Unit 2
Laser & Optical Fibers

L = Light
A = Amplification
S = Stimulated
E = Emission of
R = Radiation

Laser is a device that emits light through a process of amplification based on the stimulation emission of Electromagnetic Radiation.

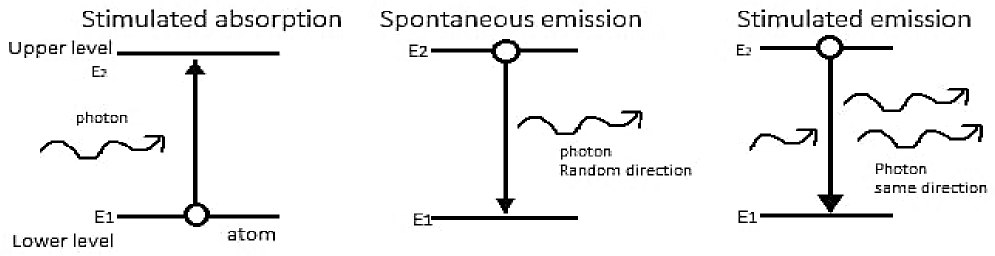
LASER

Characteristics of Laser

- *Monochromatically:* Laser light has a single wavelength or color, which means it is highly monochromatic.
- *Coherence:* Laser light waves are in phase in both space and time, making them highly coherent.
- *Directionality:* Laser emits light in a highly collimated (narrow and focused) beam, minimizing divergence.
- *High Intensity:* Laser beams have high energy concentered in a small area, leading to intense brightness.

Einstein's Theory of Laser Action

It Consists of three phenomena are:
- Stimulated Absorption
- Spontaneous Emission
- Stimulated Emission



Stimulated Absorption: Let E_1 and E_2 are the energies of ground state and excited state of an atom. Suppose if photon interacts with an atom present in ground states, then it gets excited ground state to excited state. This is called Stimulated Absorption.

Spontaneous Emission: Let E_1 and E_2 are the energies of ground state and excited state of an atom. Suppose photon interacts with an atom present in ground states, then it gets excited to excited state and the excited atom does not stay in excited state. It gets deexcitation by emitting a photon of energy $h\nu$ and this is known as Spontaneous Emission.

Stimulated Emission: Let E_1 and E_2 are the energies of ground state and excited state of an atom. Suppose if the photon interacts with an atom present in ground states, then it gets excited to excited state. Now a photon interacts with atom in excited state then the atom gets deexcitation to ground state by emitting another photon. This is known as Stimulated Emission.

EINSTEIN'S COEFFICIENTS

Einstein's Coefficients are mathematical quantities, which are a measure of the probability of the absorption or emission of light by an atom on molecule.
Let us consider an assembly of atoms which is in thermal equilibrium with radiation of frequency ν and spectral energy density ρ at temperature T.

Let N_1 and N_2 be the no. of atoms per unit volume in energy states 1 and 2 with energies E_1 and E_2.
An atom in the lower energy states E_1 can also absorb radiation and get excited to the state E_2.

- For Stimulation Absorption

$$R_{12} \propto N_1\rho$$
$$R_{12} = B_{12}N_1\rho$$

- For Spontaneous Emission

$$R_{21} \propto N_2$$
$$R_{21} = A_{21}N_2$$

- For Stimulated Emission

$$R'_{21} \propto N_2\rho$$
$$R'_{21} = B_{21}N_2\rho$$

At thermal equilibrium, Rate of Absorption = Rate of Emission

$$R_{12} = R_{21} + R'_{21}$$

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

$$\rho[B_{12}N_1 - B_{21}N_2] = A_{21}N_2$$

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

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

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

$$\rho = \frac{A_{21}/B_{21}}{\left(\frac{B_{12}N_1}{B_{21}N_2} - 1\right)} \quad \text{......... (1)}$$

According to Maxwell Boltzmann Distribution Law, $N = N_0e^{-E/kT}$

$$N_1 = N_0e^{-E_1/kT}$$

$$N_2 = N_0e^{-E_2/kT}$$

$$\frac{N_1}{N_2} = \frac{N_0e^{-E_1/kT}}{N_0e^{-E_2/kT}} = e^{(E_2-E_1)/kT}$$

$$\frac{N_1}{N_2} = e^{h\nu/kT} \quad \text{......... (2)} \qquad [\therefore E_2 - E_1 = h\nu]$$

From eq 1 and 2,

$$\rho = \frac{A_{21}/B_{21}}{\left(\frac{B_{12}}{B_{21}}e^{h\nu/kT} - 1\right)} \quad \text{......... (3)}$$

According to Max Plank Distribution Law,

$$\rho = \frac{8\pi h v^3}{c^3(e^{hv/kT} - 1)} \qquad \text{.........} (4)$$

From eq 3 and 4,

$$\frac{A_{21}/B_{21}}{\left(\frac{B_{12}}{B_{21}} e^{\frac{hv}{kT}} - 1\right)} = \frac{8\pi h v^3/c^3}{\left(e^{\frac{hv}{kT}} - 1\right)}$$

- $A_{21}/B_{21} = 8\pi h v^3/c^3$ OR $A_{21}/B_{21} \propto v^3$
- $\frac{B_{12}}{B_{21}} = 1$ OR $B_{12} = B_{21}$

These are the relation between Einstein's Coefficient.

POPULATION INVERSION

It is defined as number of atoms present excited state is greater than number of atoms present in ground state is known as Population Inversion.
Pumping: The process of achieving of Population Inversion.

Techniques of Population Inversion are:

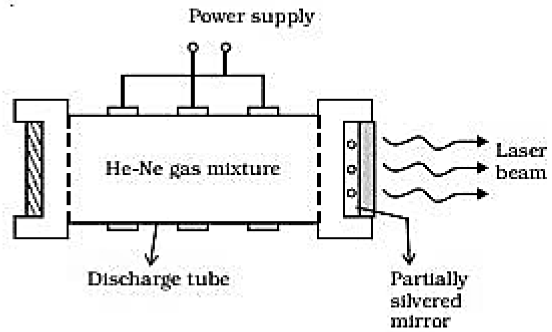
- *Optical Pumping:* It is used in solid laser. E.g. Ruby laser
- *Electrical Discharge Pumping*: It is used in gas laser. E.g. He-Ne laser
- *Chemical Pumping:* It results in excitation and hence create population inversion in few systems. E.g. HF laser (Hydrogen fluoride)
- *Injection Current Pumping:* In Semi-Conductors injection of through Current the junction results in population inversion among minority charge. E.g. PN junction Diode.

HE-NE AND SEMICONDUCTOR LASER

He-Ne Laser

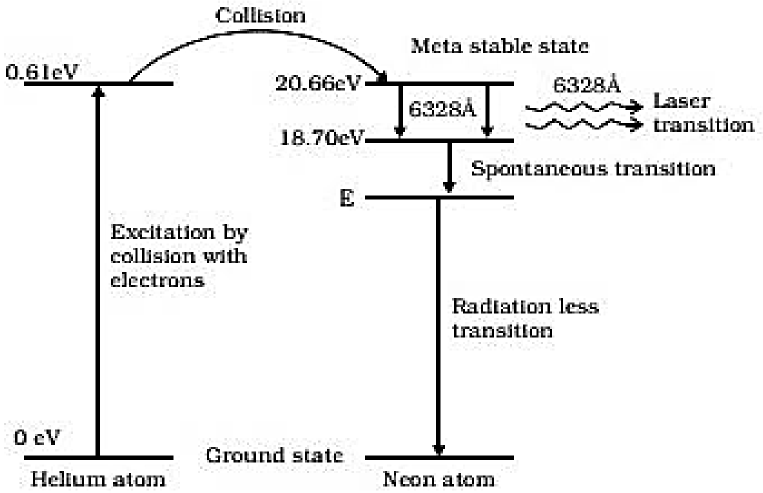
The Helium-Neon (He-Ne) laser is a type of gas laser that utilizes a mixture of helium and neon gases as its active medium. It was the first gas laser to be operated successfully, developed by Ali Javan and his co-workers in 1961.

Construction: The He-Ne laser consists of a narrow quartz discharge tube filled with a mixture of helium and neon gases, typically in a 10:1 ratio. The tube is about 80 cm in length and 1.5 cm in diameter, with its end windows set at Brewster's angle to ensure the output light is polarized. Two concave mirrors are placed at the ends of the tube to form an optical resonator cavity. One mirror is fully reflective, while the other is partially reflective, allowing the laser beam to exit.



Working Principle:

1. Excitation: A high-voltage DC power supply (2-4 kV) is applied across the gas mixture, causing electrons to collide with helium atoms, exciting them to higher energy states.
2. Energy Transfer: The excited helium atoms collide with neon atoms, transferring energy and exciting the neon atoms to metastable states.
3. Population Inversion: This process creates a population inversion between specific energy levels of the neon atoms.
4. Laser Emission: When these excited neon atoms return to lower energy states, they emit photons corresponding to a wavelength of 632.8 nm (red light). These photons are amplified within the resonant cavity, resulting in a coherent laser beam.

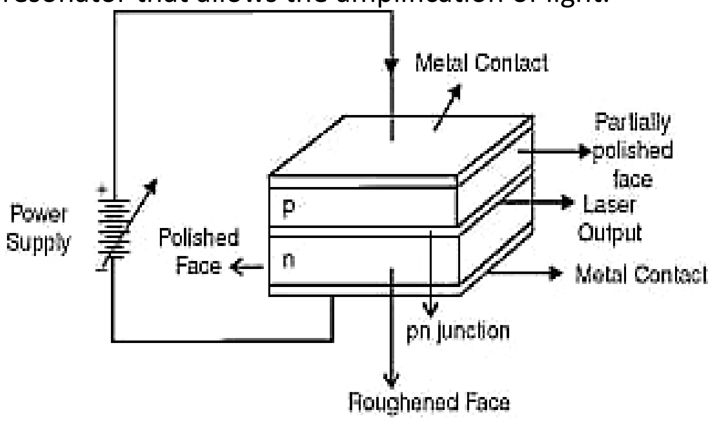


Semiconductor Laser

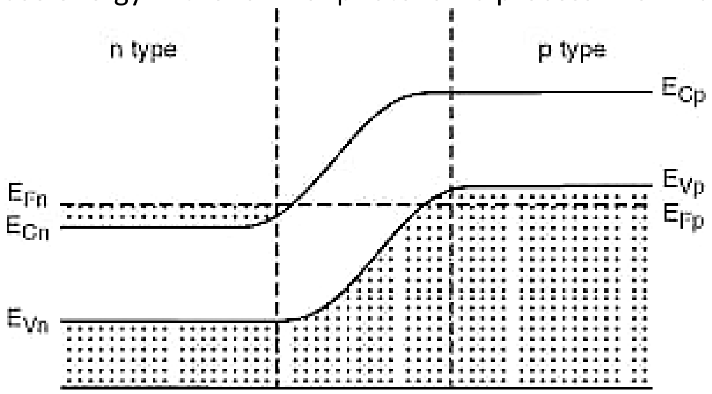
A semiconductor laser, also known as a laser diode, is a type of laser that uses a semiconductor as its active medium. These devices are compact, efficient, and widely used in various applications, including telecommunications, data storage, and medical devices.

Construction: A typical semiconductor laser consists of a p-n junction diode made from semiconductor materials such as gallium arsenide (GaAs). The construction involves the following components:

1. Active Region: This is the region around the p-n junction where electron-hole recombination occurs, leading to the emission of photons.
2. Cladding Layers: These layers surround the active region and have a lower refractive index to confine the light within the active region through total internal reflection.
3. Electrical Contacts: Metal contacts are attached to the p-type and n-type regions to inject current into the diode.
4. Reflective Coatings: The end facets of the semiconductor crystal are often coated to form mirrors, creating an optical resonator that allows the amplification of light.



Working Principle: When a forward bias voltage is applied across the p-n junction, electrons from the n-type region and holes from the p-type region are injected into the active region. When these electrons and holes recombine, they release energy in the form of photons—a process known as spontaneous emission.



Some of these photons stimulate further electron-hole recombination's, leading to more photon emissions of the same phase and direction—a process called stimulated emission. The reflective coatings at the ends of the diode form a resonant cavity, allowing photons to bounce back and forth, stimulating further emissions and amplifying the light. Once the amplification reaches a certain threshold, coherent laser light is emitted from the diode.

APPLICATIONS IN SCIENCE AND ENGINEERING

Lasers have diverse applications across science and engineering:

- *Industry:* Utilized for cutting, drilling, and welding materials like metals and ceramics.
- *Medicine:* Employed in procedures such as endoscopy and the treatment of skin conditions.
- *Military:* Applied in targeting systems and as potential directed-energy weapons.
- *Communication:* Used in fiber optics for high-speed data transmission.
- *Scientific Research:* Applied in spectroscopy, holography, and the study of chemical reactions.

OPTICAL FIBER

Optical Fiber is a technology that uses glass, plastic, thread are fibers to transmits data. A fiber optic cable consists of a bundle of glass threads which are protected by the outer covering of several jackets.
Optical Fiber uses light to carry digital signals is based on the concept of total internal reflection.

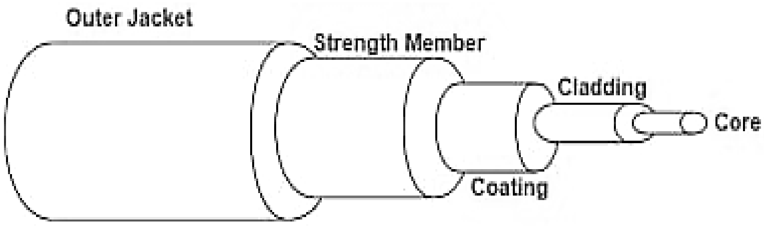
Critical Angle

The angle of incidence medium for which angle of refraction in rarer medium is 90° is called Critical Angle.

Total Internal Reflection (TIR)

When a ray of light travels from denser to rarer medium is incident at the interface of two medium at an angle the greater than the critical angle the ray is total refracted back to denser medium. This is a phenomenon of Total Internal Refraction.

Structure of Optical Fiber



It consists of essentially three regions are:

1. *Core:* Core is the innermost part of optical fiber basically made of glass and plastic of diameter of 80µm – 100µm signal transmission is performed in core.
2. *Cladding:* It is coaxial cylinder tube if diameter of 125µm – 150µm made of material having lower refractive index than core.
3. *Jacket:* The outer cylindrical coaxial tube made of plastic or polymer provided for protection from environmental changes such as transparent, humidity, electrical & magnetic field or jerks etc.

Working of Optical Fiber

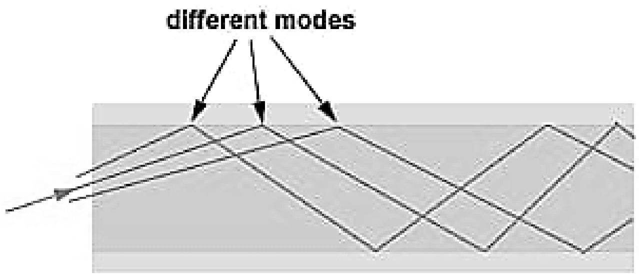
When a light ray is incident at one end of the core of the fiber, because of the small radius of fiber light ray going into the core makes an angle greater than the critical angle then TIR takes place light will be reflected back into the core and light ray repeated multiple reflections or reptations along the fiber from one end to another end.
In silica glass fiber more than 95% of light is transmitted over a distance of 1km.

To transmission of signal through optical fiber are:

- The core material should have higher reflective index (μ_{core}) than of cladding material ($\mu_{cladding}$).
- The angle of incidence should be greater than the critical angle. Abrupt refractive index

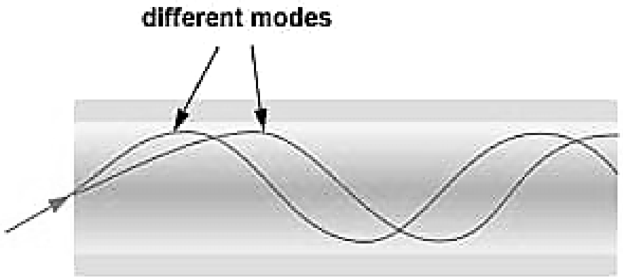
Types of Optical Fiber

Step-Index Optical Fiber: The refractive index of core medium is uniform undergoes an abrupt change at the interface of core cladding.



Step-Index Multimode Fiber

Graded-Index Optical Fiber: The Graded-Index optical Fiber has refractive index of core decreases in a parabolic manner form a maximum value at the centre of the core to a constant value of core - cladding interface.

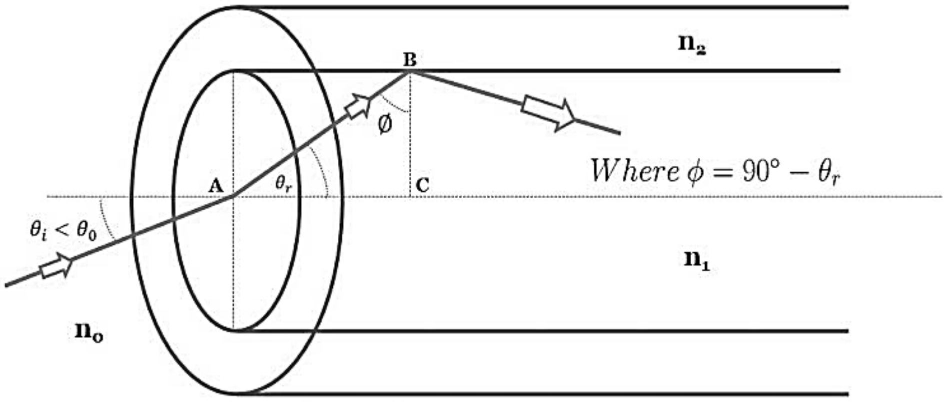


Graded-Index Multimode Fiber

ACCEPTANCE ANGLE AND NUMERICAL APERTURE

Acceptance Angle

Acceptance Angle is the maximum angle that a ray of light can have relative to the axis of the fibre and propagates down the Fiber.



$$\frac{\sin i}{\sin r} = \frac{\mu_2}{\mu_1}$$ (Applying Law of refraction at point A)

$$\frac{\sin\theta}{\sin(90° - \theta_c)} = \frac{\mu_{core}}{\mu_o}$$

$$\mu_o \sin\theta = \mu_{core}\sin(90° - \theta_c)$$

$$\mu_o \sin\theta = \mu_{core}\cos\theta_c$$

$$\mu_o \sin\theta = \mu_{core}\sqrt{1 - \sin^2\theta_c} \qquad \text{......... (1)}$$

$$\frac{\sin i}{\sin r} = \frac{\mu_2}{\mu_1}$$ (Applying Law of refraction at point B)

$$\frac{\sin\theta_c}{\sin 90°} = \frac{\mu_{cladding}}{\mu_{core}}$$

$$\sin\theta_c = \frac{\mu_{cladding}}{\mu_{core}} \qquad \text{......... (2)}$$

From eq 1 and 2,

$$\mu_o \sin\theta = \mu_{core}\sqrt{1 - \left(\frac{\mu_{cladding}}{\mu_{core}}\right)^2}$$

$$\sin\theta = \frac{\mu_{core}}{\mu_o}\sqrt{\frac{\mu_{core}^2 - \mu_{cladding}^2}{\mu_{core}^2}}$$

$$\sin\theta = \frac{\mu_{core}}{\mu_o}\frac{\sqrt{\mu_{core}^2 - \mu_{cladding}^2}}{\mu_{core}}$$

$$\boxed{\sin\theta = \frac{\sqrt{\mu_{core}^2 - \mu_{cladding}^2}}{\mu_o}}$$

If optical Fiber is placed in air $\mu_o = 1$

$$\sin\theta = \sqrt{\mu_{core}^2 - \mu_{cladding}^2}$$

$$\boxed{\theta = \sin^{-1}\sqrt{\mu_{core}^2 - \mu_{cladding}^2}}$$

Numerical Aperture

It is determining the light gathering ability of the Fiber.

$$\mathrm{N.A.} = \sin\theta = \sqrt{\mu_{core}^2 - \mu_{cladding}^2}$$

$$\mathrm{N.A.} = \sin\theta = \sqrt{(\mu_{core} + \mu_{cladding})(\mu_{core} - \mu_{cladding})}$$

$$\mathrm{N.A.} = \sin\theta = \sqrt{\frac{2\mu_{core}^2(\mu_{core} - \mu_{cladding})}{\mu_{core}}}$$

$$\boxed{\mathrm{N.A.} = \mu_{core}\sqrt{2\Delta}}$$

$$\boxed{\text{Relative Index } (\Delta) = \frac{\mu_{core} - \mu_{cladding}}{\mu_{core}}}$$