

ADVANCED ENGINEERING PHYSICS

UNIT-1 LASERS AND FIBRE OPTICS

Syllabus

Introduction to laser, characteristics of laser, Einstein coefficients and their relations, metastable state, population inversion, pumping, lasing action, Ruby laser, He-Ne laser, semiconductor diode laser, Fibre Laser concept, applications of laser(qualitative): Bar code scanner, LIDAR for autonomous vehicle.

Introduction to fibre optics, total internal reflection, geometry of optical fibre, acceptance angle, numerical aperture, classification of optical fibres, losses in optical fibre, applications of optical fiber (qualitative): optical fibre for communication system, sensor for structural health monitoring.

The branch of optical physics that deals with the theory and application of lasers is called laser physics. This branch of physics lays the foundation of quantum electronics. The word laser is an acronym and can be expanded as "light amplification by stimulating the emission of radiation."

Characteristics of Lasers

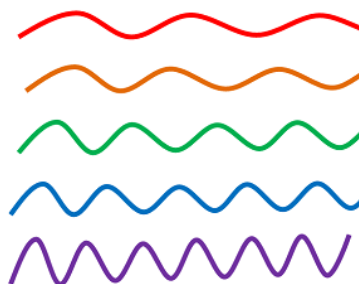
Laser light has four unique characteristics that differentiate it from ordinary light: these are,

- Coherence
- Directionality
- Monochromatic
- High intensity

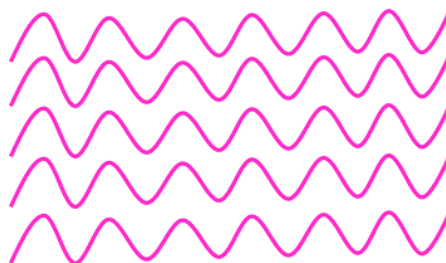
Coherence

The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors. Hence, the light waves of ordinary light sources have many wavelengths. Therefore, photons emitted by an ordinary light source are out of phase.

In laser, all the photons emitted in laser have the same energy, frequency, or wavelength. Therefore, the wavelengths of the laser light are in phase in space and time.



Incoherent light

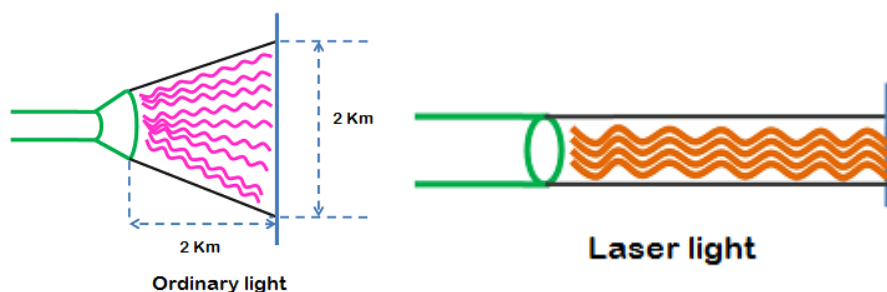


Coherent light waves

Directionality

In conventional light sources (lamp, sodium lamp and torchlight), photons will travel in random direction. Therefore, these light sources emit light in all directions.

On the other hand, in laser, all photons will travel in same direction. Therefore, laser emits light only in one direction. This is called directionality of laser light. The width of a laser beam is extremely narrow. Hence, a laser beam can travel to long distances without spreading.



Monochromaticity

Monochromatic light means a light containing a single color or wavelength. The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors. Therefore, ordinary light is a mixture of waves having different frequencies or wavelengths.

On the other hand, in laser, all the emitted photons have the same energy, frequency, or wavelength. Hence, the light waves of laser have single wavelength or color. Therefore, laser light covers a very narrow range of frequencies or wavelengths.

High Intensity

You know that the intensity of a wave is the energy per unit time flowing through a unit normal area. In an ordinary light source, the light spreads out uniformly in all directions. If you look at a 100-Watt lamp filament from a distance of 30 cm, the power entering your eye is less than 1/1000 of a watt.

In laser, the light spreads in small region of space and in a small wavelength range. Hence, laser light has greater intensity when compared to the ordinary light.

Principles of working of a laser

In lasers, photons are interacted in three ways with the atoms:

- Absorption of radiation
- Spontaneous emission
- Stimulated emission

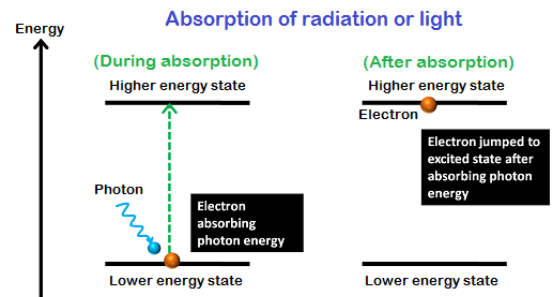
Absorption of radiation

Absorption of radiation is the process by which electrons in the ground state absorbs energy from photons to jump into the higher energy level.

Let us consider two energy levels (E_1 and E_2) of electrons. E_1 is the ground state or lower energy state of electrons and E_2 is the excited state or higher energy state of electrons.

When photons or light energy equal to the energy difference of the two energy levels ($E_2 - E_1$) is

incident on the atom, the ground state electrons gain sufficient energy and jump from ground state (E_1) to the excited state (E_2).

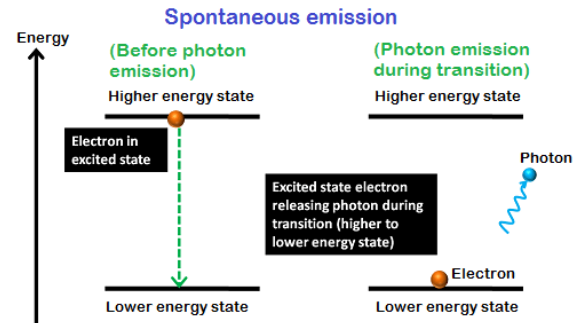


Spontaneous emission

Spontaneous emission is the process by which electrons in the excited state return to the ground state by emitting photons.

The electrons in the excited state can stay only for a short period. The time up to which an excited electron

can stay at higher energy state (E_2) is known as the lifetime of excited electrons. The lifetime of electrons in excited state is around 10^{-8} second.



Thus, after the short lifetime of the excited electrons, they return to the lower energy state or ground state by releasing energy in the form of photons.

In spontaneous emission, the electrons move naturally or spontaneously from one state (higher energy state) to another state (lower energy state) so the emission of photons also occurs naturally. Therefore, we have no control over when an excited electron is going to lose energy in the form of light.

The photons emitted in spontaneous emission process constitute ordinary incoherent light. In other words, the photons emitted in the spontaneous emission process do not flow exactly in the same direction of incident photons.

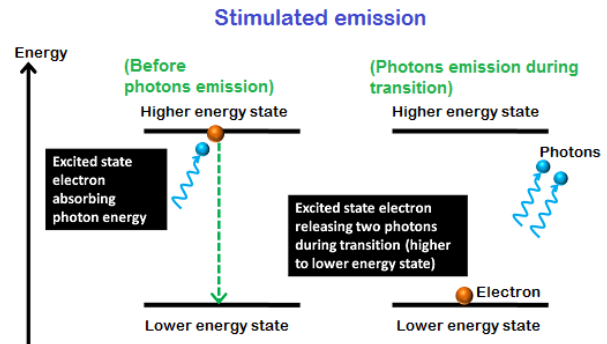
Stimulated emission

Stimulated emission is the process by which incident photon interacts with the excited electron and forces it to return to the ground state.

In stimulated emission, the light energy is supplied directly to the excited electron instead of supplying light energy to the ground state electrons.

In stimulated emission, the electrons in the excited state need not wait for completion of their lifetime. When incident photon interacts with the excited electron, it forces the excited electron to return to the ground state. This excited electron release energy in the form of light while falling to the ground state.

In stimulated emission, two photons are emitted (one additional photon is emitted), one is due to the incident photon and another one is due to the energy release of excited electron.



All the emitted photons in stimulated emission have the same energy, same frequency and are in phase. Therefore, all photons in the stimulated emission travel in the same direction.

The number of photons emitted in the stimulated emission depends on the number of electrons in the higher energy level or excited state and the incident light intensity.

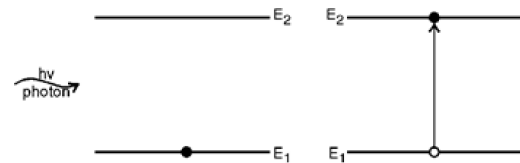
Einstein Coefficients and their Relations:

Einstein showed the interaction of radiation with the matter with the help of three processes called stimulated absorption, spontaneous emission, and stimulated emission. He showed in 1917 that for a proper description of radiation with matter, the process of stimulated emission is essential. Let us first derive the Einstein coefficient relation on the basis of the above theory: Let N_1 be the number of atoms per unit volume in the ground state E_1 and N_2 be the number of atoms per unit volume in the excited state E_2 .

Einstein Coefficient for Absorption/Stimulated Absorption:

Let $P_{12(\text{abs})}$ be the rate of absorption of light by E_1 to E_2 transitions by the process called absorption using the below process:

This rate of absorption $P_{12(\text{abs})}$ is proportional to the number of atoms N_1 per unit volume in the ground state and proportional to the energy density $u(\nu)d\nu$ of radiations. i.e.,



$$P_{12(\text{abs})} \propto N_1 u(\nu)d\nu$$

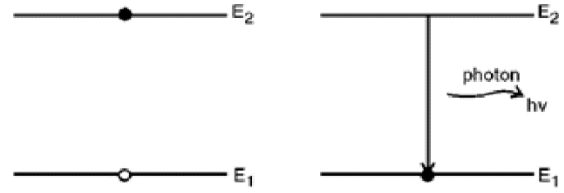
$$P_{12(\text{abs})} = B_{12} N_1 u(\nu)d\nu \quad \text{-----(1)}$$

Where B_{12} is known as the Einstein's coefficient of stimulated absorption and it represents the probability of absorption of radiation.

Einstein Coefficient for Spontaneous Emission:

Now atoms in the higher energy level E_2 can fall to the ground state E_1 automatically after 10^{-8} sec by the process called spontaneous emission using below.

The rate $P_{21(\text{spont})}$ of spontaneous emission E_2 to E_1 is independent of energy density E of the radiation field.



$P_{21(\text{spont})}$ is proportional to number of atoms N_2 in the excited state E_2 thus

$$P_{21(\text{spont})} \propto N_2$$

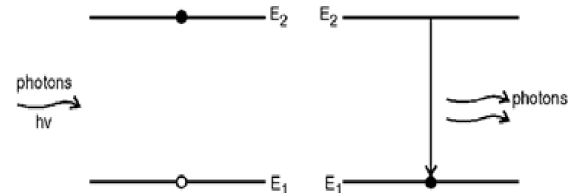
$$P_{21(\text{spont})} = A_{21} N_2 \quad \text{-----}(2)$$

Where A_{21} is known as Einstein's coefficient for spontaneous emission and it represents the probability of spontaneous emission

Einstein Coefficient for Stimulated Emission:

Atoms can also fall back to the ground state E_1 under the influence of the electromagnetic field of an incident photon of energy $E_2 - E_1 = h\nu$ by the process called stimulated emission using the below.

Rate $P_{21(\text{stimu})}$ for stimulated emission E_2 to E_1 is proportional to energy density $u(\vartheta)d\vartheta$ of the radiation field and proportional to the number of atoms N_2 in the excited state, thus



$$P_{21(\text{stimu})} \propto N_2 u(\vartheta)d\vartheta$$

$$P_{21(\text{stimu})} = B_{21} N_2 u(\vartheta)d\vartheta \quad \text{-----}(3)$$

Where B_{21} is known as the Einstein coefficient for stimulated emission and it represents the probability of stimulated emission.

Einstein Coefficient Relations

In steady-state (at thermal equilibrium), the two emission rates (spontaneous and stimulated) must balance the rate of absorption.

$$P_{12(\text{abs})} = P_{21(\text{Spon})} + P_{21(\text{Stimu})}$$

$$B_{12} N_1 u(\vartheta)d\vartheta = A_{21} N_2 + B_{21} N_2 u(\vartheta)d\vartheta$$

$$(B_{12} N_1 - B_{21} N_2) u(\vartheta)d\vartheta = A_{21} N_2$$

$$u(\vartheta)d\vartheta = \frac{A_{21} N_2}{(B_{12} N_1 - B_{21} N_2)}$$

$$\text{After rearranging, } u(\vartheta)d\vartheta = \frac{A_{21}/B_{21}}{(\frac{B_{12} N_1}{B_{21} N_2} - 1)} \quad \text{-----}(4)$$

As per the Maxwell – Boltzmann statistics, $\frac{N_1}{N_2} = e^{\frac{h\vartheta}{kT}}$

$$u(\nu)d\nu = \frac{A_{21}/B_{21}}{\left(\frac{B_{12}}{B_{21}} e^{\frac{h\nu}{kT}} - 1\right)} \quad \text{-----}(5)$$

$$\text{According to Planck's black body radiation, } \omega(\nu)d\nu = \frac{8\pi h \nu^3}{c^3(e^{\frac{h\nu}{kT}} - 1)} \quad \text{-----}(6)$$

By comparing above (5) and (6) equations,

$$\frac{B_{12}}{B_{21}} = 1 \quad \text{-----}(7)$$

$$\text{And } \frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3} \quad \text{-----}(8)$$

Equation (7) and (8) are the Einstein coefficient relations.

Significance of Einstein relations:

(a) From $\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3}$, $\Rightarrow \frac{A_{21}}{B_{21}} \propto \nu^3$ i.e., this shows that the ratio of Einstein's coefficients of spontaneous emission to the stimulated emission is proportional to the cube of frequency.

i.e., Spontaneous emitted light dominates the stimulated emission light at higher frequencies.

(b) $\frac{B_{12}}{B_{21}} = 1 \Rightarrow B_{12} = B_{21}$ i.e., the probability of stimulated absorption rate is equal to the probability of stimulated emission rate.

Population Inversion

Population inversion is the process of achieving greater population of higher energy state as compared to the lower energy state. Population inversion technique is mainly used for light amplification. The population inversion is required for laser operation.

Consider a group of electrons with two energy levels E_1 and E_2 .

E_1 is the lower energy state and E_2 is the higher energy state.

N_1 is the number of electrons in the energy state E_1 .

N_2 is the number of electrons in the energy state E_2 .

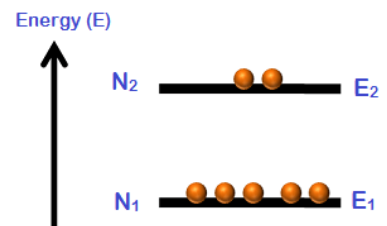
The number of electrons per unit volume in an energy state is the population of that energy state.

Population inversion cannot be achieved in a two-energy level system. Under normal conditions, the number of electrons (N_1) in the lower energy state (E_1) is always greater as compared to the number of electrons (N_2) in the higher energy state (E_2).

$$N_1 > N_2$$

When temperature increases, the population of higher energy state (N_2) also increases. However, the population of higher energy state (N_2) will never exceed the population of lower energy state (N_1).

At best an equal population of the two states can be achieved which results in no optical gain.



$$N_1 = N_2$$

Therefore, we need 3 or more energy states to achieve population inversion. The greater is the number of energy states the greater is the optical gain.

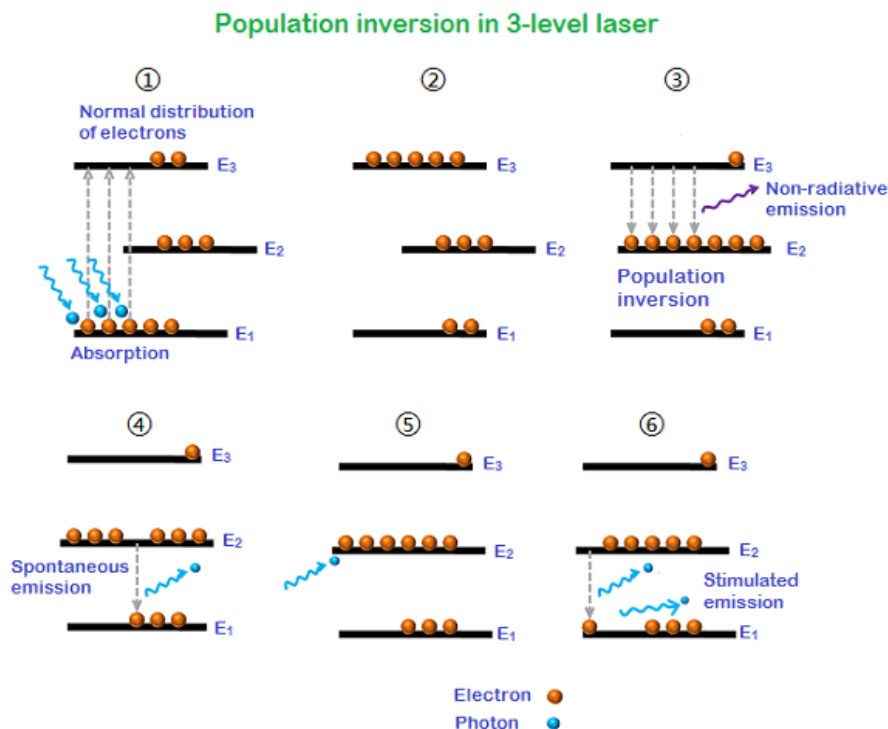
3-level Laser

Consider a system consisting of three energy levels E_1 , E_2 , E_3 with N number of electrons. The energy level E_1 is known as the ground state or lower energy state and the energy levels E_2 and E_3 are known as excited states.

Let N_1 be the number of electrons in the energy state E_1 , N_2 be the number of electrons in the energy state E_2 and N_3 be the number of electrons in the energy state E_3 . It can be simply written as $N_1 > N_2 > N_3$. The energy level E_2 is sometimes referred to as Meta stable state. To get laser emission or population inversion, the population of higher energy state (E_2) should be greater than the population of the lower energy state (E_1). The electrons in the Meta stable state E_2 will remain there for longer period because of its longer lifetime. As result, a large number of electrons accumulate in Meta stable state. Thus, the population of metal stable state will become greater than the population of energy states E_3 and E_1 . Under certain conditions, the greater population of higher energy state (E_2) as compared to the lower energy state (E_1) is achieved. Such an arrangement is called population inversion.

It can be simply written as $N_2 > N_1 > N_3$.

In a three-level energy system, we achieve population inversion between energy levels E_1 and E_2 .



Meta stable state:

The population inversion is achieved by pumping, i.e., with the help of a continuous supply of energy to the atoms in the lower energy levels and hence they will get excited to the higher energy levels. But, the atoms can not stay in the higher energy level for a longer time, they will eventually get de-excited to the lower energy levels. Due to this de-excitation process, the population inversion can not be achieved. Hence, we need an intermediate energy level or the state where the atoms can stay a bit longer or atoms can have a longer lifetime.

Pumping

Pumping is the process of achieving population inversion. There are many techniques to achieve population inversion. Depending upon the type of laser, the most commonly used pumping methods are listed below:

- a) **Optical pumping:** In this, the population inversion is achieved by means of light energy delivered from appropriate pumping source such as gaseous discharge or flash tubes. For example, in ruby laser, xenon flash tube is used.
- b) **Electric discharge pumping:** This type of pumping accomplished by means of intense electrical discharge in the medium and is particularly suited to gas media like He-Ne laser and CO₂ laser. The electric discharge converts the gas into a plasma where active centers collide inelastically with free electrons and population inversion is achieved.
- c) **Chemical pumping:** It raises active centers into the higher levels by means of suitable exothermal chemical reactions in the active medium.
- d) **Injection of current:** In this process, the charge carriers can be injected in to the materials so that the more number of electrons will be placed in the higher energy state than the ground state. This type of pumping will be used in semiconductor diode laser (Example: GaAs laser)

Conditions for achieving laser (Components of laser)

The following are the basic requirements to achieve laser

- a. Population inversion should be achieved between meta stable state and its below level by any pumping techniques
- b. The system should be at least 3 energy level.
- c. There should be a metastable state
- d. There should be an optical resonator (i.e., optical feedback is must to stimulate further emission with the emitted photons)

Types of lasers

Lasers are classified into 4 types based on the type of laser medium used:

- Solid-state laser
- Gas laser
- Liquid laser
- Semiconductor laser

Solid-state laser

A solid-state laser is a laser that uses solid as a laser medium. In these lasers, glass or crystalline materials are used. Example: Ruby laser

Gas laser

A gas laser is a laser in which an electric current is discharged through a gas inside the laser medium to produce laser light. In gas lasers, the laser medium is in the gaseous state. Example: He-Ne laser, CO₂ laser.

Liquid laser

A liquid laser is a laser that uses the liquid as laser medium. In liquid lasers, light supplies energy to the laser medium. Example: Dye laser.

Semiconductor laser

Semiconductor lasers play an important role in our everyday life. These lasers are very cheap, compact size and consume low power. Semiconductor lasers are also known as laser diodes.

Example: GaAs Laser.

Ruby Laser

The first demonstration of laser action using ruby crystal was given by T.H. Maiman in 1960. It is a solid-state laser.

Construction

Ruby is a crystal of aluminum oxide (Al₂O₃) in which some of the aluminum ions (Al³⁺) are replaced by chromium ions (Cr³⁺). This is done by doping 0.05% (by weight) small amounts of chromium oxide (Cr₂O₃) in the melt of purified Al₂O₃. The ruby crystal is in the form of a cylinder. The length of ruby crystal is usually 2 cm to 30 cm and diameter 0.5 cm to 2 cm.

Active medium or active center: Chromium ions act as active centers in ruby crystals. So it is the chromium ions that produce the laser.

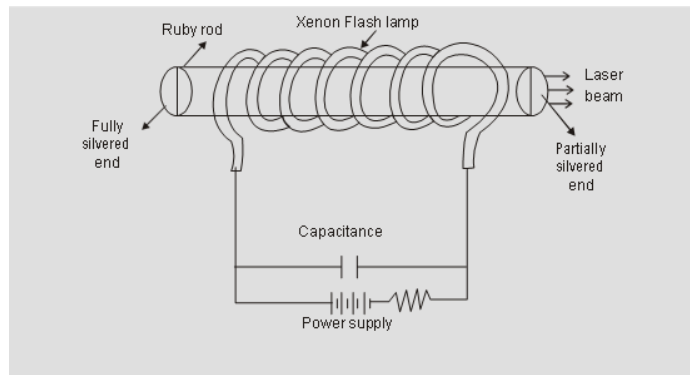
Pumping source: A helical flash lamp filled with xenon is used as a pumping source. The ruby crystal is placed inside a xenon flash lamp. Thus, optical pumping is used to achieve population inversion in ruby laser.

Optical resonator system: The ends of ruby crystal are polished, grounded, and made flat. One of the ends is completely silvered while the other one is partially silvered to get the output. Thus the two polished ends act as an optical resonator system.

Working

Ruby is a three-level laser system. Suppose there are three levels E1, E2, and (E3 & E4). E1 is the ground level, E2 is the metastable level, E3 and E4 are the bands.

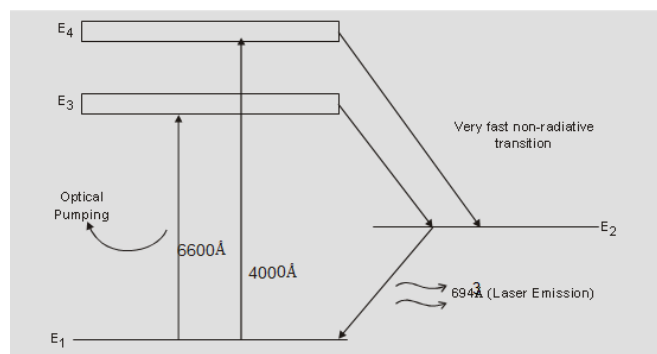
Pumping: The ruby crystal is placed



inside a xenon flash lamp and the flash lamp is connected to a capacitor. A part of this energy is absorbed by chromium ions in the ground state. Thus optical pumping raises the chromium ions to energy levels inside the bands E3 and E4. This process is called stimulated absorption. The transition to bands E3 and E4 are caused by absorption of radiations corresponding to wavelengths approximately 6600 angstroms and 4000 angstroms respectively. The levels inside the bands E3 and E4 are also known as pumping levels.

Achievement of population inversion: Cr^{3+} ions in the excited state lose a part of their energy during interaction with crystal lattice and decay to the metastable state E2. Thus, the transition from excited states to metastable states is a non-radiative transition or there is no emission of photons. As E2 is a metastable state, chromium ions will stay there for a longer time. Hence, the number of chromium ions goes on increasing in the E2 state, while due to pumping, the number in the ground state E1 goes on decreasing. As a result, the number of chromium ions becomes more in an excited state (metastable state) as compared to ground state E1. Hence, the population inversion is achieved between states E2 and E1.

Achievement of laser: Few of the chromium ions will come back from E2 to E1 by the process of spontaneous emission by emitting photons. The wavelength of a photon is 6943 Å. This photon travels through the ruby rod and if it is moving in a direction parallel to the axis of the crystal,



then it is reflected to and fro by the silvered ends of the ruby rod until it stimulates the other excited ions and causes it to emit a fresh photon in phase with the stimulating photon. Thus, the reflections

will result in stimulated emission and it will result in the amplification of the stimulated emitting photons. This stimulated emission is the laser transition. When the photon beam becomes sufficiently intense, then a very powerful and narrow beam of red light of wavelength $6943 \text{ \AA}$ emerges through the partially silvered end of the ruby crystal.

Output: The output wavelength of the ruby laser is $6943 \text{ \AA}$ and output power is 10^4 to 10^6 watts and it is in the form of pulses.

Drawbacks of ruby laser

1. The ruby laser requires a high power pumping source.
2. The laser output is not continuous but occurs in the form of pulses of microsecond duration.
3. The defects due to crystalline imperfection are also present in ruby laser.

Uses of ruby laser

1. Ruby laser has very high output power of the order of $10^4 - 10^6$ watts. It has a wavelength of 6943 Angstroms .
2. Ruby lasers are used for holography, industrial cutting, and welding.

He-Ne Laser

Helium-Neon Laser is the first gas Laser developed by Ali Javan in 1961. It is a four level laser. The first He-Ne laser emitted infrared at $1.15 \mu\text{m}$ and 632.8 nm in visible region of the spectrum.

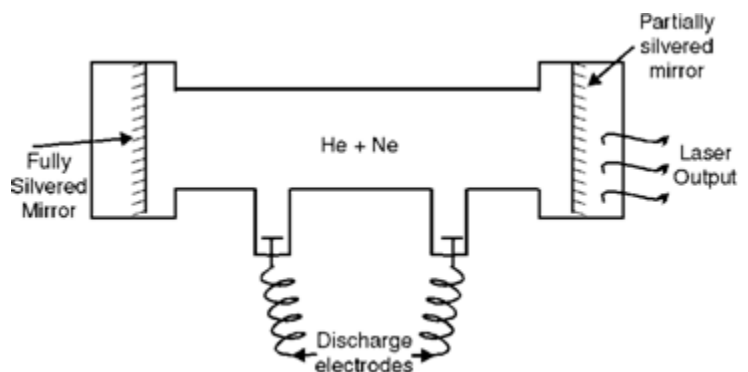
Construction of Helium-neon laser:

The helium-neon laser is a long narrow discharge tube which is made of quartz glass. A high voltage dc power supply of about 2 to 4 KV is used as pumping source. Helium and neon gas is mixed in a ratio 10:1 and is used as a gain medium. The resonating system of the He Ne laser consists of two concave mirrors, one fully reflector and other partial reflector. The fully silvered mirror will completely reflect the light whereas the partially silvered mirror will reflect most part of the light but allows some part of the light to produce the laser beam.

Working of He Ne laser:

When current flows through the gas, the energetic electrons transfer some of their energy to the helium atoms. As a result, the helium atoms in the ground state gain enough energy and jump to the excited states 2^1S_1 of energy 20.16 and 2^3S_1 level of energy

19.81 eV which is a close approximate to the energy of metastable states of Neon. After that He



atoms transferred their energy to the Ne atoms which are at ground state and excite them to the metastable states $4S$ and $5S$ and helium atoms come down to the ground state. Since $4S$ and $5S$ are metastable states for neon atoms, so it quickly attains population inversion. After some period, the metastable states electrons of the neon atoms will spontaneously fall into the next lower energy states by releasing photons. This is called spontaneous emission. For transition of the neon atoms from upper $5S$ to $4P$ level generates radiation of wavelength $3.39\mu m$ and $5S$ to $3P$ generates wavelength of $6328 \text{ \AA}$. Also, the transition from $4S$ to $3P$ gives wavelength of $1.15 \mu m$. From $3P$ to $3S$ level the atom comes down spontaneously and the atoms come back to ground state from the state $3S$ to $2P$ by the process of de-excitation by collision.

Advantages of helium-neon laser:

Helium-neon laser emits laser light in the visible portion of

the spectrum. Low cost Operates without damage at higher temperatures

Disadvantages of helium-neon laser: It has Low efficiency and low gain Helium-neon lasers are limited to low power tasks.

Semiconductor Diode laser:

It is specifically fabricated heavily doped p-n junction diode that emits laser light when it is forward biased.

Principle:

When a p-n junction diode is forward biased, the electrons from n – region and the holes from the p- region cross the junction and recombine with each other. During the recombination process, the light radiation (photons) is released from a certain specified direct band gap semiconductors like Ga-As. This light radiation is known as recombination radiation. The photon emitted during recombination stimulates other electrons and holes to recombine. As a result, stimulated emission takes place which produces laser.

Construction:

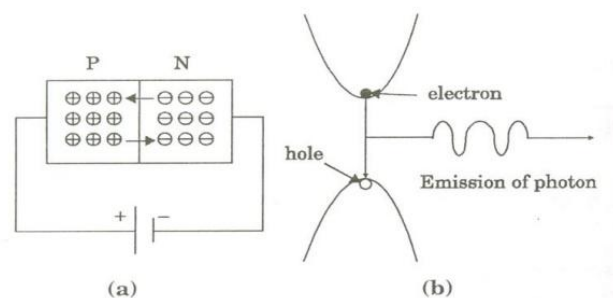
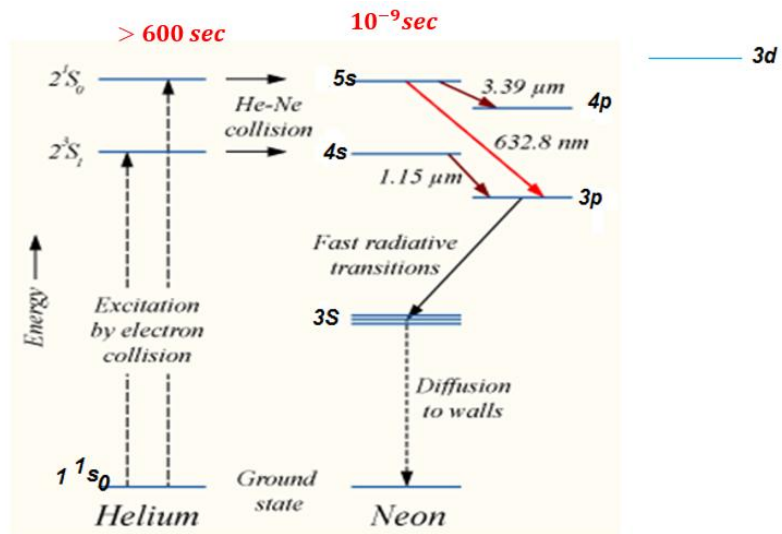
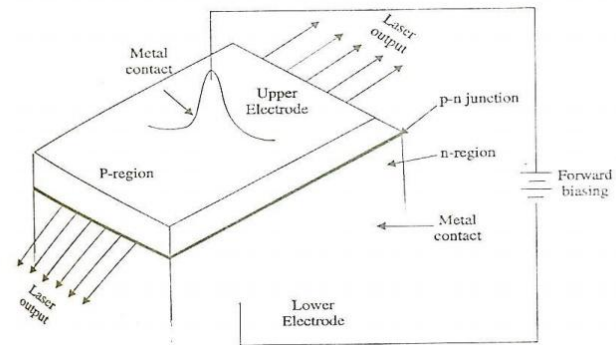


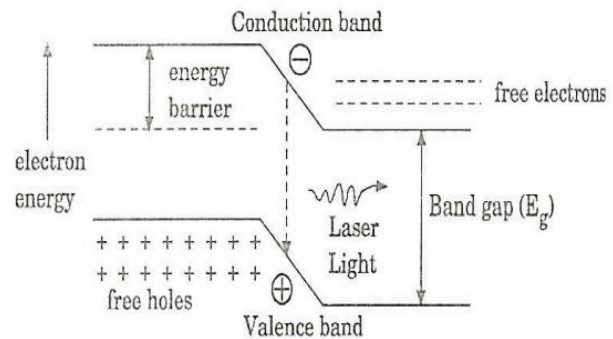
Figure shows the basic construction of semiconductor laser. The active medium is a p-n junction diode made from the single crystal of gallium arsenide. This crystal is cut in the form of a platter having thickness of 0.5mm. The photon emission is stimulated in a very thin layer of PN junction (in order of few microns). The end faces of the junction diode are well polished and parallel to each other. They act as an optical resonator through which the emitted light comes out.



Working:

Figure shows the energy level diagram of semiconductor laser.

When the PN junction is forward biased with large applied voltage, the electrons and holes are injected into junction region in considerable concentration



The region around the junction contains a large amount of electrons in the conduction band and a large amount of holes in the valence band.

If the population density is high, a condition of population inversion is achieved. The electrons and holes recombine with each other and this recombination's produce radiation in the form of light.

When the forward – biased voltage is increased, more and more light photons are emitted and the light production instantly becomes stronger. These photons will trigger a chain of stimulated recombination resulting in the release of photons in phase.

The photons moving at the plane of the junction travels back and forth by reflection between two sides placed parallel and opposite to each other and grow in strength.

After gaining enough strength, it gives out the laser beam of wavelength 8400 Å . The wavelength of laser light is given by

$$E_g = h\nu = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E_g}$$

Where E_g is the band gap energy in joule.

Characteristics:

1. Type: It is a solid state semiconductor laser.

2. Active medium: A PN junction diode made from single crystal of gallium arsenide is used as an active medium.
3. Pumping method: The direct injection of current method is used for pumping action
4. Power output: The power output from this laser is 1mW.
5. Nature of output: The nature of output is continuous wave or pulsed output.

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 CO₂ laser.
6. It can have a continuous wave output or pulsed output.

Disadvantages:

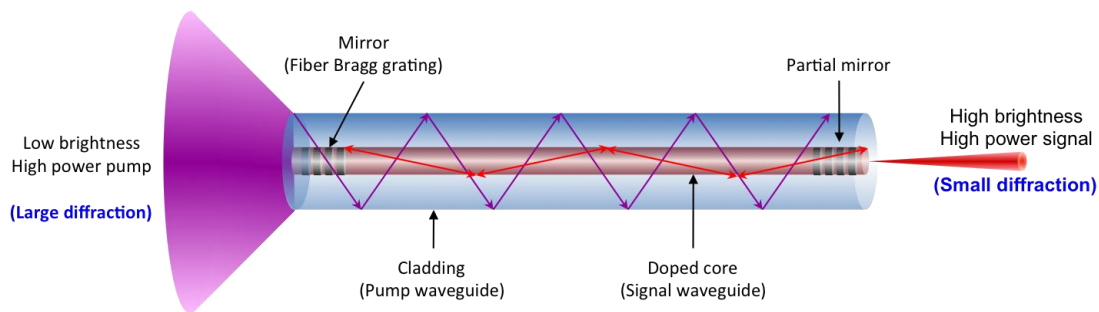
1. It is difficult to control the mode pattern and mode structure of laser.
2. The output is usually from 5 degree to 15 degree i.e., laser beam has large divergence.
3. The purity and monochromaticity are poorer than other types of laser
4. Threshold current density is very large (400A/mm²).
5. It has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

Application:

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

FIBRE LASER CONCEPT

A fiber laser is a solid-state laser whose active medium is an optical fiber doped with a rare earth element such as erbium, ytterbium, neodymium, or thulium. Laser light is generated and guided within the fiber core, resulting in efficient amplification and excellent beam quality.



Pump Source: This component provides the energy to excite the rare-earth ions in the active fibre. It is typically a high-power semiconductor laser diode. The wavelength of the pump laser is chosen to be effectively absorbed by the rare-earth doping.

Wavelength Combiner (or Pump Combiner): This optical device combines the light from one or more pump diodes into the gain fiber. This is crucial for high-power fiber lasers, which often use multiple pump diodes to achieve the necessary energy levels.

Active Gain Fiber: The heart of the fiber laser. It is a special optical fiber with a core that has been "doped" with rare-earth elements like ytterbium (Yb), erbium (Er), or neodymium (Nd).

- **Pumping:** The pump light from the pump source excites the rare-earth ions to a higher energy state.
- **Stimulated Emission:** When a spontaneously emitted photon passes by an excited ion, it stimulates the ion to release another photon with the same properties, coherently amplifying the light.

Laser Cavity (Resonator): This is where the light is repeatedly bounced back and forth through the active fiber, continuously amplifying the signal. The cavity is formed by two reflectors, which can be:

- **Fiber Bragg Gratings (FBGs):** These are mirrors created by modifying the refractive index of the fiber itself. They are highly efficient and are often used in all-fiber systems.
- **External Mirrors:** In some configurations, the cavity can be formed by discrete mirrors outside the fiber.

High Reflector (High-Reflectivity Mirror): One end of the laser cavity is formed by a mirror with very high reflectivity, ideally close to 100%. This maximizes the light reflected back into the fiber for maximum amplification.

Output Coupler (Partial Reflector): The other end of the cavity is a mirror with partial reflectivity. It allows a portion of the amplified light to escape as the final laser output, while reflecting the rest back into the cavity for further amplification.

Signal Output: This is the high-quality, high-power laser beam extracted from the output coupler.

Applications of lasers

Bar code scanner

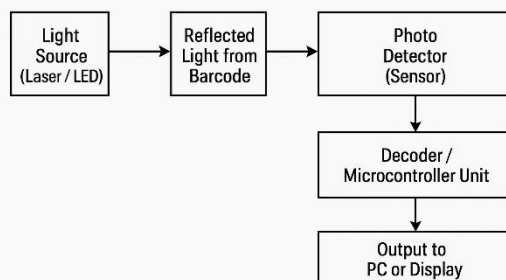
A **bar code scanner** is a device that uses a low-power semiconductor laser (typically a red laser diode) to read the information encoded in barcodes.

- When the laser beam strikes the black and white bars, the black regions absorb the light while the white regions reflect it, creating a pattern of reflected signals.
- These signals are detected by a photodiode, converted into electrical pulses, and then processed into digital data that represents product or item information

Bar code scanners are widely used in retail checkout systems, inventory management, logistics, libraries, and healthcare for quick and accurate identification of items.

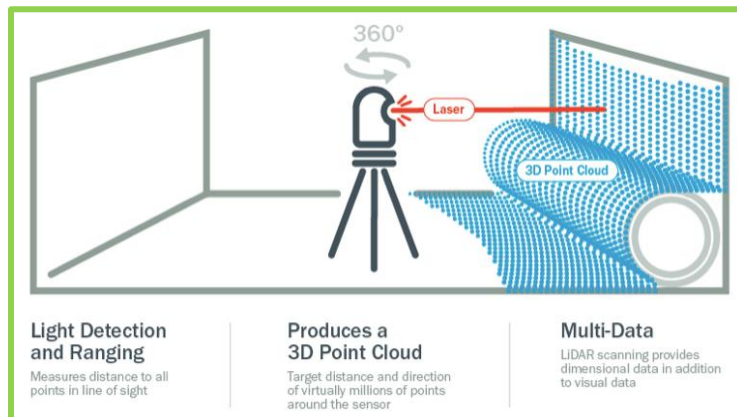


BLOCK DIAGRAM OF A BARCODE SCANNER



LIDAR for autonomous vehicles

A **LIDAR (Light Detection and Ranging)** system for autonomous vehicles uses pulsed laser beams to measure the distance between the vehicle and surrounding objects with high precision.



- The laser emits short bursts of light that reflect off objects, and the time taken for the reflection to return is measured to calculate distance.
- By rapidly scanning the environment in all directions, LIDAR creates a detailed 3D map of the surroundings, enabling the vehicle to detect obstacles, pedestrians, road signs, and lane markings.
- This real-time mapping and object detection capability is crucial for safe navigation, collision avoidance, and decision-making in self-driving cars.

More Applications of lasers

Lasers have applications in almost every field like medicine, industry, communication, and science and technology. Let us discuss these applications one by one:

a) Holography:

Holography is a technique to record the complete picture of an object, that is it will produce a three-dimensional picture.

b) Measurement of long-distance:

The beam spreading in the laser light is very small, the laser can travel long distances, without appreciable spreading. The time taken by a laser pulse to travel from laser source to a given target and back is measured. As the velocity of light is known, the distance of the target can be calculated using the relation $2d = c \times t$ where d is the distance of the target and c is the velocity of light.

c) Applications in scientific research:

Due to the coherent nature of laser light, many new optical phenomena have been observed using a laser. Using laser light we investigate the basic laws of interaction of atoms and molecules with electromagnetic waves.

d) Application in communication:

In the fiber communication system, the laser beam is used. The rate at which information is transmitted is proportional to the bandwidth of the information carrier signal.

Fiber Communication

The bandwidth is proportional to the frequency of the carrier. Since the frequency range of laser signals is quite high compared to microwaves, large bandwidth can be obtained using the optical region as compared to the microwave region.

e) Applications in Industry:

Due to the high intensity of the laser beam, the laser can be used in welding, cutting, and in producing very high temperatures. The other advantage of a laser is that the beam can be focused onto a fine spot. The small spot size implies that high energy densities are possible. Lasers are also found suitable for machining and drilling holes.

f) Lasers in Isotope separation:

The light emerging from a laser is extremely monochromatic. When laser light falls on a mixture of two isotopes, the laser light excites the atoms of only one of the isotopes thus separating it from the other isotope.

In addition to the high monochromaticity, the high intensity of the laser is also responsible for its application for isotope separation because with low-intensity beams the separation rate would be too low for practical use.

g) Applications in Medicine:

i) Laser Surgery: The focused laser beam is capable of bloodless surgery since the beam not only cuts but also welds blood vessels being cut. Laser surgery is painless because operations are very fast and there is not enough time for the patient to respond to the incision and sense pain.

ii) Lasers in Ophthalmology: Lasers are used for several years to treat the detachment of the retina. The beam is focused on a certain point of the retina after it has passed through the lens of the eye and vitreous chamber without being absorbed in them. The green beam of laser is strongly absorbed by the red blood cells of the retina and the consequent thermal effects lead to reattachment of the retina. The operation is carried out by a 0.01-sec pulse and being very short, is virtually painless. Other illnesses treated by the focused laser beam are cataracts, tumors, and glaucoma.

iii) Laser Therapy: He-Ne laser has produced a curing effect on trophic ulcers, poorly healing wounds, and bone fractures. The laser can also be guided through optical fiber into blood vessels to remove the clotting, in the case of heart patients, through heating. It has also found application in treating decaying teeth. The laser can replace dental drills.

The above are important applications of lasers in different fields, if you know more, please share in the comments section.

UNIT-1 FIBRE OPTICS

Fiber optics is the science and technology that studies how light is transmitted through thin, flexible optical fibers made of glass or plastic.

These fibers are used to transmit data, signals, or images over long distances with minimal loss.

Advantages of Optical Fiber Communications

1. Wide bandwidth

The light wave occupies the frequency range between 10^{12} Hz to 10^{16} Hz. Thus, the information carrying capability of fiber optic cables is much higher.

2. Low losses

Fiber optic cables offer very less signal attenuation over long distances. Typically, it is less than 0.5 dB/km. This enables longer distance between repeaters.

3. Immune to cross talk and Interference

Fiber optic cables have very high immunity to electrical and magnetic field. Since fiber optic cables are non-conductors of electricity hence, they do not produce magnetic field. Thus, fiber optic cables are immune to cross talk between cables caused by magnetic induction.

Fiber optic cable immune to conductive and radiative interferences caused by electrical noise sources such as lighting, electric motors, fluorescent lights.

4. Light weight & Small Size

As fiber cables are made of silica glass or plastic which is much lighter than copper or aluminum cables. Light weight fiber cables are cheaper to transport. The diameter of fiber is much smaller compared to other cables; therefore, fiber cable is small in size, requires less storage space. Fiber cables are stronger and rugged hence can support more weight.

5. Security & Environment immune

Fiber cables are more secure than other cables. It is almost impossible to tap into a fiber cable as they do not radiate signals. No ground loops exist between optical fibers hence they are more secure. Fiber cables are more immune to environmental extremes. They can operate over large temperature variations. Also, they are not affected by corrosive liquids and gases.

6. Low cost

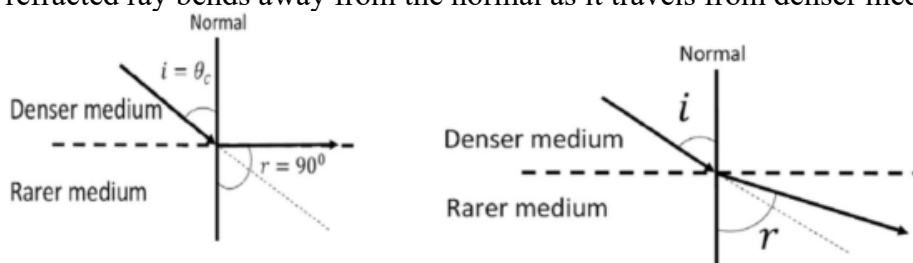
Cost of fiber optic system is less compared to any other system.

Principle of Optical Fiber (Total Internal Reflection)

Principle:

The basic principle of optical fiber in the transmission of optical signal is total internal reflection. When the light ray travels from denser medium to rarer medium the refracted ray bends away from the normal. When the angle of incidence is greater than the critical angle, the refracted ray again reflects into the same medium. This phenomenon is called **total internal reflection**.

The refracted ray bends towards the normal as the ray travels from rarer medium to denser medium. The refracted ray bends away from the normal as it travels from denser medium to rarer medium.



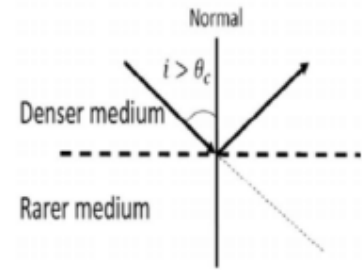
Let, a light ray traveling from denser medium (refractive index n_1) to rarer medium (refractive index n_2) with an angle of incidence i , then the angle of refraction r can be obtained by Snell's law.

$$n_1 \sin i = n_2 \sin r$$

When the angle of incidence is increased angle of refraction also increases and for a particular angle of incidence ($i = \theta_c$) the refracted ray travels along the interface of two mediums. This angle of incidence is known as **critical angle** (θ_c).

$$n_1 \sin \theta_c = n_2 \sin 90$$

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



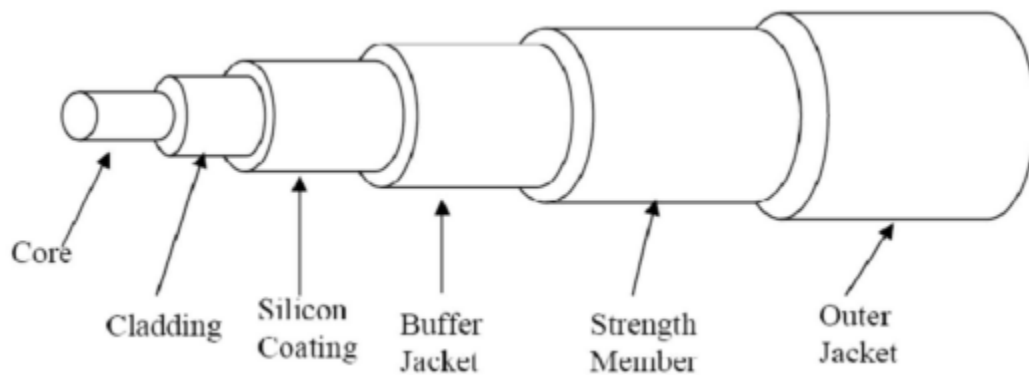
When the angle of incidence is greater than the critical angle ($i > \theta_c$)

the refracted ray again reflects into the same medium. This phenomenon is called total internal reflection.

- When ($i < \theta_c$), then the ray refracts into the secondary medium
- When ($i = \theta_c$), then the ray travels along the interface
- When ($i > \theta_c$), then the ray totally reflects back into the same medium

Geometry/Structure/Construction of optical fiber:-

The optical fiber mainly consists the following six parts as shown in figure



Core:

A typical glass fiber consists of a central core material. Generally, core diameter is $50 \mu m$. The core is surrounded by cladding. The core medium refractive is always greater than the cladding refractive index.

Cladding

Cladding refractive index is lesser than the cores refractive index. The over all diameter of cladding is $125 \mu m$ to $200 \mu m$.

Silicon Coating

Silicon coating is provided between buffer jacket and cladding. It improves the quality of transmission of light.

Buffer Jacket

Silicon coating is surrounded by buffer jacket. Buffer jacket is made of plastic and protects the fiber cable from moisture.

Strength Member

Buffer jacket is surrounded by strength member. It provides strength to the fiber cable.

Outer Jacket

Finally, the fiber cable is covered by polyurethane outer jacket. Because of this arrangement fiber cable will not be damaged during pulling, bending, stretching and rolling through the fiber cable is made up of glasses.

Acceptance angle: -

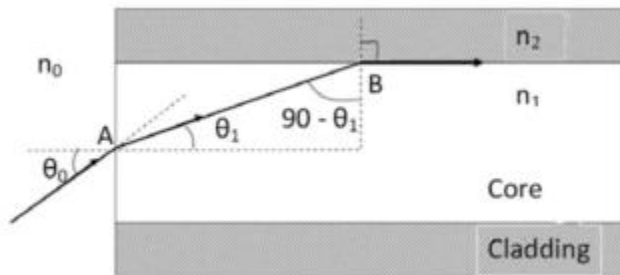
Acceptance angle is defined as the maximum angle of incidence at the interface of air medium and core medium for which the light ray enters into the core and travels along the interface of core and cladding.

Numerical Aperture:

The light gathering capacity of an optical fibre.

Let n_0, n_1 and n_2 be the refractive indices of air, core and cladding media. Let a light ray OA is incident on the interface of air medium and core medium with an angle of incidence θ_0 then the light ray refracts into the core medium with an angle of refraction θ_1 , and the refracted ray AB is again incident on the interface of core and cladding with an angle of incident $(90-\theta_1)$,

If $(90-\theta_1)$ is equal to the critical angle of core and cladding media then the ray travels along the interface of core and cladding along the path BC. If the angle of incident at the interface of air and core $\theta_1 < \theta_c$, then $(90-\theta_1)$ will be greater than the critical angle. Therefore, the total internal reflection takes place.



According to Snell's law at point A

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

$$\sin \theta_0 = \frac{n_1}{n_0} \sin \theta_1$$

According to Snell's law at point B

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

$$n_1 \cos \theta_1 = n_2$$

$$\cos \theta_1 = \frac{n_2}{n_1}$$

$$\sin \theta_1 = \sqrt{1 - \cos^2 \theta_1}$$

$$\sin \theta_1 = \sqrt{1 - \frac{n_2^2}{n_1^2}} = \frac{\sqrt{(n_1^2 - n_2^2)}}{n_1}$$

$$\sin \theta_0 = \frac{n_1}{n_0} \sin \theta_1 = \frac{n_1}{n_0} \frac{\sqrt{(n_1^2 - n_2^2)}}{n_1} = \frac{\sqrt{(n_1^2 - n_2^2)}}{n_0}$$

$$\sin \theta_0 = \frac{\sqrt{(n_1^2 - n_2^2)}}{n_0}$$

$$\theta_0 = \sin^{-1} \left(\frac{\sqrt{(n_1^2 - n_2^2)}}{n_0} \right)$$

$$\text{Acceptance angle } \theta_0 = \sin^{-1} \left(\frac{\sqrt{(n_1^2 - n_2^2)}}{n_0} \right)$$

Numerical Aperture:

Numerical aperture is defined as the light gathering capacity of an optical fiber and it is directly proportional to the acceptance angle.

Numerically it is equal to the sin of the acceptance angle.

$$NA = \sin(\text{acceptance angle})$$

$$NA = \sin \left(\sin^{-1} \left(\frac{\sqrt{(n_1^2 - n_2^2)}}{n_0} \right) \right)$$

$$NA = \frac{\sqrt{(n_1^2 - n_2^2)}}{n_0}$$

If the refractive index of the air medium is equal to unity, then

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

Fractional change in refractive index

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

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

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

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

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

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

$$\because n_1 \Delta = (n_1 - n_2)$$

$$\because n_1 \approx n_2 ; \quad n_1 + n_2 = 2n_1$$

The above equation gives a relationship between numerical aperture and fractional change in relative refractive index.

Classification of Optical Fibers

One way of classifying the fiber cables is according to the index profile at fiber.

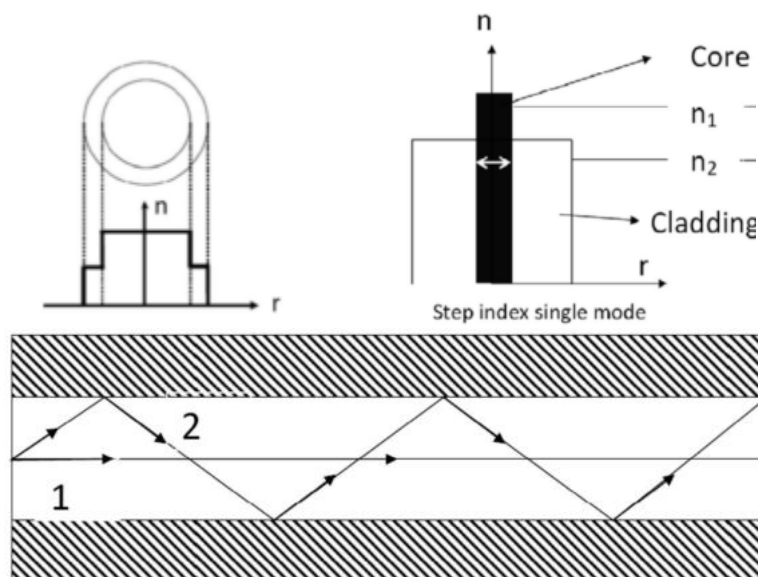
The index profile is a graphical representation of value of refractive index across the core diameter.

There are two basic types of index profiles.

1. Step index fiber.
2. Graded index fiber.

Step Index Fiber

The step index (SI) fiber is a cylindrical waveguide core with central or inner core has a uniform refractive index of n_1 and the core is surrounded by outer cladding with uniform refractive index of n_2 . The cladding refractive index (n_2) is less than the core refractive index (n_1). But there is an abrupt change in the refractive index at the core cladding interface. Refractive index profile of step indexed optical fiber is shown in figure. The propagation of light wave within the core of step index fiber takes the path of meridional ray i.e. ray follows a zig-zag path of straight-line segments. The core typically has diameter of 50-80 μm and the cladding has a diameter of 125 μm .



Graded Index fibers

The graded index fiber has a core made from many layers of glass.

In the graded index fiber, the refractive index is not uniform within the core, it is highest at the center and decreases smoothly and continuously with distance towards the cladding. The refractive index profile across the core takes the parabolic nature.

In graded index fiber the light waves are bent by refraction towards the core axis and they follow the curved path down the fiber length. This results because of change in refractive index as moved away from the center of the core.

Refractive index profile of graded index fiber is as shown:

$$n(r) = \begin{cases} n_1 \left(1 - 2\Delta \left(\frac{r}{a} \right)^\alpha \right) & \text{when } r \leq a \text{ (core)} \\ n_1 (1 - 2\Delta)^{\frac{1}{\alpha}} \approx n_2 & \text{when } r \geq a \text{ (cladding)} \end{cases}$$

where,

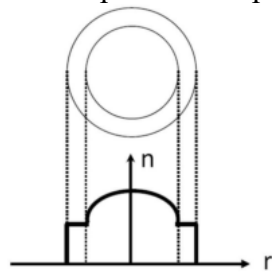
r = Radial distance from fiber axis

a = Core radius

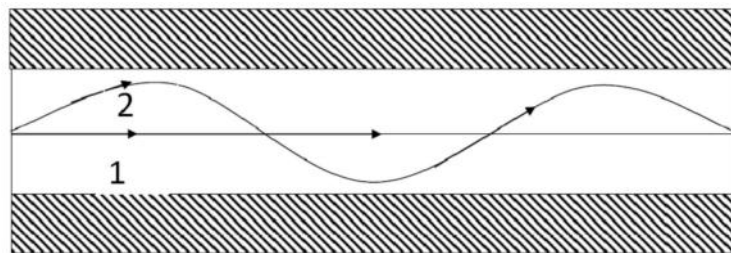
n_1 = Refractive index of core

n_2 = Refractive index of cladding

α = Shape of index profile.



Graded Index profile



Propagation of light in graded index fiber

Optic Fiber Configurations

Depending on the refractive index profile of fiber and modes of fiber there exist three types of optical fiber configurations. These optic-fiber configurations are -

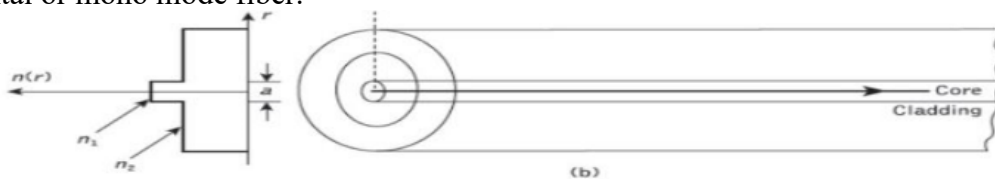
Single mode step index fiber.

Multimode step index fiber.

Multimode graded index fiber.

Single mode Step index Fiber

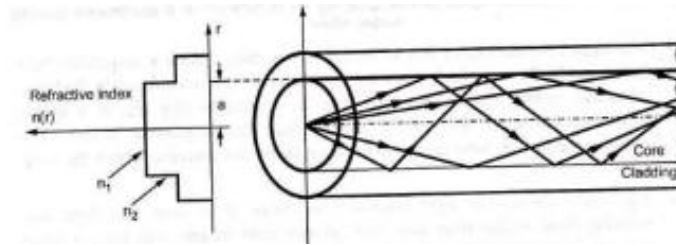
In single mode step index fiber has a central core that is sufficiently small so that there is essentially only one path for light ray through the cable. The light ray is propagated in the fiber through reflection. Typical core sizes are 2 to 15 μm . Single mode fiber is also known as fundamental or mono mode fiber.



Single mode fiber will permit only one mode to propagate and does not suffer from mode delay differences. The disadvantage of this type of cable is that because of extremely small size interconnection of cables and interfacing with source is difficult.

Multimode step Index Fiber

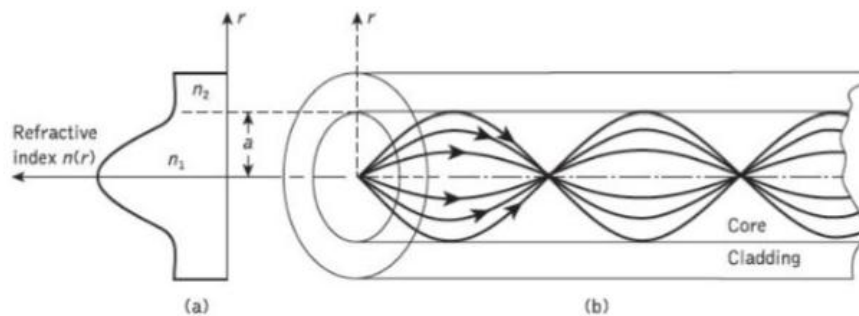
Multimode step index fiber is more widely used type. It is easy to manufacture. Its core diameter is 50 to 1000 μm i.e. large aperture and allows more light to enter the cable. The light rays are propagated down the core in zig-zag manner. There are many paths that a light ray may follow during the propagation.



The light ray is propagated using the principle of total internal reflection (TIR). Since the core index of refraction is higher than the cladding index of refraction, the light enters at less than critical angle is guided along the fiber.

Multimode Graded Index Fiber

The core size of multimode graded index fiber cable is varying from 50 to 100 μm range. The light ray is propagated through the refraction. The light ray enters the fiber at many different angles. As the light propagates across the core toward the center it is intersecting a less dense to more dense medium. Therefore the light rays are being constantly being refracted and ray is bending continuously. This cable is mostly used for long distance communication.



Losses in Optical Fibers (Attenuation)

Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber.

The reduction in amplitude of signal as it is guided through the fiber known as attenuation. It is expressed

in decibel (dB)

$$\text{dB} = 10 \log_{10} \frac{P_{out}}{P_{in}}$$

$$\alpha = -\frac{dB}{L} = \frac{1}{L} 10 \log_{10} \frac{P_{out}}{P_{in}}$$

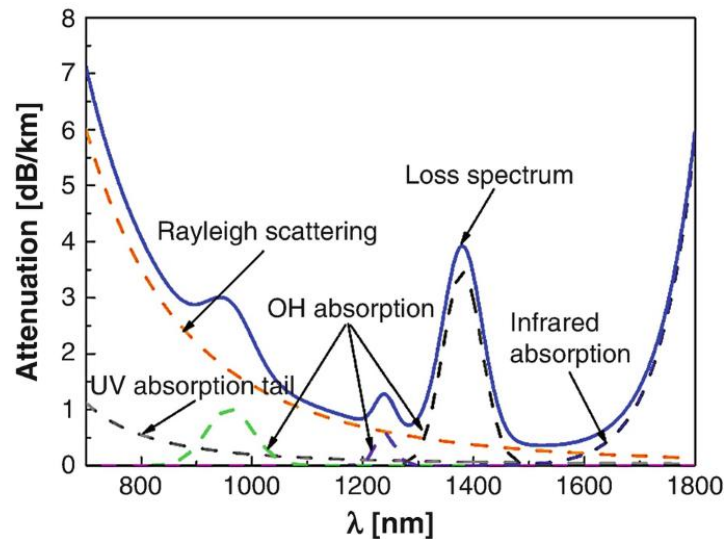
Where L=in Km

α =attenuation coefficients of fiber in dB/Km Since attenuation is loss.

In optical fibers the attenuation is mainly caused by two physical factors absorption and scattering losses. Absorption is because of fiber material and scattering due to structural imperfection within the fiber. Nearly 90 % of total attenuation is caused by Rayleigh scattering only. Microbending of optical fiber also contributes to the attenuation of signal.

Absorption Loss

Absorption loss is related to the material composition and fabrication process of fiber. Absorption loss results in dissipation of some optical power as it travels in the fiber cable. Although glass fibers are extremely pure, some impurities still remain as residue after purification. The amount of absorption by these impurities depends on their concentration and light wavelength.



Rayleigh Scattering Losses

Scattering losses exist in optical fibers because of microscopic variations in the material density and composition. As glass is composed by a randomly connected network of molecules and several oxides (e.g. SiO_2 , GeO_2 and P_2O_5), these are the major cause of compositional structure fluctuation. These two effects result in variation in refractive index and Rayleigh type scattering of light.

Rayleigh scattering of light is due to small localized changes in the refractive index of the core and cladding material.

Bending Loss

Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature. Fibers can be subjected to two types of bends:

- Macroscopic bends (having radii that are large as compared with the fiber diameter)
- Random microscopic bends of fiber axis

Losses due to curvature and losses caused by an abrupt change in radius of curvature are referred to as 'bending losses.' The sharp bend of a fiber causes significant radiative losses and there is also possibility of mechanical failure. This is shown in figure.

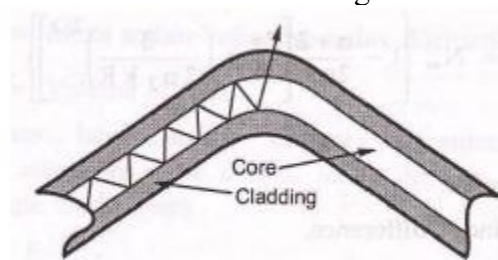
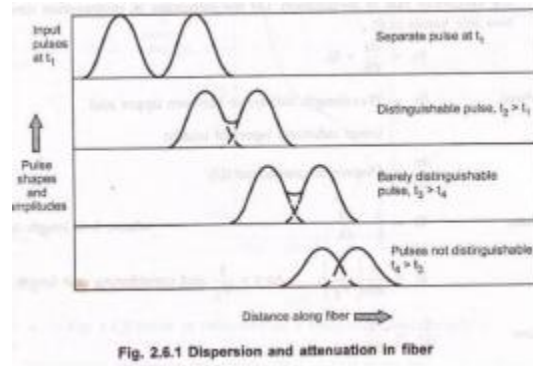


Fig. 2.4.3 Macrobending

Dispersion Loss

The pulse gets distorted as it travels along the fiber lengths. Pulse spreading in fiber is referred to as dispersion. Dispersion is caused by difference in the propagation times of light rays that take different paths during the propagation. The light pulses travelling down the fiber encounter dispersion effect because of this the pulse spreads out in time domain. Dispersion limits the information bandwidth. The distortion effects can be analyzed by studying the group velocities in guided modes.



Applications of Optical Fibers:

Optical Fiber Communication System.

Basic block diagram of optical fiber communication system consists of following important blocks.

1. Transmitter
2. Information channel
3. Receiver.

Message origin

Generally, message origin is from a transducer that converts a non-electrical message into an electrical signal. Common examples include microphones for converting sound waves into currents and video (TV) cameras for converting images into current. For data transfer between computers, the message is already in electrical form.

Modulator

The modulator has two main functions.

1. It converts the electrical message into the proper format.
2. It impresses this signal onto the wave generated by the carrier source.
3. Two distinct categories of modulation are used i.e. analog modulation and digital modulation.

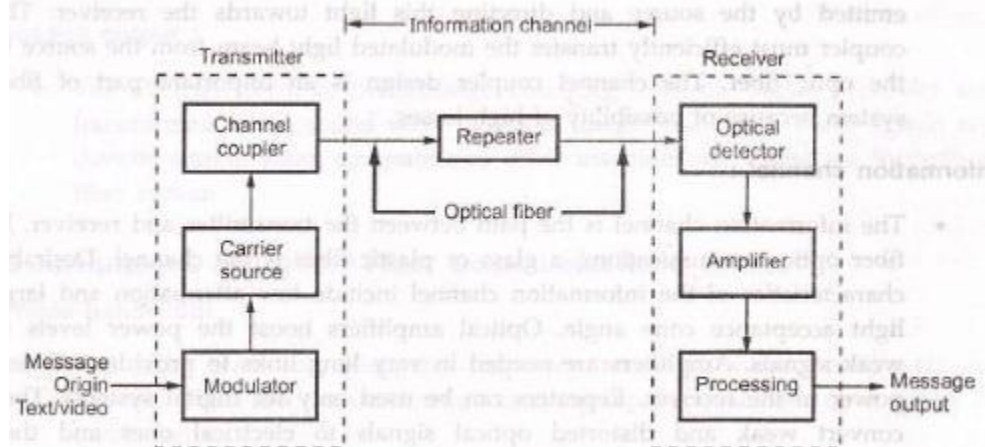


Fig. 1.2.1 Block diagram of OFC systems

Carrier source

Carrier source generates the wave on which the information is transmitted. This wave is called the carrier. For fiber optic system, a laser diode (LD) or a light emitting diode (LED) is used. They can be called as optic oscillators; they provide stable, single frequency waves with sufficient power for long distance propagation.

Channel coupler

Coupler feeds the power into the information channel. The coupler must efficiently transfer the modulated light beam from the source to the optic fiber.

Information channel

The information channel is the path between the transmitter and receiver. In fiber optic communications, a glass or plastic fiber is the channel. Desirable characteristics of the information channel include low attenuation and large light acceptance cone angle. Amplifiers are needed in very long links to provide sufficient power to the receiver. Repeaters can be used only for digital systems.

Optical detector

The information being transmitted is detected. In the fiber system the optic wave is converted into an electric current by a photo detector. The current developed by the detector is proportional to the power in the incident optic wave. Detector output current contains the transmitted information. This detector output is then filtered to remove the constant bias and then amplified.

The important properties of photo detectors are small size, economy, long life, low power consumption, high sensitivity to optic signals and fast response to quick variations in the optic power.

Signal processing

Signal processing includes filtering, amplification. Proper filtering maximizes the ratio of signal to unwanted power.

Message output

The electrical forms of the message emerging from the signal processor are transformed into a sound wave or visual image. Sometimes these signals are directly usable when computers or other machines are connected through a fiber system.

Sensors for Structural Health Monitoring (SHM):

Sensors for Structural Health Monitoring (SHM) are devices used to detect, measure, and monitor changes in structural behaviour, integrity, and performance of engineering systems such as bridges, buildings, aircraft, dams, and pipelines. These sensors provide real-time data that help in predicting failures, ensuring safety, and extending the service life of structures.

Fibre Optic Sensors for SHM

- **Fibre Bragg Grating (FBG) Sensors**
 - Work on the principle of Bragg wavelength shift when the fibre experiences strain or temperature changes.
 - Can measure **strain, temperature, and vibration** simultaneously.
 - Widely used in bridges, tunnels, aircraft, and pipelines due to high accuracy and multiplexing capability.
- **Interferometric Fibre Sensors**
 - Examples: **Fabry–Perot, Mach–Zehnder, Michelson interferometers.**
 - Detect changes in optical phase caused by strain, pressure, or temperature.
 - Highly sensitive, suitable for monitoring cracks and micro-strains in critical structures.
- **Distributed Fibre Optic Sensors (DFOS)**
 - Based on scattering mechanisms: **Rayleigh, Raman, or Brillouin scattering.**
 - Provide **continuous monitoring along the entire length of the fibre** (not just at discrete points).

- Used for long structures like bridges, tunnels, oil pipelines, and dams.
- **Intensity-Modulated Fibre Sensors**
 - Detect changes in light intensity due to bending, displacement, or pressure on the fibre.
 - Simple and low-cost, suitable for detecting cracks and structural deformations.

In SHM, **FBG sensors and Distributed Fibre Optic Sensors (DFOS)** are the most widely used because they provide precise, real-time, and long-range monitoring of structural integrity.

More Applications of Optical Fibers:

1. Internet:

Optical Fiber Cables transmit large amounts of data at a very high speed. Hence the technology is widely used in internet cables. As traditional compared to traditional copper wires, fiber optical cables are less bulky, lighter, more flexible, and carry more data.

2. Computer Networking

Networking between computers in the same building or in adjacent structures is made using optical cables easier and faster. Users can see a marked decrease in the time it takes to transfer files and information across networks.

3. Medical Applications

Optical cables are widely used in the fields of medicine and research. Optical communication is an important part of non-intrusive surgical methods, popularly known as endoscopy. Endoscopy looks inside the body without surgery.

4. Bio-Medical Research

Fiber optical are also used in microscopy and biomedical research.

5. Automotive Industry

Fiber optics cables play an important role in the lighting and security features of today's automobiles. They are widely used in lighting both the interior and exterior of vehicles. Because of its ability to conserve space and provide better lighting.

6. Mechanical Inspections

Optical fiber cable is widely used in the inspection of inaccessible places. Some such applications are on-site inspection for engineers and pipe inspection for plumbers.

7. Military and Space Applications

With the high level of data security required in military and aerospace applications, fiber optics cables offer the ideal solutions for data transmissions in these areas.