LASERS

LASER is the acronym for Light Amplification by Stimulated Emission of Radiation. Laser is a light source but quite different from conventional light sources. In conventional light sources different atoms emit radiations at different times and in different directions and there is no phase relationship between them Light from an incandescent lamp is an example of incoherent radiation and it is spread over a continuous range of wavelengths

The characteristics of laser light :

i) The light is coherent which means that waves all exactly in phase with one another It is possible to observe interference effects from two independent lasers

ii) The light is monochromatic (same frequency) in the visible region of the electromagnetic spectrum. The spread in wavelength ($\Delta\lambda/\lambda$) is extremely small. Ordinary incandescent light is spread over a continuous range

iii) The beam is very narrow, highly directional and does not diverge . The directionality of the laser beam is expressed in terms of divergence $\Delta\theta = (r_2 -- r_1)/ (D_2 -- D_1)$ where r_2 and r_1 are the radii of laser beam spots at distances D_2 and D_1, respectively.

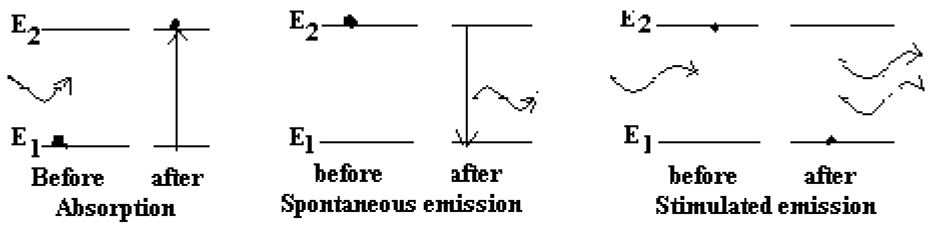
iv)The laser beam is extremely intense. The intensity of laser beam is expressed by number of photons coming out from the laser per second per unit area. It is about 10^{22} to 10^{34} photons /sec/sq cm

Lasers are based on the concept of amplification of light by stimulated emission of radiation by matter. Einstein predicted this possibility of stimulated emission in 1917 but the first laser was built bt T.A.Maiman in 1960. To explain the working principle of a laser, let us consider the interaction of photons with atoms. Let us consider a single isolated atom that can exist in only one of two states of energies E_1 and E_2. An atom can move from one energy state to another when it receives or releases an amount of energy equal to the energy difference between those tow states. There are three ways in which this atom can be caused to move from one of its two allowed states to the other ; i) absorption ii) spontaneous emission and iii) stimulated emission

Absorption: If a photon of energy $hv = E_2 – E_1$ interacts with an atom initially in the ground state of energy E_1 then the atom absorbs the incident photon and the atom will move to the upper energy state or the excited state E_2. This process is called absorption. $\mathbf{A + h\upsilon = A^*}$ where A is the atom in the lower energy state and A* is the excited state of the atom.

Spontaneous emission.: The excited state is inherently unstable because of a natural tendency of atoms to seek the lowest energy configuration. Therefore the atom in the excited state de-excites to the ground or lower excited state on its own accord with a mean time τ emitting a photon of energy $hv = E_2 – E_1$ in this process. This process is **known as 'spontaneous emission' because it is not triggered by any outside influence. $A^* = A + h\upsilon$. Atoms reside in the excited state only for a certain duration of time Δt which is inversely related to the width of the energy level through Heisenberg's uncertainty principle. In spontaneous emission, different atoms of the medium emit photons at different times randomly and in different directions. Hence there is no phase relationship among the emitted photons and so they are incoherent. The light from the glowing filament in an ordinary light bulb is an example of spontaneous emission**

Normally, the mean life of excited atoms before spontaneous emission occurs is $\sim 10^{-8}$ sec. However, there are some states for which the mean life is much longer, perhaps as long as $\sim 10^{-3}$ sec. Such states are called **metastable states** which play an essential role in laser operation



Stimulated emission: The atom in the excited state need not wait for spontaneous emission to occur. The alternative mechanism by which an excited atom can make a downward transition and emit radiation is stimulated emission The interaction of a photon of energy hv = $E_2 – E_1$ with an excited atom forces the excited atom to drop to the lower energy state E_1 and gives off a photon of energy hv .The phenomenon of forced emission of photons is called **'Stimulated Emission'**

$$A^* + h\upsilon = A + 2\,h\upsilon$$

There are now two photons, one the incident photon and the other the emitted photon. In the case of stimulated emission, since the process is forced by the incident photon , the emitted light by the atoms is in phase with that of the incident photon. The emitted photon is in every way identical to the triggering or stimulating photon. It has the same energy, direction, phase and polarization. The emitted radiation is monochromatic and coherent.

One photon induces an atom to emit a second photon.. These two photons traveling along the same direction de-excites two more atoms producing a total of four photons. In this way a chain reaction of similar processes could be triggered by such stimulated emission event. Laser light is produced in this way

Population of energy levels and thermal equilibrium:

We have seen the stimulated emission of a photon from a single atom. In the usual case, however , many atoms are present. Given a large number of atoms, in equilibrium at a certain temperature T, we may find how many atoms are in level E_1 , and how many atoms are present in level E_2.. Boltzman showed that the number of atoms N_x in the level whose energy E_x is given by

$$N_x = C\, e^{-E_x/kT} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(\,!\,)$$

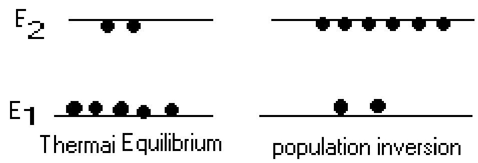
in which k is the Boltzman constant and C is another constant determined by the total number of atoms in the gas. The quantity kT is the mean energy of agitation of an atom at temperature T (Kelvin). The higher the temperature, the more atoms will acquire energy by thermal agitation (atom-atom collisions) to the level E_x.

If we apply eqn (1) to the two energy levels E_1 and E_2, and divide, the constant C cancels out and we find, for the ratio of the number of atoms in the upper energy level E_2 to the number in the lower energy level E_1

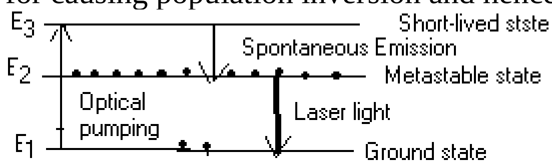
$$N_2 / N_1 = e^{-(E_2 - E_1)/kT}$$

Because $E_2 > E_1$, the ratio N_2 / N_1 is less than unity , which means that there will always be fewer atoms in the higher energy level than in the lower energy level E_1. This state is called the normal state. In a normal state, since more number of atoms are in the lower energy state than in the higher energy state , absorption is more probable than stimulated emission.

Population Inversion : Usually the number of atoms (N_1) present in the ground state (E_1) is larger than the number of atoms (N_2) present in the higher energy state (E_2). **If we can create a situation in which the number of atoms(N_2) in the higher excited state are more than the number of atoms (N_1) in the lower excited state, then such a situation is called** ***'population inversion'.*** **This is a non-equilibrium situation..** So if population is inverted, then the dominant process would be stimulated emission and results in the amplification of light or laser light



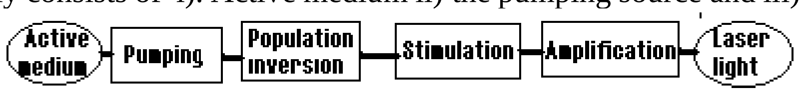
A minimum of three energy levels are required to cause population inversion between two levels. The ground state is the most populated and stable (long life time) state. Upper energy levels are normally unstable in the sense that they have short lifetimes. They decay to the lower energy states instantaneously. To cause population inversion, what is required is an upper energy level must have a reasonably long life time. Such a state is called a 'metastable state' So a ground state or a lowest energy state, an upper energy state and an intermediate metastable state are the three essential states required for causing population inversion and hence laser action



To achieve population inversion, atoms from the ground state E_1 are 'pumped' up to an excited state E_3 by some mechanism such as optical pumping or electrical discharge. The atoms decay spontaneously (in a time of approximately 10^{-8} sec) from the energy level E_3 to the lower energy state E_2. The state E_2 must be a metastable state, then the atoms stay over a very long duration of the order of milliseconds in the energy state $E_{.2.}$ The state E_2 then become more heavily populated than state E_1 and thus providing the needed population inversion. Spontaneous emission from E_2 to E_1 will generate the required photons that can trigger an avalanche of stimulated emission events from state E_2, and we have amplification of light or laser light

Laser requirements:

A laser essentially consists of i). Active medium ii) the pumping source and iii) optical resonator



Active medium : A medium in which light gets amplified is called an active medium. The active medium consists of a collection of atoms in solid, liquid or gaseous form and are responsible for stimulated emission and consequent light emission

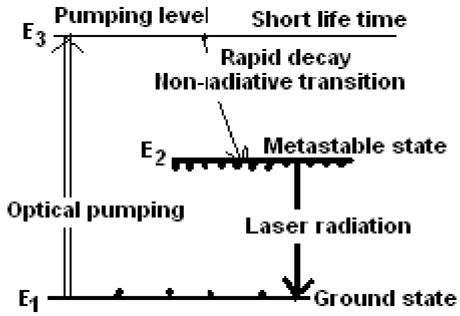
Pumping source : The process of supplying energy to the medium with a view to transfer it into the state of population inversion is known as pumping. Most commonly used techniques are i) optical pumping ii) electrical discharge and iii)direct conversion.

'Optical pumping' is the absorption of light energy from an intense continuous spectrum source that is placed so that it is surrounded by the lasing medium. In optical pumping, a light source such as a flash discharge tube is used. This method is adopted in solid state lasers such as ruby laser. In electrical discharge method, the electric field causes ionization of the medium (gas) and raises to the excited state .This technique is used in gas lasers such as He-Ne laser. In semiconductor diode laser , a direct conversion of electric energy into light energy takes place.

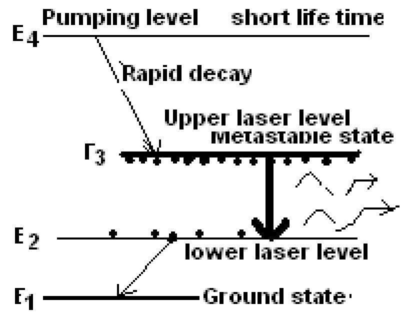
Optical resonator: Although population inversion is a necessary condition for light amplification, it alone is not sufficient to make the stimulated emissions dominate the other processes. A pair of parallel mirrors with the laser material in between helps to maintain a large radiation density in the active material. Such a device is called 'optical resonator'.

Three level laser:

A ground state, an upper energy state and an intermediate metastable are the three essential states for causing population inversion and hence laser action. The transition from E_3 to E_2 is a non-radiative transition ie., it does not cause emission of radiation.. To achieve population inversion, more than half the ground state atoms must be pumped to the upper state. Therefore high pumping power is required in the three level laser.



Threelevel laser



Four level laser

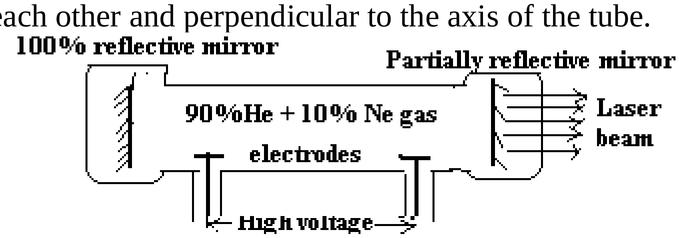
Four level laser:

In a four level laser, the laser action takes place between the metastable state and an intermediate state above the ground state Here the atoms are lifted from the ground state E_1 to the highest state E_4 of the four energy levels. The atoms decay from the energy level E_4 to the metastable state E_3 and the population of this state grows rapidly. If the life time of the E_4 level is short and that of the E_3 level is long, a population inversion can be achieved and maintained with moderate pumping. Since the ground level E_1 is not the lower laser level , there is no need to pump more than one-half of the population to the level E_4. Since E_2 is the lower laser level it is relatively easier to maintain population inversion between E_3 and E_2 continuously with moderate pumping and get continuous output. For this to happen level E_2 must decay very fast : otherwise four level laser will work in pulsed mode only. He –Ne laser is a four level laser working in continuous working mode. The advantage of the four level laser is that the maintenance of population inversion between the metastable state and the lower energy state is much easier because the state E_4 has short life time and the atoms fall to the ground state quite rapidly from this state. So a modest pumping rate would be sufficient .

Helium-Neon Laser

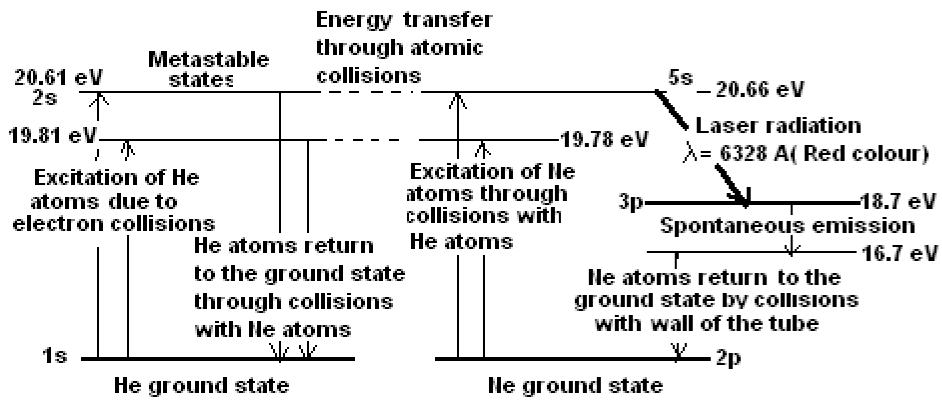
He-Ne laser is an inexpensive laser that is used by many laboratories in teaching and research.

Construction : The He – Ne laser consists of fused quartz tube with a diameter of about 1.5 cms and length of about 80 cm. The tube is filled with a mixture of helium and neon gases in the ratio of 10:1 typically at a pressure of the order of 10^{-3} atmospheres (10^{2} Pascals) . He atoms provide an efficient excitation mechanism for Ne atoms. The gas is sealed in the glass tube provided with two electrodes. The two electrodes in the quartz tube are connected to a high voltage power supply to produce electric discharge in the gas. He atoms are excited by a dc or RF discharge created by applying a high voltage 2 to 4 KV across a gas filled tube of narrow diameter. At one end of the tube, there is a perfect reflector while at the other end there is a partial reflector . The two reflectors are parallel to each other and perpendicular to the axis of the tube.



He-- Ne gas Laser

Working : Helium- Neon laser employs a four - level pumping scheme When a sufficiently high voltage is applied between the electrodes, an electric discharge occurs. The high frequency electric field ionizes some of the atoms in the mixture of helium and neon gases. The He atoms are more readily excitable than Ne atoms because they are lighter. Since the electrons have smaller mass, they acquire higher velocity due to the electric field. The energetic electrons excite ionized helium atoms through collisions to the 20.61 eV and 19.78 eV metastable (long half-life, 5 x10 $^{-6}$ sec) states.



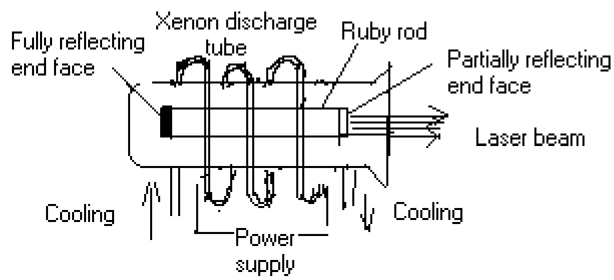
He atoms excited to these levels spend sufficiently long period of time before getting de-excited .Because of restrictions imposed by conservation of angular momentum, a helium atom with an electron excited to a 2s state(20.61 eV) cannot return to the ground state (1s) by emitting a 20.61 eV photon. Helium atoms 'pile up' in the metastable 2s state, creating a population inversion relative to the ground state..

However, the excited helium atoms can lose their energy by energy exchange collisions with neon atoms that are initially in the ground state. A helium atom, excited to a 2s state 20.61 eV above its ground state and possessing a little additional kinetic energy can collide with a neon atom in a ground state, exciting the neon atom to a 3s excited state at 20.66 eV and dropping the helium atom back to a ground state. Such an energy transfer can take place when the colliding atoms have identical energy levels. The 20.66 and 19.78 eV energy levels in Ne correspond to 20.61 and 19.81 eV energy levels in He. Thus the electric discharge through the gas mixture continuously populates the Ne atoms. Thus we have the necessary mechanism for a population inversion in neon, with more neon atoms in the 20.66 eV state than the 18.7 eV (2p) state. **The purpose of He atoms is to help achieve a population inversion in the Ne atoms which acts as the lasing medium. The population inversion is maintained because i) metastability of 20.61 eV level ensures a ready supply of neon atoms in 20.66 eV level ii) atoms in 18.7 eV level decay rapidly to the Ne ground state by spontaneous emission. When a narrow tube is used,** the neon atoms in the 16.7 eV level collide with the walls of the tube and get de-excited to the ground state.

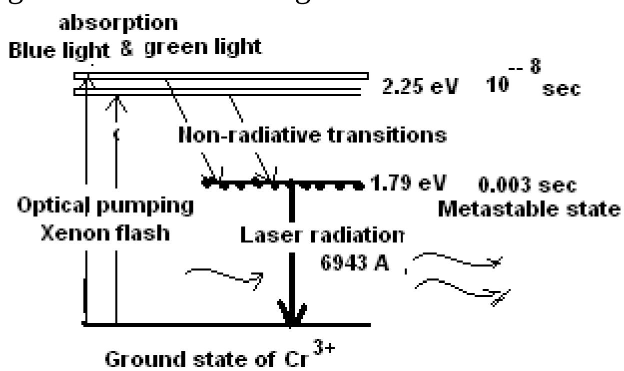
Stimulated emission from the 20.66 eV level to a 18.7 eV level results in the emission of highly coherent beam of light at 632.8 nm or 6328 A (red laser). Stimulated emission photons that are parallel to the axis, can be made to move back and forth through the discharge tube many times by successive reflections from mirrors M_1 and M_2 .This makes the stimulated emission from as many excited states as possible. A chain reaction thus builds up rapidly in this direction accounting for the inherent parallelism of the laser light. Mirror M_2 s partially transparent, so a portion of the beam emerges at each reflection to form an intense beam. The net result of all these processes taking place in a laser is a very intense, almost parallel, and highly monochromatic and spatially coherent rays. The laser beam is continuous and power output is about 50 mW

Ruby Laser: (Solid state laser)

A ruby laser is a three level solid state laser. A **Ruby (Al_2O_3 Cr_2O_3)** is a crystal of aluminum oxide Al_2O_3 with 0.05 % weight of chromium oxide Cr_2O_3. in which some of the Al $^{3+}$ ions are replaced by chromium Cr^{3+} ions .These Cr ions are responsible for the pink colour . A Cr^{3+} ion has a metastable level whose life time is about 0.003 sec. The xenon flash lamp excites the Cr^{3+} ions to a level of higher energy from which they fall to the metastable level by losing energy to other ions in the crystal



Construction : Ruby is taken in the form of a cylindrical rod and of several centimeters length and about 5 millimeters in diameter. The end faces of the rod are parallel and perpendicular to the axis of the rod. The faces are highly polished and then silvered in such a way that one end face is fully reflecting while the other end is partially reflecting and serves the purpose of optical resonator.. The rod is surrounded by a helical xenon flash tube that provides the pumping light to raise the chromium ions to upper energy level. The xenon discharge provides intense bursts of white light. Each flash of light lasts for several milliseconds. The green component of the spectrum having wavelength around 5600 A is absorbed by Cr^{3+} ions raising them from the ground state to the 2.25 eV level. The cylindrical ruby rod consumes several thousand joules of energy but only a part of it is used in pumping Cr^{3+} ions, while the rest heats up the apparatus.. Cooling arrangement is used by circulating water to remove the generated heat.



Working : The active material in the ruby laser is Cr^{3+} ions which are responsible for stimulated emission of radiations while the Al and oxygen atoms are inert. Cr has three energy levels, the ground state , 1.79 (E_2) and 2.25 eV(E_3) excited states. The green component of the xenon discharge is absorbed by the Cr^{3+} ions and are excited to the 2.25 eV energy level. This level is highly unstable. The 2.25 eV level rapidly decays to the 1.79 eV level by non-radiative transition. Part of this energy goes into the crystal lattice. The 1.79 eV state is a metastable state. Hence Cr^{3+} ions accumulate there. **After a few milliseconds, the 1.79 eV state becomes more populated relative to the ground state and hence the desired population inversion is achieved**. The spontaneous emission of a 1.79 eV photon by Cr ions at 1.79 eV level initiates the stimulated emission by other ions in a metastable state and a chain reaction is produced.

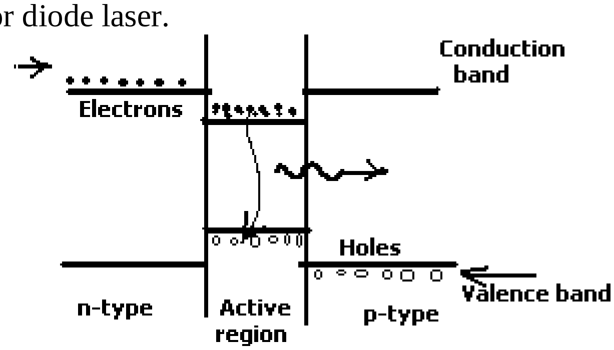
Photon beam parallel to the axis the crystal is reflected back and forth by the silvered ends and produces stimulated emission of photons. It grows in strength and some of the photons come out through the partial reflector and serves as the output laser beam. **The colour of the laser beam is red and corresponds to a wavelength of 6943 A^0 .**

The main drawback of ruby laser is that the beam is not continuous but a pulsed one. The xenon flash lasts for a few milliseconds. However, the laser does not operate through out this period. Once stimulated transitions commence, the metastable state E2 gets depopulated very rapidly and lasing action ceases. The laser becomes inactive till population inversion is once again established. Therefore the output of Ruby laser is not continuous but occurs in the form of pulses of microsecond duration. It requires high pumping power because more than half of the atoms must be pumped to the higher energy state at 2.25 eV. The efficiency of Ruby laser is very less as only the green component of the pumping light is utilized while the rest of the components of incident light are left unused. The time interval between adjacent pulses is of the order of 1 to 10 microseconds and the power output is of the order of 10 to 100 kiloWatts

Semiconductor diode laser:

The semiconductor laser is also called a diode laser. A semiconductor diode laser is a P-N junction device that emits coherent light when it is forward biased. In a semiconductor laser , the lasing medium is a solid semiconductor

The active medium is a P-N junction diode made from crystalline gallium arsenide. The P and N regions in the diode are obtained by heavily doping with suitable dopants. A simple way of achieving **population inversion** in a semiconductor diode is to dope the P-N junction heavily and forward bias the junction. When the junction is forward biased, a current is passed through a P-N junction, P region being positive biased, holes are injected from the P region into N region and N being negatively biased, electrons are injected from the N region into P region. There are many electrons in the conduction band of the N-type material and many holes in the valence band of the P-type material. Thus there is a population of the electrons. There are more electrons in the higher energy levels than in lower energy levels. The forward bias plays the role of **pumping** agent in a semiconductor diode laser.



The energy bands in a diode laser

The basic mechanism responsible for light emission from a semiconductor is the recombination of electrons and holes at P-N junction. The electrons and holes recombine and release of energy takes place in the form of photons in or very near the junction region.. The energy is called the activation energy. In germanium and silicon diodes the energy is released in the form of heat but in the case of gallium arsenide, the energy released is in the form of light The wavelength of the emitted (laser) radiation is **$\lambda = c/\nu = hc / E_g = 1.24 / E_g$ µmeters where E_g is the energy of the forbidden gap**(ev) ,**ν is the frequency of the radiation and h is the Planck's constant**. **In the case of Ga As junction which has an energy gap of 1.44 ev gives a laser beam of wavelength around 8600 A^0 (infrared radiation)). GaAsP junction produces laser**

radiation in the visible region λ = 6500 A (red colour) This photon can stimulate a second electron to fall into the valence band, producing a second photon by stimulated emission. In this way the current through the junction is great enough, a chain reaction of stimulated emission events can occur and laser light can be generated. Thus P-N junction diode acts as a laser and it's light output being highly coherent .A representation of the energy levels in a diode laser is shown in figure.. The excess of electrons (and holes) in the active region gives the lasing action

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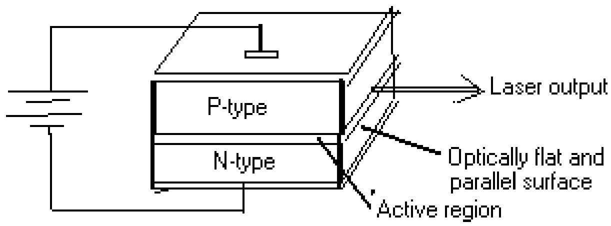


Semiconductor laser

The lasing material is a narrow (0.2 μ m) layer of a material such as GaAs (gallium arsenide), and the p-type and n-type material on each side is few micrometers in thickness .The P-N junction diode is extremely small in size. The top and bottom faces have metallic ohmic contacts to pass current through the diode. The front and rear faces are polished, parallel to each other and perpendicular to the plane of the junction. **The polished faces constitute the optical resonator that reflect a portion of the light wave to enable stimulated emission in the active region.**. The other two faces are roughed to prevent lasing action in that direction.

Semiconductor diode lasers are simple, compact and highly efficient. They require very little power input in the range of 10 mW compared with He-Ne laser that may require several watt of electrical power. Diode lasers can be powered by batteries. Efficiencies of the order of 20 % are possible. Diode lasers are less monochromatic and highly temperature sensitive. Diode lasers are commonly used in compact disc players and other optical data retrieval systems. They are also used in optical communication systems based on optical fibers.

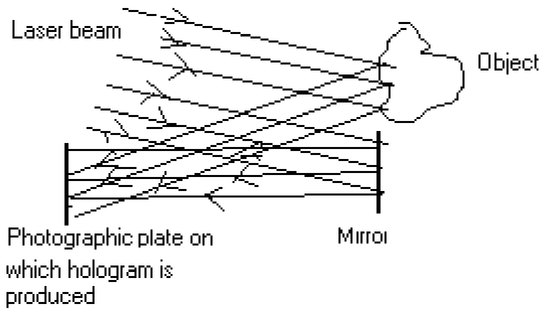
Applications of Lasers:

Industrial applications:

1) The laser beam can be focused to very small dimensions so that it can be used for industrial applications like cutting, drilling, welding and machining. A high intensity laser beam can drill a very small hole in a diamond for drawing small diameter wires
2) Laser light traverses large distances with very little divergence. Lasers are used to find precise measurement of length and surveying. Lasers are used especially in situations requiring great precision such as drilling long tunnel from both ends .
3) Laser light reflection is used in measuring the speed of automobiles, to read price information from bar codes.

Holography:

4) .



Lasers find important applications in holography. Holography is a process of producing 3-dimensional image of the objects. The laser beams reflected from the object and from the mirror (reference beam) interfere and are recorded on a photographic film in the form of interference patterns. The waves of the reference beam have the same amplitude , wavelength and phase relationship while the beams reflected from the object have different amplitudes and their phase are random. The recorded information is reproduced and observed as a 3- dimensional image of the object Holography is used in several applications -- credit cards, laser scanners at the checkout counters, computerized data storage and retrieval systems.

Computer applications:

5) By using lasers, large amount of information or data can be stored. Semiconductor diode lasers are used to reproduce music on CD players and are also used in laser printers, laser copiers , optical floppy discs ,optical memory cards

Medical applications:

6) Lasers are widely used in medicine. A laser with a narrow intense beam can be used in the treatment of a detached retina. A short burst of radiation damages only a small area of the retina and the resulting scar tissue welds the retina back to the membrane from which it has become detached.
7) Laser beams are used in surgery. Blood vessels cut by laser beams tend to seal themselves off, making it easier to control bleeding.
   Lasers are used for selective destruction of tissue such as in the removal of tumors and treatment of cancer. Lasers are also used in the removal of kidney stones removal of tooth and gum decay.
   Laser beam is sent through optical fiber to open the blocked artery region. The laser rays burn the excess growth in the blocked region and regulates the blood flow without any requirement for bypass surgery

Scientific Research: (Fusion reactions and separation of isotopes)

8) Because of extremely high temperatures obtainable at the focus of a laser beam, laser is used as an excellent tool for triggering certain chemical reactions. The temperature required to trigger a fusion reaction is of the order of 10^8 K.
   Thermonuclear materials are irradiated by intense laser pulses to trigger such reactions
9) Lasers are used for separating various isotopes, particularly for large scale enrichment of uranium for use in nuclear power reactors. The light of certain wavelengths may be absorbed by one isotope while the other isotope may not absorb it .Since laser light is highly monochromatic one may selectively excite the isotopes of one kind

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Military applications:

10) Laser beams are used in warfare for detecting and destroying airplanes , missiles and tanks. They are also used for automatic control of rockets and satellites.
11) LIDARS (**Li**ght **D**etection **A**nd **R**anging) are used to estimate the size and shape of distant objects or war weapons

Communications:

12) Lasers are used as light source to transmit audio, video signals and data to long distances without attenuation and distortion. The narrow angular spread of laser beam recommends that laser beam can be used for communication between earth and moon or to other satellites.
As laser beam is not absorbed by water, so it can be used to underwater communication network

Comparison of lasers:

	He-Ne Laser	**Ruby laser**	**SemiconductorLaser**
Efficiency	high	low	high
Laser beam	continuous highly monochromatic	pulsed monochromatic	continuous less monochromatic
Output power	≈ 50 mW	10 – 100 kW	≈ 1 W
wavelength of laser beam	6328 ^{0}A	6943 ^{0}A	8600 ^{0}A
Active medium	neon atoms	chromium ions	gallium arsenide

The efficiency of a ruby laser is very less as only green component of the pumping light is utilized and the rest are unused. The main drawback of Ruby laser is that the output beam though very intense is not continuous. Ruby laser is a pulsed one ie laser beams are emitted in the form of pulses. For continuous laser beam gas lasers are used.. The power required for pumping in gas lasers is low and efficiency is high.. Semiconductor diode lasers are simple, compact and highly efficient. They require very little power but diode lasers are less monochromatic and highly temperature sensitive

Question Bank:

1.a) Explain the terms i) spontaneous emission ii) stimulated emission and iii) population inversion
b) Describe the construction and explain the principle and working of He – Ne laser
2.a) Describe the construction and working of Ruby laser
b) Write various applications of lasers
3.a) Explain the principle and working of semiconductor laser.
b) Mention the merits and demerits of various lasers
c) Find the ratio of population of two energy levels of the Ruby laser, the transition between which is responsible for the emission of photon of wavelength λ = 6928 ^{0}A. Assume the ambient temperature as 18^{0}K

Summary:

1) LASER is an acronym for Light Amplification by Stimulated Emission of Radiation

2) The energies of atoms are quantized. Atoms can make transitions between different quantized states by emitting or absorbing a photon. The energy associated with that radiation is $h\upsilon = E_2 - E_1$ where E_2 is the energy of the excited state and E_1 is the energy of the lower excited state or ground state involved in the transition

3)When a radiation is incident on a medium, three quantum mechanical processes may occur:
i) The photons of the incident radiation are absorbed by the atoms in the medium and the atoms go into excited state. This process is called 'absorption'.
ii) The excited atoms return to the ground state on their own accord and emit the energy difference in the form of photons. This process is called 'spontaneous emission'.
iii) The excited atoms get de-excited by the incident photons and they fall to the ground state emitting the extra energy in the form of photons . This process is called 'stimulated emission'

4) When an atom in the excited state E_2 comes down to a lower energy state E_1 on its own accord by emission of photon, then such a process is called 'spontaneous emission' . The energy of this radiation is $h\upsilon = E_2 - E_1$. In spontaneous emission, there is no phase relationship among the emitted photons and so they are incoherent

5) Excitation of atoms from the lower energy state to a higher energy state due to interaction of photons with atoms is known as ' absorption'

6) The interaction of a photon of energy $h\upsilon = E_2 - E_1$ with an excited atom forces the excited atom to drop to the lower energy state by emitting a photon of energy $h\upsilon = E_2 - E_1$. There are now two photons which are identical in energy, direction , phase and polarization. Since the process is triggered by the incident photon, it is called 'stimulated emission'.

7)The characteristics of laser light are i) coherence ii) monochromaticity iii) high directionality (less divergence and iv) high intensity.

8)The different mechanisms to excite the atoms of the active medium from the ground state to a higher energy state are i) optical pumping ii) electric discharge and iii) injection of current through P-N junction

9)Laser operation requires a non-equilibrium condition called ' population inversion' in which there are more number of atoms in the higher energy state than in the lower energy state

10) For light amplification by stimulated emission of radiation , the population of excited state must be greater than the population of lower energy state. This condition is called 'population inversion'.

11) In He- Ne laser , the medium is He-Ne gas mixture and Ne is responsible for lasing action. It is a four level gas laser. High frequency electrical discharge is used for pumpining action. The wavelength of laser radiation is 6328 A. Power output is of the order of few milliwatts. Efficiency is low. The laser radiation is continuous and highly monochromatic.

12) An optical resonator is a system consisting of two mirrors, one 100% reflecting and the other partially reflecting, with an active medium in between. The mirrors promote photon multiplication along the laser axis by repeatedly reflecting the photons back and forth through the lasing medium.

13) The Ruby laser is a solid state laser with Cr^{3+} ions as active medium. A high intensity xenon flash lamp is used for optical pumping. It is a three level laser. The wavelength of laser radiation is 6943 A. The efficiency of Ruby laser is very less as only green component of the pumping light is utilized and the rest are unused. The main drawback of the Ruby laser is that the output beam though very intense is not continuous. (pulsed mode)

14)Semiconductor lasers are simple, compact and highly efficient. They require very little power. They are less monochromatic and highly temperature sensitive. the active medium is gallium ar5senide and the wavelength of laser radiation is 8600 A

15)Laser are widely used in the medical field for eye cataract surgery, welding of detached retina, dental surgery and cancer treatment

16)Lasers are used in holography. Holography is a three dimensional image of the object

17)High power lasers are used in industrial applications such as cutting, welding and drilling

OPTICAL FIBERS

Introduction:

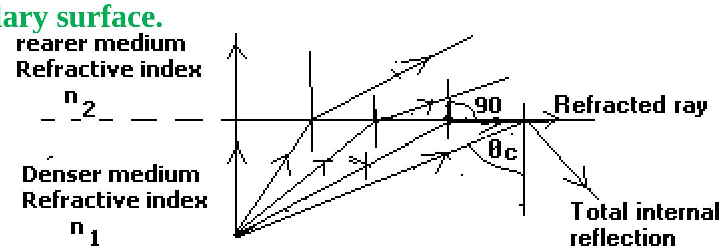
The transmission of light along transparent cylinders by multiple total internal reflection was demonstrated as early as in1870 by John Tyndall of England. It was in1927 that attempts were made to transmit television pictures using fibers. The activity on fibers began from 1950 onwards when transmission of pictures along a bundle of flexible glass fibers was carried out with remarkable success.

Optical fibers are hair-thin strands of transparent material made up of glass or plastic designed to carry electromagnetic waves of optical frequencies (visible to infrared) from one end of the fiber to the other end of the fiber by means of total internal reflection. *Optical fibers carry information over long distances in the form of pulses of light.* Optical fibers brought a revolutionary change in the communication networks of the world. **Huge quantities of information such as voice signals, video and digital data can be rapidly and efficiently transmitted from one place to another by using optical fibers**

Electronic communications use radio waves and microwaves to carry information over copper wires and coaxial cables. The rate at which information can be transmitted is directly related to the signal frequency or band-width. Light has a frequency in the range of 10^{14} to 10^{15} Hz compared to radio frequencies of 10^6 Hz and microwave frequencies of 10^{10}Hz. Therefore, the use of light waves in place of radiowaves and microwaves enhances tremendously the number of signals that can be transmitted simultaneously.

Principle:

The light that is launched at one end of the fiber has to travel through the entire length and reach the other end without much loss. Optical fibers work on the principle of total internal reflection. When a light ray passes from an optically denser medium of refractive index ,n_1 and strikes a optically rearer medium of refractive index , n_2, then the refracted ray bends away from the normal. . As the angle of incidence θ_i is increased, the angle of refraction θ_r also increases and a situation is reached when the refracted ray just grazes the surface of separation of the two media. At this position, the angle of refraction is 90^0. **The angle of incidence at which the refracted ray makes an angle of 90^0 with the normal or tangential to the surface is called the *critical angle*, θ_C. For angles of incidence greater than this critical angle θ_C, the ray cannot pass into the upper material, it is trapped in the lower material and is completely reflected at the boundary surface.**



This situation is called *total internal reflection*, occurs only when a ray is incident on the interface with a second material whose index of refraction is smaller than that of the material in which the ray is traveling The angle of refraction θ_r is given by Snell's law of refraction

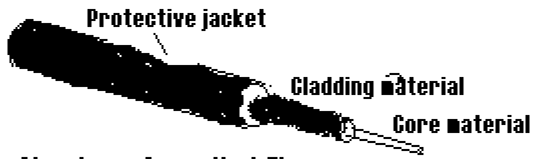
$$n_1 \sin\theta_i = n_2 \sin\theta_r,$$

We find the critical angle θ_C by putting $\theta_r = 90^0$.

$n_1 \sin\theta_C = n_2 \sin 90^0$ or **Critical angle $\theta_i = \theta_C$,** **$\sin\theta_C = (n_2/n_1)$**

The sine of the angle cannot exceed unity so that we must have $n_2 < n_1$. **So total internal reflection occurs only when a ray is incident on the interface with a second material whose index of refraction is smaller than that of the material in which the ray is traveling**

Fiber Construction:



Structure of an optical fiber

Optical fiber is a very thin flexible thread of transparent plastic or glass in which light is transmitted through multiple total internal reflections.. It consists of an innermost cylindrical region called **core.** The core is surrounded by a layer of material called the **'cladding'** . This cladding is in turn covered by a **jacket.** Light is transmitted within the core. The cladding keeps the light waves within the core because the refractive index of the cladding material is less than that of the core. The cladding also provides some strength to the core. The additional jacket protects the fiber from moisture, mechanical abrasion and contamination. Sheath or jacket also increases the mechanical strength of the fiber. Plastic fibers are more flexible and inexpensive than glass. The outer diameter of an optical fiber is about 150 μm; core diameter 10 to 50μm ; cladding diameter about 125 μm. .

The most abundant material to make optical fiber is silica (SiO_2) It has a refractive index of 1.458 at $\lambda = 8500A^0$. Materials of slightly different refractive index are obtained by doping the silica material with small quantities of oxides of germanium, boron or phosphorous. If silica is doped with GeO_2 , the refractive index of the material increases. Such materials are used as the core materials and pure silica is used as the cladding material in these cases. When silica is doped with B_2O_3 , the refractive index decreases, These materials are used for cladding materials when pure silica is used as core material. In comparison with glass, plastic fibers are flexible and inexpensive. Ordinary glass is brittle but the optical fibers made out of them are quite tough. They have a high tensile strength i.e., ability to withstand hard pulling or stretching.

The principle of optical fiber is when a beam of light enters at one end of the core, the light undergoes repeated total internal reflections from the surrounding material and propagates to the other end due to internal reflection at the core and cladding interface. Total internal reflection will occur only when

i) the refractive index of the core n_1 is slightly higher than the cladding n_2 surrounding it

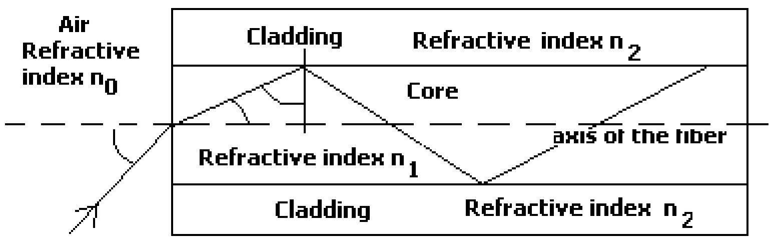
ii)the angle of incidence θ_i at the core-cladding interface must be greater than the critical angle θ_C

The light is "trapped " within the core even if the core is curved, provided the curvature is not too great. Optical fiber is made either from a single fiber or a flexible bundle or a cable. A bundle may consist of hundreds of individual fibers and each fiber carries information independently

Acceptance angle and acceptance cone:

The main function of an optical fiber is to accept and transmit as much light from the source as possible. When we launch the light beam into a fiber at its one end , the entire light may not pass through the core and propagate. Only the rays which make the angle of incidence greater than the critical angle at the core-cladding interface undergo total internal reflection and propagate through the core. The other rays are refracted into the cladding material and are lost. Hence it is very essential to know at what angle called the ***'acceptance angle'*** we have to launch the beam to enable the entire light to propagate through the core The light gathering ability of the fiber depends on two factors, namely i) core size and ii) the numerical aperture. The numerical aperture of the fiber is determined by the acceptance angle and the fractional refractive index change.

Consider a ray which is incident on the entrance aperture of a fiber making an angle θ_i with the axis. Let the refracted ray make an angle θ_r with the axis of the fiber and strikes the core-cladding interface at an angle Φ. The end at which light enters the fiber is called the launching end. Let the refractive index of the core be n_1 and the refractive index of the cladding material be n_2. In an optical fiber $n_2 < n_1$. Any light ray which travels along the core meets the cladding at the critical angle of incidence will be totally reflected. Let n_0 be the refractive index of the medium(air) from which light is launched into the fiber.



From Snell's law, we have $n_0 \sin\theta_i = n_1 \sin\theta_r$ **or** $\sin\theta_i / \sin\theta_r = n_1/n_0$ which is a constant. Obviously this ray has to suffer total internal reflection at the core - cladding interface.

$\sin\theta_r = \sin(90 - \Phi) = \cos\Phi$

$\sin\theta_i = (n_1/n_0)\sin\theta_r = (n_1/n_0)\cos\Phi$ ………………..(1)

If θ_i increases , θ_r also increases proportionately. If θ_i is increased beyond a limit, Φ will drop below the critical angle θ_C and the ray instead of suffering total internal reflection escapes from the side walls of the fiber.. If the angle of incidence Φ at the core –cladding interface is greater than the critical angle θ_C , the ray undergoes total internal reflection at the surface since $n_1 > n_2$. As long as the angle Φ is greater than θ_C, the light will stay within the fiber. Let us compute the maximum incident angle θ_i for which $\Phi = \theta_C$ such that light undergoes total reflection within the fiber.

When $\Phi = \theta_C$; $\sin(\theta_i)_{max} = (n_1/n_0)\cos\theta_C$ ……………………………..(2)

But $\sin\theta_C = 1/\mu = n_2/n_1$ where μ is the refractive index of the core relative to the cladding

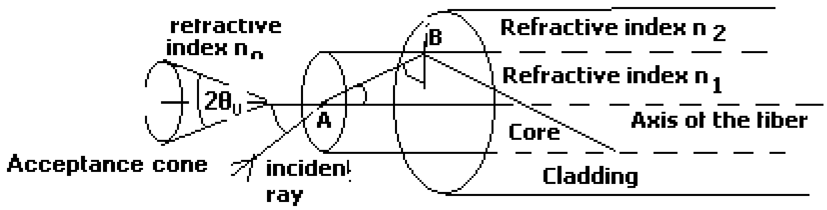
$$\cos\theta_C = \sqrt{1 - \sin^2\theta_C} = \sqrt{1 - (n_2^2/n_1^2)} = \sqrt{(n_1^2 - n_2^2)}/n_1 \quad \text{……………..(3)}$$

Substituting Eqn (3) in Eqn (2), we get

$$\sin(\theta_i)_{max} = (n_1/n_0)\sqrt{(n_1^2 - n_2^2)}/n_1 = \sqrt{(n_1^2 - n_2^2)}/n_0 \quad \text{…………..(4)}$$

Quite often the incident ray is launched from air medium for which $n_0 = 1$. Designating $(\theta_i)_{max} = \theta_0$, Eqn (4) may be simplified to

$$\mathbf{\sin\theta_0 = \sqrt{(n_1^2 - n_2^2)} \text{ or } \theta_0 = \sin^{-1}\sqrt{(n_1^2 - n_2^2)}}$$



The angle θ_0 is called the 'acceptance angle of the fiber. 'Acceptance angle' may be defined as the maximum angle that a ray can have relative to the axis of the fiber so that it propagates down the fiber suffering total internal reflections. The acceptance angle is unique for a particular fiber but different for different fibers and ***depends on the material*** **.** The light rays contained within the cone having a full angle $2\theta_0$ are accepted and transmitted along the fiber. Therefore the cone is called the **" acceptance cone".** Light incident at an angle beyond θ_0 refracts through the cladding and escapes. It is obvious that the larger the diameter of the core, the larger the acceptance angle.

Numerical Aperture:

The numerical aperture of a fiber is a measure of its light gathering power **The 'numerical aperture' (NA) is defined as the sine of the maximum acceptance angle.** It is a measure of the amount of light that can be accepted by a fiber. A larger numerical aperture implies that a fiber will accept large amount of light from the source.

Relation between fractional refractive index change and Numerical Aperture:

The fractional change in refractive index between the core and cladding is $\Delta = (n_1 - n_2)/n_1$. This is always positive since $n_1 > n_2$ for the total internal reflection to take place within the fiber..

Numerical Aperture (NA) = sin θ_0 or NA = $\sqrt{n_1^2 - n_2^2}$

$n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2)$.

Generally n_1 is slightly greater than n_2

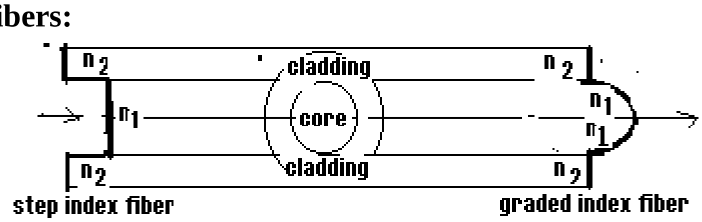
$n_1^2 - n_2^2 = 2n_1 (n_1 - n_2)\, n_1 / n_1 = 2 n_1^2 \Delta$

or Numerical Aperture NA = $\sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta}$

Numerical aperture determines the light gathering ability of the fiber. It is a measure of the amount of light that can be accepted by a fiber. NA depends on the refractive indices of the core and cladding materials and is independent of the fiber dimensions

The numerical aperture for fibers used in short distance communications is in the range of 0.4 to 0.5 while for long distance communications NA ranges from 0.1 to 0.3

Types of optical fibers:

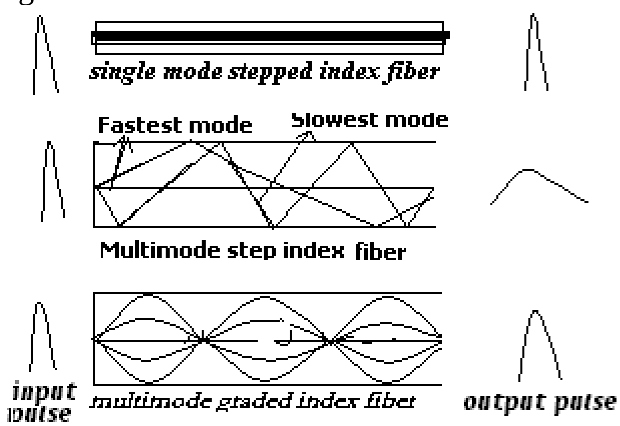


. **Optical fibers are classified based on the variation of refractive index of core. They are i) step index fiber and ii) graded index fiber**. In a step index fiber, the refractive index is constant through out the core and undergoes an abrupt change at the core- cladding boundary. Because of this abrupt change they are called step index fibers In a graded index fiber, the refractive index decreases smoothly from the center of the core to the outer surface of the fiber. It is highest at the center of the core and tapers off rapidly towards the outer surface of the core

The light that is launched at one end of the fiber within the acceptance cone alone propagates through the fiber by total internal reflection. When light is launched at one end, the light travels through the fiber in different paths. Each path is called a '*mode'* The number of modes that a fiber supports depends on the dimensions of the fiber. .**Based on the mode of propagation of light rays, fibers are of two types namely i) Single Mode Fiber (SMF) and**

ii) Multi Mode Fiber(MMF).

A single mode fiber can support only one mode of propagation In a single mode fiber the light propagates along the axis of the fiber. This is achieved by using a small refractive index difference between the core and cladding and very small core diameter of nearly 5 μm. Signal transmission capacity of these fibers is small but can carry the data at the very highest bit rates and suitable for long distance transmission.



Multimode means that several paths are available for light propagation.. A multimode fiber has a larger core diameter (50 μm) and light can take several paths in a fiber. Light propagation in this fiber is by multiple total internal reflections

In a step index multimode fiber , each light ray may be reflected hundreds or thousands of times. The rays reflected at different angles travel different distances resulting in the broadening of light pulses as they travel down the fiber.. The output pulses then no longer exactly match the input pulses, causing broadening of the signal or signal distortion. This is called 'dispersion'. The broadening of the pulse of light in the fiber as it travels plays an important role in determining the maximum rate at which information can be transmitted as well as the distance over which information can be transmitted. In multimode fibers, the signal transmission capacity is large. However, they are less suitable for long distance transmission due to large dispersion and attenuation.

In a graded index fiber the refractive index of the core varies radially. It is maximum at the center which gradually falls with increase of radius and matches at the core cladding interface with the refractive index of the cladding . The propagation of light within the core is not by total internal reflection but by refraction. Light rays travel at different speeds in different parts of the fiber. Near the outer edge the refractive index is lower. As a result rays near the outer edge travel faster than rays in the center of the core. Because of this all the rays arrive at the end of the fiber at approximately the same time. The light rays travel in the form of helical rays . In effect light rays in these fibers are continuously refocused as they travel down the fiber. This in effect reduces signal distortion. . The band –width lies between 200 MHz -Km to 600 MHz -Km

Advantages of optical fibers in communications:

i) Extremely wide band-width:
The rate at which information can be transmitted is directly related to signal frequency. Light has a frequency in the range of $10^{14} – 10^{15}$ Hz, compared to radio frequencies 10^6 Hz and microwave frequencies 10^8 -10^{10}Hz. Therefore a transmission system that operates at the frequency of light can transmit greater volume of information at a higher rate than systems that operate at radio or microwave frequencies.

ii) Optical fibers are light- weight , flexible, long life and low cost cables:
Optical fibers because of their light weight and flexibility can be handled more easily than copper cables. The life span is expected to be 20-30 years in contrast to copper cables which have life span of 12-15 years. Optical fibers are more reliable and easy to maintain. Optical fibers have the potential to transmit the signals at low cost since these fibers are made of silica which is available in abundance..

iii) Lack of cross-talk between parallel fibers:
Since optical fibers are dielectric wave guides, they are free from any electromagnetic and radio frequency interference. The cross-talk is negligible with fiber optics even when numerous fibers are cabled together. This is because the light waves propagate along the fiber are completely trapped within the fiber and cannot leak out. Because of this the cross-talk is greatly reduced

iv) Electrical insulation and noise free transmission:
Optical fibers are made from silica which is an electrical insulator Therefore they do not pick up any electromagnetic waves . The result is noise free transmission. The fiber optic cables are immune to interference caused by lightening and other electromagnetic equipment.

v) Temperature resistant:
Optical fibers have high tolerance to temperature extremes as well as to corrosive liquids and gases

vi) Signal security:
Unlike in copper cables, a transmitted signal cannot be drawn from a fiber without tampering it. Such an attempt will affect the original signal and hence can easily be detected. Thus, the optical fiber communication provides 100 % signal security

vii) Low transmission loss: Transmission losses 10 log (P_O/P_I) are very less in optical fibers compared to copper conductors. Hence optical fibers are preferred for long distance communications

Applications of optical fibers:

i) Applications of optical fibers is in the field of medicine.. Fiberscope is an instrument used for the visual examination of internal sites and organs of the human body. Optical fiber cable can be passed through the patient's throat into the stomach to search for ulcers and other abnormalities. Light is introduced in the outer fibers of the cable. It undergoes repeated total internal reflections within the fiber and is carried into the stomach by the outer fibers of the cable. The light is reflected back by the stomach wall, and transmitted out of the stomach by the inner fibers of the same cable. The image can be displayed on a TV monitor. Thus the image of the internal sites of the body can be inspected visually outside the body. Endoscopy also finds applications in the study of tissues and blood vessels far beneath the skin.
In ophthalmology , a laser beam guided by optical fibers is used to reattach detached retina and to correct defects in vision

ii) Fiberscopes are used in industry to examine welds, nozzles and combustion chamber inside the jet aircraft engines.

iii) Optical fibers are used as sensors which are devices used to measure or monitor quantities such as displacement, pressure, temperature, flow rate, liquid level and chemical composition

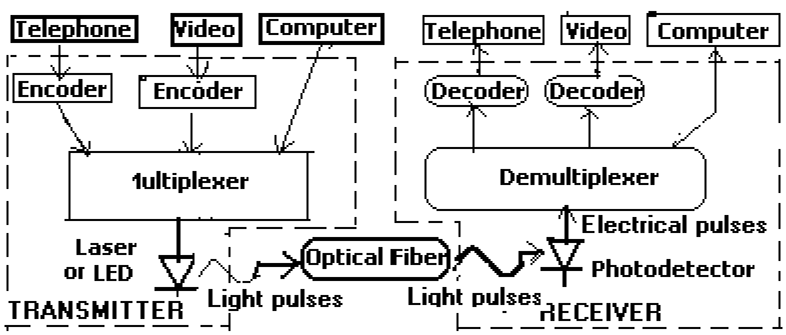
iv) Optical fibers are extensively used in communication systems:

Optical fibers have brought a revolutionary change in the communication network of the globe. Huge amount of information such as video, telephone and computer data can be rapidly and efficiently transmitted from one place to another by using optical fibers. The rate at which the information can be transmitted from one place to another is directly related to the frequency of the transmitted signals. Light has a frequency in the range of 10^{14} -10^{15} Hz, compared to radio frequencies of 10^{6} Hz and microwave frequencies of 10^{10} Hz. The information carrying capacity of the copper wires is restricted in view of the limited band-width of radio and microwaves.. Optical fibers use light waves to transmit information and so a transmission system that operates at the frequency of light can transmit information at a higher rate than that operated by radio or microwaves..

Each voice signal roughly requires 6.4 $\times 10^{4}$ bits/sec. If the data rate of the system is 1Gigabit/sec (1×10^{9} bits/sec) , the number of voice channels that can be multiplexed together is approximately 15,000 (10^{9} divided by 64000). Through one copper wire pair, only 48 independent speech signals can be sent simultaneously

Light wave communication system using optical fibers:

Fiber optics essentially deals with the communication (involving voice signals, video signals and digital data) by transmission of light through optical fibers. A fiber optics communication system essentially consists of three parts i) transmitter – a light source ii) an optical fiber – signal carrier and iii) a receiver—a light detector.



Light wave Communication system

The information that is to be transmitted can be telephone voice signals, video signals or digital data from a computer. All modern communication systems use 'digital' signals because of their excellent transmission quality . The audio and video information is in the form of analog signals (continuously variable) and this information is 'encoded' into binary digits consisting of 0's and 1's ('Encoder is an electronic circuit that converts analog signals into digital form) . All of these signals are fed to a 'multiplexer' which converts the parallel data into a single high-data-rate stream.. (multiplexer has many inputs and a single output and the control transfers the inputs to the output in a serial form). In a light wave transmitter, each '1' corresponds to the presence of an electrical pulse, each '0' corresponds to the absence of an electrical pulse. These electrical pulses are used to turn a light source on and off very rapidly, much like turning a light switch on and off. The light source can be a laser or a light emitting diode (LED) .Thus, in the transmitter in a light wave communication system, the information which is in the form of electrical pulses are used to turn a light source on and off very rapidly. All binary encoded information is thus transformed into a timed sequence of flashes of light for transmission.

Optical fiber cables are used to carry the light from the transmitter to the receiver. In the receiver, each pulse of light is detected by a photo detector. As each pulse of light arrives at the photodetector, a pulse of electrical current is produced. In this way, the optical pulses are converted back into electrical pulses. The receiver also has a 'demultiplexer' which separates the signals and convert them back to voice, video and computer data. The basic approach in a light wave communication system is information is converted into pulses of light that are transmitted over some distance through an optical fiber, then reconverted back into information

Fiber optic sensing applications (sensors):

Fiber optic sensors are transducers which generally consist of a light source coupled with an optical fiber and a light detector held at the receiver end. Fiber optic sensors are used to monitor /measure displacement, liquid level, flow, temperature, pressure, chemical composition etc. Optic fiber sensors can be divided into two types. They are a) active sensors and b) passive sensors.

Active sensors: In active sensors, the quantity to be measured acts directly on the fiber itself. Fiber itself acts as a transducing element and modifies the light passing through it

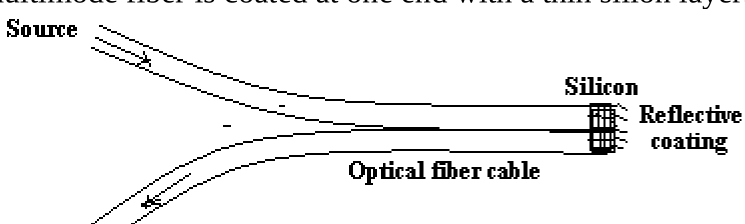
i)Intensity modulated sensors: These are based on the change in refractive index, temperature, absorption etc

ii)Phase modulated sensors: This involves the interference between the signal and reference in the interferometer. The shift in the interference fringes by the variable is recorded.

ii)Wavelength modulated sensors: In this the spectral dependent variation of absorption and emission by the variable takes place

Passive sensors: In passive sensors, the quantity to be measured acts directly on the transducing material which modifies the light. The modified light is collected through another fiber to reach the detector to sense the modification. The fiber acts merely as a transmission channel for light.

i)Temperature sensor: This is based on the absorption characteristics of silicon as a function of temperature. The multimode fiber is coated at one end with a thin silion layer.

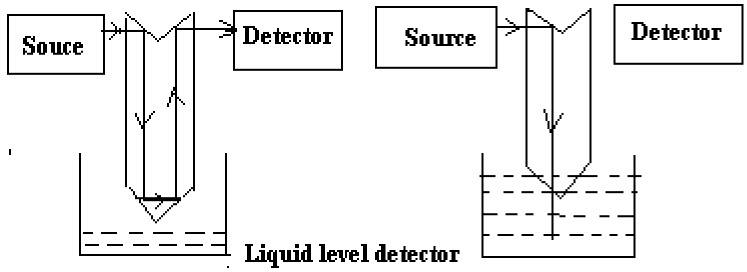


Temperature sensor

The silicon layer is in turn coated with a reflective coating at the back. The light launched into the fiber from one of its ends passed first through the fiber and then, after traveling through the silicon layer twice returns to detector. The absorption of light by silicon layer varies with temperature and the variation modulates the intensity of the light received at the detector. Temperature measurements can be made with a sensitivity of 0.001 ^{0}C

ii) Pollution detector: A smoke and pollution detector can be built using optical fibers. A beam of light radiating from one end of a fiber can be collected by another optical fiber. If foreign particles are present in the region between the two fibers, they scatter light. The variation in intensity of the light collected at the second optical fiber reveals the presence of foreign particles.

iii) Liquid level detector: An optical fiber with one of its ends chamfered is arranged at the desired height in a vessel. The refractive index of the fiber is chosen to be less than that of the liquid whose level is to be detected. A light beam entering into the fiber is internally reflected at the chamfered end and travels back to the detector. When the liquid rises and touches the fiber, the internal reflection ceases and the light is transmitted into the liquid. The indication of the liquid level is obtained at the detector



Liquid level detector

Questions that appeared in the University Examinations

1) State and explain the principle of propagation of light in optical fibers .
2) Define total internal reflection and 'acceptance angle' Write a note on optical fiber communication
3) Explain why optical communication system is attractive over other types
4) Write the applications of optical fibers
5) Define acceptance angle and Numerical aperture. Derive their expressions
6) Define total internal reflection and 'acceptance angle'. Write a note on fiber optical communication
7) Briefly advocate the use of optical fibers for communication purposes.
8) Calculate the ' Numerical Aperture' and hence 'Acceptance angle' for an optical fiber given that the refractive indices of the core and the cladding are 1.45 and 1.40 respectively

SUMMARY:

1) Optical fibers are hair thin strands of transparent material like plastic or glass that transmit light through them by total internal reflection
2) The refractive index of core is slightly greater than that of the cladding region. Hence the light launched into the core undergoes total internal reflection at the core- cladding interface and propagates through the fiber
3) An optical fiber is made up of glass or plastic. It consists of i) central region called 'core' ii) middle region called ' cladding ' and iii) outer region called ' protective sheath '
4) Light launched at one end of the fiber is accepted and propagated at the other end by total internal reflection only if it is launched within a particular angle called 'Acceptance angle θ_0 ' .When light is launched with in this angle, then the light ray strikes the core – cladding interface at an angle greater than the critical angle. The light rays that are contained within a cone of angle $2\theta_0$ are accepted and propagated through the fiber.
5) Numerical Aperture of an optical fiber is a measure of its light gathering ability of the fiber . It is defined as Sine of the maximum acceptance angle

$$\text{Numerical Aperture NA} = \sin\theta_0 \quad \text{or} \quad NA = \sqrt{n_1^2 - n_2^2}\,/\,n_0 = n_1\sqrt{2\Delta}$$

where n_1, n_2 are the refractive indices of the core and cladding respectively and n_0 is the refractive index of the medium from which the light is launched. Δ is called fractional refractive indices change
6) Propagation of light along some specified directions are called ' modes' . Optical fibers are also classified based on the number of modes of the fiber can support. If the fiber supports one

mode, then it is called ‘Single Mode Fiber ‘. If the fiber supports more than one mode, then it called ‘Multi Mode Fiber ‘ (MMF)

7) If the fiber is very thin (10 μ m), then it can support only one mode. Dispersion os less in SMF and they are used for long distance communications If the diameter of the fiber is around 50 μm , then it can support many modes. The light pulses traveling different distances reach at different times resulting in dispersion. This seriously affects the rate of transmission of data. MMF are used to transmit large amount of data for short distances

8) Optical fibers are classified based on refractive index profile of the core. If the core has uniform refractive index throughout and abruptly changes at the core cladding boundary then it is called ‘step-index fiber’ .

9) If the refractive index of the core gradually decreases from maximum value at the center of the core to the value as that of the cladding at the core- cladding interface, then it is called ‘graded index fiber’

10) The transparent materials used in the construction of optical fibers are glass and plastic

11) During signal transmission, several effects result such as spreading of pulse width called ‘ dispersion ‘.

12) The information carrying capacity of a fiber is expressed in terms of Band width – distance product.

13) The maximum transmission rate of signal through a fiber is called ‘Band – width ‘ The spreading of pulse width of transmitter signal sent through the fiber is called B.W – Dispersion - Product (BDP). This is called the quality factor of the fiber.

14) Light gets attenuated in the fiber due to i) scattering and ii) absorption

15) Light source must be monochromatic, intense, easily modulated and compact. Laser and Light emitting diodes (LED) satisfy these requirements.

16) Fiber optic sensors are devices used to measure / monitor quantities such as displacement, pressure, temperature and flow rate etc using fibers

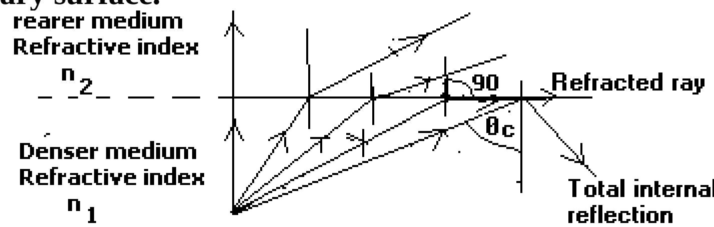
17) Fiber optic sensors are classified as i) active and ii) passive sensors. In passive sensors the quantity to be measured acts directly on the transducing material which modifies the light. In active sensors the quantity to be measured acts directly on the fiber itself. The fiber itself acts on the transducing element and modifies the light passing through it

18) Fiber optics communication system has three components i) transmitter ii) transmission path and iii) receiver.

1) State and explain the principle of propagation of light in optical fibers

The light that is launched at one end of the fiber has to travel through the entire length and reach the other end without much loss. Optical fibers work on the principle of total internal reflection. When a light ray passes from an optically denser medium of refractive index ,n_1 and strikes a optically rarer medium of refractive index , n_2, then the refracted ray bends away from the normal.

. As the angle of incidence θ_i is increased, the angle of refraction θ_r also increases and a situation is reached when the refracted ray just grazes the surface of separation of the two media. At this position, the angle of refraction is 90^{0}. **The angle of incidence at which the refracted ray makes an angle of 90^0 with the normal or tangential to the surface is called the *critical angle*, θ_C. For angles of incidence greater than this critical angle θ_C, the ray cannot pass into the upper material, it is trapped in the lower material and is completely reflected at the boundary surface.**



This situation is called total internal reflection, occurs only when a ray is incident on the interface with a second material whose index of refraction is smaller than that of the material in which the ray is traveling The angle of refraction θ_r is given by Snell's law of refraction

$$n_1 \sin \theta_i = n_2 \sin \theta_r,$$

We find the critical angle θ_C by putting $\theta_r = 90^{0}$.

$n_1 \sin \theta_C = n_2 \sin 90^0$ or **Critical angle $\theta_i = \theta_C$, $\sin \theta_C = (n_2 / n_1)$**

The sine of the angle cannot exceed unity so that we must have $n_2 < n_1$. **So total internal reflection occurs only when a ray is incident on the interface with a second material whose index of refraction is smaller than that of the material in which the ray is traveling**

The principle of optical fiber is when a beam of light enters at one end of the core, the light undergoes repeated total internal reflections from the surrounding material and propagates to the other end due to internal reflection at the core and cladding interface. Total internal reflection will occur only when

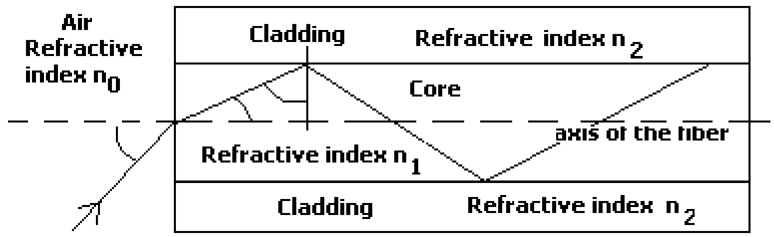
i) the refractive index of the core n_1 is slightly higher than the cladding n_2 surrounding it

ii)the angle of incidence θ_i at the core-cladding interface must be greater than the critical angle θ_C

2) Define acceptance angle and Numerical aperture. Derive their expressions

When we launch the light beam into a fiber at its one end , only the rays which make the angle of incidence greater than the critical angle at the core-cladding interface undergo total internal reflection and propagate through the core. The other rays are refracted into the cladding material and are lost. We have to launch the beam with in a certain angle called '**acceptance angle'** to enable the entire light to propagate through the core

Consider a ray which is incident on the entrance aperture of a fiber making an angle θ_i with the axis. Let the refracted ray make an angle θ_r with the axis of the fiber and strikes the core-cladding interface at an angle Φ. The end at which light enters the fiber is called the launching end. Let the refractive index of the core be n_1 and the refractive index of the cladding material be n_2. In an optical fiber $n_2 < n_1$. Any light ray which travels along the core meets the cladding at the critical angle of incidence will be totally reflected. Let n_0 be the refractive index of the medium(air) from which light is launched into the fiber.



From Snell's law, we have $n_0 \sin\theta_i = n_1 \sin\theta_r$ **or** $\sin\theta_i / \sin\theta_r = n_1/n_0$ which is a constant.
Obviously this ray has to suffer total internal reflection at the core - cladding interface.

$\sin\theta_r = \sin(90 - \Phi) = \cos\Phi$

$\sin\theta_i = (n_1/n_0)\sin\theta_r = (n_1/n_0)\cos\Phi$ ……………….(1)

If θ_i increases , θ_r also increases proportionately. If θ_i is increased beyond a limit, Φ will drop below the critical angle θ_C and the ray instead of suffering total internal reflection escapes from the side walls of the fiber.. If the angle of incidence Φ at the core – cladding interface is greater than the critical angle θ_C , the ray undergoes total internal reflection at the surface since $n_1 > n_2$. As long as the angle Φ is greater than θ_C, the light will stay within the fiber. Let us compute the maximum incident angle θ_i for which $\Phi = \theta_C$ such that light undergoes total reflection within the fiber.

When $\Phi = \theta_C$; $\sin(\theta_i)_{max} = (n_1/n_0)\cos\theta_C$ ……………………………..(2)

But $\sin\theta_C = 1/\mu = n_2/n_1$ where μ is the refractive index of the core relative to the cladding

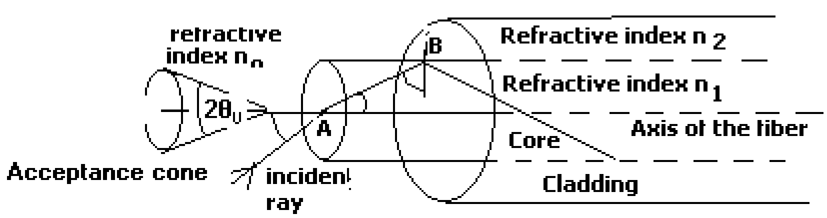
$\cos\theta_C = \sqrt{1 - \sin^2\theta_C} = \sqrt{1 - (n_2^2/n_1^2)} = \sqrt{(n_1^2 - n_2^2)}/n_1$ ……………..(3)

Substituting Eqn (3) in Eqn (2), we get

$\sin(\theta_i)_{max} = (n_1/n_0)\sqrt{(n_1^2 - n_2^2)}/n_1 = \sqrt{(n_1^2 - n_2^2)}/n_0$ ………….(4)

Quite often the incident ray is launched from air medium for which $n_0 = 1$. Designating $(\theta_i)_{max} = \theta_0$, Eqn (4) may be simplified to

$$\mathbf{\sin\theta_0 = \sqrt{(n_1^2 - n_2^2)} \text{ or } \theta_0 = \sin^{-1}\sqrt{(n_1^2 - n_2^2)}}$$



The angle θ_0 is called the 'acceptance angle of the fiber. 'Acceptance angle' may be defined as the maximum angle that a ray can have relative to the axis of the fiber so that it propagates down the fiber suffering total internal reflections. Light incident at an angle beyond θ_0 refracts through the cladding and escapes. It is obvious that the larger the diameter of the core, the larger the acceptance angle.

Numerical Aperture:

The numerical aperture of a fiber is a measure of its light gathering power **The 'numerical aperture' (NA) is defined as the sine of the maximum acceptance angle.** It is a measure of the amount of light that can be accepted by a fiber. A larger numerical aperture implies that a fiber will accept large amount of light from the source.

Relation between fractional refractive index change and Numerical Aperture:
The fractional change in refractive index between the core and cladding is $\Delta = (n_1 - n_2)/n_1$. This is always positive since $n_1 > n_2$ for the total internal reflection to take place within the fiber..

Numerical Aperture (NA) = sin θ_0 or NA = $\sqrt{n_1^2 - n_2^2}$

$n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2)$.

Generally n_1 is slightly greater than n_2

$n_1^2 - n_2^2 = 2n_1 (n_1 - n_2) n_1 / n_1 = 2 n_1^2 \Delta$

or Numerical Aperture NA = $\sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta}$

Numerical aperture determines the light gathering ability of the fiber. It is a measure of the amount of light that can be accepted by a fiber. NA depends on the refractive indices of the core and cladding materials and is independent of the fiber dimensions

3) Explain why optical communication system is attractive over other types or briefly advocate the use of optical fibers for communication purposes.

Advantages of optical fibers in communications:

i) Extremely wide band-width:
The rate at which information can be transmitted is directly related to signal frequency. Light has a frequency in the range of $10^{14} - 10^{15}$ Hz, compared to radio frequencies 10^6 Hz and microwave frequencies 10^8-10^{10}Hz. Therefore a transmission system that operates at the frequency of light can transmit greater volume of information at a higher rate than systems that operate at radio or microwave frequencies.

ii) Optical fibers are light- weight , flexible, long life and low cost cables:
Optical fibers because of their light weight and flexibility can be handled more easily than copper cables. The life span is expected to be 20-30 years in contrast to copper cables which have life span of 12-15 years. Optical fibers are more reliable and easy to maintain. Optical fibers have the potential to transmit the signals at low cost since these fibers are made of silica which is available in abundance..

iii) Lack of cross-talk between parallel fibers:
Since optical fibers are dielectric materials ,they are free from any electromagnetic and radio frequency interference. The cross-talk is negligible with fiber optics because the light waves propagate along the fiber are completely trapped within the fiber and cannot leak out

iv) Electrical insulation and noise free transmission:
Optical fibers are made from silica which is an electrical insulator Therefore they do not pick up any electromagnetic waves . The result is noise free transmission. The fiber optic cables are immune to interference caused by lightening and other electromagnetic equipment.

v) Temperature resistant:
Optical fibers have high tolerance to temperature extremes as well as to corrosive liquids and gases

vi) Signal security:
Unlike in copper cables, a transmitted signal cannot be drawn from a fiber without tampering it. Such an attempt will affect the original signal and hence can easily be detected. Thus, the optical fiber communication provides 100 % signal security

vii) Low transmission loss: Transmission losses 10 log (P_O/P_I) are very less in optical fibers compared to copper conductors. Hence optical fibers are preferred for long distance communications

4) Write the applications of optical fibers

i) Applications of optical fibers is in the field of medicine.. Fiberscope is an instrument used for the visual examination of internal sites and organs of the human body Light is introduced in the outer fibers of the cable. It is carried into the stomach by the outer fibers of the cable. The light is reflected back by the stomach wall, and transmitted out of the stomach by the inner fibers of the same cable. The image can be displayed on a TV monitor. Endoscopy also finds applications in the study of tissues and blood vessels far beneath the skin.
In ophthalmology , a laser beam guided by optical fibers is used to reattach detached retina and to correct defects in vision

ii) Fiberscopes are used in industry to examine welds, nozzles and combustion chamber inside the jet aircraft engines.

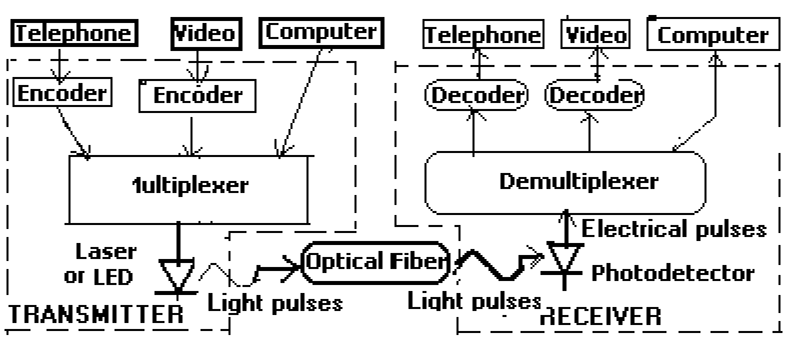
iii) Optical fibers are used as sensors which are devices used to measure or monitor quantities such as displacement, pressure, temperature, flow rate, liquid level and chemical composition

iv) Optical fibers are extensively used in communication systems:
Huge amount of information such as video, telephone and computer data can be rapidly and efficiently transmitted from one place to another by using optical fibers. The rate at which the information can be transmitted from one place to another is directly related to the frequency of the transmitted signals. Light has a frequency in the range of 10^{14} -10^{15} Hz, compared to radio frequencies of 10^{6} Hz and microwave frequencies of 10^{10} Hz.....

6). Write a note on fiber optical communication

<u>Light wave communication system using optical fibers:</u>

Fiber optics essentially deals with the communication (involving voice signals, video signals and digital data) by transmission of light through optical fibers. A fiber optics communication system essentially consists of three parts i) transmitter – a light source ii) an optical fiber – signal carrier and iii) a receiver—a light detector.



Light wave Communication system

The information that is to be transmitted can be telephone voice signals, video signals or digital data from a computer. All modern communication systems use 'digital' signals because of their excellent transmission quality . The audio and video information is in the form of analog signals (continuously variable) and this information is 'encoded' into binary digits consisting of 0's and 1's ('Encoder is an electronic circuit that converts analog signals into digital form) . All of these signals are fed to a 'multiplexer' which converts the parallel data into a single high-data-rate stream.. (multiplexer has many inputs and a single output and the control transfers the inputs to the output in a serial form). In a light wave transmitter, each '1' corresponds to the presence of an electrical pulse, each '0' corresponds to the absence of an electrical pulse. These electrical pulses are used to turn a light source on and off very rapidly, much like turning a light switch on and off. The light source can be a laser or a light emitting diode (LED) .Thus, in the transmitter in a light wave communication system, the information which is in the form of electrical pulses are used to turn a light source on and off very rapidly. All binary encoded information is thus transformed into a timed sequence of flashes of light for transmission.

Optical fiber cables are used to carry the light from the transmitter to the receiver. In the receiver, each pulse of light is detected by a photo detector. As each pulse of light arrives at the photodetector, a pulse of electrical current is produced. In this way, the optical pulses are converted back into electrical pulses. The receiver also has a 'demultiplexer' which separates the signals and convert them back to voice, video and computer data. The basic approach in a light wave communication system is information is converted into pulses of light that are transmitted over some distance through an optical fiber, then reconverted back into information