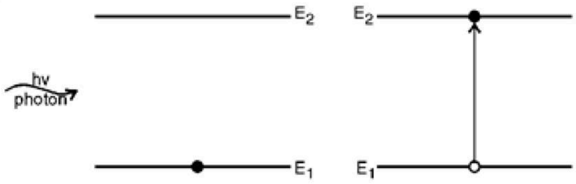
Unit-4: LASER

- The term laser stands for ***Light Amplification by Stimulated Emission of Radiation.***
- A **laser** is an opto-electronic device that produces coherent light radiation.
- A typical laser emits light in a narrow, low-divergence, monochromatic (single-coloured) beam with a well-defined wavelength.

Induced Absorption:

When an atom residing in the ground state absorbs the incident photon and jumps to some excited state then this transition is known as induced absorption.

hν = E_2-E_1



This process may be represented as

$$\mathbf{A + h\nu \rightarrow A^*}$$ *where **hν** is the energy of one photon, A denotes an atom in the lower state and **A**** *denotes an excited atom.*

The rate of absorption may be expressed as

$$\mathbf{R_{abs} = B_{12}\ \rho_{(\nu)}\ N_1} \quad \text{--------------(1)}$$

Where –

$\rho_{(\nu)}$ = Energy density of incident beam.

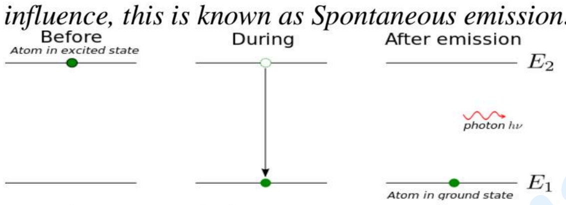
N_1 = Population of atoms in E_1

B_{12} = Einstein's coefficient of Induced absorption.

* ***B_{12}** indicates the probability of an induced absorption transition.*

Spontaneous Emission:

The process in which an excited atom emits a photon all by itself without any external influence, this is known as Spontaneous emission.



hν = E_2-E_1

This process may be represented as

$$\mathbf{A^* \rightarrow A + h\nu}$$ *where **hν** is the energy of one photon, A denotes an atom in the lower state and **A**** *denotes an excited atom.*

The rate of emission may be expressed as

$$\mathbf{R_{sp} = A_{21}\ N_2} \quad \text{-----------(2)}$$

Where –

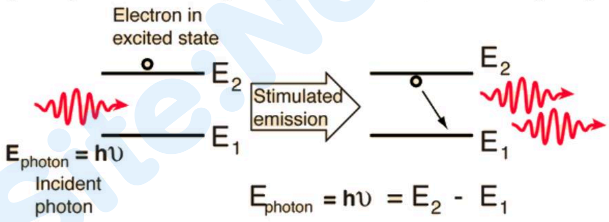
N_2 = Population of atoms in E_2

A_{21} = Einstein's coefficient of Spontaneous emission.

* *A_{21} indicates the probability of a Spontaneous emission transitions.*

Stimulated Emission

*If an exited atom is stimulated to lose its energy in such a way that transition from the excited to lower state takes place before the lapse of relaxation span (10^{-8} seconds), resulting in photon emission, then this is called **stimulated emission**.*



This process may be represented as

$$\mathbf{A^* + h\nu \rightarrow A + 2h\nu}$$ *where **hν** is the energy of one photon, A denotes an atom in the lower state and **A**** *denotes an excited atom.*

The rate of stimulated emission of photon is given by

$$\mathbf{R_{st} = B_{21}\ \rho_{(\nu)}\ N_2} \quad \text{---------------(3)}$$

Where –

$\rho_{(\nu)}$ = Energy density of incident beam.

N_2 = Population of atoms in E_2

B_{21} = Einstein's coefficient of Stimulated Emission

* ***B_{12}** indicates the probability of an induced absorption transition.*

Chief Characteristics of Stimulated Emission:

The output photons produced in this phenomenon have-

- the **same frequency**
- **same** direction
- same phase
- same state of polarization as the original photon

Comparison between Spontaneous & Stimulated Emission

Spontaneous	stimulated
1. Emission of light photon takes place immediately without any inducement.	1. Emission of a light photon is by inducement of a photon having energy equal to the emitted photon energy.
2. Polychromatic radiation	2. Monochromatic radiation
3. Incoherent radiation	3. Coherent radiation
4. Less directionality	4. High directionality
5. Less intense	5. High intense

Einstein's Relations

Under thermal equilibrium, the mean population N_1 and N_2 in the ground and excited energy levels respectively, must remain constant. This condition requires that the number of transitions from the excited state to the lower state must be equal to the number of transitions from ground state to the excited state. Thus,

$$\left.\begin{matrix} \textit{The number of atoms absorbing} \\ \textit{photons per second per unit volume} \end{matrix}\right\} = \left.\begin{matrix} \textit{The number of atoms emitting} \\ \textit{photons per second per unit volume} \end{matrix}\right\}$$

i.e $R_{abs} = R_{sp} + R_{st}$

From equations (1), (2) & (3), we can substitute

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

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

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

$$\rho(v) = \frac{A_{21}\, N_2}{(B_{12}\, N_1 - B_{21}\, N_2)} \qquad (4)$$

Dividing the N^r & D^r of the RHS by $B_{12}\, N_2$ we get

$$\rho_{(v)} = \frac{A_{21}}{B_{12}}\left[\frac{1}{\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}}}\right]$$

We know that

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

$$\frac{N_1}{N_2} = e^{\frac{h\nu}{kT}}$$

$$\rho(v) = \frac{A_{21}}{B_{12}}\left[\frac{1}{e^{\frac{h\nu}{kT}} - \frac{B_{21}}{B_{12}}}\right] \qquad (5)$$

According to Planck's Radiation Law

$$\rho(v) = \frac{8\pi h\nu^3}{c^3}\left[\frac{1}{e^{\frac{h\nu}{kT}} - 1}\right] \qquad (6)$$

Now comparing the equation (5) and equation (6)

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

From the above equation, we get

$$\boxed{B_{21} = B_{12}}$$

$$\boxed{B_{12} = B_{21} = \frac{c^3}{8\pi h\nu^3} A_{21}}$$

These two equations are known as the ***Einstein's Relations***, which exhibit relationship between Einstein coefficients.

Significance of Einstein's relations

- First relation $\mathbf{B_{21} = B_{12}}$ *signifies that when an atom with two energy levels is placed in the radiation field, the probability of an upward transition (absorption)* $\boldsymbol{B_{12}}$ *is* ***equal*** *to the probability of a downward transition (stimulated emission)* $\mathbf{B_{21}}$,
- *The second relation* $\frac{A_{21}}{B_{21}} = \frac{8\pi h \mu^3}{c^3} \upsilon^3$ *shows that the ratio of coefficients of spontaneous versus stimulation emission is proportional to the third power of the frequency of the radiation, which means that the probability of spontaneous emission* $\mathbf{A_{21}}$ ***dominates*** *over the stimulated emission* $\mathbf{B_{21}}$*more and more as the energy difference increases*

Population Inversion: ***The steady state condition of a transparent material in which the number of atoms in its excited state N_2 is larger than the number of atoms in ground/lower energy state N_1 i.e. $N_2 > N_1$, is called Population Inversion.***

If N_1 and N_2 are the populations in the ground and exited states respectively then according to Boltzmann's law the population ratio between the two energy levels is given as

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

where $E_2 - E_1$ is the difference in energy of the two states, k is the Boltzmann's constant & T is the absolute temperature.

We know that the probability of spontaneous emission dominates over the stimulated emission because population in excited state always remains less than that in ground state. However we need the population in the exited state to be reasonably more than that in the ground state. Therefore, **population Inversion is the necessary condition to obtain stimulated emissions.**

The process by which the state of population inversion is achieved in a substance is called PUMPING.

Achieving the State of Population Inversion or PUMPING.

To achieve the state of population inversion external energy is supplied to excite the atoms of the substrate to an extent and at a rate that the number of electrons in the excited state increases the number of electrons in the ground state, reasonably.

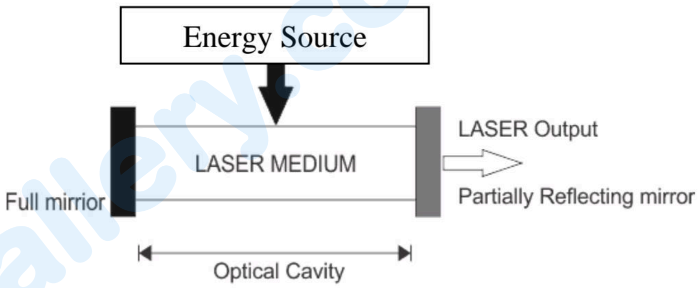
Pumping is usually done in the following ways:

1. Optical Pumping (Ruby Laser)
2. Electrical Discharge (He-Ne Laser)
3. Inelastic Atom-Atom Collision
4. Direct Conversion (Semi-conductor laser)
5. Chemical Reaction (Carbon dioxide laser)

Meta stable State

An excited energy state in which the atoms may remain longer than usual is called a meta stable state. The relaxation span in such a state is 10^{-3}sec, so that the transition to the lower state occurs by stimulated emission rather than spontaneously.

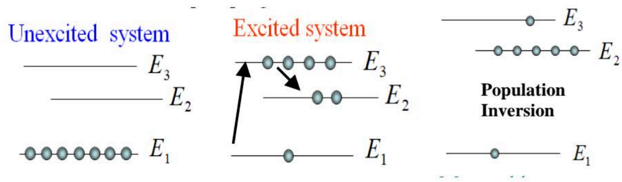
Main Components Of a Laser: **There are three major components of a lasing system**:



1. **Energy Source or a pumping system** – It is the source of energy used to excite the active medium.
   General examples are; electricity from a power supply, flash tubes, lamps, or the energy from another laser.
2. **A Working substance** – It is a suitable transparent substance (having a meta stable state) whose atoms are excited to produce the desired stimulated emission for the amplification of light.
   It may be solid, liquid, gas or a semi-conducting material.
3. **An Optical Cavity** - It is a combination of two mirrors, one at each end of the lasing medium, out of which one is 100% reflecting and the other one is a little less.
   Photons produced by stimulated emissions along the axis of the cavity are made to bounce between the two mirrors due to which the beam intensifies. Finally when it gains enough strength, it transmits out of the less reflecting mirror as the output laser beam.

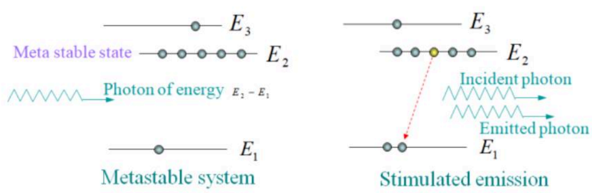
Laser Mechanism/ Principle

Step -1: Pumping:



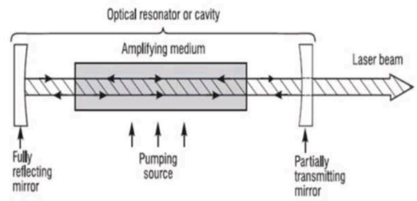
- Energy is supplied to the laser medium by the energy pumping system.
- This energy is stored in the form of excited atoms in the metastable energy levels.
- <u>Pumping must produce a state of population inversion between the metastable and ground state.</u>

Step -2 : Stimulation: When population inversion is achieved, the <u>spontaneous decay of a few electrons from the meta stable energy level to a lower energy level starts a chain reaction</u>. The photons emitted spontaneously will hit (without being absorbed) other atoms and stimulate them to make the transition from the metastable energy level to lower energy levels, emitting photons of same wavelength, phase, and direction.



Step -3 : LASING:

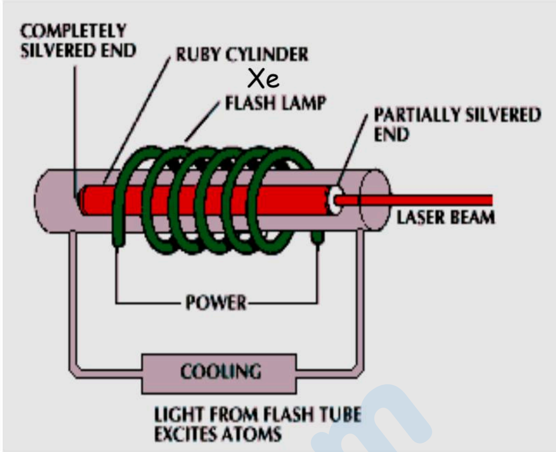
This action occurs in the optical cavity. When the photons that move along the axis of the cavity reaching perpendicularly at the mirrors, they are reflected back into the material where the chain reaction continues and the number of photons increases in the bouncing beam.
Finally when it gains enough strength, it transmits out of the less reflecting mirror as the output laser beam.



Ruby-laser:

Ruby laser was devised by Maiman in 1960. It is the first laser that was ever devised. It falls in the category of solid-state laser because the active material happens to be a crystal of Ruby.

Construction:



Energy Source**:** Xe flash lamp which emits white light.

Working Substance:

Ruby (single crystal): $Al_2O_3 + Cr$

Cr^{3+} Concentration: 0.3 – 0.5%

Shape: Cylindrical Rod.

Dimensions: Length – 10cm.

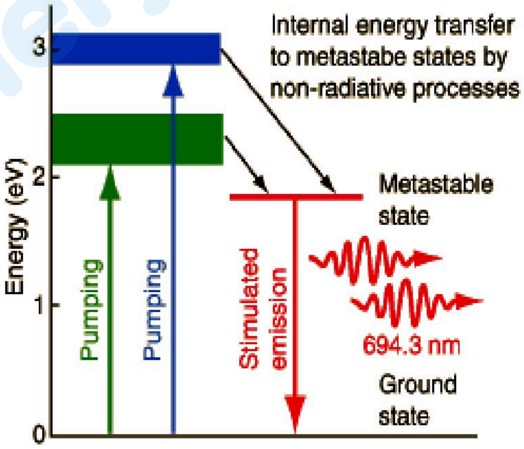
Diameter- 0.8cm

Optical Cavity**:**

- Single cylindrical crystal of ruby is taken whose ends are made flat, one of which is fully silvered & the other one is partly silvered.
- The fully silvered face of ruby rod has 100% reflection, while the partly silvered face has 90% reflection.

The cylindrical crystal is surrounded by a helical flash tube filled by xenon gas. The whole system is cooled by a coolant circulating around the ruby rod.

Working:



- White light from the Xe flash lamp enters the ruby and excites most of the chromium atoms.
- The chromium atoms are pumped by blue and green light with wave length range 400 to 550 nm, in either E_4 or E_3 levels.
- Then they fall quickly to the meta stable (E_2)level
- Population inversion is attained between E_2 & E_1
- The first spontaneous emission after 10^{-3} seconds, triggers stimulated emissions giving off red light of wavelength 694.3 nm.
- The beam bounces back and forth between the silvered ends of the optical cavity, until it gains enough energy to burst through the partially silvered end as laser light.
- The entire process repeats to give a pulsed output.

Drawbacks of Ruby Laser: -

(i) The laser requires high pumping power.

(ii) Ruby laser is less directional and has very small efficiency.

(iii) Only a small part of pumping power is utilized in the excitation of chromium ion and the rest goes in heating up of the apparatus.

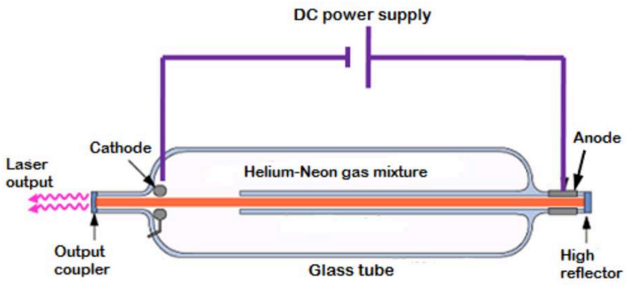
(iv) Very high heat is produced in these lasers due to which an effective cooling system is required.

(v) The laser output is pulsed and not continuous. The output occurs in the form of pulses of microsecond duration.

(vi) The defects due to crystalline imperfection also present in this laser.

Helium – Neon Laser

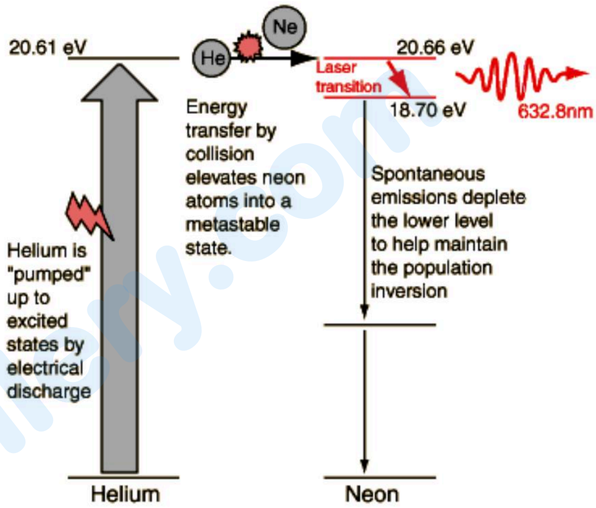
The first gas filled laser was He – Ne laser, and was discovered by Ali Javan and his associates, in1961.



Construction:

The laser is fabricated in a tube filled with a mixture of helium and neon gases in the ratio 10:1. The mixture is filled inside the long narrow discharge tube. The pressure inside the tube is maintained above 1mm Hg. At one of the ends a totally reflecting an on the other end a transmitting cavity mirrors are attached. Hence, these mirrors form a resonator.

Working:



The laser is excited by an electric discharge. This discharge first ionizes the He gas, so that the electrons flow through the gas. The electrons accelerated by the electric field release their energy to Ne gas atoms by collisions with He atoms. Hence, the population of Ne atoms in the excited states E_4 & E_3 increases rapidly in comparison to E_1 and E_2 states, reaching the state of population inversion.

The Ne atoms jump to lower levels E_2 by emitting a photon spontaneously. From level E_2, the atom can be brought to ground state through collisions with walls.

The transition of atom from E_4 to E_3 results in the emission of radiation of wavelength 632.8nm. The wavelength 632.8nm is the red light of He – Ne laser.

He-Ne laser is a continuous wave laser belonging to four level system. The light obtained from gas lasers is more directional and more monochromatic.

Laser Beam Characteristics: Light from a laser differs from light from conventional sources in a number of ways. The most sticking features of a laser beam are

(i) **Coherence: -** Laser beam is highly coherent because photons emitted by stimulated emission not only have the same energy, frequency, or wavelength but they are in phase in space and time as well.
The photons emitted from ordinary light sources not only have different energies, frequencies, wavelengths, or colors, but they are emitted in random directions. Therefore, photons emitted by an ordinary light source are out of phase.

(ii) **Directionality: -** The conventional light sources emit light in all the directions. In case of laser light is emitted only in one direction. Light from a laser diverges very little.

(iii) **Brightness / Intensity: -** Light emission from a laser source is highly intense and bright. This is because the photons emitted from a laser travel in a straight line with a very low divergence, coherently. Therefore, the number of photons per unit beam cross-section is maximum.
It can be said that the intensity of the light is defined as the energy passing normally per unit per second through a point normal to the direction of flow.
For an ordinary spherical source, at a distance R, the intensity I can be given as

$$I = \frac{P}{4\pi R^2}$$ where P is the power of the source.

(iv) **Monochromaticity: -**Light from a laser is nearly monochromatic while the light from an ordinary source is never monochromatic.

(v) **Focus-ability: -**It is possible to focus a laser beam at an extremely fine spot. The diameter of the focal spot is directly proportional to the focal length F and the diameter D of the lens used for the purpose, is given by

$$diameter\ of\ the\ focal\ spot = \frac{F}{D}\lambda$$

Laser Applications: - The most significant applications of lasers include:

(i) Lasers in Medicine

- Lasers are used for bloodless surgery.
- Lasers are used to destroy kidney stones.
- Lasers are used in cancer diagnosis and therapy.
- Lasers are used for eye lens curvature corrections.
- Lasers are used in fiber-optic endoscope to detect ulcers in the intestines.
- Lasers are used to study the internal structure of microorganisms and cells.
- Lasers are used in plasma synthesis.
- Lasers are used to remove tumors successfully.
- Lasers are used in dentistry and dental surgery.
- Lasers are used in cosmetic treatments such as acne treatment, cellulite and hair removal.

(ii) Lasers in Communications

- Laser is used in optical fiber communications to send information over large distances with low loss.
- Laser is used in underwater communication networks.
- Lasers are used in space communication, radars and satellites.

(iii)Lasers in Industries

- Lasers are used in cutting, drilling & welding.
- Lasers are used to cut glass and quartz.
- Lasers are used in electronic industries for trimming the components of Integrated Circuits (ICs).
- Lasers are used for heat treatment in the automotive industry.
- Lasers are used in barcode scanning.
- Ultraviolet lasers are used in the semiconductor industries for photolithography.
- Lasers are used to drill aerosol nozzles and control orifices within the required precision.

(iv) Lasers in Science and Technology

- A laser helps in studying the Brownian motion of particles.
- With the help of a helium-neon laser, it was proved that the velocity of light is same in all directions.
- With the help of a laser, it is possible to count the number of atoms in a substance.
- Lasers are used in reading and writing computer ROM disks.
- Lasers are used to measure the pollutant gases and other contaminants of the atmosphere.
- Lasers helps in determining the rate of rotation of the earth accurately.
- Lasers are used in computer printers.
- Lasers are used for producing three-dimensional images by holography.
- Lasers are used for detecting earthquakes and underwater nuclear blasts.
- A gallium arsenide diode laser can be used to setup an invisible fence to protect an area.

(v) Lasers in Military

- Laser range finders are used to determine the distance to an object.
- The ring laser gyroscope is used for sensing and measuring very small angle of rotation of the moving objects.
- Lasers can be used as a secretive illuminator for reconnaissance during night with high precision.
- Lasers are used anti-missile technology.
- Laser light is used in LIDAR's to accurately measure the distance to an object.

Unit 4: Fiber Optics

Fiber Optics

It is the technology of transporting light signal in a guided media.

These light signal guiding media are called wave guides.

Optical Fiber

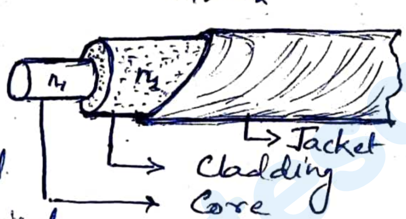
It is a wave guide through which light can be propagated in a predetermined path.

It is made up of glass or Plastic Clad Silica (PCS).

Main Components of a Optical Fiber

There are three main components of an optical fiber-

$n_1 > n_2$



(i) Core :- The central transparent cylindrical portion made of Plastic clad silica, having a large refractive index, where in the light signal is confined to propagate along the length, is called the core of the fiber.

(ii) Cladding :- A transparent covering which enfolds the core coaxially, having a refractive index less than that of the core, is called cladding.

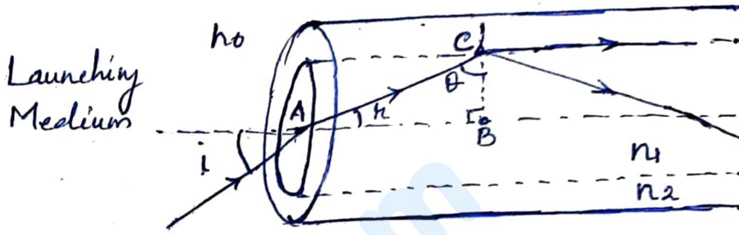
Its main function is to keep the light signal inside the core.

(iii) Jacket :- It is a protective coating over the cladding, made up of a suitable material, with a main purpose of protecting the fiber from damage due to wear and tear or external causes.

Principle of Working

The working of an optical fiber is mainly based on light propagation by Total Internal Reflection (TIR).

Light Propagation In Optical Fiber



Let there be an optical fiber of core & cladding refractive n_1 and n_2 such that $n_1 > n_2$.

An input light signal launched from a medium of refractive index n_0 is transmitted through the fiber as shown in the figure.

* At point A; according to Snell's law

$$\frac{n_1}{n_0} = \frac{\sin i}{\sin r}$$

$$\Rightarrow \sin i = \frac{n_1}{n_0} \times \sin r \quad \text{--- (1)}$$

In $\triangle ABC$; $r = 90 - \theta$

$$\Rightarrow \sin r = \sin 90 - \theta = \cos\theta$$

$\therefore$ Eq (1) becomes

$$\sin i = \frac{n_1}{n_0} \times \cos\theta$$

$$\text{or,} \quad \sin i = \frac{n_1}{n_0} \times \sqrt{1 - \sin^2\theta} \quad \text{--- (2)}$$

* At point C; light signal will propagate ~~there~~ in the core if total internal ref. is taking place at C and ahead.

Then applying Snell's law at pt. C

$$\frac{\sin\theta_c}{\sin 90} = \frac{n_2}{n_1}$$

$$\Rightarrow \sin\theta_c = \frac{n_2}{n_1} \quad \text{--- (3)}$$

From eq (2) and (3), for TIR conditions at $\theta = \theta_c$, $i = i_{max}$

②

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

$$= \frac{n_1}{n_0} \times \frac{\sqrt{n_1^2-n_2^2}}{n_1}$$

$$\sin i_{max} = \frac{\sqrt{n_1^2-n_2^2}}{n_0}$$

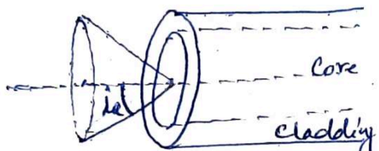
hence, $\boxed{i_{max} = \sin^{-1}\left[\frac{\sqrt{n_1^2-n_2^2}}{n_0}\right] = i_a}$;

i_a is called Acceptance Angle

Acceptance Angle – It is the maximum angle of incidence at which the light signal entering the core is propagated by total internal reflection, without getting lost in the cladding.

Acceptance Cone

An imaginary cone with in which all the light signals incident will be collected and propagated through the fiber is known as the acceptance cone.



This cone is made by an all round rotation of the incident signal entering the fiber at i_{max} Acceptance angle, about the fiber axis.

Numerical Aperture :- It is the light gathering ability of an optical fiber i.e. the amount of light that can be propagated through the fiber. It is given by –

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

Fractional/Relative Refractive Index (Δ)

It is defined as the ratio of difference in refractive indices of core and cladding to the refractive index of core.

i.e. $\Delta = \frac{(n_1-n_2)}{n_1} = 1 - \frac{n_2}{n_1}$

Relation between NA & Δ

We know that

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

If launching medium is air, $n_0 = 1$

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

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

$$= n_1 \times \sqrt{1-(1-\Delta)^2} \quad \left\{\because \Delta = 1 - \frac{n_2}{n_1}\right.$$

$$= n_1 \times \sqrt{2\Delta - \Delta^2}$$

$\because \Delta^2 << 2\Delta$, ignoring Δ^2, we get

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

Condition of light propagation in OF

TIR will take place only when angle of incidence $i \leq i_a$; Acceptance Angle

$\Rightarrow \sin i \leq \sin i_a$

or $\sin i \leq NA$

i.e. $\sin i \leq \frac{\sqrt{n_1^2-n_2^2}}{n_0}$

Modes of a Fiber and Normalized Frequency

Light signals entering in the fiber at various angles with in the range of acceptance angle, which are further allowed to propagate through the fiber are called Modes of a fiber.

The number of modes supported by a fiber are determined by a parameter called the V-number or the Normalized frequency given as –

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

where –

a – radius of the core of the fiber
λ – wavelength of the light signal
n_1 – RI of core
n_2 – RI of cladding

* If $V < 2.405$, fiber is Single Mode fiber
* If $V > 2.405$, fiber is Multimode fiber.
* If no. of allowed modes for a fiber are $\frac{1}{2}V^2$ then fiber is Step Index fiber.
* If no. of allowed modes for a fiber are $\frac{1}{4}V^2$ the fiber is Graded Index fiber.

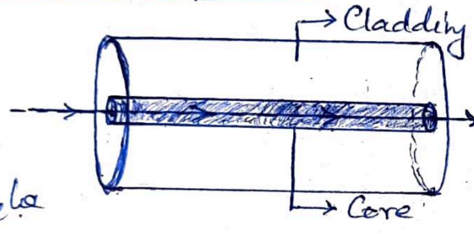
Optical Fiber Classification

Optical fibers are classified on the basis of two criterias –

(i) On the basis of allowed modes –

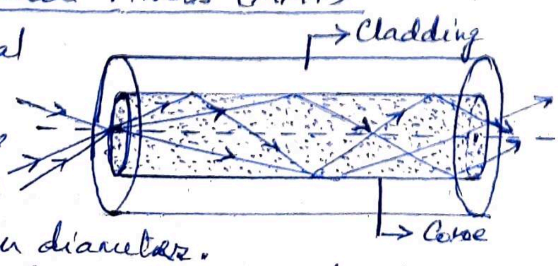
On the basis of allowed signal modes optical fibers are classified as ~~into~~ two categories

(a) Single Mode Fibers (SMF) –



- An optical fiber with a very narrow core is a Single mode fiber
- In Single mode fiber only one mode of signal propagation is possible.
- V-number for such fiber is less than 2.405.
- NA and Acceptance angles are very small for such fibers.
- Difference between core and cladding RIs is very small in such case.
- No dispersion makes it suitable for communication.
- Very less signal loss makes it more efficient.
- These fibers are costly because they are difficult to fabricate.
- Signal launching is also difficult.
- It is used for high speed, large bandwidth and long distance communication.

(b) Multimode Fibers (MMF)



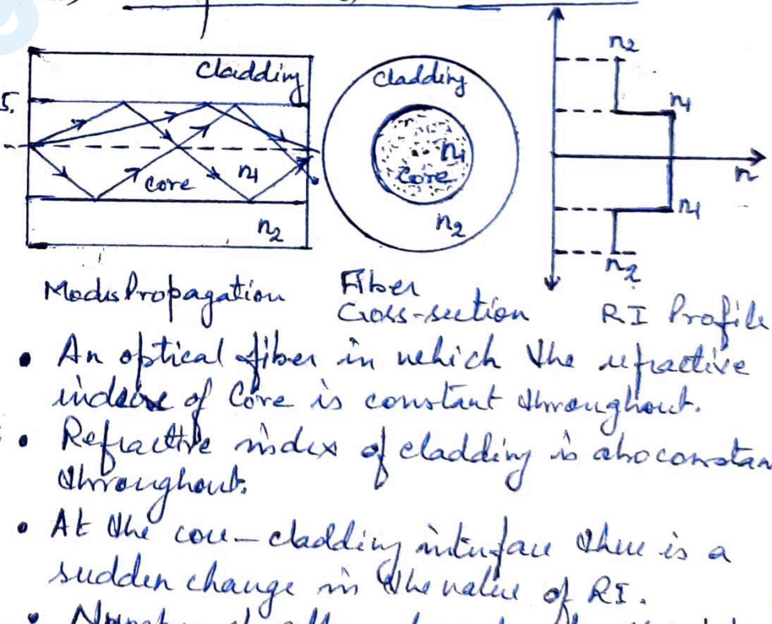
- It is an optical fiber with a wider core or having a core of larger diameter.
- In such a fiber a large number of modes are allowed to propagate.

- V-number of such fibers is more than 2.405.
- NA and acceptance angles values for such a fiber are quite large.
- Difference between the core and cladding RI's is larger than that in case of SMF.
- Due to multimode transmission, dispersion is large, so these fibers are not preferred for communication purposes.
- Easy fabrication makes the fiber cheaper.
- Signal launching doesn't not pose difficulty.
- Bandwidth length product is small.
- It is used for short distance communications only where signal distortion is not significant.

(ii) On the basis of Refractive Index Profile

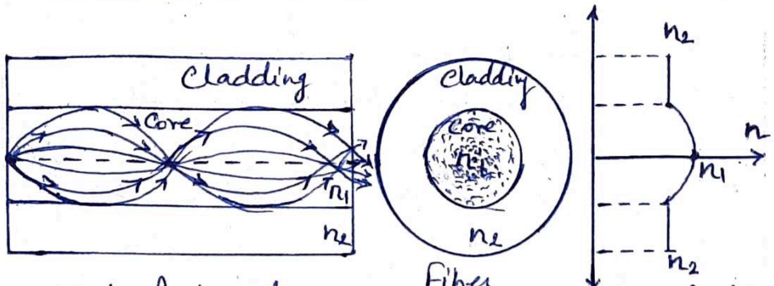
On the basis of difference between the refractive indices of core and cladding, optical fibers are classified into two categories –

(a) Step Index Fiber (SIF)



- An optical fiber in which the refractive index of Core is constant throughout.
- Refractive index of cladding is also constant throughout.
- At the core–cladding interface there is a sudden change in the value of RI.
- Number of allowed modes for this fiber is given as $\frac{1}{2}V^2$.
- Such fibers have large value of NA.
- Signal attenuation in this case is large.
- Pulse distortion is also present in such fibers.
- It offers lower bandwidth.
- Reflection losses are also present.
- It can be single mode or multimode.

(b) Graded Index Fiber. (GRIN)



Modes Propagation. Fiber Cross-section RI Profile

- An optical fiber in which the refractive index of the core changes gradually from higher to lower value, when we move radially outwards from the central axis.
- The cladding has a uniform RI.
- Number of allowed modes for this fiber is $\frac{1}{4}V^2$.
- NA value for such fibers is less.
- Signal attenuation in such fibers is less.
- Pulse distortion is minimum.
- It offers higher bandwidth.
- Reflection losses are absent.
- It supports multimode transmission only.

Attenuation

An optical signal passing through a fiber suffers a reduction in amplitude and intensity resulting in an overall loss of optical power in signal transmission. This is called attenuation.

Mathematically, it can be defined as the ratio of Input optical Power (P_i) to the output optical power (P_o).

i.e. $\alpha = \frac{10}{L} \log\left(\frac{P_i}{P_o}\right)$

Signal attenuation is expressed in terms of decibel/km (dB/km).

* For an ideal fiber $P_i = P_o$, attenuation = 0
* Permissible limit = upto 3dB
* Attenuation is wavelength dependent also.

Factors responsible for Attenuation losses:

Following three losses are mainly responsible for fiber attenuation –

(i) **Absorption Loss:**

Signal absorption is caused by basic material properties as well as the impurity of transition metal ions and the presence of (OH^-).

It occurs at all wavelengths, when electronic transitions take place with in the material and are followed by non-radiative relaxation processes.

In optical fiber it is not significantly large.

(ii) **Scattering loss:**

Scattering is also partly a material property but it also caused by the imperfection in the fiber geometry. It occurs when the mode of propagation of light is changed, such that some of the optical energy leaves the fiber.

- Rayleigh Scattering – It takes place when the signal is scattered by the microscopic inhomogeneities, microscopic fluctuations in the density of the material content, small RI irregularities caused due to impurity or bubble formation.
- Waveguide Scattering – It is caused by irregularities in the waveguide geometry and can be minimised by placing an additional silica layer over the cladding.

(iii) **Macro Bending losses:**

Tight bends of the fiber also cause some of the light not to be internally reflected but to propagate into the cladding and be lost.

(iv) **Microbending losses:** These occur when the core surface has smaller imperfections causing light refraction.

(v) Connectors & splicing imperfections also cause signal losses in fiber.

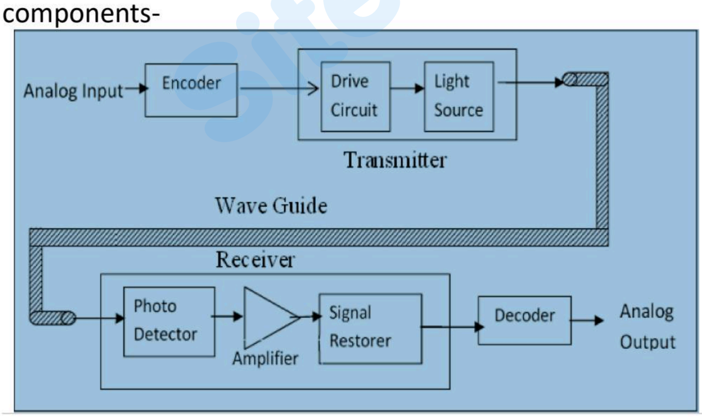
Signal Dispersion in Optical Fibres

- It is defined as the signal broadening or spreading while it propagates through the fibre.
- It occurs when a pulse sent into the fibre broadens in time during propagation, which is caused when its phase velocity depends on its frequency. Due to this, pulses launched into the fibre together emerge out at different times.
- Due to dispersion, a pulse of light travelling through a fibre not only gets attenuated but also distorted.
- Signal Dispersion in Optical Fibres is of two types-
  (i) **Modal/Intermodal Dispersion-** It occurs when each mode of signal travels different distances over the same time span, obviously they emerge out at different times leading to pulse spreading. It does not occur in single mode fibre.
  (ii) **Chromatic/Intramodal Dispersion-** It occurs when the light source feeds the signal at different frequencies including propagation delay differences between the signals of same frequencies. It causes the broadening of each transmitted mode.
  It is of two types-
    a) Material Dispersion- It is caused when there are different refractive index responses offered by the material of the fibre to different frequencies of the input signal. As different spectral components of the optical pulse have different speeds, it causes pulse spreading in time.
    b) Waveguide Dispersion- It occurs when the speed of the wave in an optical fibre varies with its frequency due to geometric reasons. It occurs for waves propagating through any inhomogeneous structure of the fibre.

The amount of wave guide dispersion depends upon the fibre design.

OPTIC - FIBER COMMUNICATION SYSTEM

An optical fiber communication system has following components-



1. **Encoder**
   Encoder is an electronic system that converts the analog information like voice, figures, objects etc., into binary data.

2. **Transmitter**
   It contain two parts, they are drive circuit and light source. Drive circuit supplies the electric signals to the light source from the encoder in the required form. The light source converts the electrical signals into optical form.
   With the help of specially made connector optical signals will be injected into wave guide from the transmitter.

3. **Wave guide.**
   It is an optical fiber which carriers information in the form of optical signals over distances with the help of repeaters. With the help of specially made connector optical signals will be received by the receiver from the wave guide.

4. **Receiver.**
   It consists of three parts; they are photo detector, amplifier and signal restorer. The photo detector converts the optical signal into the equivalent electric signals and supply to hem to amplifier. The amplifier amplifies the electric signals as they become weak during the long journey through the wave guide over longer distance. The signal restorer deeps the electric signals in a sequential form and supplies to the decoder in the suitable way.

5. **Decoder**
   It converts electric signals into the analog information.

Advantages of Optical Fiber Cable

- **Bandwidth** - Fiber optic cables have a much greater bandwidth than metal cables. The amount of information that can be transmitted per unit time of fiber over other transmission media is its most significant advantage.
- **Low Power Loss** - An optical fiber offers low power loss, which allows for longer transmission distances. In comparison to copper, in a network, the longest recommended copper distance is 100m while with fiber, it is 2km.
- **Interference** - Fiber optic cables are immune to electromagnetic interference. It can also be run in electrically noisy environments without concern as electrical noise will not affect fiber.
- **Size** - In comparison to copper, a fiber optic cable has nearly 4.5 times as much capacity as the wire cable has and a cross sectional area that is 30 times less.
- **Weight** - Fiber optic cables are much thinner and lighter than metal wires. They also occupy less space with cables of the same information capacity. Lighter weight makes fiber easier to install.
- **Security** - Optical fibers are difficult to tap. As they do not radiate electromagnetic energy, emissions cannot be intercepted. As physically tapping the fiber takes great skill to do undetected, fiber is the most secure medium available for carrying sensitive data.
- **Flexibility** - An optical fiber has greater tensile strength than copper or steel fibers of the same diameter. It is flexible, bends easily and resists most corrosive elements that attack copper cable.
- **Cost** - The raw materials for glass are plentiful, unlike copper. This means glass can be made more cheaply than copper.

Applications

- Medical- Used as light guides, imaging tools and also as lasers for surgeries
- Défense/Government - Used as hydrophones for seismic waves and SONAR, as wiring in aircraft, submarines and other vehicles and also for field networking
- Data Storage - Used for data transmission
- Telecommunications - Fiber is laid and used for transmitting and receiving purposes

- Networking - Used to connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission
- Industrial/Commercial- Used for imaging in hard-to-reach areas, as wiring where EMI is an issue, as sensory devices to make temperature, pressure and other measurements, and as wiring in automobiles and in industrial settings.
- Broadcast/CATV- Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet, video on-demand and other applications.
- Fiber optic cables are used for lighting and imaging and as sensors to measure and monitor a vast array of variables.
- Fiber optic cables are also used in research, development and testing across all the above-mentioned industries.

Short Answer Questions

1. What is optical fiber? **(2018-19)**
2. What do you mean by 'acceptance angle and acceptance cone for an optical fiber'? **(2021-22)**
3. What is 'numerical aperture'? Define it using the concept of total internal reflection.
4. Why modal dispersion is negligible in single mode fiber?
5. What is dispersion of radiation in optical fiber communication?
6. What is step index multimode fiber?
7. Why graded index optical fiber is better than multimode step index fiber?
8. What do you mean by scattering losses in fiber?
9. Give few important applications of optical fiber. **(2018-19, 15-16)**
10. What do you understand by attenuation in optical fiber? **(2018-19)**
11. What precautions are needed to minimize the material dispersion? **(2016-17)**

Numerical Problems

1. A step index fiber has core and cladding refractive indices 1.466 and 1.460 respectively. If the wavelength of light 0.85 m is propagated through the fiber of core diameter 50 µm, find the normalized frequency and number of mode supported by the fiber. [V= 24.75; N= 306] **(2021-22, 18-19)**
2. A silica glass optical fiber has a core refractive index of 1.500 and cladding refractive index of1.450. Calculate the numerical aperture, acceptance angle and critical angle of the filter. [NA= 0.385; i_a= 22.63^0; θ_c= 75.3^0] **(2021-22, 16-17)**
3. A communication system uses 10 Km fiber having a loss of 2.5 dB/Km compute the output power if the input power is 500µW? **(2021-22)**
4. A step index fiber has core refractive index 1.468 and cladding refractive index 1.462. Compute the maximum radius allowed for fiber, if it support only one mode at a wavelength 1300 nm. **(2015-16)**
5. The velocity of a light in the core of silica fiber is 2×10^8 m/s and the critical angle at the core cladding interface is 60°. Determine:
   i)The refractive index of the core and cladding.
   ii) The numerical aperture for the fiber **(2018-19)**
6. If fractional difference between core and cladding refractive indices of the optical fiber is 0.0135 and numerical aperture is 0.2425, calculate the refractive indices of core and cladding materials.

Long Answer

1. Explain the propagation mechanism inside the fiber optic system? What is the advantage of fiber optics technology in communication system?
2. Describe an optical fiber. Explain basic principle of optical fiber. Discuss fiber classification?
3. Discuss different types of pulse dispersion in optical fiber.
4. Discuss the propagation mechanism and communication in optical fibers. Also discuss about the power loss in optical fibers. **(2015-16)**
5. Explain acceptance angle and acceptance cone of an optical fiber. What do you mean by numerical aperture? Derive expressions for them. **(2018-19)**
6. Explain single and multimode fibers. Differentiate single mode from multimode fiber.
7. What do you understand by attenuation in optical fiber? Discuss the important factors responsible for the loss of power in optical fiber.
8. Discuss the different types of losses in an optical fiber. **(2016-17)**
9. What is optical fiber communication? Classify the optical fibers and explain it in detail.
10. What do you understand by modes of an optical fiber? Discuss propagation of light in single mode, multimode and graded index fiber. **(2018-19, 16-17)**