LASERS AND FIBER OPTICS

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LASERS

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation.

The term “LASER" originated as an acronym for "light amplification by stimulated emission of radiation".

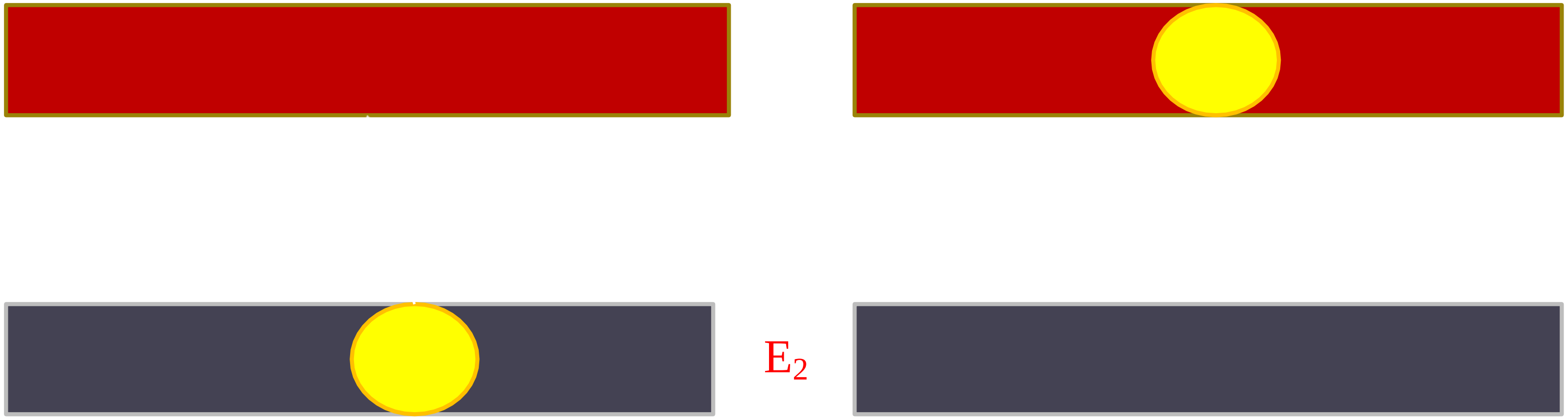
Stimulated emission was first used by Townes and Schawlov in USA & Bosov & Prokhrov in USSR.

Maiman demonstrated the first Laser in 1960.

Mechanism of Light Emission

surrounding, the emission of light is the result of:

Absorption: If a photon of energy $h\nu_{12}(E_2-E_1)$ collides with an atom present in the ground state of energy $E_{1,}$ then the atom completely absorbs the incident photon and makes transition to excited state E_2.

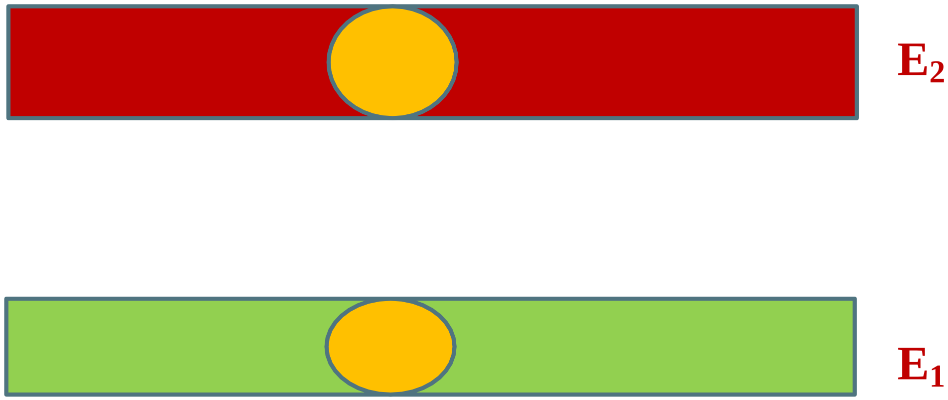


BeforeAbsorption **AfterAbsorption**

Spontaneous emission

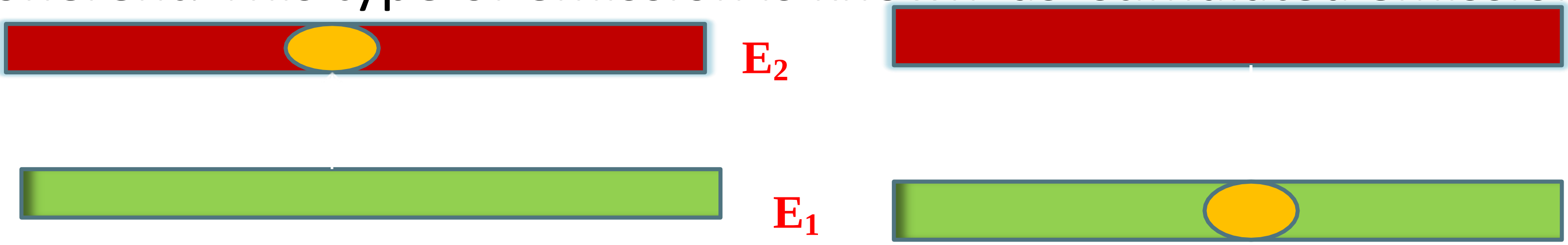
atom initially present in the excited state makes transition voluntarily on its own ,without any aid of external stimulus or an agency , to the ground state and emits a photon of energy $h\nu=E_2-E_1$. The period of stay of the atom (electron) in the excited state is called its life time.

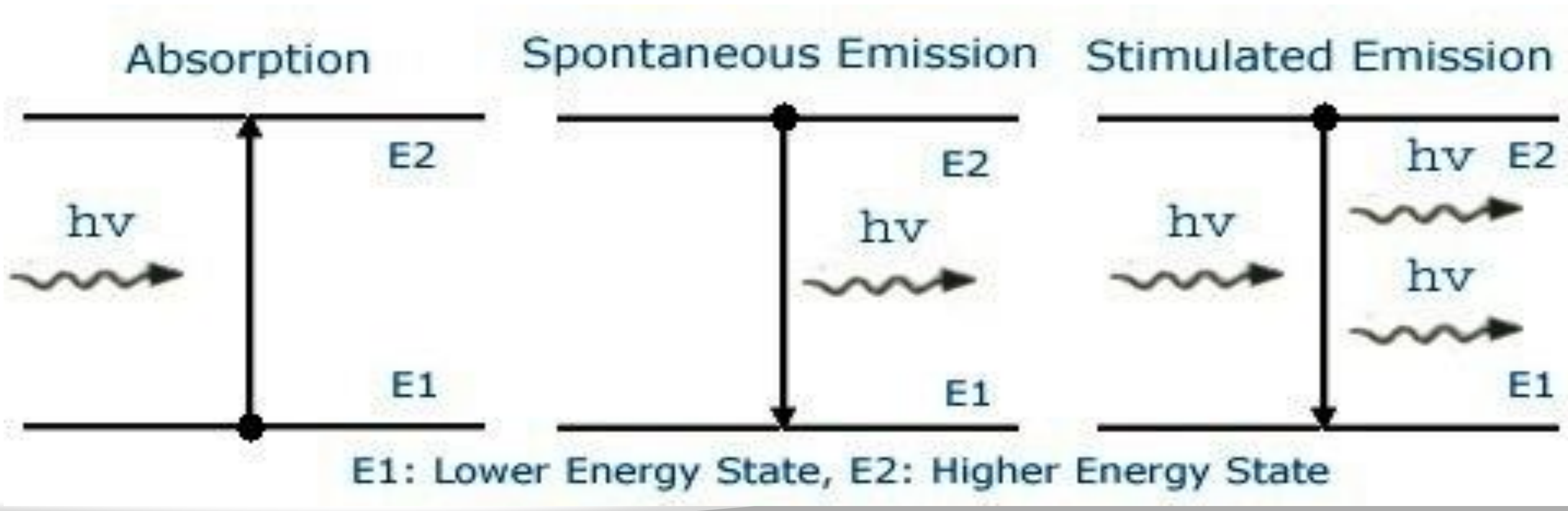
This process of emission of light is called spontaneous emission.



Stimulated Emission

A photon having energy $h\nu_{12}$ (E_2-E_1) impinges on an atom present in the excited state and the atom is stimulated to make transition to the ground state. This gives off a photon of energy $h\nu_{12}$. The emitted photon is in phase with the incident photon. These are coherent. This type of emission is known as stimulated emission.





Difference between Spontaneous and Stimulated Emission of radiation

Spontaneous Emission of Radiation	Stimulated Emission of Radiation
❖ It is a Polychromatic radiation.	❖ It is a Monochromatic radiation.
❖ It has less intensity.	❖ It has High intensity.
❖It has less directionality and more angular spread during propagation.	❖It has high directionality and so less angular spread during propagation.
❖It is Spatially and temporally incoherent radiation.	❖It is Specially and temporally coherent radiation.
❖ In this emission ,light is not amplified.	❖ In this emission , light is amplified.
❖Spontaneous emission takes place when excited atoms make a transition to lower energy level voluntarily without any external stimulation.	❖Stimulated emission takes place when a photon of energy equal to $h\,\nu_{12}$ $(=E_2\text{-}E_1)$ stimulates an excited atom ,to make transition to lower energy level.
❖In a single downward transition, Spontaneous emission results in the emission of one photon.	❖In a single downward transition , Stimulated emission results in the emission of two photons.
❖Ex: Light from an ordinary electric bulb, Light from an LED.	❖ Ex: Light from a Laser source.

Characteristics of Laser light

- High Monochromaticity
- High degree of coherence
- High directionality
- High brightness

Characteristics of Laser light

1. High Monochromaticity :

- In laser radiation, all the photons emitted between discrete energy levels will have same wavelength.
- As a result the radiation is monochromatic in nature.
- Due to the stimulated characteristic of laser light, the laser light is more monochromatic than that of a convectional light.
- laser radiation -the wavelength spread = 0.001 nm
- So it is clear that the laser radiation is highly monochromatic

Characteristics of Laser light

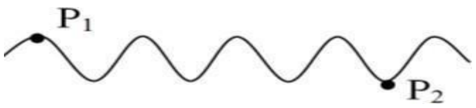
2. High degree of coherence :

- Coherence is the property of the wave being in phase with itself and also with another wave over a period of time, and space or distance. There are two types of coherence
- Temporal coherence
- Spatial coherence.
- For laser radiation all the emitted photons are in phase, the resultant radiation obeys spatial and temporal coherence.

Characteristics of Laser light

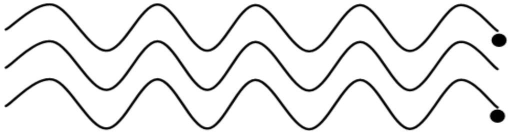
- **Temporal coherence (or longitudinal coherence):-**

The predictable correlation of amplitude and phase at one point on the wave train w .r. t another point on the same wave train, then the wave is said to be temporal coherence.



- **spatially coherence (or transverse coherence).**

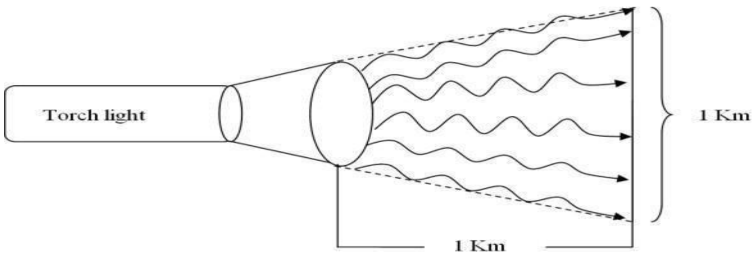
The predictable correlation of amplitude and phase at one point on the wave train w. r .t another point on a second wave, then the waves are said to be spatially coherence (or transverse coherence).

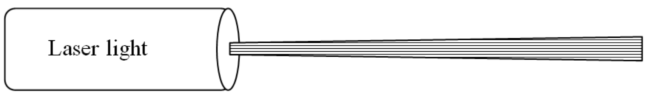


Characteristics of Laser light

3. High directionality :

- The light ray coming ordinary light source travels in all directions, but laser light travels in single direction.
- For example the light emitted from torch light travels 1km distance it spreads around 1 km wide.
- But the laser light spreads a few centimeters distance even it travels lacks of kilometer distance.





Characteristics of Laser light

- The directionality of laser beam is expressed in terms of divergence Ø

$$\text{Ø} = \frac{arc}{radius} = \frac{\mathrm{d2} - \mathrm{d1}}{\mathrm{s2} - \mathrm{s1}}$$

- Where d_2 and d_1 are the diameters of laser spots at distances of s_2 and s_1 respectively from laser source.

- For laser light divergence ϕ = $10^{-3} radians$.

- Since the divergence of light is very low, so we say that the laser light having highly directional.

Characteristics of Laser light

4. High Brightness:

The Laser beam is highly bright (intense) as compared to the conventional light because more light is concentrated in a small region.

It is observed that the intensity of 1mV laser light is 10,000 times brighter than the light from the sun at the earth's surface.

The number of photons coming out from a laser per second per unit area is about 10^{22} to 10^{34} where as the number of photons coming out per second per unit area of a black body at 1000K having a wavelength of 6000 is 10^{16}

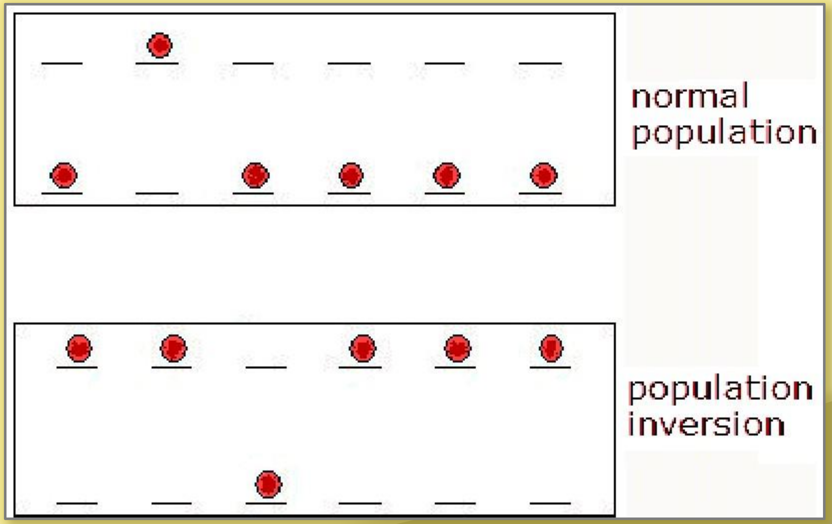
Laser light is coherent and so at a time many photons are in phase and they superimpose to produce a wave of larger amplitude.

The intensity is proportional to the square of the amplitude and hence the intensity of the resultant laser beam is very high.

Population Inversion

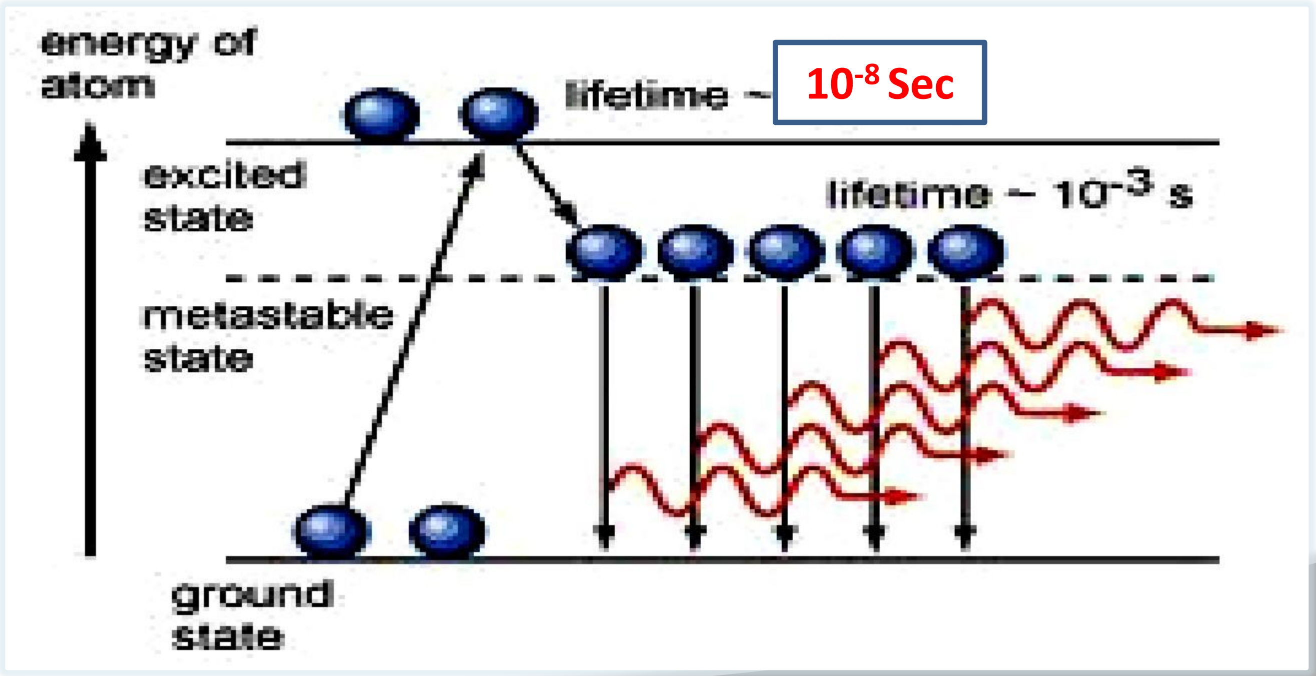
- Usually in a system, the number of atoms (N_1) present in the ground state (E_1) is larger than the number of atoms (N_2) present in the higher energy state. The process of making $N_2>N_1$ is called population inversion.
- Conditions for population inversion are:
- The system should posses at least a pair of energy levels ($E_2>E_1$), separated by an energy equal to the energy of a photon (hv).
- There should be a continuous supply of energy to the system such that the atoms must be raised continuously to the excited state

Population inversion can be achieved by a number of ways. Some of them are,
(i) Optical pumping
(ii) Electrical discharge
(iii) Inelastic collision of atoms
(iv) Chemical reaction and
(v) Direct conversion



Meta Stable state

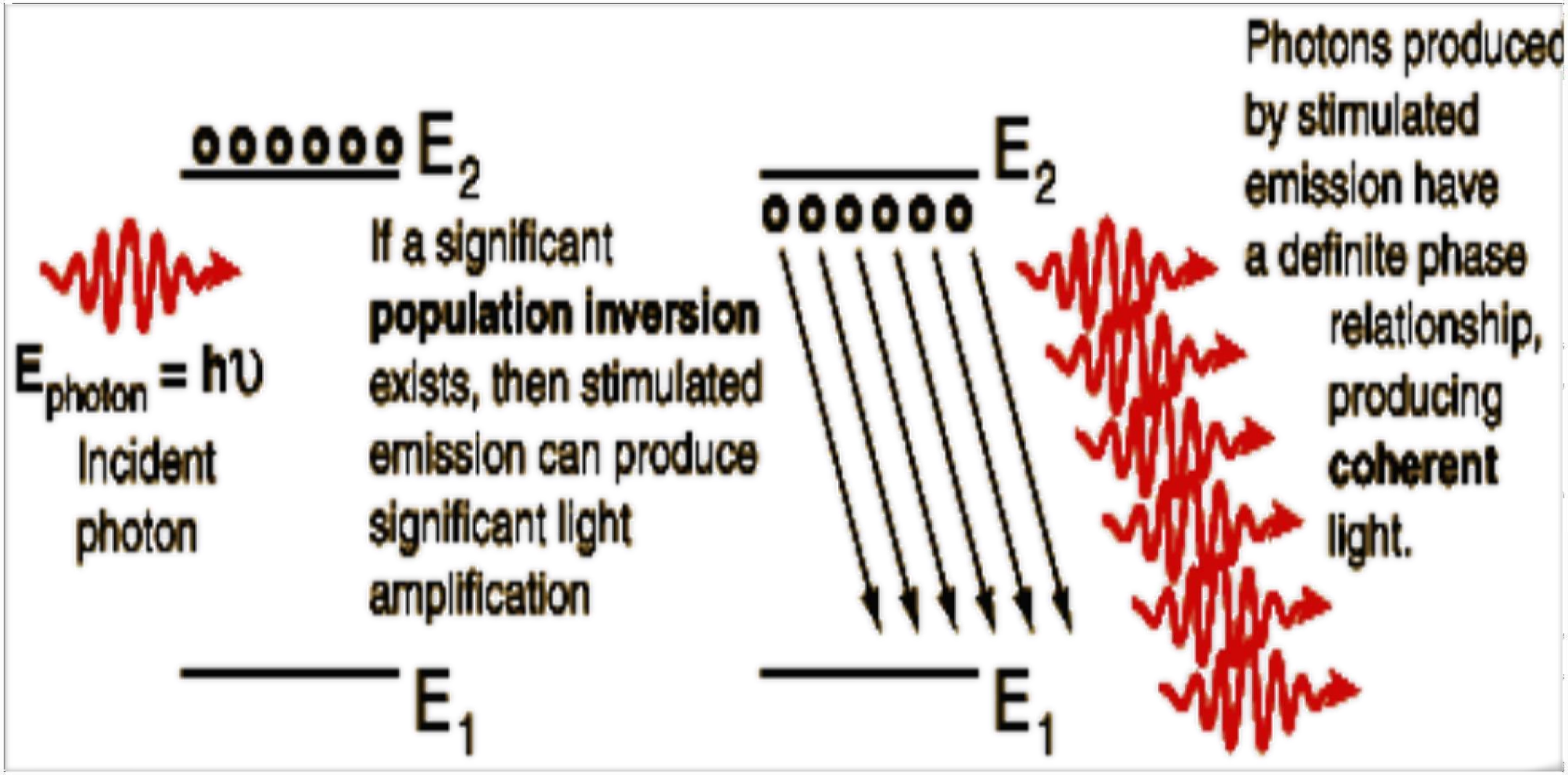
- An excited state with relatively more life time(10^{-3} sec) is Meta stable state.
- The necessary condition for population inversion is the presence of a meta stable state.



Lasing Action

1. Pumping:- The process of sending atoms from lower energy state to higher energy state is called Pumping. Different pumping mechanisms are adopted depending on the type of the laser. For Ruby laser, Optical pumping is adopted. For He-Ne laser, the pumping mechanism is Electric discharge. In Semi-conductor laser, it is Direct conversion and in the case of CO_2 laser, the mechanism is Chemical reaction.
2. Population inversion :- Population inversion can be achieved with the presence of a meta stable state.
3. Stimulated emission of radiation :- Photons produced by stimulated emission are in phase and they produce coherent light.

Lasing Action



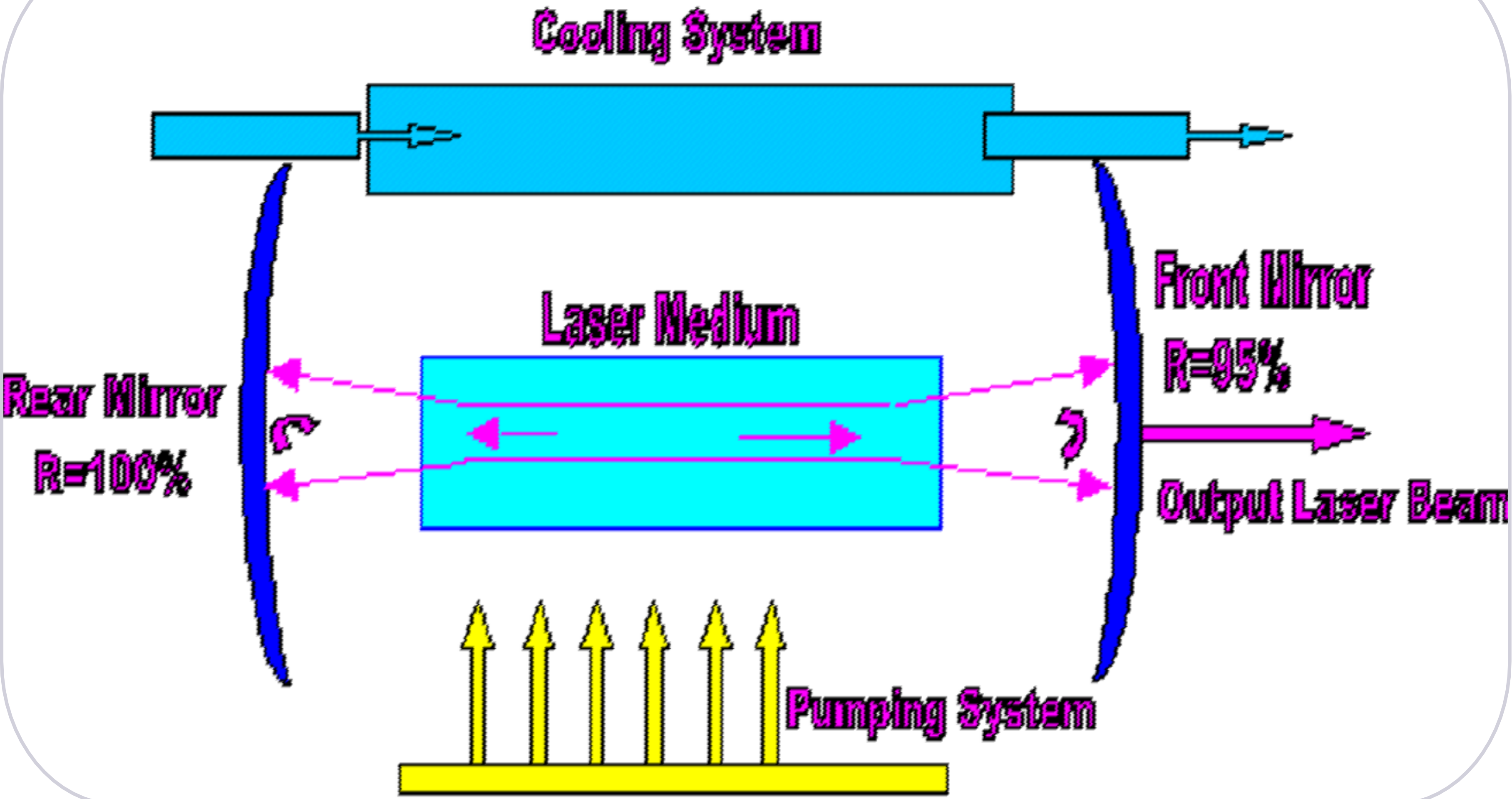
Laser System

1. An Active medium, with a suitable set of energy levels to support laser action. For example, in Ruby laser, Cr^{3+} ions are the active laser particles.

2. Energy source, (Source of Pumping) in order to establish population inversion.

3. An Optical Cavity or Resonator to introduce optical feedback and so maintain the gain of the system overcoming all losses. Depending on the type of the system, optical feedback is provided with the help of dielectric mirrors or polished and coated ends of a crystal rod or cleaved crystal face.

An Optical Cavity or Optical Resonator



Einstein coefficients:

Relation between Einstein coefficients (B_{12}, A_{12} & B_{21}):

Upward transition (Stimulated absorption):

Stimulated absorption rate depends upon the number of atoms available in the lowest energy state as well as the energy density of photons.

$$\text{Stimulated absorption rate } \alpha.\rho(\upsilon)$$

$$\text{Stimulated absorption rate } \alpha.N_1$$

$$\text{Stimulated absorption rate} = B_{12}\rho(\upsilon)N_1 \ldots\ldots\ldots\ldots(1)$$

Where B_{12} is the Einstein coefficient of stimulated absorption.

Downward transition (Emission):

Spontaneous emission: The atom in the excited state returns to ground state emitting a photon of energy (E) = E2 – E1 =hv, spontaneously known as spontaneous emission. The spontaneous emission rate depends up on the number of atoms present in the excited state.

$$\text{Spontaneous emission rate } \alpha.N_2$$

$$\text{Spontaneous emission rate} = A_{21}N_2 \ldots\ldots\ldots\ldots(2)$$

Where A_{21} is the Einstein coefficient of spontaneous emission.

Stimulated emission: The atom in the excited state can also returns to the ground state by applying external energy, thereby emitting two photons which are having same energy as that of incident photon. This process is called as stimulated emission. Stimulated emission rate depends upon the number of atoms available in the excited state as well as the energy density of incident photons.

$$\text{Stimulated emission rate } \alpha N_2$$

$$\text{Stimulated emission rate } \alpha . \rho(\upsilon)$$

$$\text{Stimulated emission rate } = B_{21}\rho(\upsilon)N_2 \ldots\ldots\ldots\ldots(3)$$

Where B_{21} is the Einstein coefficient of stimulated emission

At thermal equilibrium

Up ward transition = Down ward transition

$\therefore$ *Stimulated absorption = spontaneous emission + stimulated emission*

$$B_{12}\rho(\upsilon)N_1 = A_{21}N_2 + B_{21}\rho(\upsilon)N_2$$

$$(B_{12}N_1 - B_{21}N_2)\rho(\upsilon) = A_{21}N_2$$

Stimulated emission rate $= B_{21}\rho(\upsilon)N_2$..............(3)

Where B_{21} is the Einstein coefficient of stimulated emission

At thermal equilibrium

Up ward transition = Down ward transition

∴ Stimulated absorption = spontaneous emission + stimulated emission

$$B_{12}\rho(\upsilon)N_1 = A_{21}N_2 + B_{21}\rho(\upsilon)N_2$$

$$(B_{12}N_1 - B_{21}N_2)\rho(\upsilon) = A_{21}N_2$$

$$\rho(\upsilon) = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

$$\rho(\upsilon) = \frac{A_{21}N_2}{B_{21}N_2(\frac{B_{12}N_1}{B_{21}N_2} - 1)}$$

$$\rho(\upsilon) = \frac{A_{21}}{B_{21}(\frac{B_{12}N_1}{B_{21}N_2} - 1)}$$

According to Boltzman distribution law

$$N_1 = N_0 e^{-E_1/kT}$$

$$N_2 = N_0 e^{-E_2/kT}$$

$$\frac{N_1}{N_2} = e^{E_2 - E_1/KT} = e^{\frac{h\upsilon}{KT}}$$

$$\therefore \rho(\upsilon) = \frac{A_{21}}{B_{21}(\frac{B_{12}}{B_{21}} e^{\frac{h\upsilon}{KT}} - 1)} \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

According to the plank energy distribution law

$$\rho(\upsilon) = \frac{8\pi h\upsilon^3}{c^3(e^{\frac{h\upsilon}{KT}} - 1)} \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

On comparing Eq (4) *and* (5)

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\upsilon^3}{c^3} \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Nd: YAG laser

Nd: YAG laser is a neodymium based laser. Nd stands for Neodymium (rare earth element) and YAG stands for Yttrium Aluminum Garnet (Y_3Al_5 O_{12}) . It is a four level solid state laser.

Principle: The active medium Nd: YAG rod is optically pumped by Krypton flash tubes. The Neodymium ions (Nd3+) are raised to excited levels. During the transition from meta stable state to ground state, a laser beam of wavelength 1.064µm is emitted.

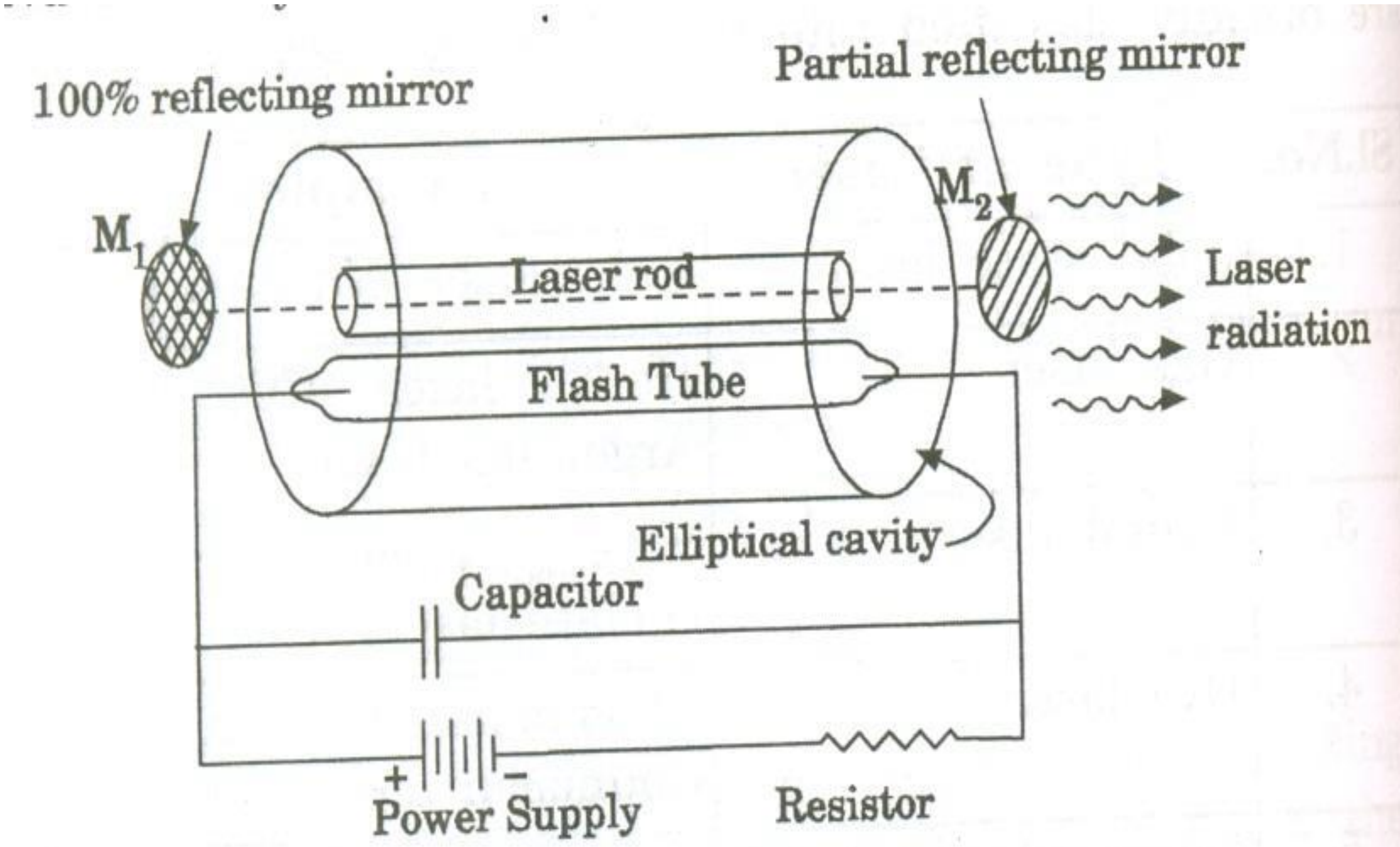
Construction: The construction of Nd: YAG laser is as shown in the figure. A small amount of Yttrium ions (Y^{3+}) is replaced by Neodymium (Nd^{3+}) in the active element of Nd: YAG crystal.

Nd:YAG Laser

Construction:

- This active element is cut into a cylindrical rod. The ends of the cylindrical rod are highly polished and they are made optically flat and parallel.
- This cylindrical rod (laser rod) and a pumping source (flash tube) are placed inside a highly (reflecting) elliptical reflector cavity.
- The optical resonator is formed by using two external reflecting mirrors. One mirror (M1) is 100% reflecting while the other mirror (M2) is partially reflecting.
- **Working:** Figure shows the energy level diagram for Nd: YAG laser. These energy levels are those of Neodymium (Nd^{3+}) ions.

Nd:YAG Laser


100% reflecting mirror
Partial reflecting mirror
M_1
M_2
Laser rod
Flash Tube
Laser
radiation
Elliptical cavity
Capacitor
+
–
Power Supply
Resistor

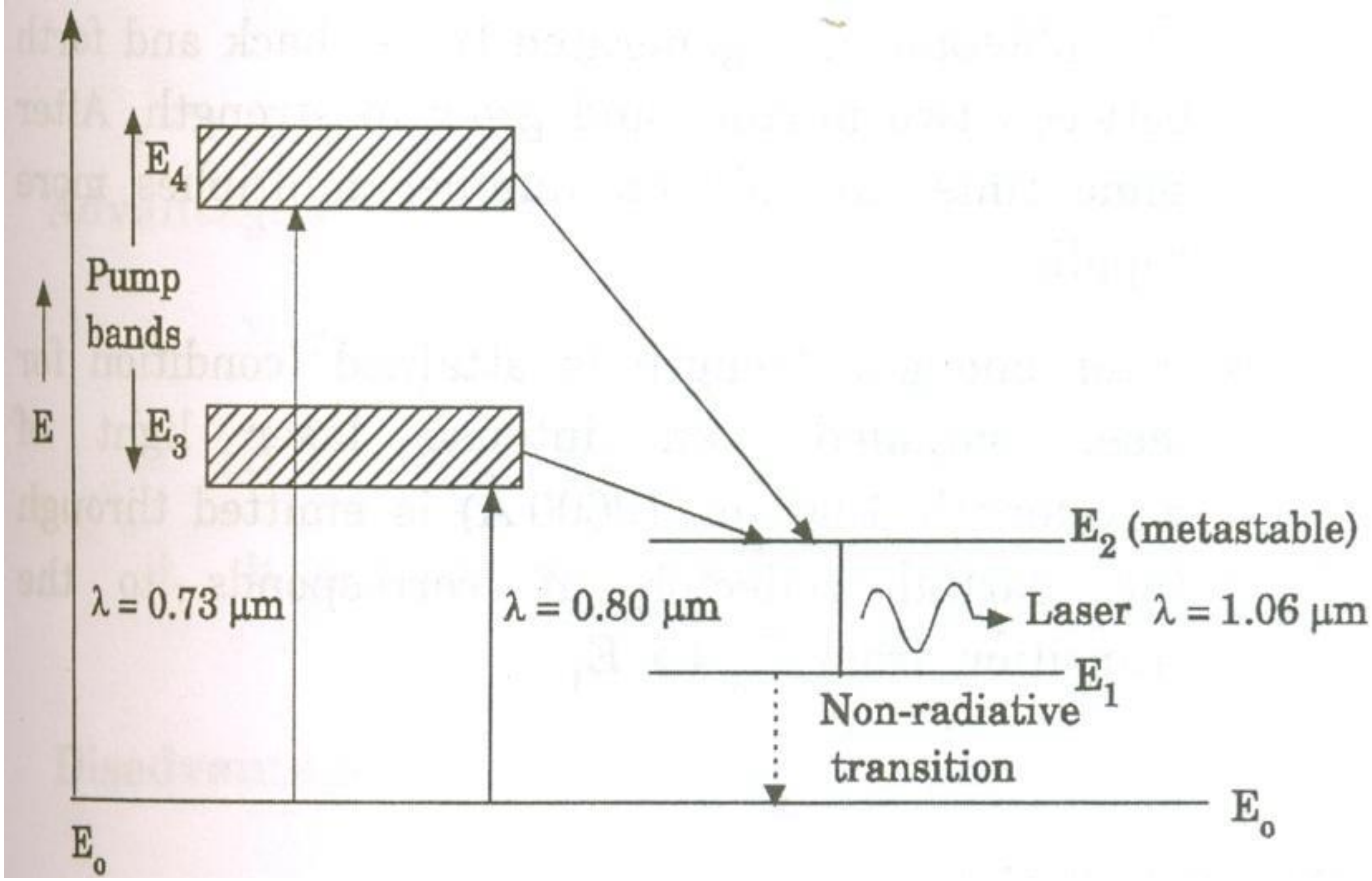
NDYAG - Laser

- 1. When the krypton flash lamp is switched on, by the absorption of light radiation of wavelength 0.73µm and 0.8µm, the Neodymium(Nd^{3+}) atoms are raised from ground level E0 to upper levels E3 and E4 (Pump bands).

- 2. The Neodymium ions atoms make a transition from these energy levels E2 by non-radiative transition. E2 is a metastable state.

- 3. The Neodymium ions are collected in the level E2 and the population inversion is achieved between E2 and E1.

- 4. An ion makes a spontaneous transition from E2 to E1, emitting a photon of energy hγ. This emitted photon will trigger a chain of stimulated photons between E2 and E1.



5. The photons thus generated travel back and forth between two mirrors and grow in strength. After some time, the photon number multiplies more rapidly.

6. After enough strength is attained (condition for laser being satisfied), an intense laser light of wavelength 1.06µm is emitted through the partial reflector. It corresponds to the transition from E2 to E1.

Characteristics:

1. **Type:** It is a four level solid state laser.
2. **Active medium**: The active medium is Nd: YAG laser.
3. **Pumping method:** Optical pumping is employed for pumping action.
4. **Pumping source**: Xenon or Krypton flash tube is used as pumping source.
5. **Optical resonator:** Two ends of Nd: YAG rod is polished with silver (one end is fully silvered and the other is partially silvered) are used as optical resonator.
6. **Power output:** The power output is approximately 70 watt.
7. **Nature of output:** The nature of output is pulsed or continuous beam of light.
8. **Wavelength of the output**: The wavelength of the output beam is 1.06μm(infra-red)

Advantages: Advantages: 1. It has high energy output. 2. It has very high repetition rate operation 3. easy to achieve population inversion.

Disadvantages: The electron energy level structure of Nd3+ in YAG is complicated.

Nd-YAG Laser - Applications

1. It finds many applications in range finders and illuminators.

2. It is widely used in engineering applications such as resistor, trimming scribing, micro machining operations as well as welding, drilling etc.

3. It finds many medical applications such as endoscopy, urology,

neurosurgery, ENT, gynecology, dermatology, dental surgery and general surgery.

Helium-Neon(He-ne)laser

- The best-known and most widely used He-Ne laser operates at a wavelength of 632.8 nm in the red part of the visible spectrum.
- It was developed at Bell Telephone Laboratories in 1962.
- Helium-Neon is a gas laser.
- It is a continuous four level laser.
- Active medium: Helium and Neon gases in the ratio of 10:1 respectively. Ne atoms are responsible for lasing action.
- Energy Source: Two electrodes are fixed near the ends of the tube to pass electric discharge through the gas.

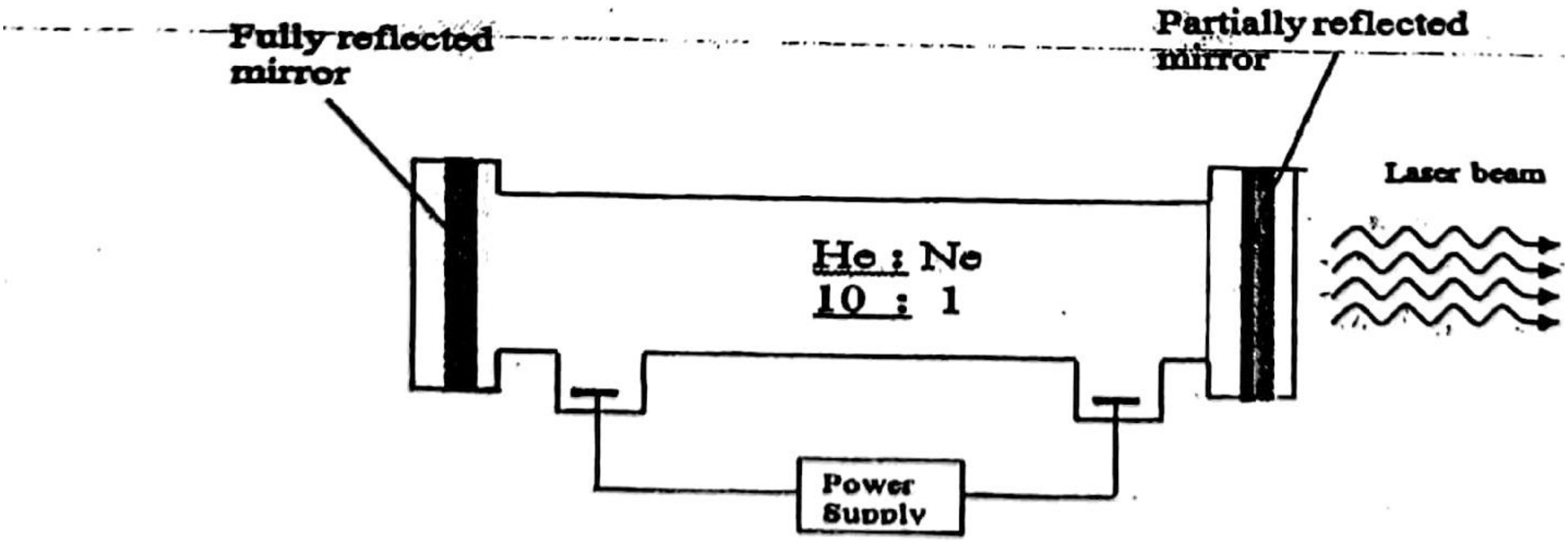
Helium-Neon(He-ne)laser

Construction:

- He-Ne laser consists of a long, narrow cylindrical tube made up of fused quartz, of diameter around 2 to 8 mm and length around 10 to 100 cm.
- The tube is filled with helium and neon gases in the ratio of 10:1. The pressure of the mixture of gases inside the tube is nearly 1 mm of Hg.
- Two electrodes are fixed near the ends of the tube to pass electric discharge through the gas.
- Two optically plane mirrors are fixed at the two ends of the tube.
- One of the mirrors is fully silvered so that nearly 100% reflection takes place and the other is partially silvered, so that 1% of the light incident on it will be transmitted.

He - Ne laser:

He-Ne laser was the first gas laser fabricated by Ali Javan and others in 1961.



1. Active medium: mixture of He and Ne in the ratio 10:1
2. Active centers: Ne atoms
3. Pumping method: Electrical pumping
4. Exciting Source: Electric discharge
5. Resonating Cavity: Partially & fully reflecting Mirrors
6. Power output: 0.5-50 mW
7. Nature of output: Continuous waveform
8. Wavelength of laser: 6328 Å.

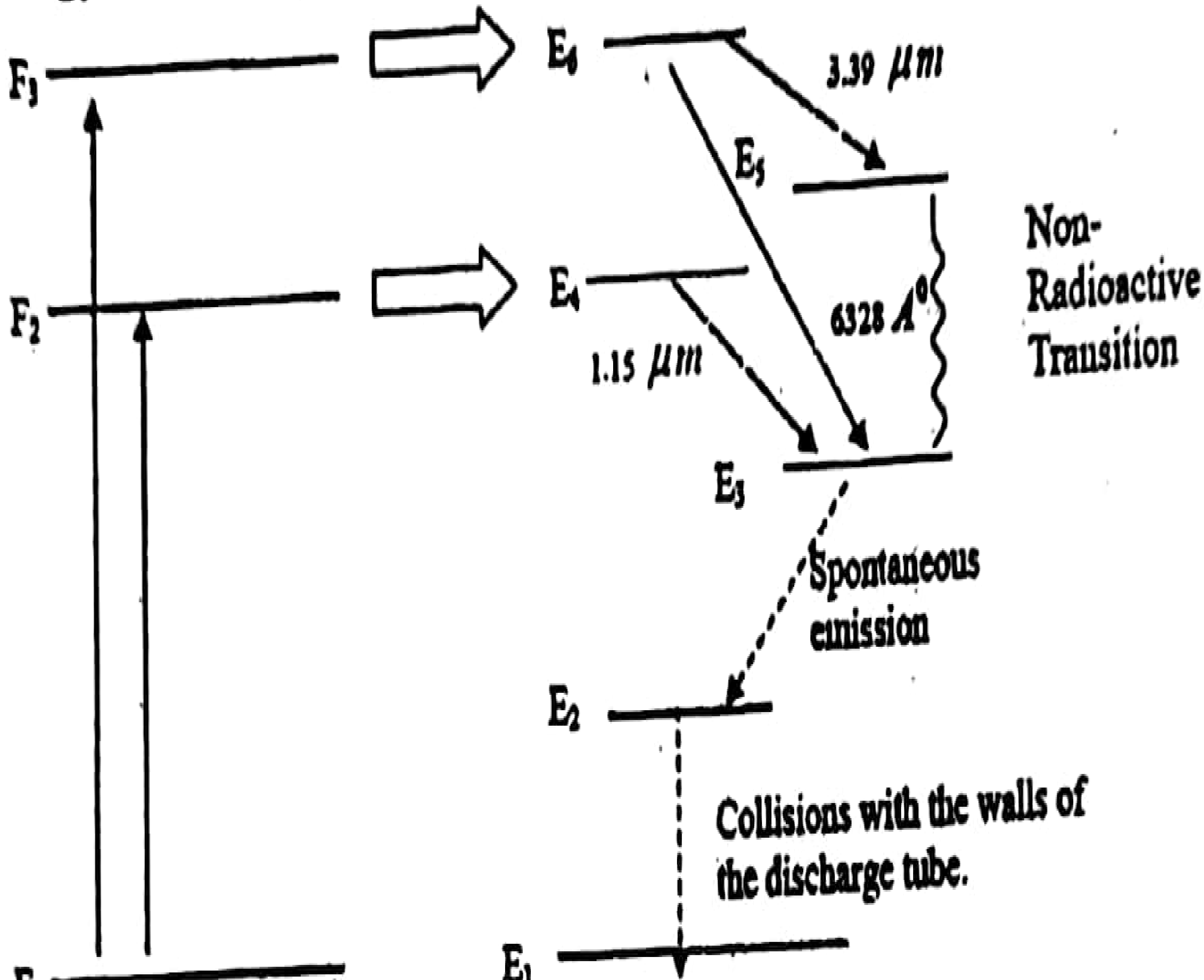
Helium-Neon(He-ne)laser

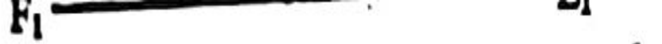
Construction:

In He-Ne gas laser, He and Ne gases are taken in the ratio 10:1 in the gas discharge tube of length 80 cm and diameter 1 cm made up of quartz. Two reflecting mirrors are fixed on either ends of the discharge tube, in that, one is partially reflecting and the other is fully reflecting which serve as optical cavity or resonator. The out power of these lasers depends on the length of the discharge tube and pressure of the gas mixture.

When the two windows are set at Brewster's angle, the output laser is linearly polarized.

Working (Energy level diagram):





When the electric discharge passed through the gas mixture, accelerated electrons collide with He atoms and excite them to higher levels F_2 and F_3. These states are metastable states, so the He atoms stay longer time in these states. During this time He atoms collide with Ne atoms in the ground level E_1 and exchange energy through collisions. This results in the excitation of Ne atoms to the levels E_4 and E_6 and de-excitation of He atoms to ground state F_1.

Due to the continuous excitation of Ne atoms, population inversion is achieved between the higher levels E_4 (E_6) and lower levels E_3 (E_5). The transitions $E_6 \rightarrow E_5$: λ=3.39 μm and $E4 \rightarrow E_3$: λ = 1.15 μm corresponds to IR region. The transition $E_6 \rightarrow E_3$ corresponds to visible red light λ= 6328 Å. The Ne atoms present in the E_3 level are de-excited into E_2 level, by spontaneously emitting a photon of wavelength 6000 Å. When a narrow discharge tube is used, the Ne atoms present in the level E_2 collide with the walls of the tube and get de-excited to ground level E_1. The excitation and de-excitation of He and Ne atoms is a continuous process and thus it gives continuous laser radiations.

Advantages:

1. He-Ne laser emits continuous laser radiation.
2. Due to the setting of end windows at Brewster's angle, the output laser is linearly polarized.
3. Gas lasers are more monochromatic and directional when compared with the solid state laser.

Applications: He-Ne laser is applied in the following fields,

1. Interferometry
2. Laser printing
3. Bar-code reading
4. In metrology in surveying, alignment etc.,
5. In three dimensional recording of objects called holography.

Applications of Lasers

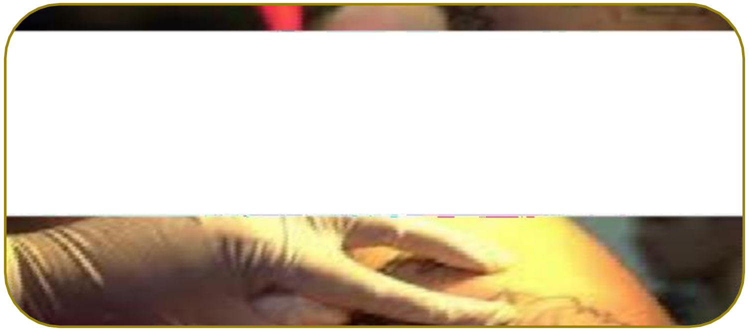
Lasers in medicine:

Lasers are used in eye surgery, especially to attach the detached retina.

❖Lasers are used for treatments such as plastic surgery, skin injuries and to remove moles, tattoos and tumours developed in skin tissue.

❖Lasers are used in stomatology- the study of mouth and its

Lasers in Eye surgery



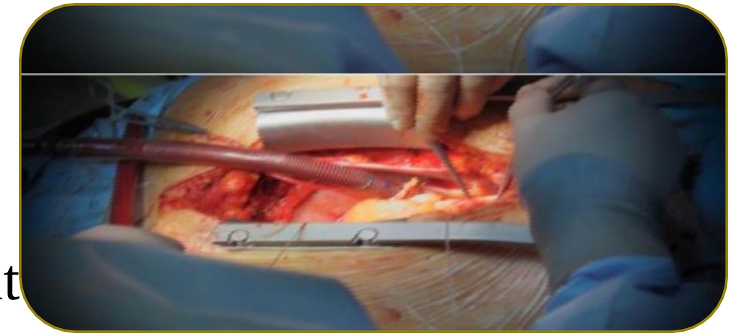
Lasers in tattoo removal

Lasers used in stomatology

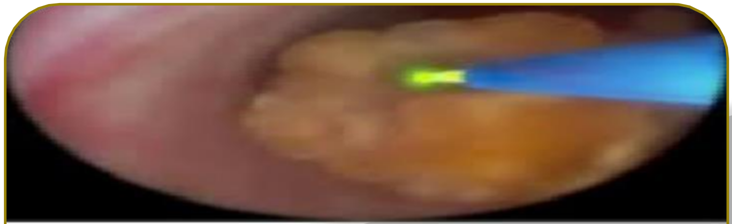
Applications of Lasers

- Laser radiation is sent through optical fibre to open the blocked artery region.
- Lasers are used to destroy kidney stones and gall stones.
- Lasers are used in cancer diagnosis and therapy
- Lasers are used in blood loss less surgery.
- Lasers are used to control hemorrhage.
- Using CO_2 laser, liver and lung treatment can be carried out.
- Lasers are used in endoscopes, to detect hidden parts.
- Laser Doppler velocimetry is used to measure the velocity of blood in blood vessels.

Red Argon laser used in throat cancer treatment



Lasers used to open artery block



Lasers used to destroy kidney stones

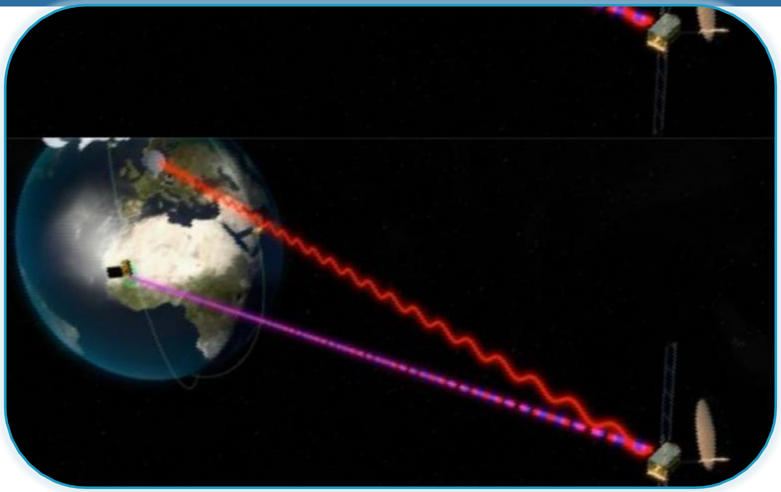
Applications of Lasers

Lasers in Communication:

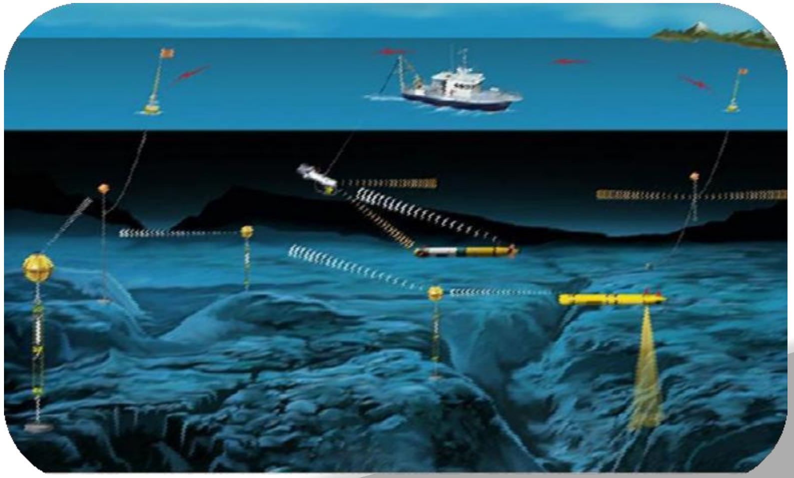
Lasers are used in Optical fibre communication as light source to transmit audio, video signals and data to long distances without attenuation and distortion.

Laser beam can be used for the communication between the earth and the moon or to other satellites.

Laser beam can be used for under water communication, as laser radiation is not absorbed by water.



Lasers in Satellite communication



Lasers in under water communication

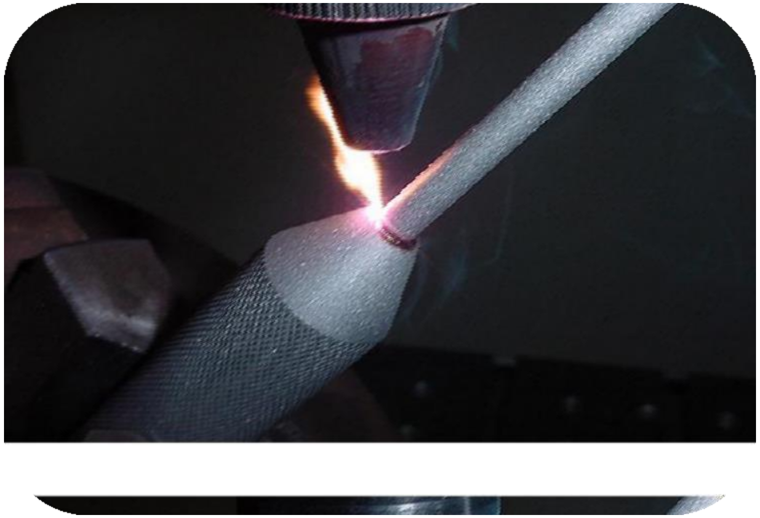
Applications of Lasers

Lasers in Industry:

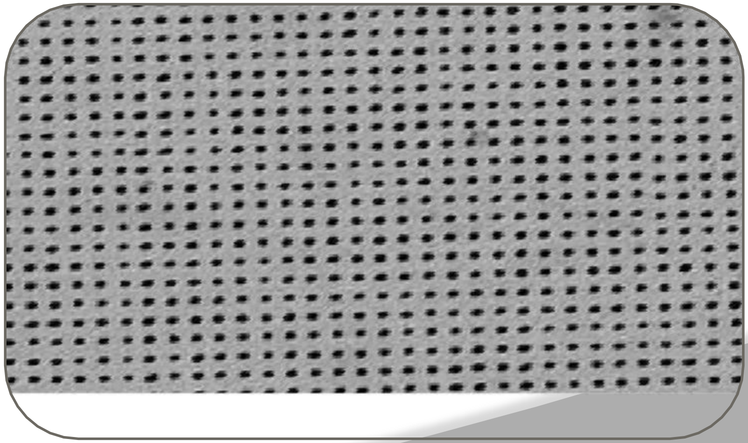
Lasers are used for welding. Dissimilar metals can be welded using lasers.

Holes with controlled precision can be drilled in steel, ceramics, diamond and alloys, using lasers.

Lasers are widely used in electronic industry in trimming the components of ICs.



Lasers used in welding



Drilling Steel foil for high density filters

Applications of Lasers

- Lasers are used in cutting metal sheets, diamond and cloths. In the mass production of stitched clothes, lasers are used to cut the cloth in a desired dimension, all at once.
- Lasers are used for surface treatment. Laser beam is used in selective heat treatment for tempering the desired parts in automobile industry.

Cutting wood using laser

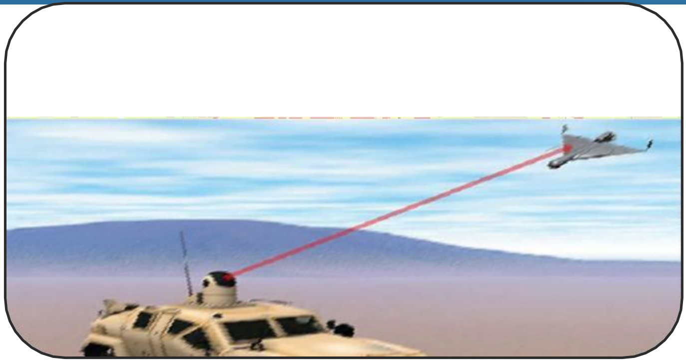
Laser surface treatment to change the micro structure of metals through controlled heating and cooling.

The world's first all-diamond ring, cut with Laser

Applications of Lasers

Lasers in Military:

- Focusing of high energetic laser beam for few seconds, destroys aircrafts, missiles, etc. These rays are called death rays.
- The vital part of the enemy’s body can be evaporated by focusing a highly convergent laser beam from a laser gun.
- LIDAR (Light Detecting And Ranging) is used to estimate the size and shape of distant objects or war weapons.



Laser armed Humvees shooting a Drone

Soldiers using laser gun

Lasers beams of RMR LIDAR at ALOMAR Observatory

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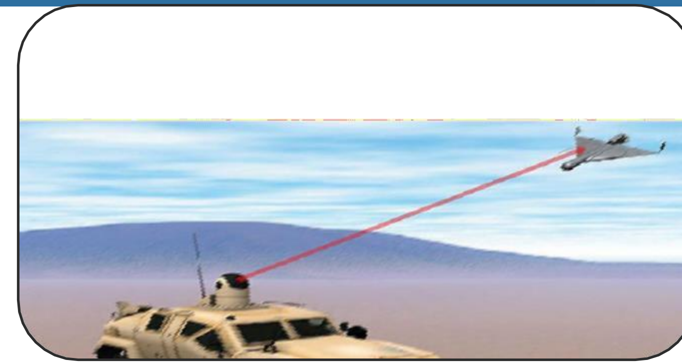

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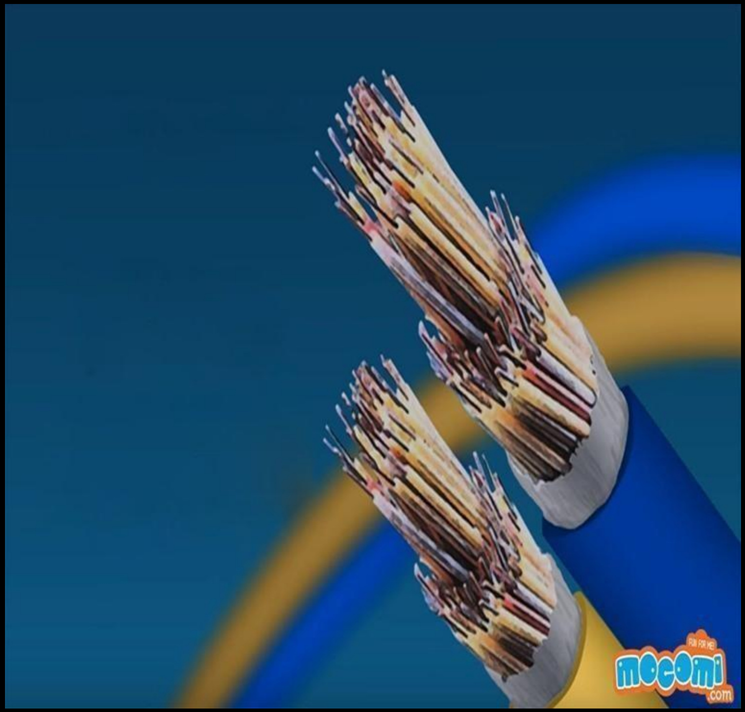
FIBER OPTICS

Optical fibers are widely used in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidths(data rates) than wire cables.

Fibers are used instead of metal wires because signals travel along them with less loss and are also immune to electromagnetic interference.

Fibers are also used for illumination, and are wrapped in bundles so that they may be used to carry images.



Fibre Optic cable

Structure of an Optical Fibre

Structure of an optical fiber consists of three parts.

The core, the cladding and the coating (or buffer or outer jacket).

The core:

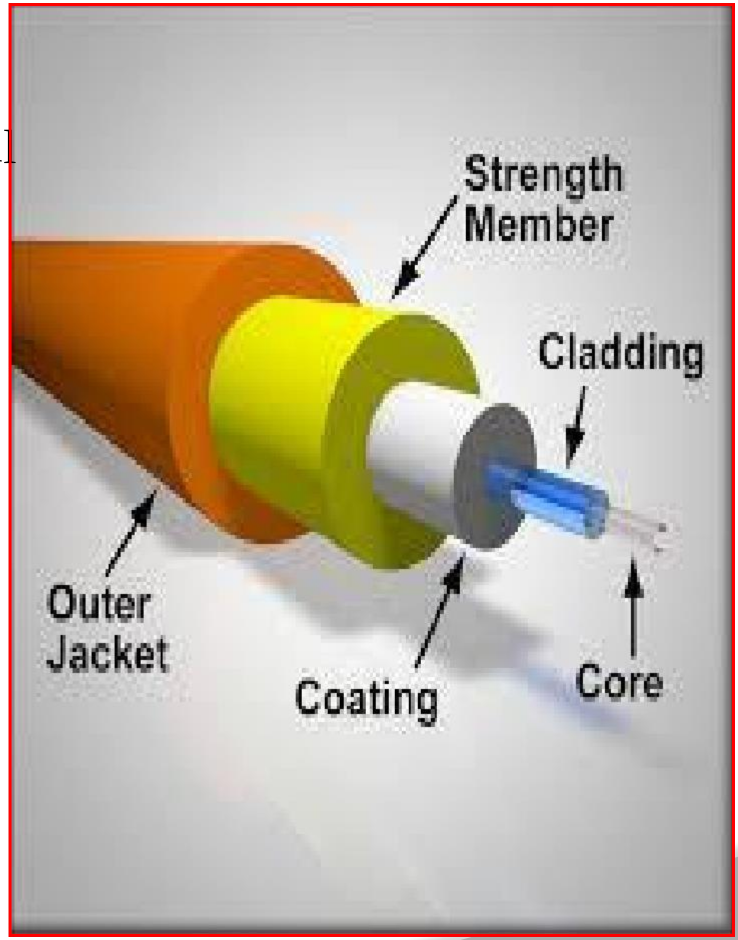
- The core is a cylindrical rod of dielectric material.
- Light propagates mainly along the core of the fiber.
- The core is generally made of glass.
- The core is described as having an index of refraction n_1.

The Cladding:

- The core is surrounded by a layer of material called the cladding, which is generally made of glass or plastic.
- The cladding layer is made of a dielectric material with an index of refraction n_2.
- The index of refraction of the cladding material is less than that of the core material.

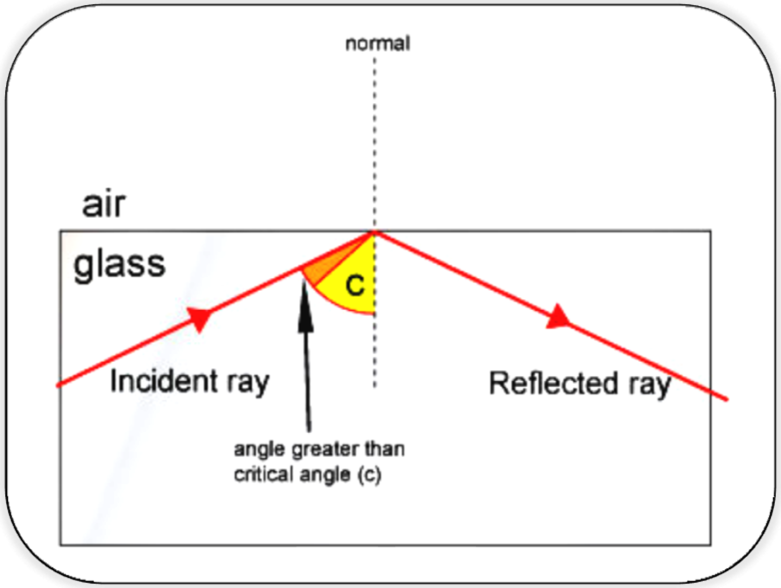
Buffer:

- The coating or buffer is a layer of material used to protect an optical fiber from physical damage.
- The material used for a buffer is a type of plastic.



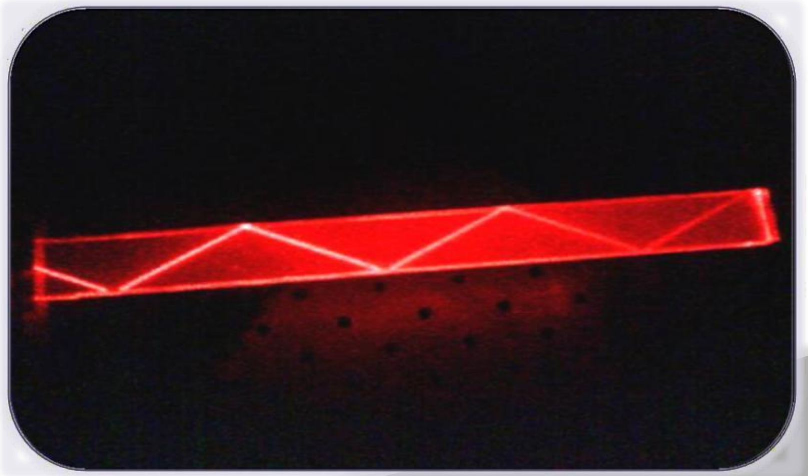
Principle of Optical Fibre

- Optical fibre carries light from one end of the fibre to the other by total internal reflection.
- When a ray of light passes from an optically denser medium into an optically rarer medium, the refracted ray bends away from the normal.



Total internal reflection: When a light ray, travelling from an optically denser medium into an optically rarer medium, is incident at an angle greater than the critical angle, then the ray is totally reflected back into the same the laws of medium by obeying reflection. This phonomenon is known as total internal reflection.

Total Internal Reflection



Internally reflected light ray

Condition for Total Internal Reflection

Let the reflective indices of core and cladding materials be n_1 and n_2 respectively.

According to the law of refraction,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Here, $\theta_1 = \theta_c$ and $\theta_2 = 90$

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

$$\sin\theta_c = {}^{n_2}/n_1$$

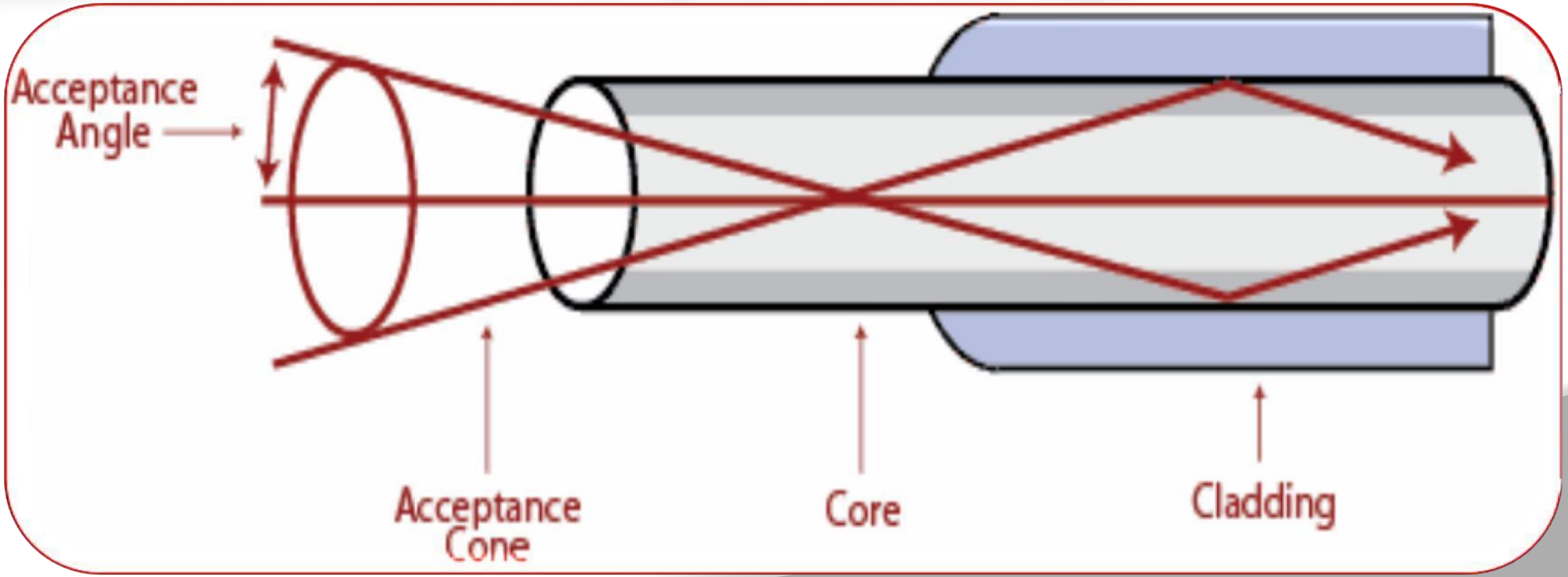
$$\theta c = \sin^{-1}({}^{n_2}/n_1) \qquad \rightarrow (1)$$

Equation (1) is the expression for condition for total internalreflection.

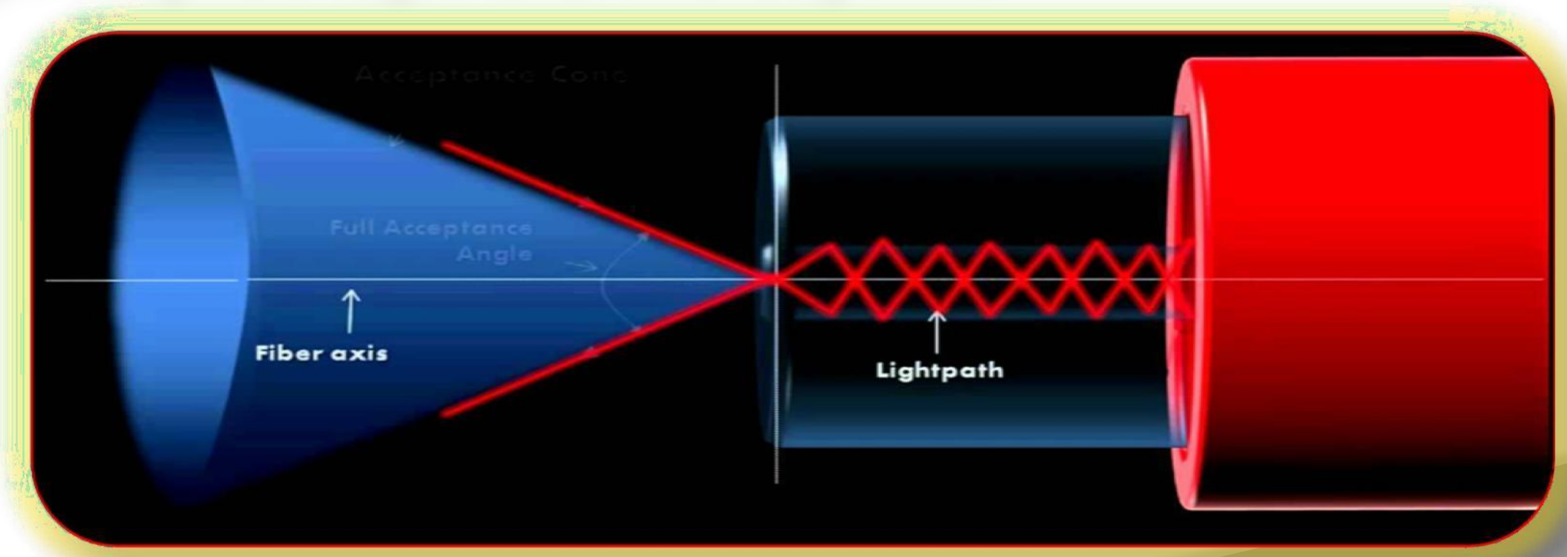
In case of total internal reflection, there is absolutely no absorption of light energy at the reflecting surface.

Acceptance angle and Acceptance cone

- Acceptance angle is the angle at which the beam has to be launched at one of its ends, in order to enable the entire light to propagate through the core.
- The acceptance angle is the maximum angle that a light ray can have with the axis of the fiber to propagate through the fiber.
- **Acceptance angle:** It is defined as the maximum angle of incidence at the end face of the optical fibre, for which the ray can be propagated through the core material. It is also called as Acceptance cone half angle.



- **Acceptance cone:** **The cone obtained by rotating a ray at the end face of an optical fibre, around the fibre axis with the acceptance angle, is known as acceptance cone.**
- **Light launched at the fiber end within this acceptance cone alone will be accepted and propagated to the other end of the fiber by total internal reflection.**
- **Larger acceptance angles make launching easier.**



Acceptance cone

Equation for Acceptance angle

- For light rays to propagate through the optical fibre, by total internal reflection, they must be incident on the fibre core within the angle θ_o , called the acceptance angle.
- Applying Snell's law at B,

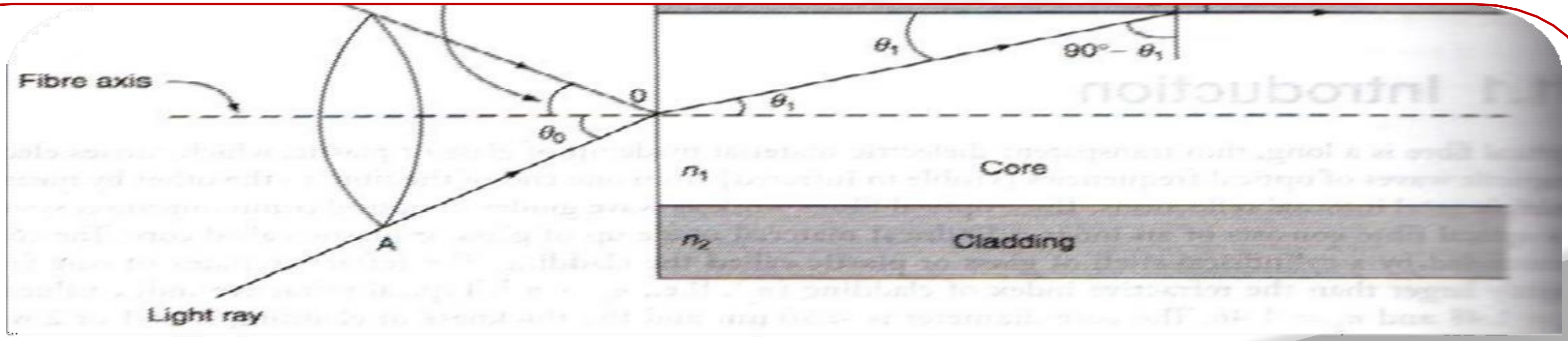
$$n_1 \sin(90^o-\theta_1) = n_2 \sin 90^o$$

$$n_1 \cos \theta_1 = n_2$$

$$\cos \theta_1 = n_2/n_1$$

$$\text{or } \sin\theta_1 = (1-\cos^2\theta_1)^{1/2}$$

$$=\{1-(n_2^2/n_1^2)\}^{1/2} \text{ …….. (1)}$$



Applying Snell's law at O,

$$n_o \sin\theta_0 = n_1 \sin\theta_1$$

$$\text{or } \sin\theta_0 = (n_1/n_0) \sin\theta_1 \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Substituting eq. (1) in eq. (2),

$$\sin\theta_0 = (n_1/n_0)(1 - n_2^2/n_1^2)^{1/2}$$

$$= \frac{(n_1^2 - n_2^2)^{1/2}}{n_0} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

As the fibre is in air, $n_0 = 1$

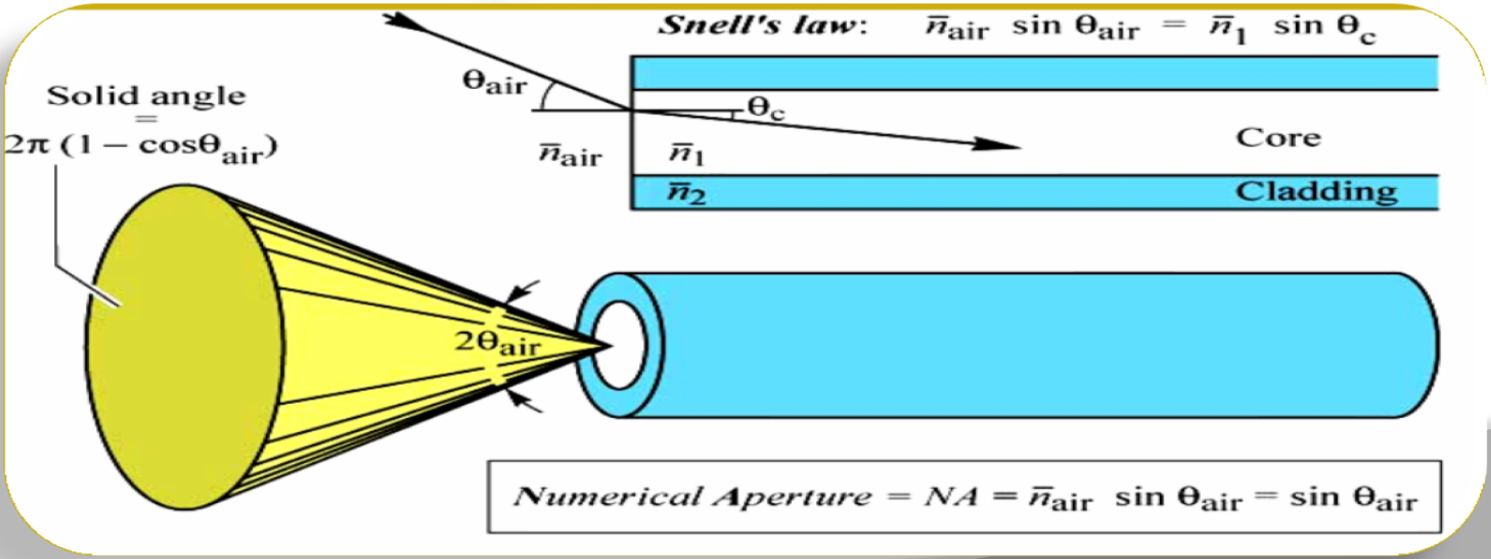
Therefore, eq. (3) becomes

$$\sin\theta_0 = (n_1^2 - n_2^2)^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Eq. (4) is the equation for Acceptance angle.

Numerical Aperture (NA)

- Light gathering capacity of the fiber is expressed in terms of maximum acceptance angle and is termed as "Numerical Aperture".
  - Light gathering capacity is proportional to the acceptance angle θ_o.
- So, numerical aperture can be represented by the sine of the acceptance angle of the fibre i.e., sin θ_o.
- For example, the light acceptance angle in air is $\theta_{air} = 11.5^o$ for a numerical aperture of NA=0.2.



Expression for Numerical aperture:

According to the definition of Numerical aperture (NA),

$$NA = \sin\theta_0 = (n_1^2 - n_2^2)^{1/2} \quad \rightarrow (1)$$

Let „Δ‟ the fractional change in the refractive index, be the ratio between the difference in the refractive indices of core and cladding material respectively.

$$\text{i.e., } \Delta = \frac{n_1 - n_2}{n_1} \quad \rightarrow (2)$$

$$\text{or } \Delta n_1 = n_1 - n_2 \quad \rightarrow (3)$$

Eq. (1) can be written as,

$$NA = (n_1^2 - n_2^2)^{1/2}$$

$$= \{(n_1 - n_2)(n_1 + n_2)\}^{1/2} \quad \rightarrow (4)$$

Substituting eq. (3) in eq. (4),

$$NA = \{(\Delta n_1)(n_1 + n_2)\}^{1/2}$$

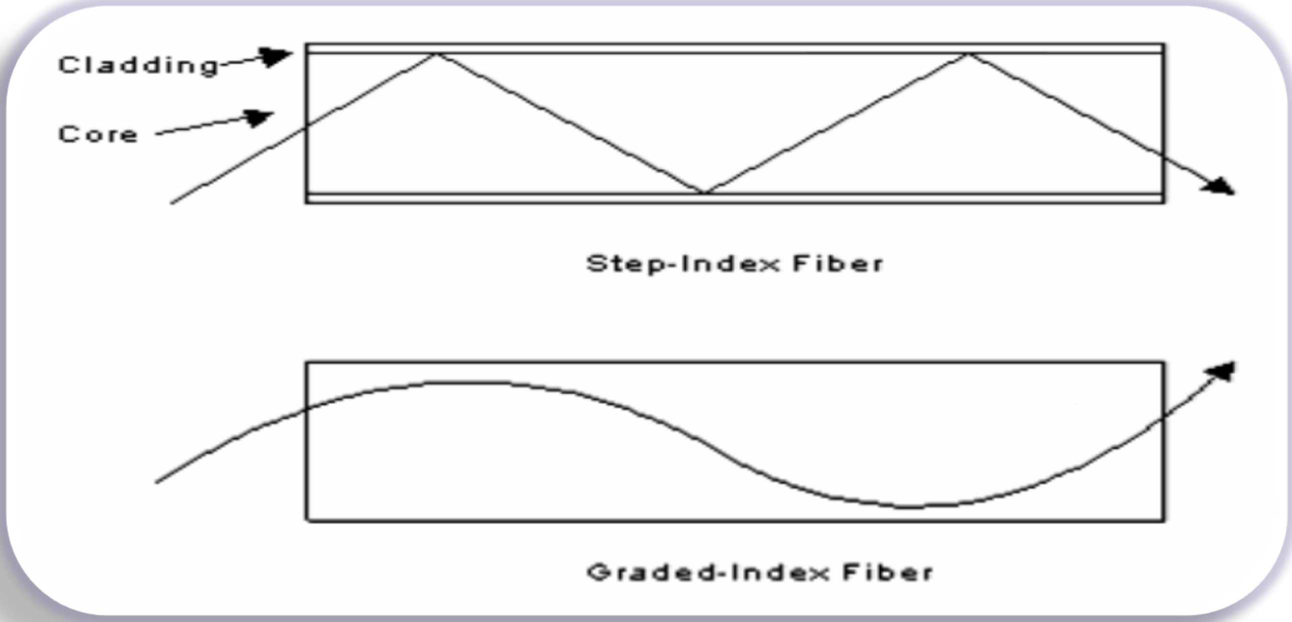
As $n_1 \approx n_2$, $n_1 + n_2 = 2n_1$

And therefore, Numerical Aperture $= (2n_1^2\Delta)^{1/2} = n_1(2\Delta)^{1/2}$ $\rightarrow (5)$

From equation (5) it is seen that numerical aperture depends only on the refractive indices of core and cladding materials and it is independent on the fiber dimensions.

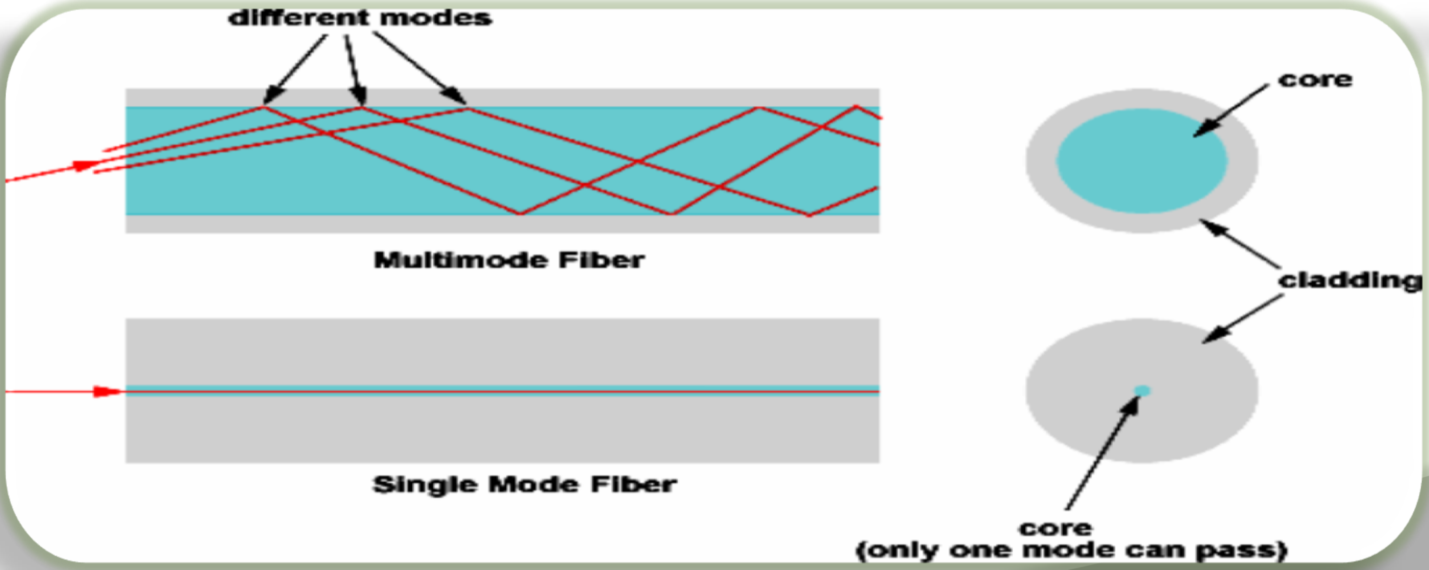
Types of Optical Fibres

- Based on the variation of refractive index of core, optical fibers are divided into: (1) step index and (2) graded index fibers.
- In all optical fibers, the refractive index of cladding material is uniform.



Light path through Step- index and Graded index Fibre

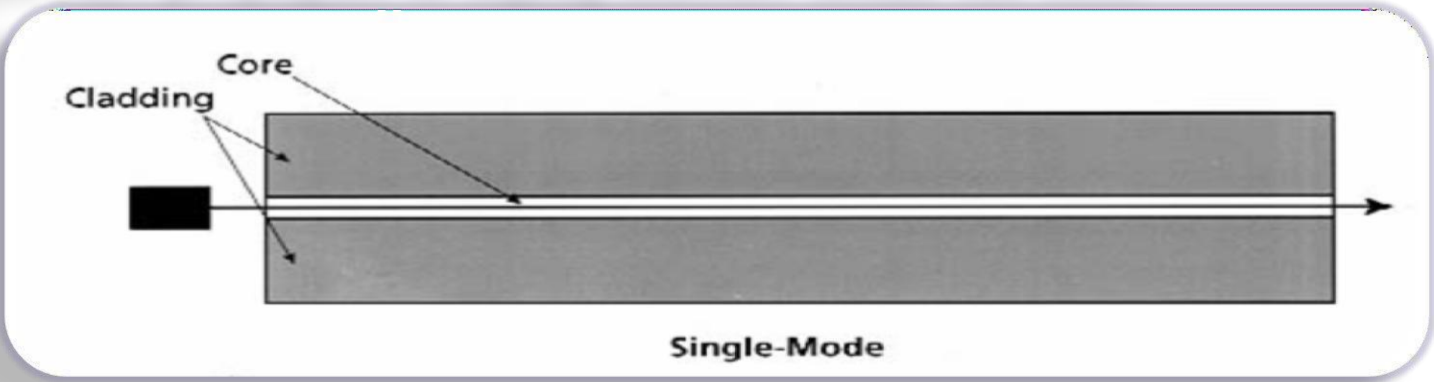
- Based on the mode of propagation, all the fibers are divided into: (1) single mode and (2) multimode fibers.
- Mode means, the number of paths available for light propagation in the fiber. If there is only one path for the ray propagation, it is called a single mode fiber. If the number of paths is more than one, then it is called a multi mode fiber.

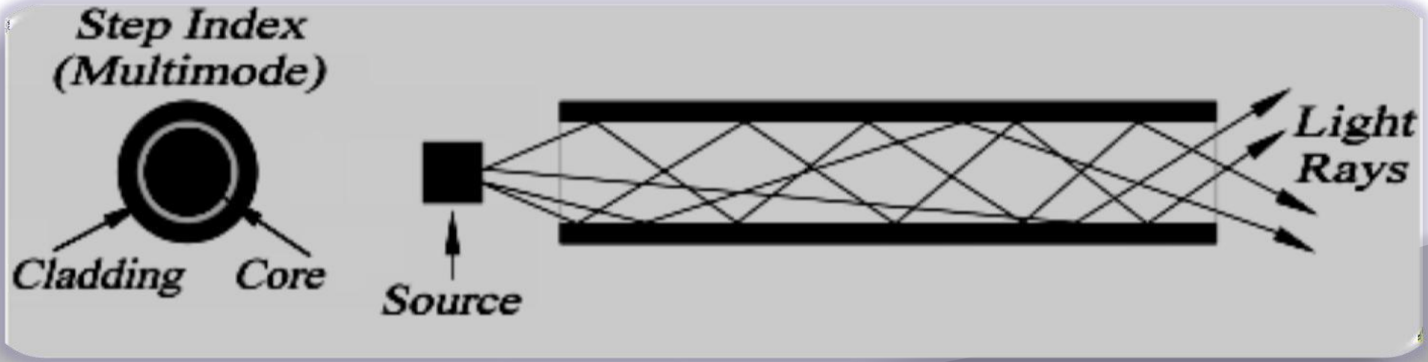


Single mode and Multi mode propagation of light

Step index optical fibre

- Based on the mode of propagation of light rays, step index fibers are of 2 types: a) single mode step index fiber & b) multimode step indexfibers.
- The light rays propagate in zigzag manner inside the core.

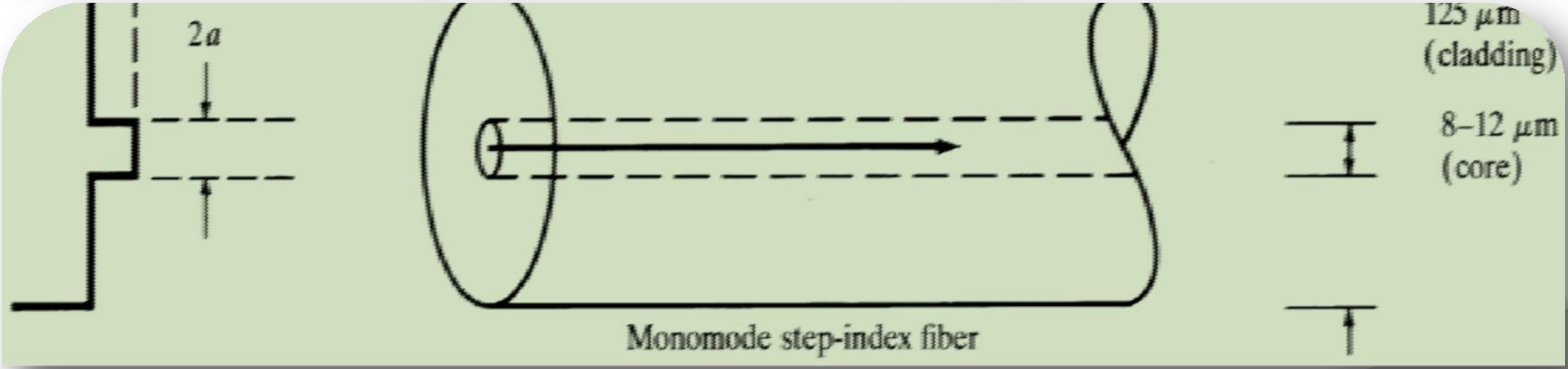




Multi mode Step index optical Fibre

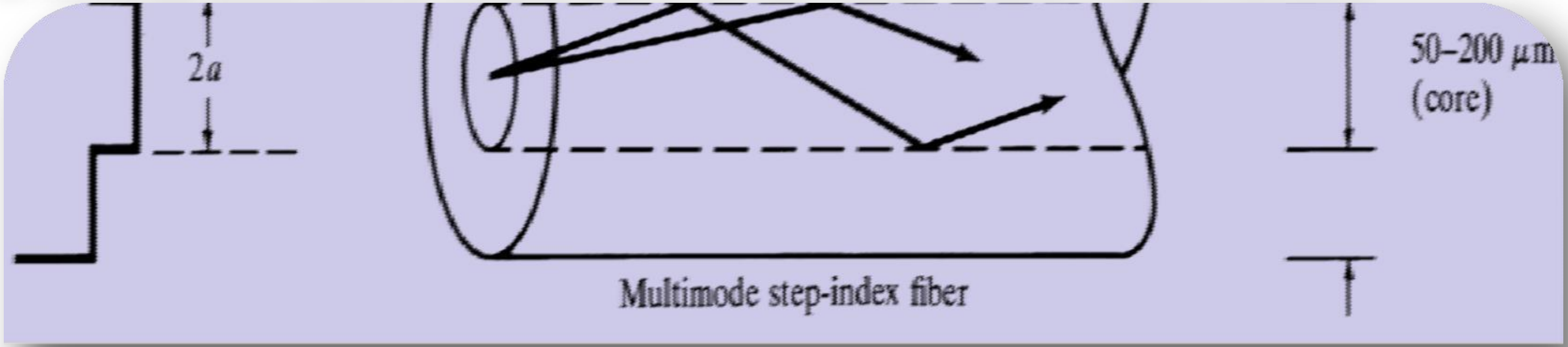
Refractive index profile in Single mode Step index fibre

- The refractive index is uniform throughout the core of this fibre.
- As we go radially in this fibre, the refractive index undergoes a step change at the core-cladding interface.
- The core diameter of this fibre is about 8 to 10 µm and outer diameter of cladding is 60 to 70 µm.
- In this fibre, the transmission of light is by successive total internal reflections i.e. it is a reflective type fiber.
- These fibres are mainly used in submarine cable system.



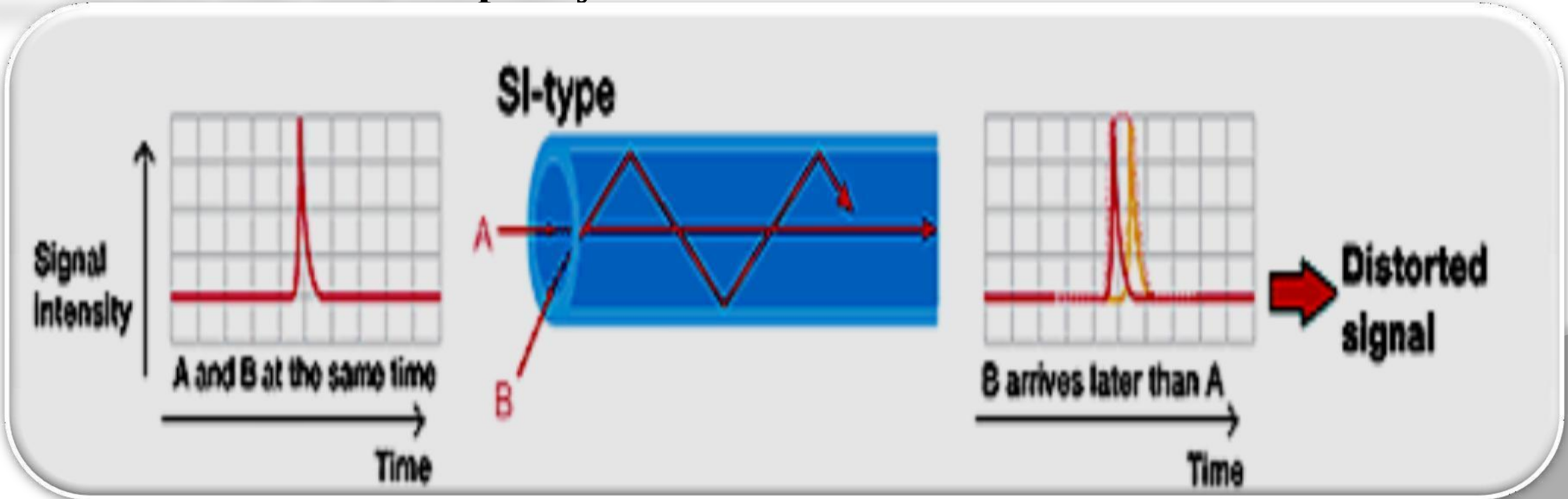
Refractive index profile in Multimode Step index fibre

- Its core and cladding diameters are much larger to have many paths for light propagation.
- The core diameter of this fiber varies from 50 to 200 μm and the outer diameter of cladding varies from 100 to 250 μm.
- Light propagation in this fiber is by multiple total internal reflections i.e., it is a reflective type fiber.
- It is used in data links, which have lower band width requirements.



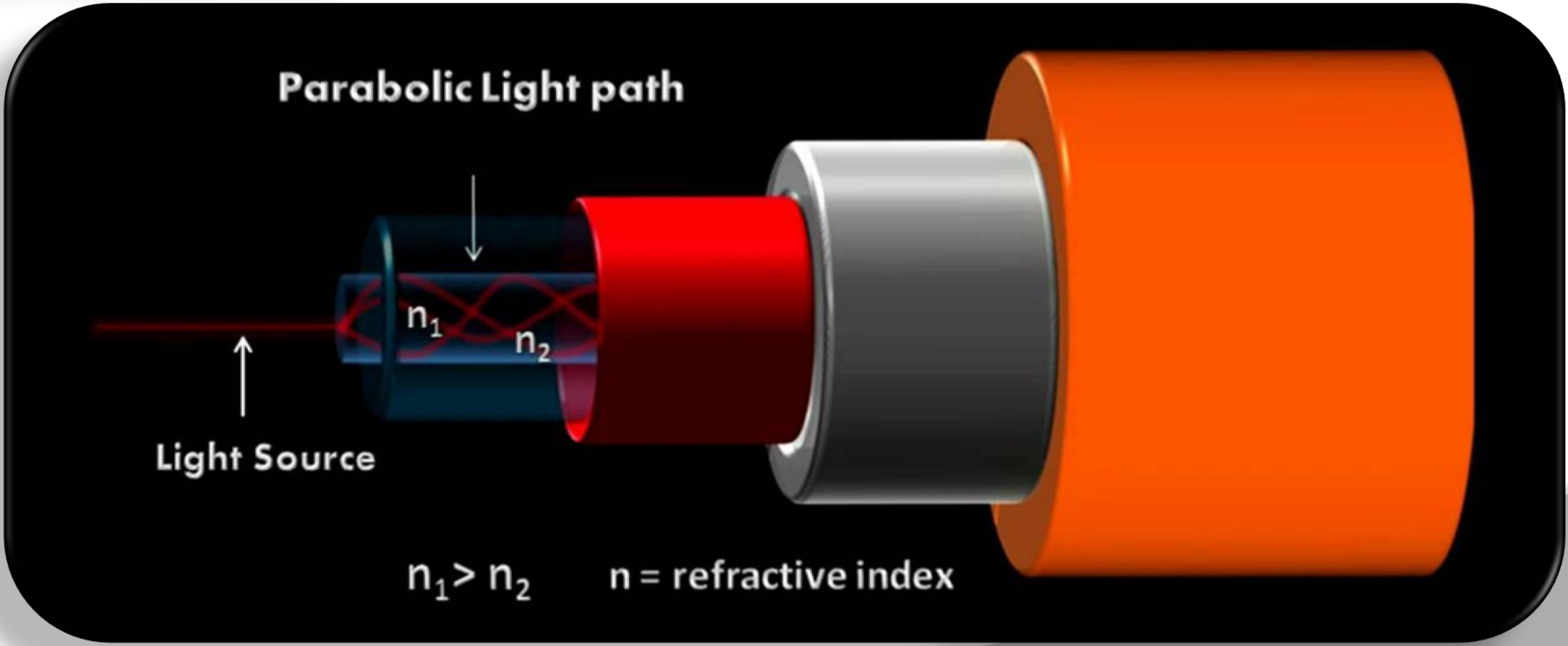
Transmission of signal in step index fibre

- Generally the signal is transmitted through the fiber in digital form i.e. in the form of 1"s and 0"s.
- In multimode fibre, the pulse which travels along path A (straight) will reach first at the other end of fiber. Next, the pulse that travels along with path B (zigzag) reaches the other end.
- Hence, the pulsed signal received at the other end is broadened. This is known as intermodal dispersion.
- This imposes limitation on the separation between pulses and reduces the transmission rate and capacity.



Graded index optical fibre

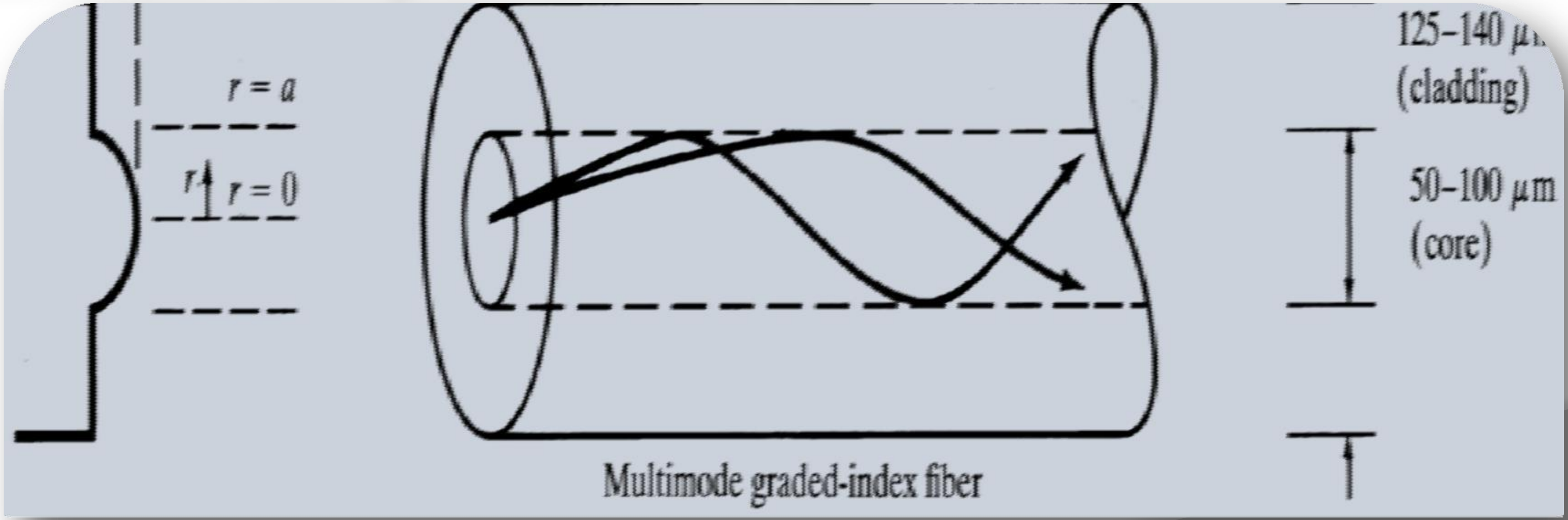
- To overcome the problem of inter modal dispersion caused due to step index optical fibres, graded index fibers are used.
- This fiber can be single mode or multimode fiber.
- Light rays propagate in the form of skew rays or helical rays. They will not cross the fiber axis.



Multimode Graded index optical fibre

Refractive index profile in Multimode graded index fibre

- In this fiber, the refractive index decreases continuously from center radially to the surface of the core.
- The refractive index is maximum at the center and minimum at the surface of core.
- The diameter of the core varies from 50 to 200µm and the outer diameter of the cladding varies from 100 to 250 µm.
- The refractive index profile is circularly symmetric.

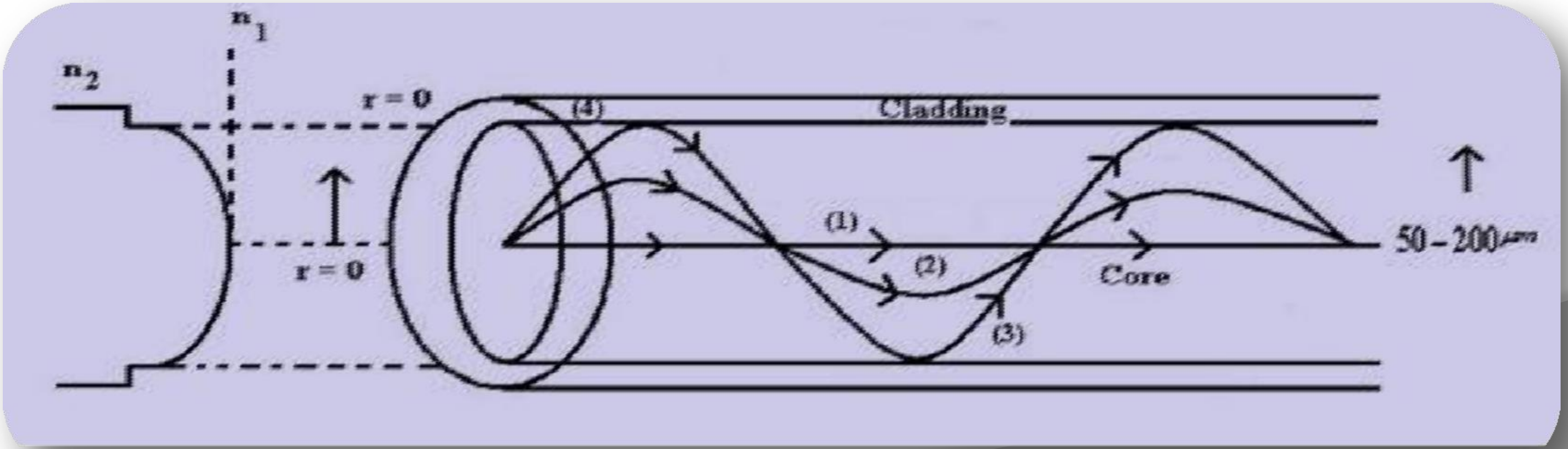


Explanation:

- As refractive index changes continuously radially in core, light rays suffer continuous refraction in core.
- The propagation of light ray is not due to total internal reflection but by refraction.
- In graded index fiber, light rays travel at different speed in different paths of the fiber.
- Near the surface of the core, the refractive index is lower, so rays near the outer surface travel faster than the rays travel at the center.
- Because of this, all the rays arrive approximately at the same time, at the receiving end of the fiber.

Transmission of signal in graded index fibre

- consider ray path 1 along the axis of fiber and another ray paths 2 and3.
- Along the axis of fiber, the refractive index of core is maximum, so the speed of ray along path 1 is less.
- Path 2 is sinusoidal and it is longer. This ray mostly travels in low refractive region and so the ray 2 moves slightly faster.
- Hence, the pulses of signals that travel along path 1, path 2 and path 3 reach the other end of the fiber simultaneously. Thus, the problem of intermodal dispersion can be reduced to a large extent using graded index fibers.



Differences between Single mode and Multimode fibers

Single mode Fibre	Multimode Fibre
✓In single mode fiber there is only one path for ray propagation.	✓In multimode fiber, large number of paths are available for light ray propagation.
✓A single mode step index fiber has less core diameter (<10 μm) and the difference between the refractive indices of core and cladding is very small.	✓Multi mode step index fibers have larger core diameter (50-200μm) and the difference between the refractive indices of core and cladding is large.
✓In single mode fibers, there is no dispersion.	✓Signal distortion and dispersion takes place in multimode fibers.
✓Signal transmission capacity is less but the single mode fibres are suitable for long distance communication.	✓Signal transmission capacity is more in multimode fibres. They are less suitable for long distance communication.
✓Launching of light into single mode fibers is difficult.	✓ Launching of light into multimode fibers is easy.
✓Fabrication cost is very high.	✓ Fabrication cost is less.

Attenuation in Optical Fibres

- Attenuation is the loss of power suffered by the optical signal as it propagates through the fiber.
- It is also called fiber loss.
- Signal attenuation is defined as "the ratio of the input optical power (P_i) into the fiber to the output optical power received (P_o) at the other end of the fiber".
- The attenuation coefficient of the signal per unit length is given as,

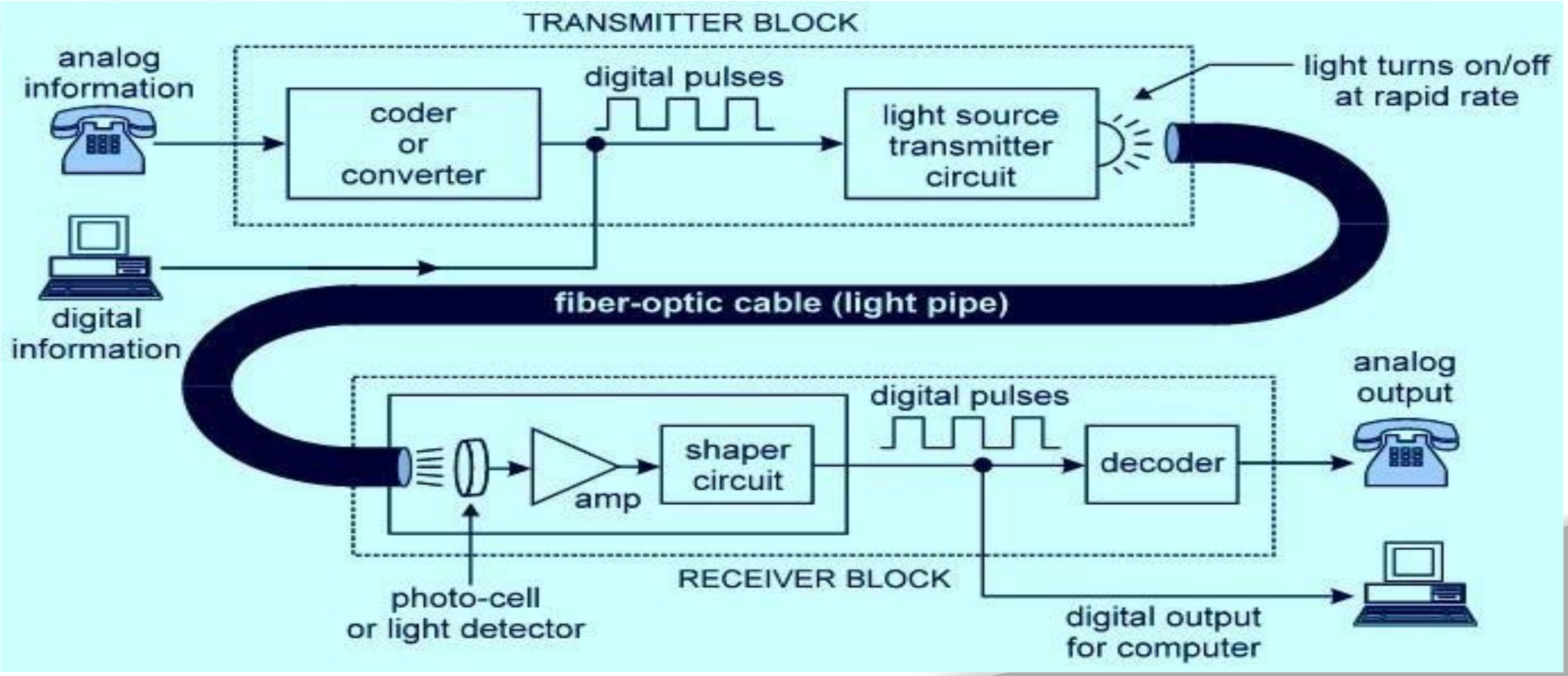
$\alpha = 10/L \log (Pi/Po)$ dB/km Where, L is the length of the fibre.

- The mechanisms through which attenuation takes place are

1. Absorption losses.
2. Scattering losses.
3. Bending losses.
4. Micro bending and Wave guide losses.

Optical Fibres in Communication

1. Optical fibre communication system essentially consists of three parts namely, (a) Transmitter (b) Optical fibre and (c) Receiver.
2. The Transmitter includes modulator, encoder, light source, drive circuits and couplers.
3. Basically, the fibre optic system simply converts an electrical signal to binary data by an encoder.



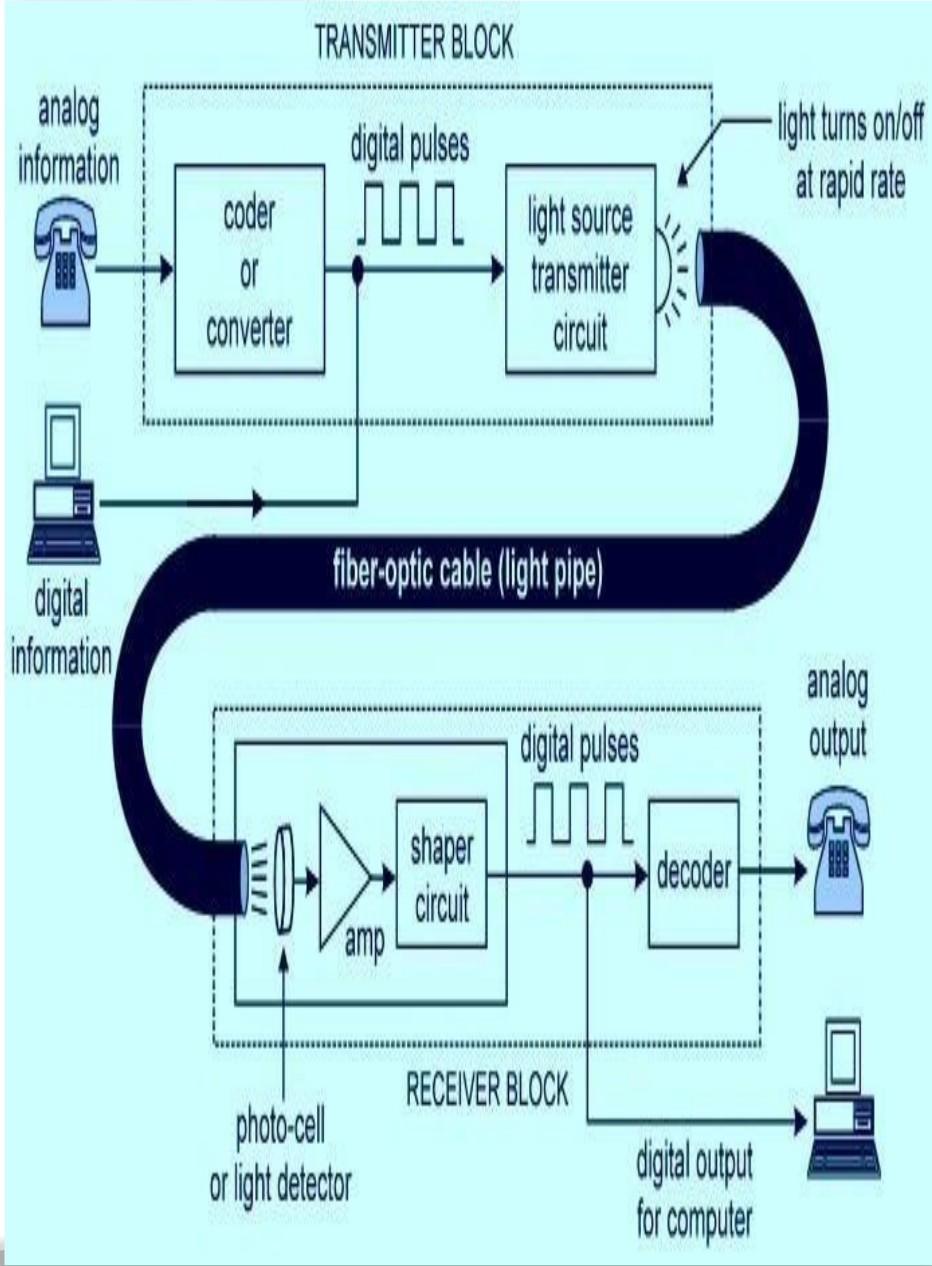
Block diagram of Optical Fibre communication system

- This binary data comes out as a stream of electrical pulses and these pulses are converted into pulses of optical power, by modulating the light emitted by the the light source.

- This means that the laser drive circuit directly modulates the intensity of the laser light with the encoded digital signal.

- This digital optical signal is launched into the optical fibre cable.

- The Couplers in the transmitter, couple the transmitted light signals



- Finally, at the end of the optical fibre, the signal is fed to the receiver.

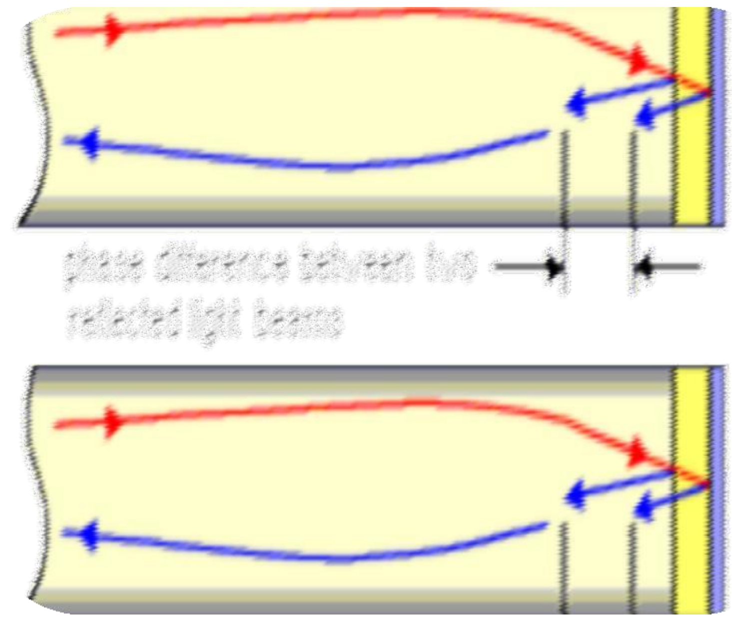
- The Receiver consists of a light detector, which can either be an Avalanche Photo Diode (ADP) or a Positive Intrinsic Negative(PIN) diode.

- In the photo detector, the signal is converted into pulses of electric current, which is then fed to the decoder, which converts the sequence of binary data stream into an analogue signal.

Applications of Optical Fibres

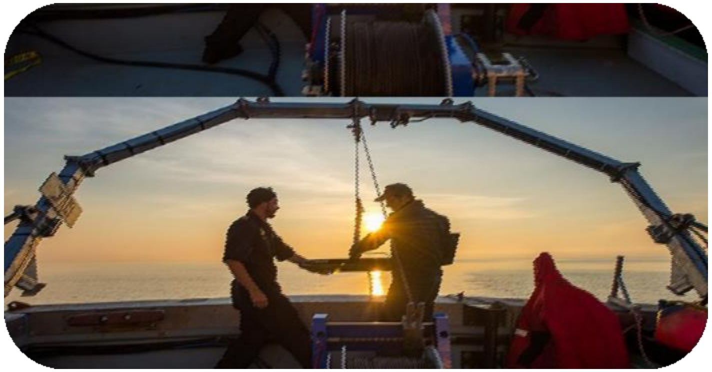
Sensors:

- Fibers have many uses in remote sensing. In some applications, the sensor is itself an optical fiber.
- Optical fibers can be used as sensors to measure strain, temperature, pressure and other quantities.
- Extrinsic fiber optic sensors has the ability to reach places which are otherwise inaccessible. An example is the measurement of temperature inside aircraft jet engines.
- Extrinsic sensors can also be used in the same way to measure the internal temperature of electrical



Fibre optic temperature sensor using Phase interference

- Optical fiber can be used to transmit power using a photovoltaic cell to convert the light into electricity.
- Fiber optics are used to connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission.
- They are also used in military as hydrophones for seismic and SONAR uses, as wiring in aircraft, submarines and other vehicles and also for field networking.
- Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet, video on-demand and



Fibre optics used in SONAR

Fibre optic cable system in Internet

Telecommunication:

- Optics fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals.
- Unlike electrical cables, fiber optics transport information far distances with few repeaters.
- Fiber optic cables can carry a large number of different signals simultaneously through a technique called wavelength division multiplexing.
- Optical fibers are ideally suited

Optical fibres used in Telecommunication

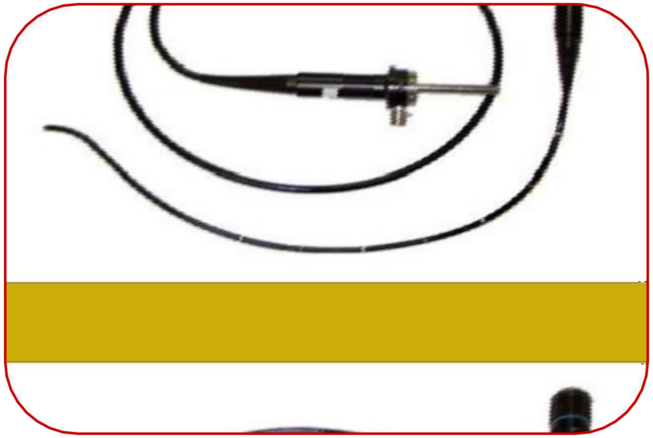
Medical Applications:

- Optical fiber is used in imaging optics. They are used as light guides in medical and other applications where bright light needs to be shone on a target without a clear line-of-sight path.
- A coherent bundle of fibers is used, along with lenses, for a long, thin imaging device called an endoscope, which is used to view objects through a small hole.
- Medical endoscopes are used for surgical procedures to view the internal parts of the human body.
- Industrial endoscopes are used for inspecting anything hard to reach, such

Optical fibre enabling the physician to look and work inside the body without performing surgery

Based on application, the endoscopes are classified into:

- Gastro scope is used to examine the stomach.
- Bronchoscope is used to see the upper passage of lungs.
- Ortho scope is used to see the small spaces within joints.
- Could scope is used to test female pelvic organs.
- Peritonea scope is used to test the abdominal cavity , lower parts of liver and gall bladder.
- In Ophthalmology, lasers guided by the fibres is used to reattach the detached retina.



A flexible Endoscope

Image of a Bronchoscope

DEFINITIONS

- **Amplitude - (s_o) Maximum value of the displacement of a particle in a medium (radius of circular motion).**
- **Wavelength - (l) The spatial distance between any two points that behave identically, i.e. have the same amplitude, move in the same direction (spatial period)**
- **Wave Number - (k) Amount the phase changes per unit length of wave travel. (spatial frequency, angular wavenumber)**
- **Period - (T) Time for a particle/system to complete one cycle.**
- **Frequency - (f) The number of cycles or oscillations completed in a period of time.**
- **Angular Frequency - (w) Time rate of change of the phase.**

1. An optical fibre has a core material of refractive index 1.55 and the cladding material of refractive index 1.50 and light is launched into it in air. Calculate its numerical aperture.

Given data Refractive index of core, $n_1 = 1.55$

Refractive index of cladding, $n_2 = 1.50$

Solution Numerical aperture of the optical fibre,

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

$$\Rightarrow \sqrt{1.55^2 - 1.50^2}$$

$$\sqrt{2.40 - 2.25} = \sqrt{0.15} = 0.39$$

Acceptance angle

$\theta = \sin^{-1}(0.39)$

2. Calculate the angle of acceptance of a given optical fibre if the refractive indices of the core and cladding are 1.563 and 1.498, respectively.

Given data Refractive index of core, $n_1 = 1.563$

Refractive index of cladding, $n_2 = 1.498$

Solution

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

For a positive crystal like quartz, the path difference is given by $(\mu_e - \mu_o)t$. The thickness of the crystal required to produce a path difference of $\lambda/2$ is

$$(\mu_e - \mu_o)\, t = \lambda/2$$

i.e.
$$t = \frac{\lambda}{2(\mu_e - \mu_o)} \quad (5)$$

Applications Some of the applications of the HWP are given below:

(i) The HWP produces a phase difference of π between the ordinary and extraordinary rays.

(ii) The emergent beam from a HWP is a plane polarised light.

(iii) It rotates the azimuth of a beam of plane polarised light by 90°, provided the incident light makes an angle of 45° with the optic axis of the half wave plate.

Limitation The thickness of a HWP is cut in such a way that it can produce a path difference of $\lambda/2$ between the ordinary and extraordinary rays. Therefore, it is useful only for a particular wavelength.

3.5 ENGINEERING APPLICATIONS OF POLARIZATION

1. Polarization is used to differentiate longitudinal and transverse wave.
2. Phenomenon of polarization is used in glare-reducing sun glasses.
3. It is used to perform stress analysis tests on transparent plastics with polarized filters.
4. Polarization is used to produced and show 3D movies.
5. Polarization is utilized for mirrors used in automobile industries.
6. Polarization is used to know the specific rotation of linearly polarized light when it passes through liquids containing optical active substance.
7. It is used in the measurement of photo elasticity.
8. Polarization is used in infrared spectroscopy.
9. Polarization of cosmic microwave background is used to study physics of early universe.

SOLVED PROBLEMS

1. Calculate the thickness of a quarter wave plate for a monochromatic light having a wavelength of 600 nm, if the refractive indices of ordinary and extraordinary rays in the medium are 1.5442 and 1.5533 respectively.

Given data Wavelength of the monochromatic light,

$$\lambda = 600 \text{ nm} = 600 \times 10^{-9} \text{ m}$$

Ordinary ray refractive index, $\mu_o = 1.5442$

Extraordinary ray refractive index, $\mu_e = 1.5533$

Solution

$$t = \frac{\lambda}{4(\mu_o - \mu_e)}$$

$$t = \frac{600 \times 10^{-9}}{4 \times (1.5533 - 1.5442)}$$

$$= \frac{6 \times 10^{-7}}{0.0364} = 164.84 \times 10^{-7}$$

$$= 16.484\ \mu\text{m}$$

$$= 0.0165 \text{ mm}$$

2. Find the minimum thickness of half wave and quarter wave plates for a light beam ($\lambda = 589.3$ nm) if $\mu_o = 1.65833$ and $\mu_e = 1.48640$.

Given data Wavelength of the light beam, $\lambda = 589.3$ nm

$$= 589.3 \times 10^{-9} \text{ m}$$

Ordinary ray refractive index, $\mu_o = 1.65833$

Extraordinary ray refractive index, $\mu_e = 1.48640$

Solution (i) For half wave plate

$$t = \frac{\lambda}{2(\mu_o - \mu_e)}$$

$$t = \frac{589 \times 10^{-9}}{2(1.65833 - 1.48640)} = \frac{589 \times 10^{-9}}{2 \times 0.17193}$$

$$= \frac{589 \times 10^{-9}}{0.34386} = 1.713 \times 10^{-6} \text{ m}$$

$$= 0.001713 \times 10^{-3} \text{ m}$$

$$t = 0.001713 \text{ mm}$$

(ii) For quarter wave plate

$$t = \frac{\lambda}{4(\mu_o - \mu_e)}$$

$$t = \frac{589.3 \times 10^{-9}}{4(1.65833 - 1.48640)} = \frac{589.3 \times 10^{-9}}{4 \times 0.17193}$$

$$= 8.5689 \times 10^{-7} \text{ m}$$

$$= 0.8568 \times 10^{-6} \text{ m}$$

$$t = 0.000857 \text{ mm}$$

In this grating, two orders can be seen.

4. A grating has 6000 lines/cm. Find the angular separation between two wavelengths of 500 nm and 510 nm in the 3rd order.

Given data Number of lines in the grating,

$$N = \frac{1}{e+d}\ 6000 \text{ lines/cm}$$

$$= 6000 \times 10^2 \text{ lines/m}$$

Order $n = 3$

Solution We know that $(e + d) \sin\theta = n\lambda$

$$\sin\theta = \frac{n\lambda}{e+d} = nN\lambda$$

For first wavelength, $\lambda_1 = 500 \text{ nm} = 500 \times 10^{-9} \text{ m}$

$$\sin\theta_1 = 3 \times 6000 \times 10^2 \times 500 \times 10^{-9}$$

$$\sin\theta_1 = 0.9$$

$$\theta_1 = \sin^{-1}(0.9) = 64°9'$$

Similarly,

$$\lambda_2 = 510 \text{ nm} = 510 \times 10^{-9} \text{ m}$$

$$\sin\theta_2 = 3 \times 6000 \times 10^2 \times 510 \times 10^{-9}$$

$$= 0.918$$

$$\theta_2 = \sin^{-1}(0.918)$$

$$\theta_2 = 66°38'$$

Angular separation between two wavelengths in third order

$$= \theta_2 - \theta_1$$

$$= 66°38' - 64°9'$$

$$= 2°29'$$

6. In a Newton's rings experiment, ... 18th ring was 0.65 cm ... 0.35 cm and the diameter of the ... of the light used is 6000Å then find the radius of curvature of the plano-convex lens.

Given data Diameter of the 18th ring = 0.65 cm

Diameter of the 8th ring = 0.35 cm

Wavelength of the light, $\lambda = 6000$ Å

Solution Radius of curvature of the plano-convex lens is

$$R = \frac{D_n^2 - D_m^2}{4(n-m)\lambda}$$

$$\Rightarrow \quad R = \frac{(0.65)^2 - (0.35)^2}{4(18-5) \times 600 \times 10^{-8}}$$

$$= \frac{0.4225 - 0.1225}{24 \times 10^{-4}} = \frac{0.3}{24} \times 10^4 = 125 \text{ cm}$$

∴ radius of curvature of the plano-convex lens is 125 cm.

7. In a Newton's rings experiment, the diameter of the 12th ring changes from 1.45 cm to 1.25 cm when a liquid is introduced between the lens and the glass plate. Find the refractive index of the liquid.

Given data Diameter of the 12th ring in air medium, $D_{12} = 1.45$ cm

Diameter of the 12th ring in a liquid, $D'_{12} = 1.25$ cm

Solution

$$D_n^2 = \frac{4n\lambda R}{\mu}$$

$$(D_{12})^2 = \frac{4n\lambda R}{\mu} = \frac{4 \times 12\lambda R}{1} \qquad \therefore \mu = 1 \text{ for air}$$

$$(D'_{12})^2 = \frac{4 \times 12\lambda R}{\mu}$$

From the above relation,

$$\mu = \frac{(D_{12})^2}{(D'_{12})^2} = \frac{(1.45)^2}{(1.25)^2} = \frac{2.1025}{1.5625} = 1.3456$$

∴ refractive index of the liquid is 1.3456.