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Lasers: *Characteristics of LASER, Interaction of radiation with matter, requisites of a Laser system. Construction and working of semiconductor laser. Application of Laser: Bar code scanner, Laser printer, Laser cooling numerical problems.*

Optical Fibers: *Propagation mechanism, Numerical aperture derivation, Modes of propagation. Attenuation in fiber, Discussion of block diagram of Point-to-Point communication, Optical fiber sensor. Numerical problems.*

Introduction:

LASER is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Laser device produces a beam of coherent, monochromatic, intense and directional light. Hence laser light is highly organized when compared with the ordinary light. This is because the waves of a laser beam move in phase with each other travel in a narrow path in one direction. In the case of an ordinary light it spreads out, travels in different directions and hence it is incoherent. On account of the special properties, lasers are the most versatile and exploited tools in different fields such as Engineering, Medicine, Defence, Entertainment, Communication etc., Other common applications of laser include reading the bar code, cutting and welding metals, displays in light shows, playing music, printing documents, guiding missile to its target and so on.

Characteristics of Laser beam

- **Directionality:** The design of the resonant cavity, especially the orientation of the mirrors to the cavity axis ensures that laser output is limited to only a specific direction. Since laser emits photons in a particular direction, the divergence is less when compared the other ordinary sources.

- **Monochromacity:** The laser beam is characterized by a high degree of mono-chromaticity (single wavelength or frequency) than any other conventional monochromatic sources of light. Ordinary light spreads over a wide range of frequencies, whereas laser contains only one frequency. The spectral bandwidth is comparatively very less when compared to ordinary light. Hence the degree of mono chromaticity is very high in lasers.

- **Coherence:** The degree of coherence of a laser beam is very high than the other sources. The light from laser source consists of wave trains that are in identical in phase. Laser radiation has high degree of special (with respect to Space) and temporal (with respective to time) coherence.

- **High Intensity:** The laser beam is highly intense. Since wave trains are added in phase and hence amplitudes are added. Laser light emits as a narrow beam and its energy is concentrated in a small region. Since all the energy is concentrated in the particular focus point, it is highly intense and bright. When laser beam is focused on a surface, the energy incident is of the order of millions of joules.

- **Focus ability:** Since laser is highly monochromatic, it can be focused very well by a lens. It is so sharp the diameter of the spot will be close to the wavelength of the focused light. It can be focused to a very small area $0.7\mu m^2$. Since even laser is not ideally monochromatic the spot diameter in actual cases will be 100 to 150 times larger than the wavelength.

Basic principles: Interaction of Radiation with Matter

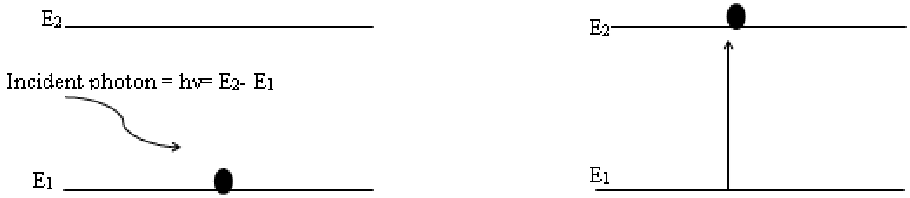
Production of laser light is a consequence of interaction of radiation with matter under appropriate conditions. The interaction of radiation with matter leads to transition of the quantum system such as an atom or a molecule of the matter from one quantum energy state to another quantum state.

A material medium is composed of identical atoms or molecules each of which is characterized by a set of discrete allowed energy levels. 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 two states, which is termed as a quantum jump or transition.

Consider a two energy level system with energies E_1 and E_2 of an atom. E_1 is the energy of lower energy state and E_2 is the energy of excited state. The energy levels E_1 and E_2 are identical to all the atoms in the medium. The radiation (either absorbed or emitted) may be viewed as a stream of photons of energy $(E_2-E_1)=h\nu$, interacting with the material. These interactions lead to any one of the following

- Induced Absorption of radiation
- Spontaneous emission of radiation
- Stimulated emission of radiation

Induced Absorption:
Excitation of atoms by the absorption of photons is called induced absorption.



An atom in the lower energy state E_1absorbs the incident photon of energy (E_1-E_2) and goes to the excited state $E_{2.}$ This transition is known as absorption. For each transition made by an atom one photon disappears from the incident beam.

For an atom A, stimulated absorption transition can be expressed as

$$A \quad + \quad h\nu \longrightarrow A^* \quad \text{(excited state)}$$

The number of absorption transitions per second per unit volume occurring in the material at any instant of time will be proportional to

(i) The number of atoms in the ground state N_1

(ii) Energy density of the incident radiation ($U\nu$)

Rate of induced absorption = $B_{12}U\nu N_1$

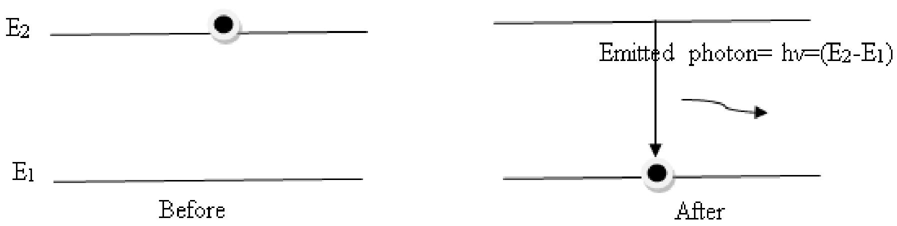
Where B_{12} is proportionality constant which gives the probability of absorptions and it is called Einstein co-efficient of absorption. Since the number of atoms in the lower energy state is greater, the material absorbs more number of the incident photons.

Spontaneous Emission:

An atom which is at higher energy state E_2 is unstable, spontaneously returns to the lower energy state E_1 on its own during which a single photon of energy $(E_2\text{-}E_1) = h\upsilon$ is emitted, the process is known as spontaneous emission.

Spontaneous transition can be expressed as

$$A^* \longrightarrow A + h\upsilon$$



The number of spontaneous transitions per second, per unit volume depends on the number of atoms N_2 in the excited state.

Therefore, the rate of spontaneous emission = $A_{21}N_2$

Where A_{21} is proportionality constant which gives the probability of spontaneous emission and it is called Einstein co-efficient of spontaneous emission of radiation.

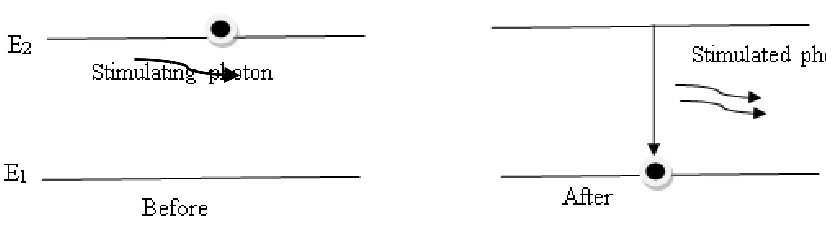
The process has no control from outside. The instant of transition, directions of emission of photons, phases of the photons and their polarization states are random quantities. There will not be any correlation among the parameters of the innumerable photons emitted spontaneously by the assembly of atoms in the medium. Therefore the light generated by the source will be *incoherent* (ex: light emitted from conventional sources).

Stimulated Emission:

Emission of photons by an atomic system with an external influence is called stimulated emission. A mechanism of forced emission was first predicted by Einstein in 1916 in which an atom in the excited state need not wait for the spontaneous emission to take place. A photon of energy $h\upsilon = (E_2 - E_1)$, can induce the excited atom to make downward transition and emit light. Thus, the interaction of a photon with an excited atom triggers it to drop down to the ground state (lower energy) by emitting a photon. The process is known as induced or stimulated emission of radiation.

Stimulated emission transition can be expressed as

$$A^* + h\upsilon \longrightarrow A + 2h\upsilon$$



The number of stimulated transitions per sec per unit volume in the material is proportional to

(i) The number of atoms in the excited state N_2

(ii) Energy density of the incident radiation ($U\nu$)

Rate of stimulated emission$= B_{21} U\nu N_2$

Where B_{21} is proportionality constant which gives the probability of stimulated emissions and it is called Einstein co-efficient of induced (stimulated) emission.

The process of stimulated emission has the following properties.

I. The emitted photon is identical to the incident photon in all respects. (It has the same frequency; it will be in phase and will travel in the same direction and will be in the same state of polarization).
II. The process can be controlled externally.
III. Stimulated emission is responsible for laser.

Some basic definitions

1. **Atomic system:**
   It is a system of atoms or molecules having discrete energy levels.

2. **Active medium**
   It is the medium in which light amplification takes place. The medium may be solid, liquid or a gas. Out of the different atoms in the medium a small fraction of atoms are responsible for stimulated emission and consequent light amplification. They are called active centres

3. **Energy density**
   The energy density U_ν refers to the total energy in the radiation field per unit volume per unit frequency due to photons. It is given by the Plank's distribution law
$$U_\nu = \frac{8\pi h\nu^3}{c^3}\left[\frac{1}{e^{\frac{h\nu}{kT}} - 1}\right]$$

4. **Population**
   It is the number density (the number of atoms per unit volume) of atoms in a given energy state.

5. **Boltzmann factor**
   It is the ratio between the population of atoms in the higher energy state to the lower energy state under thermal equilibrium. If N_2 is

the number density of atoms in the energy state E_2 and N_1 is the number density of atoms in the ground state then

According to Boltzmann condition $N_1 > N_2$ and $\frac{N_2}{N_1} = e^{-\frac{h\nu}{kT}}$

6. **Population inversion**

   It is the condition such that the number of atoms in the higher energy (N_2) state is greater than the number of atoms in the ground state (N_1). i.e, $N_2 > N_1$

If $N_2 > N_1$, it is non-equilibrium condition and it is called population inversion.

Expression for energy density of incident radiation in terms of Einstein coefficients:

Consider an atomic system interacting with radiation field of energy density U_γ. Let E_1 and E_2, be the two energy states of atomic system ($E_2 > E_1$). Let us consider atoms are to be in thermal equilibrium with radiation field, which means that the energy density U_γ is constant in spite of the interaction that is taking place between itself and the incident radiation. This is possible only if the number of photons absorbed by the system per second is equal to the number of photons it emits per second by both the stimulated and spontaneous emission processes.

We know that

The rate of induced absorption $= B_{12}U\nu N_1$,

The rate of spontaneous emission $= A_{21}N_2$

The rate of stimulated emission $= B_{21}U\nu N_2$

N_1 and N_2 are the number of atoms in the energy state E_1 and E_2 respectively, B_{12}, A_{21} and B_{21} are the Einstein coefficients for induced absorption, spontaneous emission and stimulated emission respectively.

At thermal equilibrium,
Rate of induced absorption = Rate of spontaneous emission + Rate of stimulated emission

$$B_{12}N_1U_\gamma = A_{21}N_2 + B_{21}N_2U_\gamma$$

or

$$U_\gamma (B_{12}N_1 - B_{21}N_2) = A_{21}N_2$$

$$U\gamma = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

By rearranging the above equation, we get

$$U\gamma = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}N_1}{B_{21}N_2} - 1}\right] \quad \text{---------} \quad (1)$$

In a state of thermal equilibrium, the populations of energy levels E_2 and E_1 are fixed by the Boltzmann factor. The population ratio is given by,

$$\frac{N2}{N1} = e^{-(\frac{E2-E1}{kT})}$$

$$N_2 = N_1 e^{-\left(\frac{E_2-E_1}{kT}\right)} = N_1 e^{-\frac{h\gamma}{kT}}$$

$$Since\ \left(E_2 - E_1 = h\nu\right)$$

$$\therefore \quad \frac{N_1}{N_2} = e^{\frac{h\gamma}{kT}}$$

$\therefore$ Equation (1) becomes,

$$U\gamma = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}}{B_{21}} e^{\frac{h\gamma}{kT}-1}}\right] \quad \text{------} \quad (2)$$

According to Planck's law of black body radiation, the equation for Uγ is,

$$U_\nu = \frac{8\pi h\nu^3}{c^3}\left[\frac{1}{e^{\frac{h\nu}{kT}}-1}\right] \text{-------}(3)$$

Now comparing the equation (2) and (3) term by term on the basis of positional identity we have

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\gamma^3}{c^3} \text{ and } \frac{B_{12}}{B_{21}} = 1 \qquad \text{or} \qquad B_{12} = B_{21}$$

This implies that the probability of induced absorption is equal to the probability of stimulated emission. Due to this identity the subscripts could be dropped, and A_{21} and B_{21} can be simply represented as A and B and equation (3) can be rewritten.

∴ At thermal equilibrium the equation for energy density is

$$U\gamma = \frac{A}{B}\frac{1}{[e^{\frac{h\gamma}{kT}} - 1]}$$

(Think: Even though the probability of induced absorption is equal to the probability of stimulated emission, the rate of induced absorption is not equal to rate of stimulated emission. Why?)

Conditions for light amplification:-

Conditions for laser emission can be studied by taking the ratios of rate of stimulated emission to spontaneous emission and rate of stimulated emission to absorption.

At thermal equilibrium,

$$\frac{\text{Rate of Stimulated Emission}}{\text{Rate of Spontaneous Emission}} = \frac{B_{21}N_2U_\nu}{A_{21}N_2} = \frac{B_{21}U_\nu}{A_{21}}$$

Since, $B_{21}/A_{21} = C^3/8\pi h\nu^3$ = constant,

This suggests that in order to enhance the number of stimulated transitions the radiation density $U\nu$ should be made high.

$$\frac{\text{Rate of Stimulated Emission}}{\text{Rate of Induced absorption}} = \frac{B_{21}N_2U_\nu}{B_{12}N_1U_\nu} = \frac{B_{21}N_2}{B_{12}N_1}$$

($B_{21}/B_{12} = 1$)

The stimulated emission will be larger than the absorption only when $N_2 > N_1$. If $N_2 > N_1$ the stimulated emission dominates the absorption otherwise the medium will absorb the energy. This condition of $N_2 > N_1$ is known as ***inverted population state or population inversion.***

Requisites of a laser system:

The essential components of a laser are

- ***An active medium*** to support population inversion.
- ***Pumping mechanism*** to excite the atoms to higher energy levels.
- ***Population inversion***
- ***Metastable state***
- ***An optical cavity or optical resonator.***

Active medium:

It is the material medium composed of atoms or ions or molecules in which the laser action is made to take place, which can be a solid or liquid or even a gas. In this, only a few atoms of the medium (of particular species) are responsible for stimulated emission. They are called active centers and the remaining medium simply supports the active centers.

Pumping Mechanism:

To achieve the population inversion in the active medium, the atoms are to be raised to the excited state. It requires energy to be supplied to the system. The process of supplying energy to the medium with a view to transfer the atoms to higher energy state is called **pumping.**

Important pumping mechanisms are

a) ***Optical pumping***: It employs a suitable light source for excitation of desired atoms. This method is adopted in solid state lasers (ex: Ruby laser and Nd:YAG laser).

b) ***Electric discharge***: In this process an electric field causes ionization in the medium and raises it to the excited state. This technique is used in gas lasers (ex: Ar^+ laser).

c) ***Inelastic atom-atom collision*** **:**In this method a combination of two types of gases are used, say A and B. During electric discharge A atoms get excited and they now collide with B atoms so that B goes to excited state. This technique is used in gas lasers (ex: He-Ne laser).

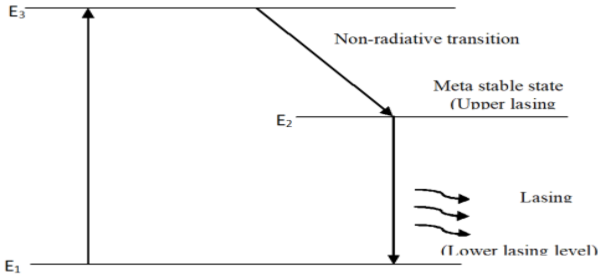
d) ***Direct conversion*** : In this process electrical energy is directly converted into light energy. This technique is used in semiconductor lasers (ex: GaAs laser).

Population Inversion and Meta stable state:

In order to increase stimulated emission it is essential that $N_2 > N_1$ i.e., the number of atoms in the excited state must be greater than the number of atoms in the ground state. Even if the population is more in the excited state, there will be a competition between stimulated and spontaneous emission. The possibility of spontaneous emission can be reduced by using intermediate state where the life time of atom will be little longer **(10^{-6} to 10^{-3}s)** compared to excited state (10^{-9} s). This intermediate state is called **metastable state** and it depends upon the nature of atomic species used in the active medium.

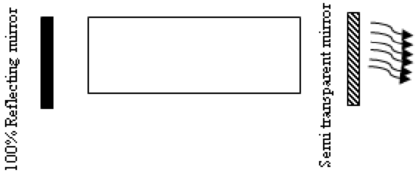
Principle of pumping scheme:

Consider three energy levels E_1, E_2 and E_3 of a quantum system of which the level E_2 is metastable state. Let the atoms be excited from E_1 to E_3 state by supply of appropriate energy. Then the atom from the E_3 state undergoes downward transition to either E_1or E_2 states rapidly. Once the atoms undergo downward transitions to level E_2 they tend to stay, for a long interval of time, because of which the population of E_2 increases rapidly. Transition from E_2 to E_1 being very slow, in a short period of time the number of atoms in the level E_2 is far greater than the level E_1. Thus Population inversion has been achieved betweenE_1 and E_2 . The transition from meta stable state to ground state is the lasing transition. It occurs in between upper lasing E_2 and lower lasing level E_1.



Optical resonator:

- An optical resonator generally consists of two plane mirrors, with the active material placed in between them. One of the mirrors is semi-transparent while the other one is 100% reflecting. The mirrors are set normal to the axis of the active medium and parallel to each other.



- The optical resonant cavity provides the selectivity of photon states by confining the possible direction of photon propagation, as a result lasing action occurs in this direction.

- The distance between the mirrors is an important parameter as it chooses the wavelength of the photons. Suppose a photon is travelling between two reflectors, it undergoes reflection at the mirror kept at the other end .the reflected wave superposes on the incident wave and forms stationary wave such that the length L of the cavity is given by $L = n\,\frac{\lambda}{2}$

$$\text{Hence } \lambda = \frac{2L}{n}$$

Where, L is the distance between the mirrors, λ is the wavelength of the photon, n is the integral multiple of half wavelength

The wavelengths satisfying the above condition are only amplified. Hence the cavity is also called resonant cavity.

The main Role of the optical resonator is to

- Provide positive feedback of photons into the active medium to sustain stimulated emission and hence laser acts as a generator of light.

- Select the direction of stimulated photons which are travelling parallel to the axis of optical resonator and normal to the plane of mirrors are to be amplified. Hence laser light is highly directional.

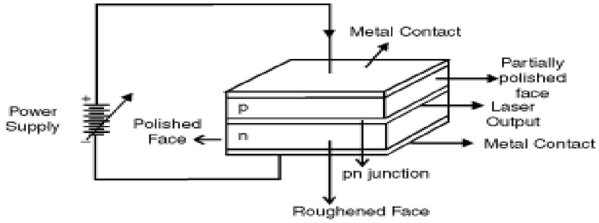
- Builds up the photon density (U_ν) to a very high value through repeated reflections of photons by mirrors and confines them within the active medium.

- Selects and amplifies only certain frequencies of stimulated photons which are to be highly monochromatic and gives out the laser light through the partial reflector after satisfying threshold condition.

Semiconductor diode Laser

A semiconductor diode laser is a specially fabricated p-n junction device that emits coherent light when it is forward biased. The first semiconductor lasers were made by R.N. Hall and his co-workers in 1962 using gallium arsenide (GaAs), which is a direct band gap semiconductor. Diode lasers are portable and used in optical communications, CD players, CD-ROM drives, optical reading, high speed laser printing etc.

Principle: The semiconductor laser is based on the principle of the emission of the recombination energy in the form of light. In normal state of a semiconductor the conduction band is sparsely occupied by electrons and valence band is occupied by large number of electrons and small number of holes. The electron-hole recombination is the basic mechanism involved in the emission of light in semiconductor lasers. They are made using direct band gap semiconductors such as GaAs, CdSe, GaAlAs etc .By heavily doping the p-n junction and by applying a high current density, the stimulated emission of light is produced and hence the laser operation is made possible in the semiconductor laser.



Construction: A schematic diagram of semiconductor laser is as shown in the diagram. The semiconductor laser consists of heavily doped n - GaAs and p - GaAs. The diode chip is 500μm long and about 100 μm wide and thick. The junction (active region) lies in a horizontal plane through the centre. The top and bottom faces are metallized and ohmic contacts are provided to pass the current through the diode. The front and rear faces polished, parallel to each other and perpendicular to the plane of the junction. The polished faces constitute the Fabry- perot resonator. The other two sides of the diode are roughened to prevent lasing action in that direction. The diode is forward biased, with a voltage nearly equal to the bad gap voltage of the material.

Working:

- The energy band diagram of a heavily doped p-n junction is shown in figure (a). Due to heavy doping on the n-side, the donor levels are broadened and extend into the conduction band and the Fermi level E_F is pushed in to the conduction band. The electrons occupy the portion of the conduction band below the Fermi level between E_F and E_C.

- Similarly on the heavily doped p-side, Fermi level E_F lies within the valence band. The holes occupy the portion of the valence band above E_F and E_V. At the condition of thermal equilibrium Fermi level is uniform across the junction as shown in the figure (a).

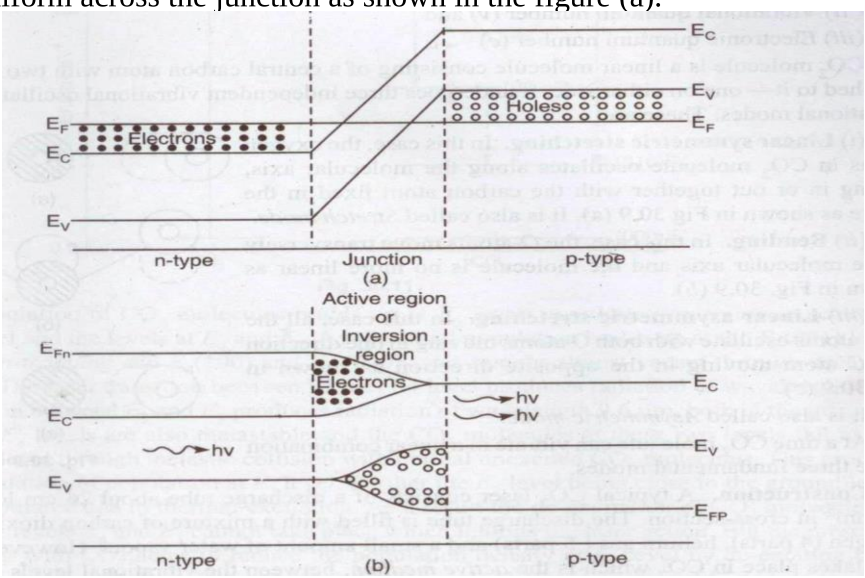


Figure (a) and (b): Energy band diagram of a heavily doped p-n junction

- When the junction is forward biased, electrons from the n region and holes from the p region are injected into the junction region. This is how pumping action takes place in a p-n junction semiconductor laser.

- For small values of forward bias current, the electron holes recombine and the recombination brings about spontaneous, non-coherent emission of photons in all directions. At this stage the junction acts as a light emitting diode (LED).

- As the forward bias current is increased the intensity of light increases but when the forward bias reaches the threshold values the carrier concentration in the junction region rises to a very high value. In the junction region attains a very high concentration of electrons in the conduction band and at the same time a very high concentration of holes in the valence band as shown in figure (b).

- As a result the upper energy level in the narrow junction region has a high electron population whereas the lower energy levels in this region are vacant, thereby giving rise to the condition of population inversion. This narrow region in which population inversion takes place is known as ***'Inversion region'*** or '**Active region**'.

- Initially, when a recombination of electron-hole pair takes place between the conduction and valence band leads to spontaneous emission of photons. The spontaneous photons moving in the junction plane stimulate the conduction electrons to jump to the vacant states of the valence band and produces coherent radiation giving rise to laser action. GaAs laser emits at a wavelength of 9000A^o in infrared region.

- Semiconductor lasers are very compact, efficient and can be easily fabricated. But their spectral purity is low and emission pattern is broad. Hence, monochromatic property, coherence and directional characteristic properties are not good as that of the other types of lasers.

Characteristics

TITLE	Description
Type	Solid State Semiconductor laser.
Active Medium	The active medium of a semiconductor laser is a p-n junction.
Pumping Method	Direct conversion method.
Power output	The power output from this laser is 1mW.
Nature of output	Continuous-wave or pulsed output.
Wavelength of output	8300 to 9000**Å**.

Advantages:

1. It is very small in dimension. The arrangement is simple and compact.
2. It exhibits high efficiency.
3. The laser output can be easily increased by controlling the junction current.
4. It is operated with lesser power than ruby and CO_2 laser.
5. It requires very little auxiliary equipment
6. It can have a continuous wave output or pulsed output.

Disadvantages:

1. It is difficult to control the mode pattern and structure of laser.
2. The output is usually from 5 to 15^o i.e., laser beam has large divergence.
3. The purity and mono-chromaticity are poorer than other types of laser
4. Threshold current density is very large (400A/mm2).
5. It has poor coherence and poor stability.

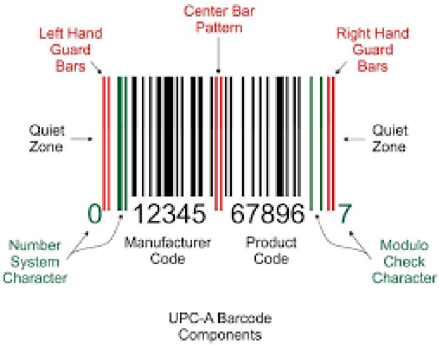
Applications:

1. It is widely used in fiber optic communication.
2. It is used to heal the wounds by infrared radiation.
3. It is used in laser printers and CD writing and reading.

Application of Lasers

Bar code scanner:

Bar scanner is an optical scanner that can read printed barcodes for identifying the product. A bar code consists of a series of strips of dark and white bands. These white and dark bands are of different widths separated from each other by specific distances that contain all the information about the product. A laser is used to scan the bar code with the help of rotating mirror. Typical scanning speeds are about 200 m/s. When the laser beam is incident on the barcode, the amount of light scattered depends on whether the strip strip is black or white. Since the bars are separated by variable distance, light intensity varies with time and is recorded by photodetector. The signal is fed into an amplifier and later to a decoder which displays the information on a monitor and also sends it to product inventory system.



Laser Printing:

From last few years, there has been tremendous increase in the use of computers as an aid to the management, processing and dissemination of information. The peripheral device required by the computer for all these applications is the printer. Today, use of computers in large data processing installations places very high demand on printers as regards its speed, character flexibility, and print quality. The conventional impact printers can no longer meet these demands because of their limited speed and character flexibility. In the new generation printers, printing method is based on the principle of electrophotography.

A laser printer makes use of a beam of light for printing. The light of the laser changes the electrical charge on the drum, wherever it hits, as the paper passes through the printer. The laser beam strikes at the surface of the drum and this is known as a photo receptor. By changing the charge on the drum, the laser beam can print patterns onto the photo receptor. Once the design created on the drum, it coated with toner from a toner cartridge. In most of the cartridges, the toner is black, but the laser printers are also coloured.

Laser printers work by laying down an array of tiny, evenly spaced dots of “ink” on the paper. The dots are so small, and they blend so seamlessly that text looks very nearly as clean as what you get from a traditional typesetting machine. The quality you get from your laser printer depends mostly on the resolution, the fineness of the dots it uses to print the images. Resolution measured in dots per inch (dpi), which is how many dots it can write a long with a line, either vertically or horizontally. Most laser printers have had 300 dpi resolutions, but 600 dpi is just now becoming the new standard.

Laser cooling:

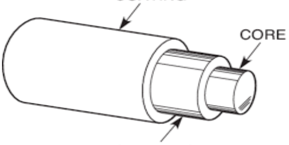
It is the process of using the force exerted by laser to cool the atoms to lower temperature essentially amounts to reducing their speed. It is based on the fact that when an atom absorbs or emits photon its momentum changes.

The phenomenon of laser cooling has been used in physics to limit the motion of thermal motion of atoms. Atom emitted from an oven will have spread of velocities around some average value. If this atomic beam encounters an encounters a laser beam in the opposite direction, the atoms gets slow down. Atoms have characteristic energy levels that allow them to absorb and emit radiation of specific frequencies. Atoms moving with respect to the laser beam will see the laser frequency shifted because of the Doppler effect. For example, atoms moving towards the laser beam will encounter a laser with high frequency and atoms moving away from the laser beam will encounter a laser beam with low frequency. Even atoms moving in the same direction within the beam of atoms will see slightly different frequencies depending on the velocities of the various atoms. Now if the frequency of the laser beam is tuned to the precise frequency seen by the faster atoms so that those atoms can be excited by absorbing the radiation, those faster atoms will be slowed down by absorbing the momentum of the laser radiation. Essentially the phenomenon can be viewed as scattering of a photon by an atom. Every atom or an ion has momentum given by the de Broglie relation $p=h/\lambda$. The atoms slow down because photons strike them in opposite direction. As the atom slow down, they see that the Doppler shifted frequencies of the laser change, and the atoms no longer absorb the laser radiation. They continue with lower velocity and velocity spread.

By using the six intersecting laser beams coming in different angles atoms are essentially isolated and average velocity is zero. With this technique atoms have been cooled to temperature below 0.2 μK.

OPTICAL FIBERS

Optical fibres are the light guides used in optical communications as wave-guides. They are thin, cylindrical, transparent flexible dielectric fibres. They are able to guide visible and infrared light over long distances. The working structure of optical fibre consists of three layers. Core- is the inner cylindrical layer which is made of glass or plastic. Cladding- which envelops the inner core. It is made of the same material of the core but of lesser refractive index than core. The core and the cladding layers are enclosed in a polyurethane jacket called sheath which safeguards the working structure of fibre against chemical reactions, mechanical abrasion and crushing etc.

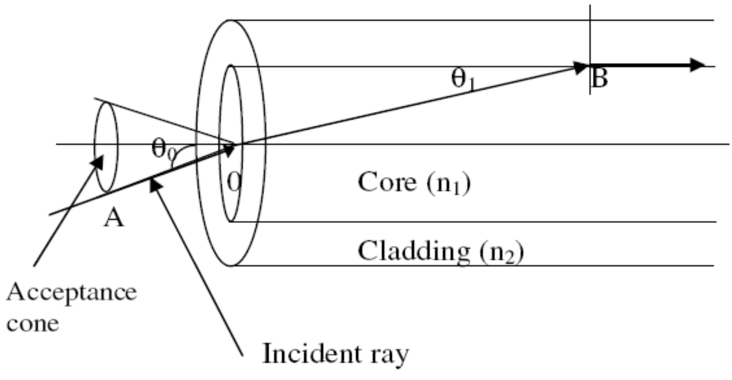


Propagation mechanism in Optical fibre:

In optical fibres light waves can be guided through it, hence are called light guides. The cladding in an optical fibre always has a lower refractive index (RI) than that of the core. The light signal which enters into the core can strike the interface of the core and the cladding at angles greater than critical angle of incidence because of the ray geometry. The light signal undergoes multiple total internal reflections within the fibre core. Since each reflection is a total internal reflection, the signal sustains its strength and also confines itself completely within the core during propagation. Thus, the optical fibre functions as a wave guide.

Numerical Aperture and Ray Propagation in the Fibre:

Consider an optical fibre consists of core and cladding material placed in air medium. Let n_0, n_1 and n_2 be the refractive indices of surrounding air medium, core and cladding material respectively. The RI of cladding is always lesser than that of core material ($n_2 < n_1$) so that the light rays propagate through the fibre. Let us consider the special case of ray which suffers critical incident at the core cladding interface. The ray travels along AO entering into the core at an angle of θ_0 with respect to the fibre axis. Let it be refracted along OB at an angle θ_1 in the core and further proceed to fall at critical angle of incidence ($= 90-\theta_1$) at B on the interface of core and cladding. Since it is critical angle of incidence, the refracted ray grazes along core and cladding interface.



It is clear from the figure that a ray that enters at an angle of incidence less than θ_0 at O, will have to be incident at an angle greater than the critical angle at the core-cladding interface, and gets total internal reflection in the core material. When OA is rotated around the fibre axis keeping θ_0 same, it describes a conical surface, those rays which are funneled into the fibre within this cone will only be totally internally reflected and propagate through the fibre. The cone is called acceptance cone.

The angle θ_0 is called the wave guide acceptance angle or the acceptance cone half-angle which is the maximum angle from the axis of optical fibre at which light ray may enter the fibre so that it will propagate in core by total internal reflection.

Sin θ_0 is called the numerical aperture (N.A.) of the fibre. It determines the light gathering ability of the fibre and purely depends on the refractive indices of core, cladding and surrounding medium.

Let n_0, n_1 and n_2 be the refractive indices of surrounding medium, core and cladding respectively for the given optical fibre.
By applying the Snell's law at O,

$$n_0 sin\theta_0 = n_1 sin\theta_1$$

$$sin\theta_0 = \frac{n_1}{n_0} sin\theta_1 \text{------------}(1)$$

At the point Bon the core and cladding interface, the angle of incidence = $90-\theta_1$
Applying Snell's law at B

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

or $$n_1 cos\theta_1 = n_2$$

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

From equation (1)

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

$$sin\theta_0 = \frac{n_1}{n_0}\sqrt{1-\frac{n_2^2}{n_1^2}} = \frac{n_1}{n_0} x \sqrt{\frac{n_1^2-n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2-n_2^2}}{n_0}$$

If the medium surrounding the fibre is air, then $n_0 = 1$,

Therefore, $$sin\theta_0 = \sqrt{n_1^2-n_2^2}$$

$\sin\theta_0$ = Numerical aperture: NA

Therefore, $NA = sin\theta_0 = \sqrt{n_1^2-n_2^2}$

If θ_i is the angle of incidence of an incident ray, then the ray will be able to propagate,

If $\theta_{i<}\theta_0$

or if $\sin\theta_i < \sin\theta_0$

or $\sin\theta_i < NA$

Fraction Index Change (Δ):

The fractional index change Δ is the ratio of the difference in the refractive indices between the core and the cladding to the refractive index of core of an optical fibre. It is also known as relative core clad index difference, denoted by Δ.

If n_1 and n_2 are the refractive indices of core and cladding, then,

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

Relation between NA and Δ

We have RI change $\Delta = \frac{n_1 - n_2}{n_1}$

Or $\Delta n_1 = (n_1 - n_2)$-----------(1)

We know that,

$$N.A. = \sqrt{n_1^2 - n_2^2}$$

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

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

Since $n_1 \sim n_2$, $(n_1 + n_2) = 2n_1$

Therefore,

$$N.A. = \sqrt{2n_1^2\Delta}$$

$$N.A. = n_1\sqrt{2\Delta}$$

We can see that, the value of NA can be increased by increasing the value of Δ, so as to receive maximum light into the fibre. However, fibres with large Δ will not be useful for optical communication due to the occurrence of a phenomenon inside the fibre called multipath dispersion or intermodal dispersion. This phenomenon introduces a time delay factor, in the travel length and may cause distortion of the transmitted optical signal. This leads to pulse broadening, which in turn limits the communication distance.

Modes of Propagation:

The possible number of paths of light in an optical fibre determines the number of modes available in it. It also determines the number of independent paths for light that a fibre can support for its propagation without interference and mixing.

We may have a single mode fibre supporting only one signal at a time or multimode fibre supporting many rays at a time.

Such number of modes supported for propagation in the fibre is determined by a parameter called V-number. If the surrounding medium is air then the V- number is given by

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

or

$$V = \frac{\pi d}{\lambda}(NA)$$

where d is the core diameter, n_1 is the refractive index of core, n_2 is the refractive index of the cladding and λ is the wavelength of the light propagating through the fibre.

$$V = \frac{\pi\ 2r}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{(r)2\pi}{\lambda}\sqrt{n_1^2 - n_2^2} = r.k\sqrt{n_1^2 - n_2^2}\ .$$

Where k is the propagation constant ($k = 2\pi/\lambda$)

If fibre is surrounded by a medium of refractive index n_0, then

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

For step index fibre, the number of modes $\approx \frac{V^2}{2}$

For graded index fibre, the number of modes $\approx V^2/4$

Types of Optical fibres:

The optical fibres are classified under 3 categories. They are

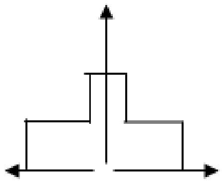
a) Step index Single mode fibre (SMF)
b) Step index multi modefibre (MMF)
c) Graded index Multi Mode Fibre (GRIN)

This classification is done depending on the refractive index profile and the number of modes that the fibre can guide.

Refractive Index Profile (RI):

Generally in any types of optical fibre, the refractive index of cladding material is always constant and it has uniform value throughout the fibre. But in case of core material, the refractive index may either remain constant or subjected to variation in a particular way.

This variation of RI of core and cladding materials with respect to the radial distance from the axis of the fibre is called refractive index profile. This can be represented as follows,



RI profile of Step index fibre

X axis: Radial distance from the centre of the fibre

Step index Single mode fibre (SMF):

A single mode fibre has a core material of uniform refractive index (RI) value. Similarly cladding also has a material of uniform RI but of lesser value. This results in a sudden increase in the value of RI from cladding to core. Thus its RI profile takes the shape of a step. The diameter value of the core is about 8 to 10 μm and external diameter of cladding is 60 to 70 μm. Because of its narrow core, it can guide just a single mode as shown in Figure. Hence it is called single mode fibre. Single mode fibres are most extensively used ones and they constitute

80% of all the fibres that are manufactured in the world today. They need lasers as the source of light. Though less expensive, it is very difficult to splice them (joining of optical fibres). Since single mode is propagating through the fibre, intermodal dispersion is zero in this fibre. They find particular application in submarine cable system.

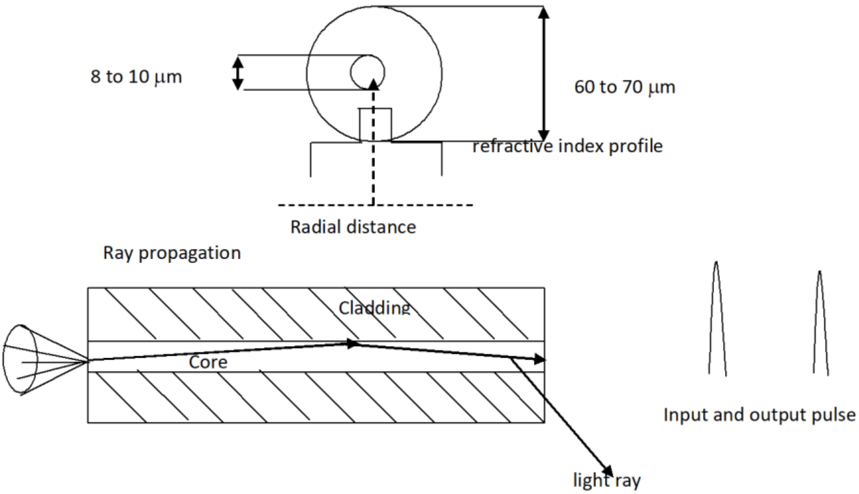


Fig: Step Index Single Mode Fibre

Step index multimode fibre (MMF):

The geometry of a step-index multimode fibre is as shown in below figure. It’s construction is similar to that of a single mode fibre but for the difference that, its core has a much larger diameter by the virtue of which it will be able to support propagation of large number of modes as shown in the figure. Its refractive index profile is also similar to that of a single mode fibre but with larger plane regions for the core.

The step-index multimode fibre can accept either diode laser or LED (light emitting diode) as source of light. It is the least expensive of all. Since multi modes are propagating through this fibre with different paths, intermodal dispersion is maximum in this fibre. Its typical application is in data links which has lower bandwidth requirements.

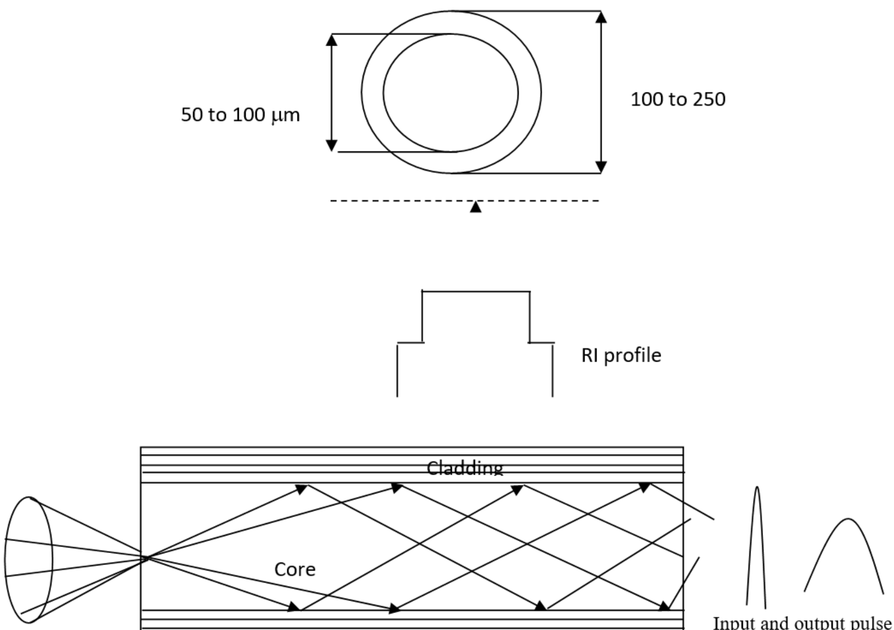


Fig. Step index multimode fibre

Graded index multimode fibre (GRIN)

The construction of Graded index fibre is similar to that of multimode step-index fibre, except for the refractive index of the core. The refractive index of the core varies across the core diameter (radially graded) as shown in figure, while the refractive index of the cladding is fixed. In this fibre, a number of modes can be transmitted. The rays move in a sinusoidal path through the core. Light travels at lower speed in the high-index region. Since the fastest components of the ray take the longer path and the slower components take the shorter path in the core, the travel time of the different modes will be almost same. This reduces the effect of intermodal dispersion and hence losses are minimum with little pulse broadening. These fibres are most suitable for large bandwidth, medium distance and medium bit rate communication systems. For such cables, either a laser or LED source can be used to couple the signal into the core.

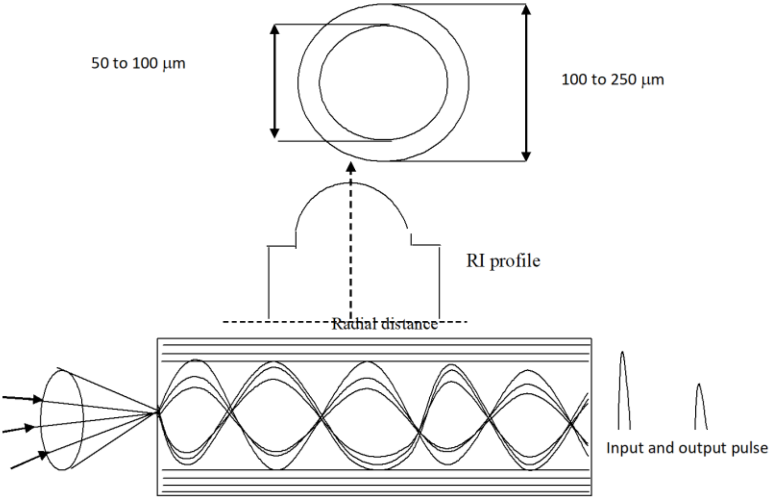


Fig. Graded index multimode fibre

Differences between single and multimode fibres:

Single mode fibre	Multi modefibre
• Only one mode can be propagated • Smaller core diameter • Low dispersion of signal • Can carry information to longer distances • Launching of light and connecting two fibres are difficult	• Allows large number of modes for light to pass through it • Larger core diameter • More dispersion of signal • Information can be carried to shorter distances only • Launching of light and connecting of fibres is easy

Differences between step and graded index fibres:

Step index fibre	Graded index fibre
• Refractive index of core is uniform • Propagation of light is in the form of meridional rays • Step index fibres has lower bandwidth • Distortion is more (in multimode) • No. of modes for propagation $N_{step} = V^2/2$	• Refractive index of core is not uniform • Propagation of light is in the form of skew rays • Graded index fibres has higher bandwidth • Distortion is less • No. of modes for propagation $N_{grad} = V^2/4$

Attenuation in optical fibres:

The total energy loss suffered by the signal due to the transmission of light in the fibre is called **attenuation.**

The important factors contributing to the attenuation in optical fibre are i) Absorption loss ii) Scattering loss iii) Bending loss iv) Intermodal dispersion loss and v) coupling loss.

Attenuation is measured in terms of attenuation co-efficient and it is the loss per unit length. It is denoted by symbol α. Mathematically attenuation of the fibre is given by,

$$\alpha = -\frac{10 \times \log_{10}\left(\frac{P_{out}}{P_{In}}\right)}{L} \text{ dB/km}$$

Where P_{out} and P_{in} are the power output and power input respectively, and L is the length of the fibre in km.
Therefore, Loss in the optical fibre = α x L

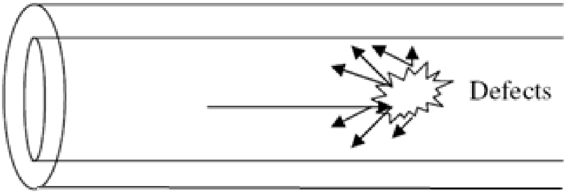
1. Absorption loss:

There are two types of absorption;
(a) Absorption by impurities.
(b) Intrinsic absorption.

In the case absorption by impurities, the type of impurities is generally transition metal ions such as iron, chromium, cobalt and copper. During signal propagation when photons interact with these impurities, the electron absorbs the photons and get excited to higher energy level. Later these electrons give up their absorbed energy either as heat energy or light energy. The re-emission of light energy is of no use since it will usually be in a different wavelength or at least in different phase with respect to the signal. The other impurity which would cause significant absorption loss is the OH^- (Hydroxyl) ion, which enters into the fibre constitution at the time of fibre fabrication. **In Intrinsic absorption** it is the absorption by the fibre itself, or it is the absorption that takes place in the material assuming that there are no impurities and the material is free of all in homogeneities and this sets the lowest limit on absorption for a given material.

2. Scattering loss:

The signal power loss occurs due to the scattering of light energy due to the obstructions caused by imperfections and defects, which are of molecular size, present in the body of the fibre itself. The scattering of light by the obstructions is inversely proportional to the fourth power of the wavelength of the light transmitted through the fibre. Such a scattering is called Rayleigh scattering. The loss due to the scattering can be minimized by using the optical source of large wavelength.



3. **Bending losses (radiation losses):**

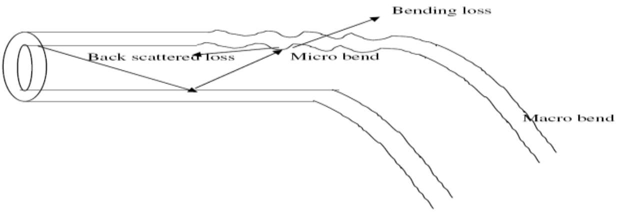
There are two types of bending losses in optical fibre a) macroscopic and b) microscopic bending loss.

a) Macroscopic bends:

Macroscopic bends occurs due the wrapping of fibre on a spool or turning it around a corner. The loss will be negligible for small bends but increases rapidly until the bending reaches a certain critical radius of curvature. If the fibre is too bent, then there is possibility of escaping the light ray through cladding material without undergoing any total internal reflection at core-cladding interface.

b) Microscopic bends:

This type of bends occurs due to repetitive small-scale fluctuations in the linearity of the fibre axis. Due to non-uniformities in the manufacturing of the fibre or by non-uniform lateral pressures created during the cabling of the fibre. The microscopic bends cause irregular reflections at core-cladding interface and some of them reflects back or leak through the fibre. This loss could be minimized by extruding a compressible sheath over the fibre which can withstand the stresses while keeping the fibre relatively straight.



2 **Coupling losses:**

Coupling losses occur when the ends of the fibres are connected. At the junction of coupling, air film may exist or joint may be inclined or may be mismatched and they can be minimized by following the technique called splicing.

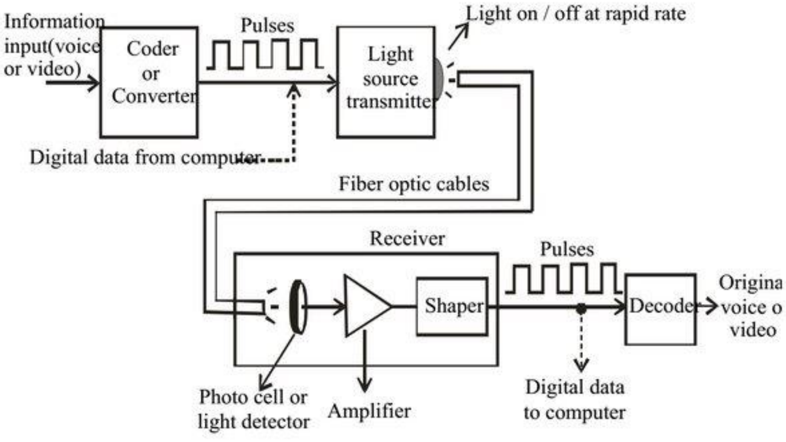
Applications of Optical Fibres:

Point-to-point Communication

The use of optical fibres in the field of communication has revolutionized the modern world. An optical fibre acts as the channel of communication (like electrical wires), but transmits the information in the form of optical waves. A simple p to p communication system using optical fibres is illustrated in the figure.

The main components of p to p communication is

1) An optical transmitter, i.e., the light source to transmit the signals/pulses
2) The communication medium (channel) i.e., optical fibre
3) An optical receiver, usually a photo cell or a light detector, to convert light pulses back into electrical signal.



The information in the form of voice or video to be transmitted will be in an analog electric signal format. This analog signal at first converted into digital electric (binary) signals in the form of electrical pulses using a Coder or converter and fed into the optical transmitter which converts digital electric signals into optic signals. An optical fibre can receive and transmit signals only in the form of optical pulses. The function of the light source is to work as an efficient transducer to convert the input electrical signals into suitable light pulses. An LED or laser is used as the light source for this purpose. Laser is more efficient because of its monochromatic and coherent nature. Hence semiconductor lasers are used for their compact size and higher efficiency.

The electrical signal is fed to the semiconductor laser system, and gets modulated to generate an equivalent digital sequence of pulses, which turn the laser on and off. This forms a series of optical pulses representing the input information, which is coupled into the optical fibre cable at an incidence angle less than that of acceptance cone half angle of the fibre.

Next the light pulses inside the fibre undergo total internal reflection and reach the other end of the cable. Good quality optical fibres with less attenuation to be chosen to receive good signals at the receiver end.

The final step in the communication system is to receive the optical signals at the end of the optical fibre and convert them into equivalent electrical signals. Semiconductor photodiodes are used as optical receivers. A typical optical receiver is made of a reverse biased junction, in which the received light pulses create electron-hole charge carriers. These carriers, in turn, create an electric field and induce a photocurrent in the external circuit in the form of electrical digital pulses. These digital pulses are amplified and re-gain their original form using suitable amplifier and shaper. The electrical digital pulses are further decoded into an analogues electrical signal and converted into the usable form like audio or video etc.,

As the signal propagates through the fibre it is subjected to two types of degradation. Namely attenuation and delay distortion. Attenuation is the reduction in the strength of the signal because power loss due to absorption and scattering of photons. Delay distortion is the reduction in the quality of the signal because of the spreading of pulses with time. These effects cause continuous degradation of the signal as the light propagates and may reach a limiting stage beyond which it may not be retrieve information from the light signal. At this stage repeater is needed in the transmission path.

Reciever	Amplifier	Transmitter

An optical repeater consists of a receiver and a transmitter arranged adjacently. The receiver section converts the optical signal into corresponding electrical signal. Further the electrical signal is amplified and recast in the original form and it is sent into an optical transmitter section where the electrical signal is again converted back to optical signal and then fed into an optical fibre.

Finally at the receiving end the optical signal from the fibre is fed into a photo detector where the signal is converted to pulses of electric current which is then fed to decoder which converts the sequence of binary data stream into an analog signal which will be the same information which was there at the transmitting end.

Optical fiber sensors and phase modulators:

Optical fibers can be used as sensors. They are transducers, which generally consists of a light source coupled with an optical fibre and a light detector held at the receiver end. Optical fibre may be single mode or multimode. Fibre optic sensor can be used to measure physical parameters like pressure, temperature, strain, the acoustic field, magnetic field etc., by knowing variation in the intensity or phase modulation of an optic wave propagating through the fibre. The advantages of these sensors are that they are lighter, occupy lesser volume and are cheaper.

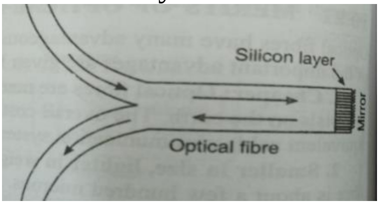
1. Temperature Sensors

There are two techniques to measure temperature using optic fibre. One is intensity modulated and the other one is the phase modulated sensor.

a) Intensity modulated sensor.

Principle: In this technique, temperature is measured by the modulation of intensity of the reflected light from a target. Silicon layer is used as target in this technique. The operation of the temperature sensor is based on the 1 micrometer wavelength light-absorption characteristics of silicon as a function of temperature. The amount of light absorbed by the silicon layer (target) varies depending on the temperature. The change in the intensity of the reflected light (from target) is proportional to the change in temperature detected by photo detector.

Construction: Schematic diagram of intensity modulated fibre optic temperature sensor is shown. The fibre is coated at one end with a thin silicon layer. The silicon layer is in turn coated with a reflective coating at the back. The silicon layer acts as the sensing element.

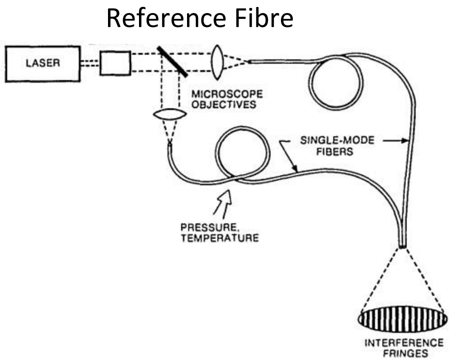


Working: The light from a laser source is launched into the fibre from one of the ends of one of its branches. It passes first through the fibre and then through the silicon layer. The mirror coating at the other end of the silicon layer reflects the light back which again travels through the silicon layer. The reflected light emerges out through another branch of multimode fibre and is collected by a photo detector. The amount of light by the 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.

b) **Phase modulated temperature sensor.**

Principle: This sensor is based on phase variation resulting due to the variation of refractive index of the optical fibre under the influence of temperature.

Construction: The construction of phase modulated temperature sensor is pictorially shown below. It can be used as pressure sensors also.



The above diagram represents a single mode fibre sensor and the arrangement is known as the Mach-Zehnder arrangement. Laser light from a laser source is made to fall on a beam splitter which divides the light into two parts and sends light through the sensing fibre and the reference fibre. Light passing out of the two fibre elements is fed to a detector, which measures the difference in phase of the two light waves. Accurate measurements of the temperature may be obtained from these patterns.

Working: Light from the source is divided into two parts by the beam splitter. One part is allowed through sensors fibre, and the other part is passed through the reference fibre. Light rays entering the fibres are coherent and have the same phase. Prior to heating or applying pressure, the optical path length of the two fibre elements is same and hence both the outputs will be in phase. When the sensor fibre is subjected to heating or under pressure, the temperature or pressure causes a change in the refractive index of the optical fibre. Therefore, the light coming out of the two fibres at the other end will have phase difference due to difference in optical path difference caused by the heating or applying pressure. When the rays are superposed, they interfere and interference pattern will be observed. As temperature or pressure increases, the phase difference between the two outputs increases and is observed as a displacement of the fringe pattern. By determining the fringe displacement, we can determine the magnitude of temperature or pressure.

Further reading: Displacement sensor, Force sensors and Liquid Level Detector.

Advantages over conventional communication:

1) Large Bandwidth: Optical fibres have a wider bandwidth (when compared to conventional copper cables). This helps in transmitting voice, video and data on a single line and at very fast rates (10^{14} bps as compared to about 10^4 bps in ordinary communication line)
2) Electromagnetic Interference (EMI): EMI and disturbance in the transmission is a very common phenomenon in ordinary copper cables. However, the optical fibre cables are free from EMI, since Electromagnetic radiation has no effect on the optical wave. Hence, there is no need to provide specially shielded conditions for the optical fibre.
3) Low attenuation: Compared to metallic cables, optical fibres have a low attenuation level (as they are relatively independent of frequency). The loss in optical fibres is very low, of the order of 0.1 to 0.5 dB/km of transmission.
4) Electrical Hazards: Since, optical fibres carry only the light signals, there are no problems of short-circuiting and shock hazards.
5) Security: Unlike electrical transmission lines, there is no signal radiation around the optical fibre, hence the transmission is secure. The tapping of the light waves, if done, leads to a loss of signal and can be easily detected.
6) Optical fibre cables are small in size, light weight and have a long life.

Disadvantages:

- Fibre loss is more at the joints if the joints do not match (the joining of the two ends of the separate fibres are called splicing)
- Attenuation loss is large as the length of the fibre increases.
- Repeaters are required at regular interval of lengths to amplify the weak signal in long distance communication.
- Sever bends will increase the loss of the fibre. Hence, the fibre should be laid straight as far as possible and avoid severe bends.

Note:

- Point to Point haul communication system is employed in telephone trunk lines. This system of communication covers the distances 10 km and more. Long-haul communication has been employed in telephone connection in the large cities of New York and Los Angeles. The use of single mode optical fibres has reduced the cost of installation of telephone lines and maintenance, and increased the data rate.
- Local Area Network (LAN) Communication system uses optical fibres to link the computer-oriented communication within a range of 1 or 2 km.
- Community Antenna Television (CATV) makes use of optical fibres for distribution of signal to the local users by receiving a multichannel signal from a common antenna.

Sl.No	**Laser : short answer questions**	CO's
1.	Define the terms: a. Spontaneous emission. b. Stimulated Emission. c. Active medium. d. Population inversion.	1
2.	Explain use of laser range finder in defence.	2
3.	Give any two differences between the laser light and ordinary light.	2
Sl.No	**Laser : Long answer questions**	
4.	Explain the requisites of a laser system.	2
5.	With energy level diagram of semiconductor diode laser, explain the working of diode laser.	3
6.	Discuss the conditions required for laser action.	2
7.	Write a note on measurement of pollutants in atmosphere using laser.	2
8.	Explain the three processes which take place when radiation interacts with matter.	2
9.	Explain the terms stimulated emission and population inversion. Obtain an expression for energy density of photons in terms of Einstein's co-efficient.	2&3
10.	Explain the characteristics of a laser beam.	
11.	Explain the working principle of a semiconductor laser using band diagram and discuss its advantages.	

SI. No	**Optical Fiber – short answer questions**	**CO**
1	Give reason • Optical fibres are immune to electromagnetic interference. • Intermodal dispersion is minimum in GRIN compared to MMSI fibre. • Repeaters are used in the path of optical fibres in point to point communication system.	1

2	Explain the terms a. Acceptance angle b. Cone of acceptance c. Numerical aperture d. Modes of propagation e. Attenuation.	1
3	Explain attenuation losses in optical fibres.	2
4	Write any two advantages of optical fibre communication over normal communication.	2
5	Explain propagation mechanism in optical fibres.	2
6	Distinguish between step and graded index fibres.	2

S. No	**Optical Fiber : Long answer questions**	**CO's**
1	With the help of ray diagram, explain the working principle of optical fibres.	1&2
2	Derive an expression for acceptance angle of an optical fibre in terms of refractive indices.	1&2
3	What is numerical aperture? Obtain an expression for numerical aperture in terms of refractive indices of core and cladding and arrive at the condition for propagation.	
4	Explain the terms 1) modes of propagation and 2) types of optical fibres	1
5	What is attenuation? Explain the different losses in optical fibres.	2
6	With the help of a block diagram explain point to point communication.	2
7	Discuss the advantages and disadvantages of an optical communication system.	1

Sample Problems:

1. Calculate the ratio of
   i) Einstein Coefficients, ii) Stimulated to spontaneous emissions, for a system at 300K in which radiations of wavelength 1.39μm are emitted.

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3} = \frac{8\pi h}{\lambda^3} = 6.2x10^{-15}$$

Since $B_{12} = B_{21}$ we can write $\frac{A_{21}}{B_{21}} = 6.2x10^{-15}$

We have

Rate of stimulated emission/Rate of spontaneous emission

$$= \frac{B_{12} N_2 U_\nu}{A_{21} N_2} = \frac{B_{21}}{A_{21}} U_\nu$$

But $$U_\nu = \frac{8\pi h\nu^3}{c^3}\left[\frac{1}{e^{\frac{h\nu}{kT}} - 1}\right] = \frac{A_{21}}{B_{21}}\left[\frac{1}{e^{\frac{h\nu}{kT}} - 1}\right]$$

Therefore rate of stimulated emission/rate of spontaneous emission

$$= \frac{B_{21}}{A_{21}} x \frac{A_{21}}{B_{21}}\left[\frac{1}{e^{\frac{h\nu}{kT}} - 1}\right] = \left[\frac{1}{e^{\frac{h\nu}{kT}} - 1}\right] = 10^{-15}$$

2. Calculate on the basis of Einstein's theory, the number of photons emitted per second by a He-Ne laser source emitting light of wavelength 6328A^o with an optical power of 10mW.

$$P = \frac{E}{t} = \frac{n\Delta E}{t} = \frac{nhc}{\Delta\lambda t}$$

Hence $$\frac{n}{t} = \frac{P\Delta\lambda}{hc}$$

$$= 3.182x10^{16}$$

3. Calculate the numerical aperture, relative RI difference, V- number and number of modes in an optical fibre of core diameter 50μm. Core and cladding Refractive indices 1.41 and 1.40 at λ= 820nm.

$(NA)^2 = (n_1^2 - n_2^2)$ $\therefore$ NA = 0.1676 $\Delta = \frac{n_1 - n_2}{n_1} = 0.007$

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

=32

Hence no of modes= $V^2/2$ = 512.

4. An optical fibre has clad of RI 1.50 and NA 0.39. Find the RI of core and the acceptance angle.

$(NA)^2 = n_1^2 - n_2^2$ $\theta_o = \sin^{-1} 0.39$

$(0.39)^2 = n_1^2 - (1.50)^2$ $= 22.96^o$

$n_1 = 1.54$

5. The NA of an OF is 0.2 when surrounded by air. Determine the RI of its core. Given The RI of cladding as 1.59. Also find the acceptance angle when it is in a medium of RI 1.33.

$(NA)^2 = (n_1^2 - n_2^2)$ $\theta_o = 8.64^o$

$n_1 = 1.60$

6. A glass clad fibre is made with core glass of RI 1.5 and cladding is doped to give a fractional index difference of 0.0005. Determine
   a) The cladding index.
   b) The critical internal reflection angle.
   c) The external critical acceptance angle
   d) The numerical aperture

7. The attenuation of light in an optical fibre is estimated at 2.2dB/km. What fractional initial intensity remains after 2km & 6km?L = 2 : P_{out}/P_{in} = 36.3% | L=6 : P_{out}/P_{in} = 4.79%

8. Find the attenuation in an optical fibre of length 500m, when a light signal of power 100mW emerges out of the fibre with a power 90mW.

$$\alpha = \frac{-10\log_{10}\left(\frac{p_{out}}{P_{in}}\right)}{L} = 0.915\text{dB/km}$$

9. A semiconductor laser emits green light of 551 nm. Find out the value of its band gap. $E_g = hc/\lambda = 2.25$ eV

10. The probability of spontaneous transition is given as 0.08 in a laser action which results with the radiation of 632.8 nm wavelength. Calculate the probability of stimulated emission. (Ans. 1.22×10^{13})
11. Calculate the critical angle if the refractive indices of optical fibre are 1.5 & 1.48. (Ans. $\theta_c = 80.63^o$)

12. The optical fibre power after propagating through a fibre of 1.5 km length is reduced to 25% of its original value. Compute the fibre loss in dB/km. (Ans. 4 dB/km)

13. The ratio of population of two energy levels out of which one corresponds to metastable state is 1.059×10^{-30}. Find the wavelength of light emitted at 330K.

$$\frac{N_2}{N_1} = 1.059x10^{-30}, \quad T=330K, \quad \lambda=?$$

Constants $h=6.63 \times 10^{-34}$ Js, $K= 1.38 \times 10^{-23}$ J/K, $C= 3 \times 10^{8}$ m/s

Using the relation for Boltzmann's factor

$$\frac{N_2}{N_1} = e\frac{-h\nu}{kT} = e\frac{-hc}{\lambda kT}$$

$\lambda = 632.8$nm.