Unit 2: Laser& Optic Fibre

Syllabus

Laser

- Basics of laser and its mechanism, characteristics of laser
- Semiconductor laser: Single Hetro-junction laser
- Gas laser: CO_2 laser
- Applications of lasers: Holography, IT, industrial, medical

Optic Fiber

- Introduction, parameters: Acceptance Angle, Acceptance Cone, Numerical Aperture
- Types of optical fiber- step index and graded index
- Attenuation and reasons for losses in optic fibers (qualitative)
- Communication system: basic building blocks
- Advantages of optical fiber communication over conventional methods

Pre-requisites

Atomic structure, energy levels of electrons, coherence, monochromaticity, critical angle,

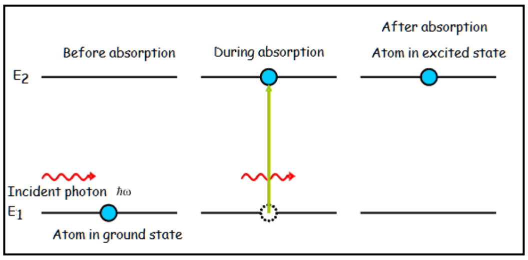
2.1 Basics of laser

The term LASER is acronym for Light Amplification by Stimulated Emission of Radiations. The output of a laser is intense, monochromatic, coherent and highly directional. Laser has applications in a wide variety of fields such as industry, communication, medical, information technology, etc.

Absorption:

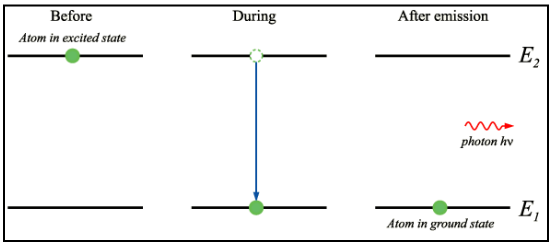
Suppose an atom is in the lower energy level E_1.If a photon of energy $E_2 - E_1$ is incident on the atom, it imparts its energy to the atom. The atom absorbs the energy of the incident photon and jumps to the excited state E_2.

Such transition is called absorption. As absorption process is induced by a photon, it is also called as **induced absorption**.



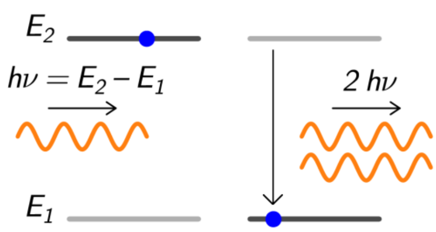
Spontaneous emission:

When an atom at lower energy level is excited to a higher energy level, it cannot stay in the excited state for a relatively longer time of about few nanoseconds (10^{-9} s).The atom reverts to the lower energy state by emitting a photon of energy $h\nu = E_2 - E_1$. The emission of photon occurs on its own and without any external impetus given to the excited atom. Such emission is called **spontaneous emission**.



Stimulated emission

If an atom in the excited state interacts with a stimulating photon (photon 1) with energy $h\nu = E_2 - E_1$, it induces the excited atom to make a downward transition well before the atom can make spontaneous emission. The atom emits energy in the form of another induced photon (photon 2) of energy $h\nu = E_2 - E_1$ as it drops to the lower energy state. The stimulating photon (photon 1) is not affected. This



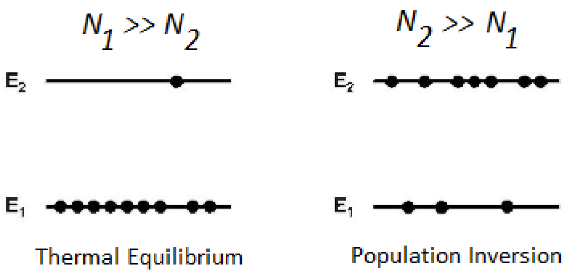
phenomenon of forced emission of photon by an excited atom due to action of an external photon is called **stimulated emission**. Both photons are of same frequency and are coherent.

Significance of Stimulated Emission in laser

- The stimulating photon (photon 1) and induced photon (photon 2) propagates in the same direction.
- The induced photon has features identical to that of the inducing photon. It has same frequency, phase and polarization as that of the stimulating photon.
- For one photon interacting with an excited atom, there are two photons emerging. These two photons stimulated emission of further photons and this builds up an avalanche.
- All waves are in phase, coherent and interfere constructively.
- Since the number of atoms in the material is very large, coherent emission leads to an enormously high intense light and thus light is amplified.
- Thus, the process of stimulated emission of light is the key to operation of laser.

Population inversion

If N_1 and N_2 are number of atoms in the ground and excited energy levels respectively, then in thermal equilibrium, it is preferred that number of atoms in ground energy level are more than excited energy level,
Thus in thermal equilibrium or normal state:
$N_1 >> N_2$



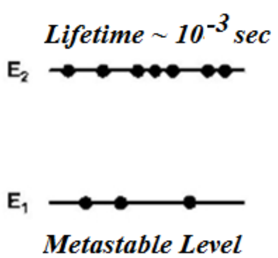
Population inversion is the condition of the material in which population of higher energy level $N_2$is far more than the population of the lower energy levelN_1.
Thus in population inversion: $N_2 >> N_1$

Significance of Population Inversion in laser

- Production of laser requires coherent and intense beam. This requires triggering the atoms in the excited state (metastable state) by the process of stimulated emission.
- If density of atoms in excited states is far more as compared to thermal equilibrium state, the process of stimulated emission can trigger more and more atoms in the excited state to make the transition to ground state.
- Thus, when population inversion is achieved and stimulated emission is initiated, it can build a strong and intense radiation.

Metastable state

An atom can be excited to a higher level by supplying energy to it. Normally, excited atom has short lifetime and release their energy in few nanoseconds (10^{-9} seconds) through spontaneous emission. It means atoms do not stay in the excited state to be stimulated and rapidly return to the ground state.Metastable state is particularly an excited state of an atom that has a longer lifetime of around 10^{-6} to 10^{-3} seconds. This is 10^3 to 10^6 times the lifetime of an ordinary excited energy level.

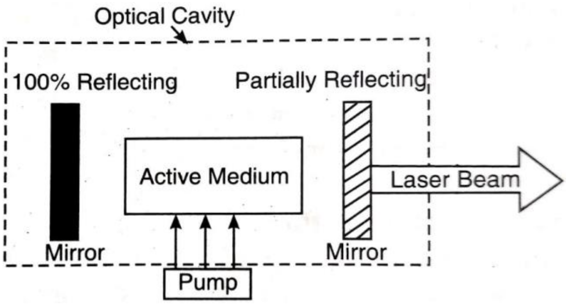


Significance of metastable state

Atoms excited to a metastable state remain excited for longer duration and it allows accumulation of a large number of excited atoms at that level. This can lead to development of condition of population inversion. There would be no population inversion and hence no laser action possible without the metastable state.

Components of laser

The essential components of laser are (i) active medium, (ii) a pumping agent (iii) optical resonator.



Active Medium

The active medium is the material in which the laser action takes place. The most important requirement for the laser medium is that it should be able to obtain population inversion. The active medium may be of any type solid, liquid or gas.

A small fraction of atoms of a particular type have energy level system suitable for achieving population inversion. Such atoms can produce more stimulated emission and cause amplification of light. Those atoms, which cause laser action, are called **active centers**. The rest of the medium acts as host and supports active centers. The medium hosting the active centers iscalled the active medium.

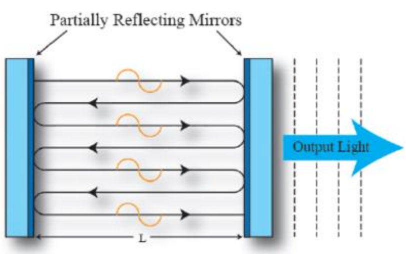
Pumping

For achieving and maintaining the condition of population inversion, we have to raise continuously the atoms in the lower energy level to the upper energy level. It requires energy to be supplied to the system. Pumping is a process of supplying the energy. It is an external source that supplies energy needed to transfer the laser medium into the state of population inversion.

There are number of techniques for pumping viz. optical pumping, electrical discharge and direction conversion, etc. In Optical pumping an external light source is flashed on material to supply energy to the system. This is employed in solid state lasers. In electric discharge, the electrical field causes ionization of the medium and raises it to the excited state.

Optical resonator

In laser, the active medium is the amplifier. It is converted into oscillator through the feedback mechanism by optical resonator. Optical resonator plays a role of giving positive feedback to the medium through reflected photons. It consists of a pair of optically plane parallel mirrors enclosing laser medium between them. One of the mirrors is fully reflecting and other is partially reflecting. The laser output is obtained through partially reflecting mirror.



Significance of optical resonator

- The primary function of optical resonator is to provide positive feedback of photons into the medium so that stimulated emission is sustained and the amplification of light.
- The laser oscillation is initiated by photons spontaneously emitted by some of the excited atoms. Each spontaneous photon can trigger many stimulated emission along the path of its travel.
- As initial spontaneously emitted are in different directions, the stimulated photons would travel in different directions. Optical resonator selects the direction in which the light is to be amplified; and the direction is the optical axis of the pair of mirrors. Photons emitted in other directions are lost. Thus, <u>optical cavity makes the laser beam directional</u>.
- Optical cavity selects and amplifies only certain frequencies causing the laser output to be highly monochromatic.

Lasing action in brief [For understanding]

Active Medium → Active Centers → Pumping → Excited State → Population Inversion → Metastable state → Spontaneous emission → Stimulated emission → Optical resonator → Laser output

Steps	Component	Action / Role played
Step 1	Active Medium	Any medium that is capable of producing laser
Step 2	Active Centers	The atoms in active medium producing laser output
Step 3	Pumping	Process of supplying energy to the medium / active centers
Step 4	Excited state	A state of higher energy having lifetime of about 10^{-9} sec
Step 5	Population inversion	A large number of atoms taken to the metastable state compared to ground state
Step 6	Metastable state	An excited state having lifetime of about 10^{-6} to 10^{-3} sec. The atoms decays to metastable state from excited state
Step 7	Spontaneous emission	Some of the excited atoms in the metastable state decays to ground state giving out spontaneous emission in random direction
Step 8	Stimulated emission	Each spontaneous photon triggers many stimulate emissions along directions of its propagation and amplification of light is achieved
Step 9	Optical resonator	Majority of photons traveling along the axis cause stimulated emission and are reflected back on reaching the end mirrors. They travel towards the opposite mirror and on their way stimulate more and more atoms and build up photon strength.
Step 10	Laser output	At the partially reflecting mirror, light is transmitted. It is a loss of energy from the resonator. When the losses at the mirrors and within the medium are balance gain, a steady and strong laser beam will emerge from the partially reflecting mirror.

Characteristics of Laser

The important characteristics of a laser beam are:

1. **High directionality:** The conventional sources emit light uniformly in all directions. Lasers emit light only in one direction as the photons travelling along the optical axis of the system are selected and tuned with the help of optical resonator.
2. **Negligible divergence:** Light from conventional sources spreads out in the form of spherical wave fronts and hence it is highly divergent. The divergence (or angular spread) of laser beam is extremely small of the order of 10^{-3} radians.
3. **High intensity:** The intensity of light from a conventional source decreases rapidly with distance as it spreads out in space. Laser emits light in the form of a narrow beam. As the energy is concentrated in a very narrow region, its intensity is very high and stays constant with distance.
4. **High coherence:**Coherence is a measure of light waves in phase. Conventional sources have coherence lasts to few millimeters. The light emitted by laser source is highly coherent and are of same frequency. In case of laser, a large number of identical photons are emitted through stimulated emission and remain in phase. Depending on the intensity and type, , laser beam may remain coherent for few hundred kilometers.
5. **Highly monochromatic:** The light from conventional monochromatic sources spreads over a wavelength range of 100 Å to 1000 Å. The laser light is highly monochromatic and contains a very narrow range of few angstroms < 10 Å.

Semiconductor diode laser [For understanding]

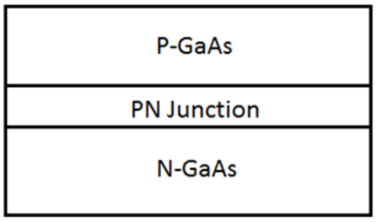
- A semiconductor diode laser is a specially fabricated PN junction device, which emit coherent light when it is in forward bias. Diode lasers are remarkably small in size (0.1 mm dimension). They have high efficiency of around 40%.
- Modulating the biasing current easily modulates the laser output. They operate at low power. In spite of their small size and low power requirement, they produce good output power.
- Diode lasers are used in optical fiber communications, CD players, optical reading, laser printer, etc.
- Among the semiconductors, there are two different groups. They are direct band gap and indirect band gap semiconductors.
- Direct band gap semiconductors is the one in which a conduction band electrons can recombine directly with a hole in the valence band. The recombination process leads to emission of light. Most of the compound semiconductors belong to this group.
- In indirect band gap semiconductors, direct recombination of conduction band electrons with a hole in valence band is not possible. The recombination of electron and hole produces heat in the material. Silicon and germanium belong to this group.
- Lasers are made using direct band gap semiconductors. Gallium Arsenide (GaAs) diode is an example of semiconductor diode laser.

Types of semiconductor diode lasers

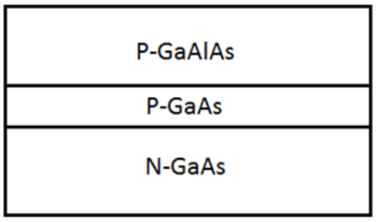
Broadly there are two types of semiconductor diode laser. They are known as homojunction semiconductor laser and heterojunction semiconductor laser.

Homojunction Semiconductor Laser:A diode laser which makes use of the same material on the both sides of the junction is called as homojunction diode laser.Example: Gallium Arsenide.

Homojunction Semiconductor Laser:A diode laser which makes use of different materials on the both sides of the junction is called as heterojunction diode laser. These are further classified into single heterojunction diode lasers and double heterojunction diode laser. Example: a junction laser having GaAs on one side and GaAlAs on the other side.



Homojunction Laser



Single Heterojunction Laser

Drawbacks of homojunction laser:

1. In homojunction laser, the active region is not well defined due to the diffusion length of the carriers.
2. The semiconductor has nearly uniform refractive index throughout. Therefore, light can diffuse from active layer into the surrounding medium. As a result, the cavity losses increase.
3. High threshold currents are required and the laser cannot be operated continuously at room temperature.

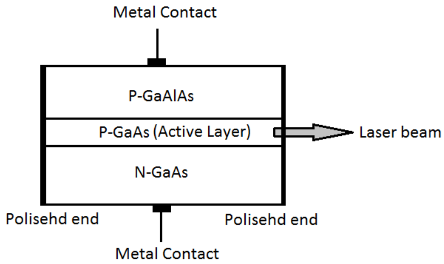
Advantages of heterojunction laser:

1. Another layer of p-type GaAlAs (a fraction of doping of Al) is superimposed on regular p-type GaAs layer.
2. This doping of Al reduces the index of refraction. It builds up population inversion at lower forward bias current. Also, it results into better confinement of the laser light into optical cavity.
3. This leads to lower losses, low current requirement, reduces damage and longer lifetime for diodes.

2.1.2 Semiconductor Laser: Single hetero-junction laser

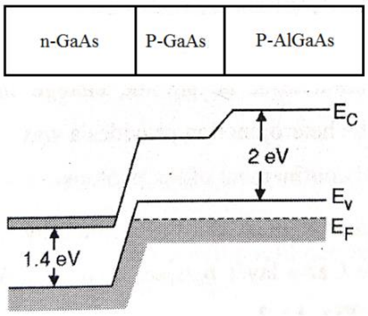
The simplest of the heterojunction diode laser is single heterojunction diode laser. It consists of different material on either side of active region.

Construction

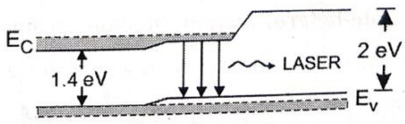


- A PN junction semiconductor diode laser diode is fabricated using n-type GaAs and p-type GaAs semiconductors.
- It consists of three layers:
  Substrate is n-type GaAs
  Active layer is a thin p-type GaAs in which laser action takes place.
  An additional layer of p-type AlGaAs is grown over the top of the p-type GaAs. The material GaAlAs has a wider energy gap and lower refractive index than GaAs.
- The boundary between p-GaAs layer and p-AlGaAs is heterojunction.
- The top and bottom faces are metalized and metal contacts are provided to pass the 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 constitutes optical resonator which is called as Fabry-Perot resonator.

Working



Equillibrium Mode



Forward bias mode

Pumping:It is provided by the forward bias

Population inversion and role of heterojunction

- The thickness of active region is made small, so that a smaller drive current is required.
- When forward bias is applied, the electrons are injected from n-GaAs layer into active layer of p-GaAs.
- The bandgap of p-AlGaAs is large (around 2eV) as compared to p-GaAs (around 1.4 eV). As injected electrons cannot overcome this band gap, a large number of electrons are concentrated in p-GaAs active layer. This results into a large concentration of electrons in conduction band and simultaneously a large number of holes in valence band. Thus, population inversion is achieved quickly in active region at low threshold current.

Spontaneous emission: Recombination of electrons and holes in active region leads to spontaneous emission of photons

Stimulated emission: These spontaneous photons propagating in active layer stimulate conduction electrons to jump into vacant states in valence band and produces stimulated photons.

Cavity resonator: The reflection of photons from polished ends within the active layer provides feedback for lasing action and laser oscillations starts.After attaining sufficient strength, laser beam emerges out from diode.

Role of heterojunction for photon confinement:As the refractive index of p-GaAs is higher than the refractive index of p-AlGaAs, the photons (laser light)are reflected back into p-GaAs active region and are trapped within the active region and travels in one direction only. This creates a waveguide effect.

Advantages of heterojunction laser:

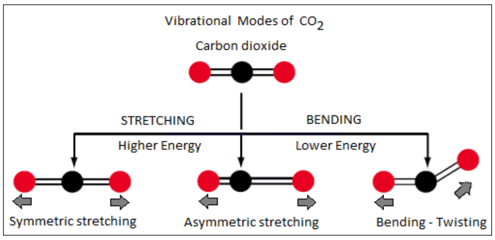
- High efficiency even at room temperature
- Less operating current is required
- Threshold current density is less, due to which continuous laser output is possible

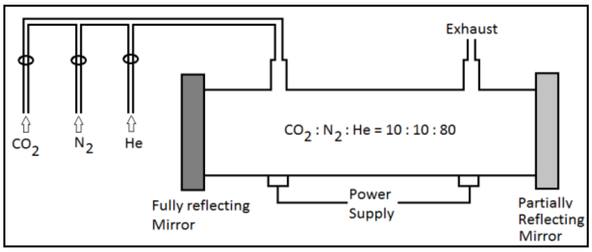
2.1.3CO_2 laser

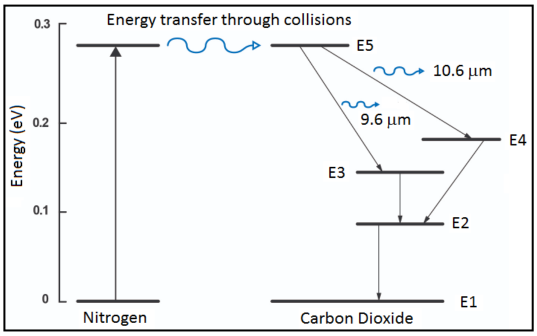
The Carbon dioxide (CO_2) laser is a molecular gas laser based on a gas mixture carbon dioxide (CO_2), Helium (He) and Nitrogen (N_2) as the gain medium. Depending on manufacturing, continuous output power varies between a few watts to several hundred watts.

Principle of CO_2 laser

CO_2 is a linear molecule and with carbon atom in the middle.It undergoes three independent vibration oscillations. Transitions to the symmetric stretching mode and bending modes correspond to wavelengths of 10.6 μm and 9.6 μm respectively.







Working of CO_2 laser

A mixture of CO_2, Nitrogen and Helium is taken into a discharge tube powered by a by a power supply. Gases are filled inside the tube with pressure 10% CO_2, 10% Nitrogen and 80% Helium.Fully reflecting mirror and partially reflecting mirror are fitted on the either side of the tube for re-circulation of the laser light inside the tube. The output power of CO_2 laser depends on its diameter.

Pumping: Electric discharge is created in the laser tube. The energy of accelerating electrons is transferred to Nitrogen and they accumulate to metastable state. Nitrogen molecules collide in elastically with CO_2 molecules by collision. Thus, CO_2 molecules are moved to excited E_5 level.

Population Inversion: E_5 is a higher energy level, while energy levels E_3 and E_4 are lower metastable levels of CO_2.Due to buildup of CO_2 molecules in higher E_5 energy level, population inversion takes place in E_5, and E_3 and E_4 energy levels.

Active medium: Lasing action takes place in CO_2 which is active medium. Nitrogen and Helium improves efficiency of lasing action.

Spontaneous emission: Random and spontaneous photons emitted by few atoms of E_5 level.

Cavity resonator: The randomly emitted photons travel back and forth between the end mirrors and helps in stimulated emission of photons. These re-circulated photons build up along the axis of axis of discharge tube (optical cavity). Oscillations takes place in between two vibrational levels of CO_2.

Laser output: The transition between $E_5 \rightarrow E_4$ produces IR radiations of wavelength 10.6 μm and the transition between $E_5 \rightarrow E_3$ produces IR radiations of wavelength 9.6 μm.

De-excitation:CO_2 molecules in E_4 and E_3 levels falls to lower energy level E_2 which is close to ground level. Helium atoms colloids with CO_2 molecules in E_2 level and reduce their population.The de-exited CO_2 molecules are again excited due to collision of nitrogen and are taken into upper excited state E_5. This helps in maintaining continuous laser output.

Advantages of CO_2 laser

- It has very high power output with relative efficiency of around 30-40%, which is better than He-Ne and argon laser
- It operates in continuous mode
- CO_2 laser are low cost and have good beam quality
- It generates high power output which ranges from few watts to 15 KW.
- Used primarily for materials processing applications.

2.1.4 Applications of Laser

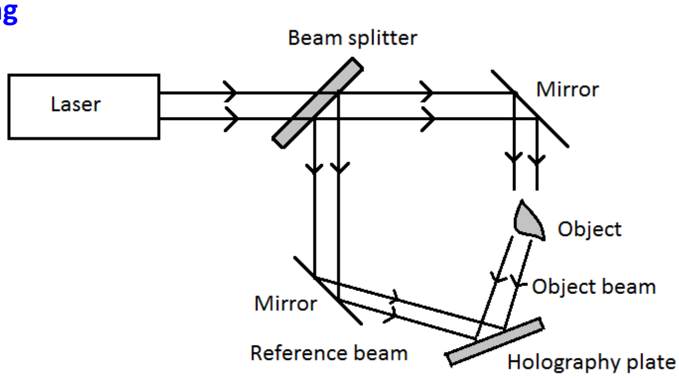
(a) Holography

Holography: Holography is a technique that allows the light scattered from an object to be recorded and later reconstructed.It appears as if the object is in the same position relative to the recording medium as it was when recorded. The image changes as the position and orientation of the viewing system changes in exactly the same way as if the object were still present, thus making the recorded image (hologram) appears three dimensional.

Difference between holography and photography: The major difference between holography and photography is that in photography there is a point-to-point recording of the intensity of light rays that make up an image.In holography amplitude and phase of light are recorded by interference.

Use of laser in holography: The recording process in holography is based on the principle of interference. For recording and for sustained interference, it is required that the light waves should have perfect coherence. Laser is used for recording and reconstruction of hologram due to its unique characteristic of high coherence and less divergence.

Holograph Recording



Principle: The recording of hologram is based on the phenomenon of interference.

Components: It requires a laser source, a plane mirror or beam splitter, an object and aphotographic plate.

Beam Splitter: A laser beam from the laser source is incident on a beam splitter. The function of the beam splitter is to split the laser beam.

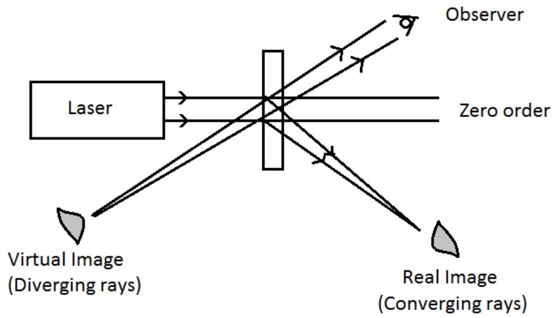
Reference beam: One part of splitted beam is reflected from beam splitter and strikes on the photographic plate. As there is no modification in its properties, this beam is called reference beam.

Object beam: The other part of splitted beam is transmitted from beam splitter. This beam strikes on the photographic plate after suffering reflection from the various points of object. This beam is called object beam.

Interference: The object beam reflected from the object interferes with the reference beam when both the beams reach the photographic plate. The superposition of these two beams produces an interference pattern (in the form of dark and bright fringes).

Photographic plate: This interference pattern is recorded on the photographic plate. The photographic plate with recorded interference pattern is called hologram. Photographic plate is also known as Gabor zone plate in honor of Denis Gabor who developed the phenomenon of holography.Each and every part of the hologram receives light from various points of the object. Thus, even if hologram is broken into parts, each part is capable of reconstructing the whole object.

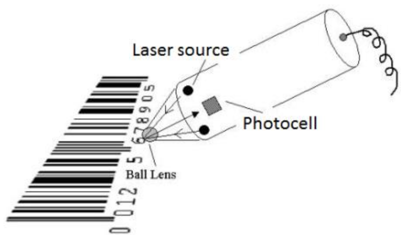
Reconstruction of holograph



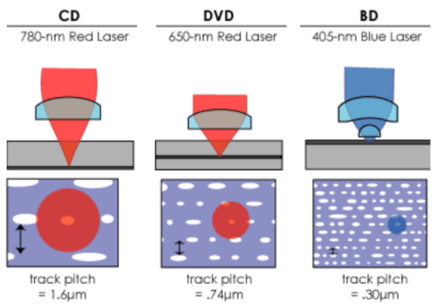
Illumination: In the reconstruction process, the hologram is illuminated by laser beam.This beam is called reconstruction beam which is identical to reference beam used in construction of hologram.
Diffraction: The hologram acts a diffraction grating. This reconstruction beam will undergo phenomenon of diffraction during passage through the hologram. The reconstruction beam after passing through the hologram produces a real as well as virtual image of the object.
Real and Virtual image: One of the diffracted beams emerging from the hologram appears to diverge from an apparent object when project back. Thus, virtual image is formed behind the hologram at the original site of the object and real image in front of the hologram. Thus an observer sees light waves diverging from the virtual image and the image is identical to the object.
Three dimensional characteristics: If the observer moves round the virtual image then other sides of the object which were not noticed earlier would be observed. Therefore, the virtual image exhibits all the true three dimensional characteristics.

(b) Information Technology

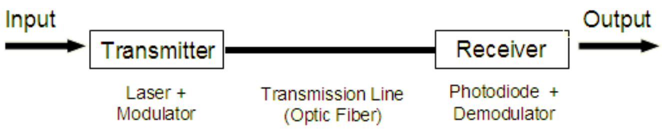
Barcode scanners: Barcode is a machine-readable code in the form of numbers and a pattern of parallel lines of varying widths. They are printed on an object for quick identification. Laser scanners are used for decoding the barcode information on the products by moving laser to illuminate the barcode. The reflected light is received back by barcode scanner and the information is decoded.



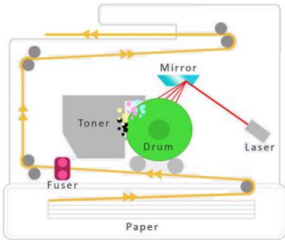
Optical discs (CD/DVD/Blue-ray):
The surface of the CD/DVD/Blue-ray disc contains one long spiral track of data. Along the track, there are flat reflective areas and non-reflective bumps. A flat reflective area represents a binary 1, while a non-reflective bump represents a binary 0. The CD/DVD/Blue-ray drive shines a laser at the surface. It can detect the reflective areas and the bumps by the amount of laser light they reflect. The drive converts the reflections into 1s and 0s to read digital data from the disc. Audio CD use infrared lasers. DVDs use a shorter-wavelength red laser. Blue-Ray disc uses blue-light lasers to read and store data at an even higher density.



Fiber-optic communication systems: Optical fibers are widely used in communications for transmission over longer distances and at higher bandwidths. Laser is used in optical fibers for carrying digital signal in the form of light, because of its characteristics monochromaticity, coherence. The laser is highly monochromaticand contains a very narrow range of few angstroms < 10 Å. Depending on the intensity and type, , laser beam may remain coherent for few hundred kilometers. Due to these properties laser is most suitable for carrying signal through optical fibers.



Lasers in printer / photocopy machines: A laser printer is a widely used computer printer. The laser insider the laser printer is made on/off rapidly as per the instructions of printing in the form for binary data 0/1. This laser beam scans back and forth across a drum inside the printer creating image to be print in the form pattern of static electricity. When the drum rotates through toner powder it gets stuck on to the drum due to static electricity pattern created on the drum. Finally, a fuser unit bonds the toner to the paper by pressing.



(c) Industrial Applications

In industry lasers are used almost in every field such as mechanical, electronics, textiles, etc. Lasers are preferred particularly because of the high intensity light is focused at a narrow area with high directionality. The main advantage of using laser is desired operation can be performed without any mechanical contact.

Welding: Laser welding has advantage to melt the material to adesired depth by minimizing surface vaporization. Mostly, continuous lasers of the infraredCO_2 and Nd:YAG lasers are used. The main advantage of using laser in welding is that it is a contact-less process and hence chances of introduction of impurity are minimized. Another advantage is it requires very less input power for laser to be operated as compared to traditional welding. This also reduces heating losses at the point of welding. Also a quick cooling can be carried out at the spot of welding as it is a contact-less process. The laser welding has application in every field of industry including electronics, microelectronics, automobile, etc.

Drilling: Laser drilling is based on removing material by vaporization. The beam intensity should be higher than for welding. With lasers, a drill hole as small as 10 μm can be drilled. The vaporized material is removed with the help of a gas jet. Pulsed ruby and neodymium lasers are commonly used for drilling holes of small l/D ratio, where l is the thickness of the work and D is the hole diameter.

Cutting: Laser cutting is preferred for some low thermal conductivity materials. Continuous CO_2 lasers of up to15 kW are used for industrial laser cutting metals such as titanium, low-carbon steels, and stainless steels cut and to cut non-metallic materials such as ceramics, plastics, wood, textile,paper, and glass. The advantage of laser cutting is that it has fast cutting speed; the cutting in various shapes is possible. Also the laser cutting process can be atomized for good quality of the cut andlimited area of thermal effect.

Hardening: Heat treatment is a process, which is done to harden material and certain material. The process is more preferred in tooling and automotive industry. Heat treating converts the surface layer to crystalline state which is harder and resistant to wear for strengthening cylinder blocks, gears, camshafts, etc. In general, CO_2 lasers about 1kW outputting operating in continuous more are preferred in heat treatment.

(d) Medical Field

1. Lasers are used for surgical removal of tissue. CO_2 laser beams are strongly absorbed by the water in the tissue and thus burns them.
2. Laser (~ 1 μm) can penetrate the eye and can be used for welding retina or cutting internal membranes for eye surgery.
3. Laser beams are also used for correcting visual defects by removing tissue from the cornea and reshaping the transparent outer layer of the eye, thus adjusting the short-sightedness or long-sightedness.
4. With the help of optical fiber, laser is used for destroying kidney stones. The laser energy splits the stones into fragments.
5. Laser is used for the treatment of skin conditions. Pulsed lasers can be used for bleaching or removing stains on the skin.
6. Laser is also used to perform cosmetic surgery for removal of hair and wrinkles.

Questions on Laser

6 marks

1. With the help of energy band diagram explain construction and working of single heterojunction semiconductor laser. ***[Oct 19, 6m]***
2. With the help of energy band diagram explain construction and working of CO_2 laser.
3. What is holography? State its principle. Explain the process of holography recording and reconstruction.

3/4 marks

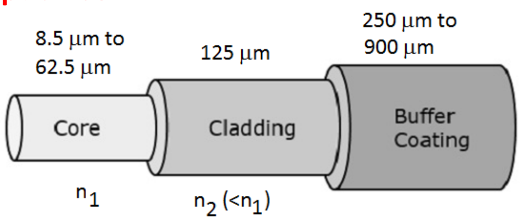
1. What is laser? State characteristics of laser. Explain in brief any one industrial application of laser. ***[Oct 19, 6m]***
2. Explain stimulated emission of radiations. Explain its significance in production of laser. ***[Oct 19, 4m]***
3. Explain population inversion. Explain its significance in production of laser.
4. Explain pumping. Explain its significance in production of laser.
5. Explain optical resonator. Explain its significance in production of laser.
6. Explain metastable level. Explain its significance in production of laser.
7. State the characteristics of a laser beam and explain any one of them in brief.
8. What is the difference between normal photography and holography? Which property of laser is most useful to record a holograph and why?
9. Explain the process of recording Hologram with the help of LASER.
10. State applications of laser in the field of information technology. Explain any one in brief.
11. State industrial applications of laser. Explain any one in brief.
12. State medical applications of laser. Explain any one in brief.

2.2 Optic Fibers

An optical fiber is a cylindrical dielectric waveguide made of transparent electric (glass or clear plastic), which guides light waves along its length by the process of total internal reflection. Optical fibersuse the science of transmitting data, voice, and images by the passage of light through thin, transparent fibers. In telecommunications, fiber optic technology has virtually replaced copper wire in long-distance telephone linesat higher bandwidths (data rates).

2.2.1 Basics of Fiber Optics

Construction of a typical optic fiber



A typical optical fiber has in general three coaxial regions.

1. The innermost cylindrical region is the light guiding region known as the **core**. In general, the diameter of core is of the order of 8.5 μm to 62.5 μm.
2. Core is surrounded by a coaxial middle region known as **cladding**. The diameter of cladding is of the order of 125 μm. The refractive index of cladding (n_2) is always lower (by around 1%) than that of the core (n_1).The purpose of the cladding is to make the light to be confined to the core by the process of total internal reflection.
3. The outermost region is called the **sheath** or a **protective buffer coating**. If is a plastic coating given to the cladding for extra protection to optical fiber from extreme physical and environmental conditions. The buffer is elastic in nature and prevents abrasions. The coating can vary in size from 250 μm to 900 μm.

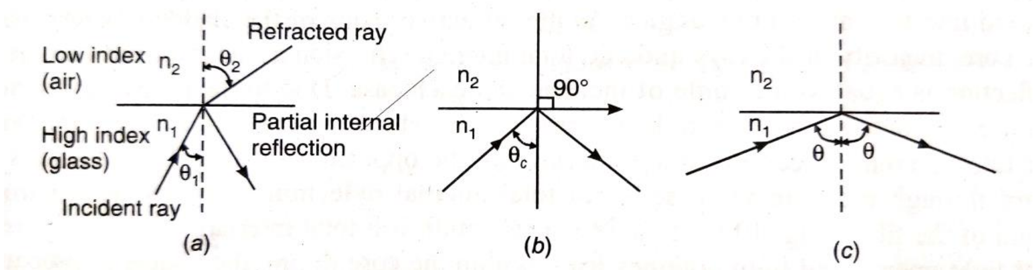
Critical Angle (θ_c) and Total internal reflection

Critical angleis the angle of incidence for which the refracted ray grazes the interface between the dense and the rare medium. At the angle greater than critical angle rays of light passing through a denser medium to the surface of a less dense medium are no longer refracted but totally reflected.

When a light ray passes from denser medium to rare medium, it is bending away from the normal in the rare medium. The Snell's law can be written as

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{n_1}{n_2}$$

Where, θ1 is the angle of incidence of light ray in the denser medium and θ_2 is the angle of refraction in the rarer medium. Also $n_1 > n_2$. When the angle of incidence, θ_1 in the denser medium is increased, the transmission angle θ_2 increases and the ray bend more away from the normal.



At some particular angle θ_c, the refracted ray grazes the boundary surface so that θ_c=90^0. At angles greater than θ_c, there are no refracted rays. The rays are reflected back into the denser medium. Thus,

- If θ_1<θ_c, the ray refracts into the rarer medium
- If θ_1 = θ_c, the ray grazes the interface between the rare and dense medium
- If θ_1>θ_c, the ray is reflected back into the denser medium

Let $n_1$isrefractive index of core and $n_2$is refractive index of cladding. Then according to Snell's law,

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

At critical angle, θ_1= θ_c
As the refracted ray grazes surface, θ_2=90^0, and sin θ_r=1

Thus,
$$\frac{\sin\theta_c}{1} = \frac{n_2}{n_1}$$
$$\sin\theta_c = \frac{n_2}{n_1}$$
$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

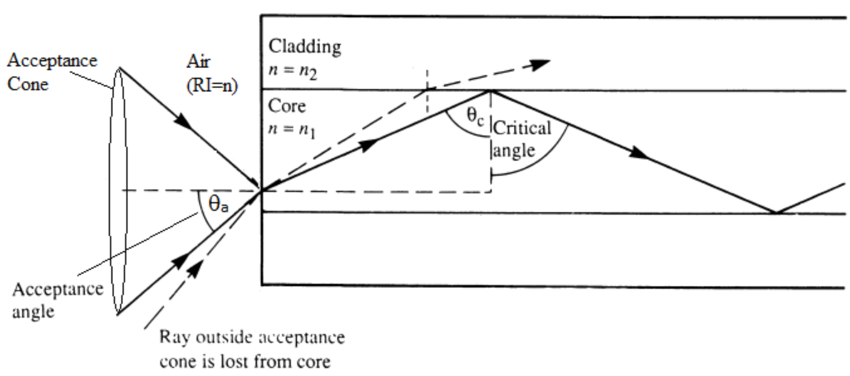
The phenomenon in which light is totally reflected from denser to rarer medium boundary is known as **total internal reflection**.

In optical fiber, total internal reflection at the fiber wall can occur and light propagates down the fiber, in following two conditions.

1. The refractive index of the core material, n_1, must be slightly greater than that of the cladding n_2.
2. At the core-cladding interface, the angle of incidence between the rays and the normal to the interface must be greater than critical angle. The rays that are incident at smaller angles are refracted into the cladding and are lost.

Acceptance angle and acceptance cone

When a light beam enters into a fiber at one end, the entire light may not pass through the core and propagate.**Acceptance angle** is the maximum angle that a light ray can have relative to the axis of the fiber for which, inside the core, the light undergoes total internal reflection.



Thus, only those rays that are incident on the face of the fiber making angle less than acceptance angle will undergo repeated total internal reflections and reach the other end of the fiber.

If n_1 is refractive index of core, n_2 is refractive index of cladding and n is refractive index of medium through which light rays are entering, then it can be shown that

Acceptance angle $\theta_a = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n}\right)$

If the medium through which light entering is air, *n*=1 and acceptance angle is given by

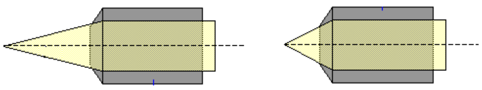
Acceptance angle $\theta_a = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$

The light rays contained within the cone having a full angle 2α are accepted and transmitted along the fiber. Acceptance cone is derived by rotating the acceptance angle about the axis of optical fiber.

Thus, $Angle of acceptance cone = 2 \times Acceptance angle = 2 \times \theta_a$

Numerical Aperture(NA)

The main function of an optical fiber is to accept and transmit as much light from the source as possible. The light gathering ability of a fiber depends on two factors, namely core size and the numerical aperture. Numerical Aperture is the measure of the ability of an optical fiber to collect or confine the incident light ray inside it. It is among the most basic property of optical fiber.



Numerical Apertureis defined as the sine of the acceptance angle. Thus,

$$Numerical\ Aperture = \sin(\theta_a) = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

If medium at the entrance is air, then $Numerical\ Aperture = \sin(\theta_a) = \sqrt{n_1^2 - n_2^2}$

2.2.2: Types and Classification of Optic Fibers

Light is electromagnetic radiation and it has oscillating electric and magnetic fieldsassociated with it. Depending on the transmission mode, the axis of oscillation in electromagnetic transmission may have different orientations to the direction of travel.

In the **Transverse Electric and Magnetic (TEM) mode**, both the electric field and the magnetic field (which are always perpendicular to one another in free space) are transverse to the direction of travel. In the **Transverse Electric (TE) mode**, the electric field is transverse to the direction of propagation while the magnetic field is normal to the direction of propagation.In the **Transverse Magnetic (TM) mode**, the magnetic field is transverse to the direction of propagation while the electric field is normal to the direction of propagation.

In simple terms, these modes can be visualized as the possible number of allowed paths of light in an optical fiber. The paths are all zigzag paths except the axial direction. The waves traveling along certain zigzag paths will be in phase and undergo constructive interference, while the waves interfering along certain other paths will be out of phase and diminish due to destructive interference. The light ray paths along which the waves are in phase inside the fiber are known as **modes**.

Optical fibers are classified into two types based on number of modes transmitted:

(a) Single Mode Fiber (SMF), and
(b) Multimode Fiber (MMF)

Optical fibers are classified into two types based on number relation between refractive index of core and cladding

(a) Step index fiber, and
(b) Graded index fiber

Overall, optical fibers are classified into three types based on number of modes and relation between refractive index of core and cladding.

(i) Step index single mode fiber (SMF)
(ii) Multimode step-index fiber (MMF)
(iii) Graded index (multimode) fiber (GRIN)

Step index Fibers

- The refractive index of the fiber changes abruptly at the core-cladding boundary. If ***r*** is the radial distance from axis and ***a*** is diameter, the variation of refractive index can be represented as

  For core : $n(r) = n_1$; $r < a$

  For cladding : $n(r) = n_2$; $r < a$
- **Relation between RI : $n_2 = n_1 (1 - \Delta)$**

  (Where Δ is difference in RI of core and cladding)

Single Mode Fiber (SMF)

- A single mode step index (SMF) fiber has a very fine thin core of diameter of 8 to 12 μm. It is surrounded by cladding of lower refractive index of diameter of 125 μm. Cladding is surrounded by protective layer or sheath.
- Light travels in SMF along a single path that is along the axis. The difference in refractive indices $\Delta = n_1 - n_2$ and NA are very small. They also has low acceptance angle. Therefore, light coupling into the fiber becomes difficult. Costly laser diodes are required to launch light into SMF.

Step Index Multimode Fiber (MMF)

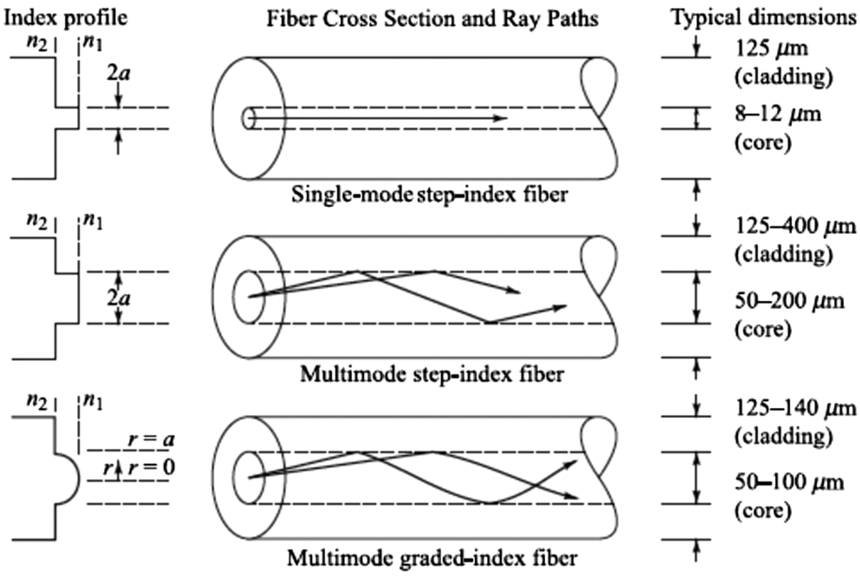
- A multimode step index fiber (MMF) has a core of diameter of 50 to 100μm. It is surrounded by cladding of lower refractive index of diameter of 150 to 250μm. Cladding is surrounded by protective layer or sheath.
- MMF allows finite number of guided modes. The direction of polarization, alignment of electric and magnetic fields will be different in rays of different modes. Many zigzag paths of propagation are permitted in MMF. Light travels in MMF along a single path that is along the axis. Path length for high order mode is shorter than low order mode. Hence, lower modes reach the end of the fiber earlier than higher order mode after some time delay.

Graded index Fibers

- A graded index fiber is a multimode fiber with a core consisting of concentric layers of different refractive indices. Therefore, the refractive index of the core varies with radial distance from the fiber axis. It has high value at the centre and falls with increasing radial distance from the axis.
- The variation of refractive index of the core with radius measured from the centre is

  Relation between RI : $\Delta = \frac{n_1 - n_2}{n_1}$

  Where, n_1 is maximum refractive index at the core axis
- The refractive index changes gradually from core to cladding. As a result light ray bent away from the normal. The process continues till the condition for total internal reflection is met. Then the ray ravels back towards the core axis, again being continuously refracted. The light undergoes periodic variation in refraction through the fiber till it undergoes total internal reflection.
- In graded index fiber, rays making larger angles with the axis traverse longer path but they travel in a region of lower refractive index and hence at higher speed of propagation. Consequently, all rays travelling through the fiber, irrespective of their modes of travel, will have almost the same optical path length and reach the output end of the fiber at the same time.



Sr.	Description	Single Mode	Multimode
1	*Number of modes*	Transmit a single mode during transmission	Transmit more than one mode during transmission
2	*Diameter of single core*	Very small (5 – 10 μm)	Larger than single mode (50 μm or more)
3	*Difference in refractive index of core and cladding*	Very small	Very large
4	*End to end connections*	Easy	Difficulty
5	*Intermodal dispersion (time difference between entry and arrival of optical signal)*	There is no intermodal dispersion	They suffer from intermodal dispersion
6	*Applications*	Long distance transmission	Short distance transmission

Sr.	Description	Step Index Fiber	Graded Index Fiber
1	*Variation in RI of core and cladding*	Varies step-by-step	Varies with radial distance
2	*RI difference at core-cladding interface*	Larger difference	Smaller difference
3	*Transmission of modes*	Transmission of single and multimode signals	Transmission of Multimode signal
4	*Intermodal dispersion*	Larger	Less
5	*Bandwidth for multimode transmission*	Lower bandwidth due to lower numerical aperture	Higher bandwidth due to high numerical aperture
6	*Proparation of rays*	Light rays propagate as meridional rays since they cross axis of core	Light rays propagated as skws rays as they do not pass through axis of core
7	*Pattern of Propagation of rays*	Zigzag manner	Either spherical or helical
8	*Applications*	Long distance transmission	Short distance transmission

Relation between Numerical Aperture (NA) and Fractional Refractive Index (Δ)

Fractional change in refractive index $\quad \Delta = \frac{n_1 - n_2}{n_1}$

Numerical Aperture $\quad \sqrt{n_1^2 - n_2^2} \quad$ (for air)

We can write, $\quad n_1^2 - n_2^2 = (n_1 + n_1)(n_1 - n_1) = \frac{(n_1+n_1)}{2}\frac{(n_1-n_1)}{n_1}2n_1$

Since $\quad n_1 \cong n_2, (n_1 + n_2) \cong 2n_1$

Thus $\quad n_1^2 - n_2^2 = 2n_1^2\Delta$

Therefore, $\quad NA = \sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta}$

Thus, $\quad NA = n_1\sqrt{2\Delta}$

2.2.3 Attenuation / Losses in optic fibers

Attenuation

As a light signal propagates through a fiber, it suffers loss of amplitude and change in shape. When optical signal propagates through an optical fiber, due to loss of amplitude its power decreases exponentially with the distance. This is called as attenuation.

The attenuation is defined as the ratio of the optical output power from a fiber of the length L to the input optical power.

If, $\quad P_i$ = power of optical signal at launch

$\quad P_o$ = power of optical signal emerging at other end

Then, $\quad P_o = P_i e^{-\alpha L}$

Where, α is called the fiber attenuation coefficient expressed in units of km^{-1}. Taking logarithm of both the sides of the above equations, we get

$$\alpha = \frac{1}{L}\ln\frac{P_i}{P_o}$$

In the units of dB/km, α is defined through the equation

$$\alpha = \frac{10}{L}\log\frac{P_i}{P_0}$$

The unit of measurement of attenuation is dB/km.

Different Factors Responsible for Attenuation

There are various factors that are responsible for attenuation in optical fibers. They are broadly divided into two categories: intrinsic and extrinsic attenuations. Intrinsic attenuation is caused by materials inherently present in the fiber, while extrinsic attenuation is caused by external factors such as bending. The factors that affect the transmission of light waves through optical fibers are:

A. Intrinsic Attenuation

Intrinsic attenuation results from materials inherent to the fiber. It is caused by impurities present in the fiber. Intrinsic attenuation can be further classified into two components Material absorption Rayleigh scattering and dispersion.

(i) Absorption by material

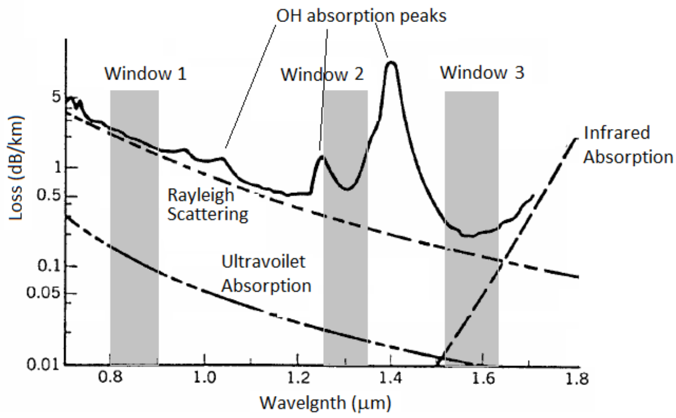
Absorption by hydroxyl ions: Material absorption occurs as result of imperfections and impurities in the fiber and accounts for 3-5% of fiber attenuation. The most common impurity is hydroxyl molecule (OH^-), which remains as a residue despite stringent manufacturing processes. They result from presence of water remnants of water during manufacturing or humidity in environment. Natural impurities in the glass also absorbs light signal. The metal ions such as copper, nickel, etc also absorb the light signal.

Absorption by pure glass (Electron absorption): Even a highly pure glass absorbs light in specific wavelength regions. Strong electronic absorption occurs at UV wavelengths, while vibrational absorption occurs at IR wavelength.

Remedial for absorption:Losses due to impurities can be reduced by better manufacturing processes. In improved fibers, metal ions are practically negligible. However, the losses caused by OH ions cannot be sufficiently reduced. Propagation of light sets an upper limit of 1700 nm, above which the infrared absorption losses are very high. Thus light of wavelength less than 1700 nm is preferred.

(ii) Rayleigh Scattering

- Rayleigh scattering oaccount for majofity of attenuation in optical fiber (about 96%). Local microscopic density variation in glass causes local variation in refractive index.
- These variations are inherent in manufacturing process and cannot be eliminated. These variations scatter the light in all directions, which is known as Rayleigh scattering.



Remedial for Rayleigh scattering:Rayleigh scattering loss greatly depends on the wavelength. It varies as$1/\lambda^4$. Thus Rayleigh scattering sets a lower limit on wavelength that can be transmitted by a glass at about 800 nm. Below which the scattering loss is very high.

Wavelength windows for optical fibers:

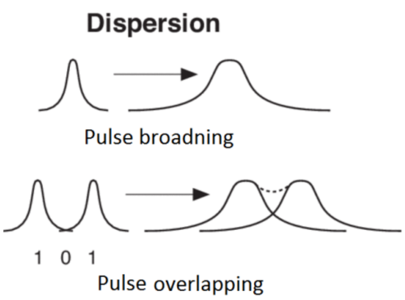
For better performance, choice of wavelength is based on minimizing losses. There are three principal windows corresponding to specific wavelength regions in which attenuation is low.

Sr.	Windows	Wavelength range (in nm)	Approx. Loss (dB/km)
1	Window 1	820 – 880	2.2
2	Windows 2	1200 – 1320	0.6
3	Windows 3	1550 - 1610	0.2

The range of 1550 – 1610 nm is most preferable for optical fiber communication due to minimum intrinsic losses.

(iii) Distortion or pulse-dispersion:

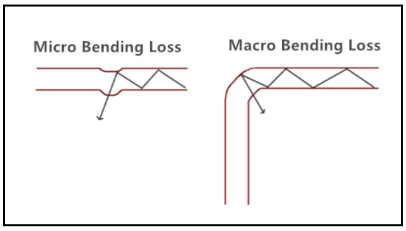
- In optical fiber communication system, information is coded in the form of discrete pulses of light and is transmitted through the fiber. The pulses are given specific width, amplitude and interval.
- During the propagation through optical fibers, the pulse gets broaden and spread into a wider time interval because of the different time taken by different rays propagating through the optical fiber. This is known as distortion or pulse-distortion.



- Due to pulse broadening and overlapping, the output gets distorted.

B. Extrinsic Attenuation - Bending

When an optical fiber is bent, it imposes strain at the area of bend. It affects the refractive index at the bend and the critical angle. As a result, the condition of total internal reflection is not satisfied. Hence, light traveling in the core can refract out and causes loss.

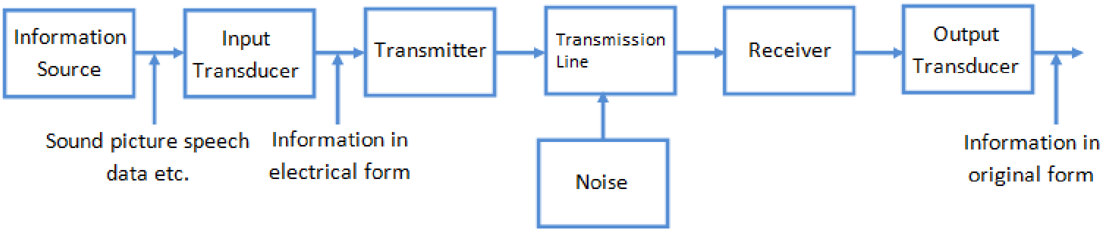


Micro-bending losses: A micro-bend is a small-scale distortion localized in a small area. It might be created in the fiber due to several factors such as temperature, stress, manufacturing process or during installation process. The light rays gets scattered at the micro-bend and are lost.

Macro-bending losses: A macro-bend refers to a large-scale bend that is visible. A large strain is placed at the region of bend and radiative losses occur. To prevent macro-bend, optical fiber has a minimum bend radius that should not be exceeded. Also, improper cabling, bending a fiber optic cable tighter, exerting external force may cause deformation in optic fiber and itcan cause damage, which in turn, results into increasing the losses.

2.2.4: Communication system: basic building blocks

The most important application of optical fibers is in the field of communication as information channel or transmission medium. The essential components of a communication system are information source, input transducer, transmitter, communication channel, receiver and destination.



(i) **Information Source:** A communication system serves to communicate a message or information. The information can be in the form of audio or video

(ii) **Input Transducer:** A transducer converts input signal into electrical signal. For example, a transducer is microphone which convert audio signal into electrical signal.

(iii) **Transmitter:**The function of the transmitter is to process the electrical signal from different aspects. In long-distance radio communication, signal amplification is necessary before modulation.Modulation is the main function of the transmitter. In modulation, the message signal is superimposed upon the high-frequency carrier signal.

(iv) **Transmission Line:** Transmission line is the medium through which the message travels from the transmitter to the receiver. In case of microwave links, the transmitted signal is radiated as an electromagnetic wave in free space. Microwave links are used in long distance telephone transmission.An optical fiber is a low-loss, well-controlled, guided optical medium. Optical fibers are used in optical communications.

(v) **Noise:** During the process of transmission and reception the signal gets distorted due to noise introduced in the system.Noise is an unwanted signal which tends to interfere with the required signal. Noise signal is always random in character. Noise may interfere with signal at any point in a communication system.

(vi) **Receiver:**The main function of the receiver is to reproduce the message signal in electrical form from received signal. The reproduction of original signal is done by a process known as the demodulation or detection. Demodulation is the reverse process of modulation carried out in transmitter.

(vii) **Output Transducer:** Output transducer is the final stage which is used to convert an electrical message signal into its original form.For example, in radio broadcasting, the destination is a loudspeaker which works as a transducer i.e. converts the electrical signal in the form of original sound signal.

The use of optic fiber has tremendously improved the data carrying capacity. For example, a typical optical band of 250 MHz can accommodate about 3×10^7 TV programmes at a time. Similarly, it can carry about 4×10^{10} telephone calls simultaneously.

2.2.5: Advantages of fiber optic fiber communication

1. **High data carrying capacity**
   - Optical fiber can carry very high frequencies (~ 10^{14} Hz) which are helpful in carrying more information i.e. more phone lines or more TV programs or more data.
   - As optical fibers are thinner, more fibers can be bundled together for increasing data carrying capacity.
2. **High quality signal transmission**
   - Signals from one optic fiber do not interfere with those of other fibers. This does not degrade the signal quality. No leakage of information is possible.
   - The signal degradation due to negligible as compared to conventional copper wires as there are no I^2R losses.
   - Optic fibers are made from dielectric material which provides isolation between transmitter and receiver.
3. **No pick up of stray signal i.e. noise**
   - As optic fibers are made up of either glass or plastic, they do not pick up stray signal or noise like copper wire does either due to transmitted signal or due to external factors.
   - Thus the effect of external electromagnetic interference, lightning, external magnetic field, nuclear radiation is minimal.
4. **Cost effective**
   - Optical fibers are typically made from silica. They are very cost effective as they are manufactured in bulk mass production.
5. **Small size, Light weight and flexible**
   - Optic fibers are of small size, light weight and are flexible. Due to this advantage, they are very helpful in Medical imaging: in bronchoscopes, endoscopes, laparoscopes and mechanical imaging: inspecting mechanical welds in pipes and engines in airplane, rockets, space shuttle, etc
6. **Less power consumption**
   Optical fiber consumes less power for its operation as compared to metal wires.
7. **High Tolerance and corrosion resistant**
   Optic fibers can tolerate extreme temperature variations (in some cases even upto 800^0C). Corrosion due to water or chemicals is minimal for optic fibers.
8. **Idle for carrying digital signal**
   Optical fibers are very much suitable for carrying digital signals that are ideally suited for computer networks. As large amount of data can be transmitted they are very useful in broadband internet, LAN, etc.

Shortcomings of optic fiber

- Higher initial cost in installation.
- Higher interfacing cost.
- It requires remote electric power when transmitted through sea water.
- Optic fibers are more expensive for repair/maintain.

Questions on Unit 2: Optic fibers

6 marks

1. Describe attenuations in optic fiber viz. absorption, dispersion and bending and ways to overcome the losses.
2. State factors for attenuation and losses in optical fiber. Explain any two factors in brief. ***[Oct 19, 5m]***
3. Explain in brief (a) single mode and (b) multimode optic fibers.
4. Explain in brief (a) step-index and (b) graded-index optic fibers.

3/4 marks

1. What are optic fibers? Explain its construction and principle in brief.
2. Define the following and give equations wherever necessary (a) Critical angle (b) total internal reflection (c) acceptance angle
3. Define the following and give equations wherever necessary (a) acceptance angle (b) acceptance cone (b) Numerical aperture.
4. Define acceptance angle and acceptance cone. What is their significance in optic fiber?
5. What is total internal reflection? Explain its significance in optic fiber communication.
6. Define critical angle. Explain its significance in optic fiber communication.
7. Define numerical aperture. Explain its significance in optic fiber communication.
8. Differentiate between single mode and multimode optic fibers.
9. Differentiate between step-index and graded-index optic fibers.
10. Explain basic building blocks of a communication system.
11. State the advantages of optic fiber communication over conventional systems.

Numerical on Optic Fiber

Formulae

Critical Angle (θ_c)

$\sin\theta_c = \frac{n_2}{n_1}$ or $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

Acceptance angle and acceptance cone

- $\theta_a = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$
- $Angle\ of\ acceptance\ cone = 2 \times Acceptaance\ angle = 2 \times \theta_a$

Numerical Aperture

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

Step Index Fiber

Relation between RI : $n_2 = n_1 (1 - \Delta)$

(where Δ is difference in RI of core and cladding)

Graded Index fibers:

Relation between RI : $\Delta = \frac{n_1 - n_2}{n_1}$

Relation between NA and Δ : $NA = n_1\sqrt{2\Delta}$

Step index fiber

Example:\
For an optic fiber placed in air, if acceptance angle is 52.74^0, calculate numerical aperture.

Solution: $\theta_a = 52.74^0$

$NA = \sin(\theta_a) = \sin(52.74) = 0.7958$

Example:\
Calculate numerical aperture of an optic fiber with refractive indices of core and cladding 1.546 and 1.378 respectively.

Solution: $n_1 = 1.378$, $n_2 = 1.546$

$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.546)^2 - (1.378)^2} = 0.700$

Example:\
A step index fiber has core and cladding refractive indices of 1.65 and 1.48. Calculate values of critical angle, numerical apertureand acceptance angle if it is placed in air. ***[Oct 19, 4m]***

Solution: $n_1 = 1.65$, $n_2 = 1.48$

Critical angle = $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.48}{1.65}\right) = \sin^{-1}(0.896) = 63.76^0$

$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.65)^2 - 1.48)^2} = 0.729$

Acceptance angle = $\theta_a = \sin^{-1}(NA) = \sin^{-1}(0.729) = 46.84^0$

Example:\
For a step index fiber with a core refractive index of 1.46 and a numerical aperture of 0.65, calculate the refractive index of cladding. Also calculate the maximum angle at entrance when fiber is placed in air. ***[Oct 19, 4m]***

Solution: $n_1 = 1.46$, NA = 0.65

$NA = \sqrt{n_1^2 - n_2^2}$ or $(NA)^2 = n_2^2 - n_1^2$

$n_2 = \sqrt{n_1^2 - (NA)^2} = \sqrt{(1.46)^2 - (0.65)^2} = 1.307$

$\theta_a = \sin^{-1}(0.65) = 40.54^0$

Example:*An optic fiber has acceptance angle 30^0 and refractive index of core 1.4. Calculate refractive index of cladding.*

Solution: Acceptance angle = $\theta_a = 30^0$

$NA = \sin(\theta_a) = \sin(30) = 0.5$

$NA = \sqrt{n_1^2 - n_2^2}$

$n_2 = \sqrt{n_1^2 - (NA)^2} = \sqrt{(1.4)^2 - (0.5)^2} = 1.307$

Example:*If the angle for acceptance cone of an optical fiber is 68.16^0, calculate maximum entrance angle and numerical aperture. If the refractive index of cladding is 1.52, calculate refractive index of core.*

Solution: Angle for acceptance cone = $2\theta_a = 68.16^0$

Maximum entrance angle = Angle of incidence = $\theta_a = 34.08^0$

$NA = \sin(\theta_a) = \sin(34.08) = 0.56$

$NA = \sqrt{n_1^2 - n_2^2}$

$n_1 = \sqrt{n_2^2 + (NA)^2} = \sqrt{(0.56)^2 + (1.52)^2} = 1.62$

Example:*Calculate fractional index change for a given optical fiber if refractive indices of core and cladding are 1.563 and 1.498 respectively.*

Solution: Fractional index change $\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.563-1.498}{1.563} = 0.0415$

Q7: Calculate refractive indices of the core and cladding material of an optical fiber if numerical aperture is 0.22 and fractional index change is 0.012.

Solution: $NA = n_1\sqrt{2\Delta}$

$0.22 = n_1\sqrt{2 \times 0.012}$

$n_1 = \frac{0.22}{0.155} = 1.42$

Fractional index change $\Delta = \frac{n_1 - n_2}{n_1}$

$0.012 = \frac{1.42 - n_2}{1.42}$

$n_2 = 1.403$

Example:*Find the fractional refractive index and numerical aperture for an optical fiber with refractive indices of core and cladding as 1.5 and 1.49 respectively.*

Solution: Fractional index change $\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.5-1.49}{1.5} = 0.0067$

$NA = n_1\sqrt{2\Delta} = 1.5 \times \sqrt{2 \times 0.0067} = 0.174$

Graded index fiber

Example:*A glass clad fiber is made with core glass of refractive index 1.5 and cladding is doped to give a fractional index difference of 0.0005. Find (a) cladding index (b) critical internal reflection angle (c) external critical acceptance angle (d) numerical aperture*

Solution:

(a) Refractive index of cladding $\Delta = \frac{n_1 - n_2}{n_1}$

$0.0005 = \frac{1.5 - n_2}{1.5}$

Thus, $n_2 = 1.49925$

(b) Critical angle $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.49925}{1.5}\right) = 88.2^0$

(c) Acceptance angle $\theta_a = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$

$\theta_a = \sin^{-1}\left(\sqrt{1.5^2 - 1.49925^2}\right) = 2.72^0$

(d) Numerical Aperture $NA = n_1\sqrt{2\Delta} = 1.5\sqrt{2 \times 0.0005} = 0.0474$