are mainly 4 types of sensors. Intensity modulated, phase modulated, wavelength - modulated and polarisation modulated.

Out of these 4 types the first two are widely used.

Intensity modulated sensor.

In this sensor the measured quantity causes a change in intensity of the received light and we can record the change in intensity and thereby get the correct measurement.

eg:- pressure sensor.



The main parts are a light source, a sensor probe, fibre cable and a photodetector. Here LED is used as source of light. probe is in the form of reflecting diaphram. Light gets reflected from the diaphram and it is detected by the photodetector. Change in pressure causes bending of diaphram. This will change the numerical aperture of the fibre. This produces a modulation in the intensity of light transmitted by the fibre.

These type of sensors are used for monitoring pressure changes in arteries, bladder etc. Also used in chemical industry (for monitoring gaseous reactants)

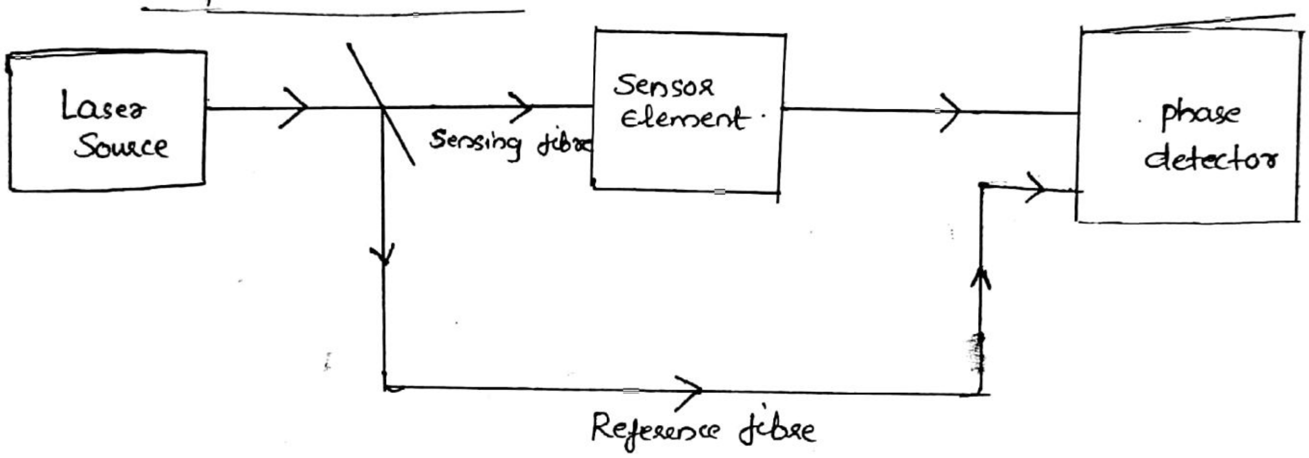
phase modulated Sensor.

In these sensors the external changes cause a change in the phase of light. This phase change can be measured by interferometric technique. eg. Temparature measurements.

Light from highly monochromatic source is split equally by a beam ~~of~~ splitter and sent through the sensing fibre and reference fibre.

As the sensor element is heated the fibre elongates and the path travelled by the light increase through it. This produces a phase difference between two lights reaching the detector. The phase change can be detected by using interferometer. It is related to the temparature. We can also measure pressure, strain, magnifield etc.

Temparature Sensor.



⑧ Give Some applications of optic fibre in the following fields.

a) Industrial & Technological.

b) Medical.

Ans:-

a) Industrial & Technological. applications

1. Optical fibres are used as sensors to measure or monitor displacement, pressure, temparature, flow rate, liquid level, chemical composition etc.

2. Optical fibres has wide applications in security alarm system, electronic instrumentation system, industrial automation etc.

3. They are used in Cable TV, CCTV, LAN, WAN etc.

4. They are used for signalling and decorative purposes

5. Fibre optic systems maintain high secrecy, so they are used in difence communication systems in controlling ships, aircrafts, submarines, missiles etc.

b) Medical applications.

1. Optical fibre are used as biosensors to measure and monitor many significant parameters in the human body, including temparature, blood pressure, blood flow, oxygen saturation levels and to estimate the proportion of haemoglobin in the blood.

2. They are used to test the tissues and blood vessels which are far below the skin.

3. They are also used to examine heart, pancreas etc.

4. Endoscope is a tubular optical instrument using optical fibre to visualise the internal parts of human body without performing surgery. There are different types of endoscopes.

5. Gastroscope is used to examine the stomach and to photograph tumors and ulcers.

Problems

1. A fibre cable has an acceptance angle of 30° and a core of refractive index 1.4. Calculate the refractive index of cladding.

(Hint: $NA = \sin\alpha_m = \sqrt{n_1^2 - n_2^2}$, $n_1 = 1.4$, $\alpha_m = 30^\circ$. Ans. $n_2 = 1.308$)

2. Calculate the fibre acceptance angle for a step index fiber with $n_1 = 1.53$ and $n_2 = 1.5$

[Hint: $\sin\alpha_m = \sqrt{n_1^2 - n_2^2}$ Ans: $\alpha_m = 17.6^\circ$]

3. An optical fiber has a NA of 0.2 and cladding of refractive index 1.59 Determine refractive index of core and the acceptance angle in water. μ of water is 1.33

[Hint: $NA = \sqrt{n_1^2 - n_2^2}$ and $\sin\alpha_m = \dfrac{\sqrt{n_1^2 - n_2^2}}{n_a}$. $n_a = 1.33$

Ans: $n_1 = 1.602$, $\alpha_m = 8.7^\circ$]