Unit-III

PHOTONICS and FIBER OPTICS

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- Einstein's coefficients
- He-Ne laser
- Nd:YAG Laser
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- Types of optical fiber *(Single mode & Multimode, Step index & Graded index)*
- Advantages & Application
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Module1

PHOTONICS

Introduction:

The word laser is the acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Laser is light source which produce highly coherent, monochromatic & intense beam of light. Due to this reason a beam of laser light can travels a long distance with very small divergence. The laser can play very important role in the field of scientific & technology, industry, communication & medicine. Laser is nothing but energy packet called photon having energy E= hυ.

Properties (Characteristics) of laser:

Following are the some important characteristic of laser.

i) Laser is highly monochromatic i.e. it has only one (single) wavelength.

ii) It is highly coherent i.e. all the waves emitted are in phase with each other.

iii) It is highly intense. A light from1 mW laser is 10000 times brighter than sun light.

iv) It is highly directional. Light emitted from laser travels in same direction.

v) It has very small divergence (spreading). Therefore it can cover a long distance without spreading.

Mechanism of Laser:

1) Absorption:

Let E_1 is lower energy level (ground state) & E_2 is higher level (excited state) in an atom as show below.

Energy gap (Eg) between E_1 & E_2 is

$Eg = E_2 - E_1 = h\upsilon$

Atoms are initially present in the ground state,
When light photon having energy **hυ** is incident on it then atom in lower energy level (E_1) absorbs incident energy and goes to higher energy level (E_2). This transition is called Absorption or excitation of atom.

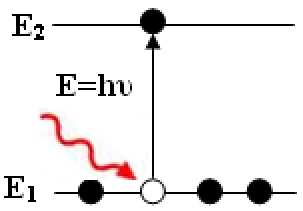


Fig. Absorption of Photon energy

2) Spontaneous Emission:

Def^n: The process in which the atom present in excited state return to ground state on its own or naturally without action of external force with emission of photon are called spontaneous emission.
When atom absorbed energy & going in excited state in excited state atom will be leave up to very small time i.e. in the range of **~ 10^{-8} sec** called **life time** after completing this time atom is become unstable & tries to come at ground state, during this transition absorbed energy is emitted in the form of photon having energy **E=hυ**, this emission is known as the spontaneous emission.

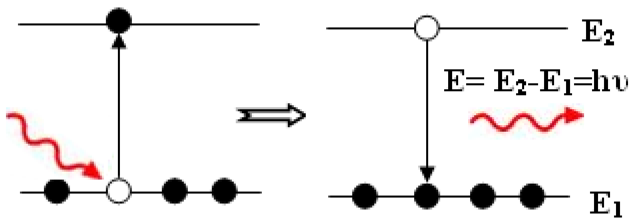


Fig. Spontaneous emission

3) Stimulated Emission:

In addition to absorption and spontaneous emission, there is a third possibility according to which **induced photon of energy E=hυ trigger excited atom to make downward transition with emission of two identical and coherent photon of same energy and traveling in the same direction, this phenomenon is called Forced emission or Stimulated emission.**

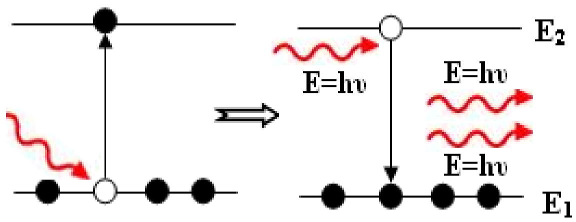


Fig. Stimulated Emission

Difference between Spontaneous emission and Stimulated emission:

Sr. No.	Spontaneous emission	Sr. No.	Stimulated emission
1)	It is a natural process.	**1)**	Artificial, induced process.
2)	Cannot be controlled.	**2)**	Can be controlled effectively.
3)	Atom in higher state return to ground state after completion of life time.	**3)**	Atom in higher state return to ground state after completion of life time.
4)	Only one photon emitted, which is not identical and coherent.	**4)**	Two identical and coherent photons are emitted.
5)	No multiplication of photons takes place.	**5)**	Multiplication of photons takes place.
6)	Not useful for LASER.	**6)**	Essential for LASER.
7)	No need of Metastable state.	**7)**	Metastable state is not necessary.

4) Life Time: The time for which an atom can remain in the excited state is called life time of an atom. Life time of excited hydrogen atom is of the order of 10^{-8} sec., however some of the excited states have longer life time i.e. 10^{-3} sec.

5) Population inversion:

Def^{n}: When number of atom in higher energy level greater than number of atom in ground energy level is known as population inversion.

The capacity of atoms or number atoms in any state is referred as its population. Let us consider two atomic level systems in which numbers of atoms in ground state energy level are N_1 and number atoms in higher energy level are N_2. Initially ground state is completely filled (N_1) and excited state is partially filled hence **$N_1 > N_2$** as shows in figure.

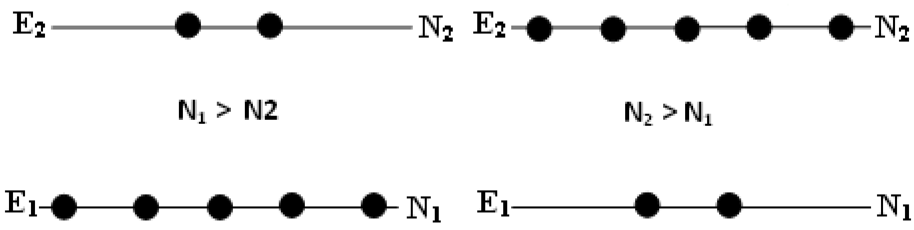


Fig. (a) Normal State *Fig. (b) Population Inversion*

Population inversion is the state of system in which numbers of atoms in excited state (N_2) are greater than number of atoms in ground state (N_1) i.e. **$N_2 > N_1$**.

Population inversion is important for generation of Laser.

6) Metastable State:

Def^{n}: The Metastable state is an excited state in which atom remain for longer time i.e. in terms of millisecond (10^{-3} sec).

This property of metastable state is essential for achieving a population inversion. Due to more life time large numbers of atoms are gathering in excited state, hence population inversion is achieved. The transition from metastable state to lower state always gives stimulated emission, hence laser beam.

7) Pumping:

Def^{n}: The process of raising large number of atoms from lower energy level (ground state) to higher energy level (excited state) is called pumping.

Types of pumping:

Pumping is of four types

i) Optical pumping: in optical pumping strong light source is used for excitation.

ii) Electrical pumping: The excitation is carried out by using electron beam or potential difference.

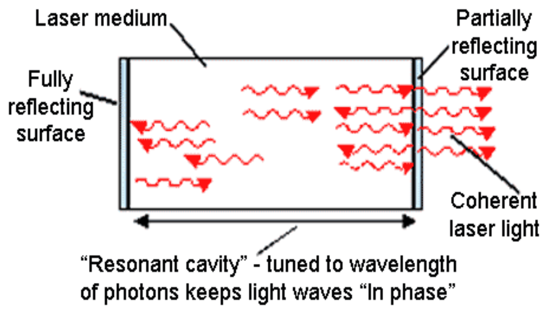
iii) Chemical pumping: the energy release from chemical reaction is used for excitation.

iv) Direct pumping: direct conversation of electrical in to light is used for excitation.

8) Active medium: A medium in which population inversion is achieved. **Or** the material used for generation of laser is called active medium.

9) Resonance cavity:

A resonance cavity consist of an active medium bound between two mirrors or highly reflecting surfaces as shown in fig. the two mirror along with active medium forms a cavity called resonance cavity.



In order to arrange constructive interference the distance 'L' between the two mirrors should be integral multiple of half wavelength. i.e. $L = m\frac{\lambda}{2}$ where m= integer & m >0.

Einstein's coefficient:

Einstein was the first to calculate the probability of such transition assuming the atomic system to be in equilibrium with electromagnetic radiation.

Under thermal equilibrium the number of upward transition is equal to number of downward transition per unit volume per second.

Rate of Absorption = Rate of Emission

$(R_{12})_{absption} = (R_{21})_{spont} + (R_{21})_{stimulated}$

$\mathbf{B_{12}N_1I\upsilon = A_{21}\,N_2 + B_{21}N_2I\upsilon}$ **…… (1)**

$B_{12}N_1I\upsilon - B_{21}N_2I\upsilon = A_{21}\,N_2$

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

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

Divide Numerator & denominator of above equation by $B_{21}N_2$

$$I_v = \frac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}}{B_{21}}\frac{N_1}{N_2} - 1}$$

$$\text{but}, N = e^{\frac{-E}{KT}}, \qquad \therefore N_1 = e^{\frac{-E_1}{KT}} \;\; \& \; N_2 = e^{\frac{-E_2}{KT}}$$

$$\therefore \frac{N_1}{N_2} = \exp\left(\frac{E_2 - E_1}{KT}\right) = \exp\left(\frac{hv}{KT}\right)$$

$$\therefore I_v = \frac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}}{B_{21}}\exp\left(\frac{hv}{KT}\right) - 1} \qquad \dots\dots(2)$$

Equation (2) must agree with Plank's energy distribution formula which is given by

$$I_v = \frac{8\pi hv^3}{c^3}\frac{1}{\exp\left(\frac{hv}{KT}\right) - 1} \qquad \dots\dots(3)$$

Comparing equation (2) and (3) we get,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi hv^3}{c^3} \qquad \dots\dots(4a)$$

$$\frac{B_{12}}{B_{21}} = 1 \; or \; B_{12} = B_{21} \dots\dots(4b)$$

Equation (4a) and (4b) are called Einstein's relation.

The ratio of spontaneous to stimulated emission is proportional to v^3.

The ratio of spontaneous to stimulated emission is

$$\frac{A_{21}N_2}{B_{21}N_2 I_v} = \frac{A_{21}}{B_{21}I_v} \quad \dots \dots (5)$$

Using equation (3) and (5)

$$R = \frac{A_{21}/B_{21}}{A_{21}/B_{21}} \ e^{h\nu/KT} - 1$$

$$R = \ e^{h\nu/KT} - 1 \quad \dots \dots \quad (6)$$

Therefore at thermal equilibrium at temperature T for $\nu \ll \frac{kT}{h}$, the number of stimulated emission exceeds the spontaneous emission, while for $\nu \gg \frac{kT}{h}$, the number of spontaneous emission exceeds the number of stimulated emission.

Pumping Scheme:

Any atom has large number of energy levels but for pumping process only few are useful.

There are different pumping schemes

1) Three level pumping schemes
2) Four level pumping schemes

1) Three level pumping schemes:

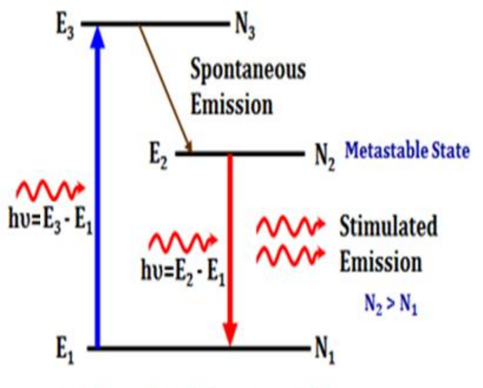


Fig. Three-level Pumping Scheme

- Let us assume that an atomic system has three energy levels as shown in figure.
- E_1 is ground state, E_3 is excited state and E_2 an intermediate state.
- When light of energy hν = E_3 - E_1 is incident than the atoms from state E_1 are excited to E_3 state.
- The lifetime of E_3 state is very short 10^{-8} sec, atoms do not stay for longer time and make downward transition to E_2 and E_1.
- E_2 is metastable state with lifetime of the order of milliseconds, so atoms stay at E_2 for comparatively longer time. A state of population inversion is achieved between E_2 and E_1.
- The photon (Laser) with energy hν = E_2 – E_1 triggers stimulated emission as shown in fig.

2) Four level pumping schemes:

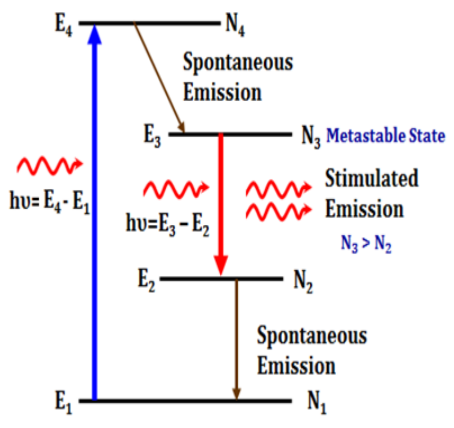


Fig. Four-level Pumping Scheme

- It involves four energy levels.
- Pumping lifts the active centers from E_1 to E_4 when a light of energy hν = E_4 - E_1 is incident on it.
- E_4 to E_3 is a nonradioactive transition.
- Atoms accumulates in the state E_3 which is metastable state and stays there for a comparatively longer period of time. Whereas E_2 is virtually empty. Therefore, a state of population inversion is achieved between E_3 and E_2.
- The photon (Laser) with energy hν = E_3 – E_2 triggers stimulated emission as shown in fig.
- From E_2 atoms undergo nonradioactive transition to ground state E_1 and will be once again available to participate in the process.
- Less pumping power is required to maintain population inversion so four level pumping schemes is superior to three level.

Types of laser:

Laser is of four types,

1) **Solid state laser:** eg. Ruby laser, Nd: YAG laser
2) **Liquid laser:** eg. Dye laser
3) **Gas laser:** eg. CO_2 laser, He-Ne laser
4) **Semiconductor laser:** eg. Diode laser.

He-Ne laser:

The He-Ne gas laser was first fabricated by A. jawan in 1960.The gas atom is characterized by sharp energy level as compare to solid so for continuous laser beam gas laser are used.

The advantages of gas lasers are they highly monochromatic & stability of frequency.

Principal: In He-Ne laser, He take part in excitation only and Ne take part in emission. The energy of He transfer to Ne atoms by resonance transfer phenomenon.

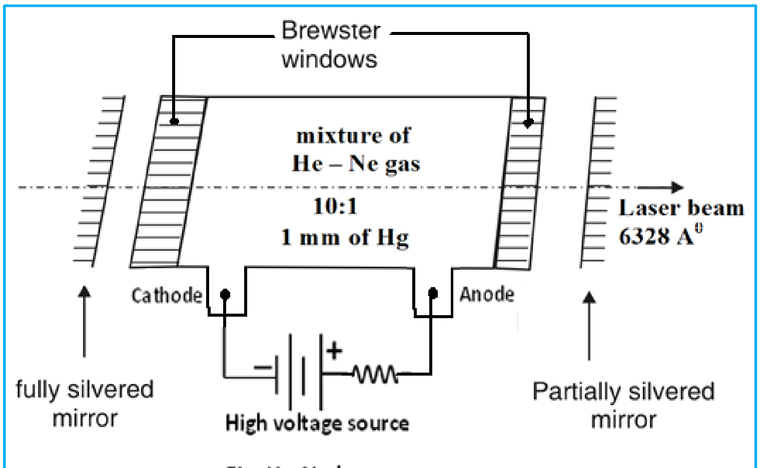
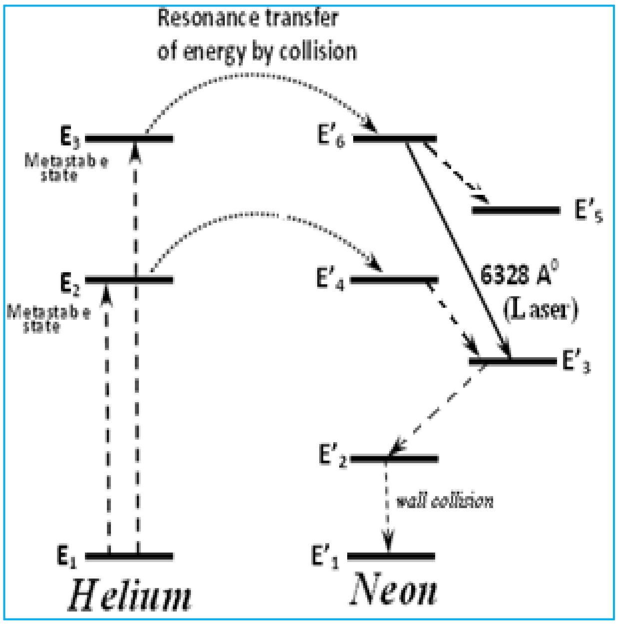


Fig. He-Ne laser

Construction:

The He-Ne laser consists of long, narrow discharge tube which is generally made up of Quartz material having length of 80cm & width of 1.5cm. A mixture of He and Ne gas is filled inside the tube in the proportion of 10:1 and at the pressure of 1mm of Hg (mercury). Both side of tube are sealed with Brewster window and coated with reflecting material. One side is completely (100%) reflecting and another side is partially (99%) reflecting is known as resonant cavity, the laser beam is coming from partially reflecting surface. The active material is He-Ne mixture is pumping by using ac or dc electric energy as shown in fig.



Working:

Let E_1, E_2, E_3 are the energy levels of **He** and E'_1, E'_2, E'_3, E'_4, E'_5, E'_6 are the energy levels of **Ne** as shown in fig. The **E_2 and E_3 energy level of He is exactly equal to E'_4 and E'_6 energy level of Ne.**

When a potential of 1KV is applied across the tube, the gas present inside tube start discharging, which result in generation of free electrons. The electrons produced are colloids with He atoms and excitation of He take place.

Where laser action occurs in "Ne" gas & "He" is added for excitation purposes.

He goes to E_2 & E_3 energy level which are metastable state, therefore remain there for relatively long time and population inversion is achieve. When He atom present in E_2 & E_3 collide with Ne, all the energy of He transfer to Ne by resonance transfer and Ne goes to excited state E'_4 and E'_6.

Due to population inversion in E_2 & E_3 of **"He"**, E'_4 and E'_6energy level of **"Ne"** also populated and given rise to following radiations,

The transition from E'_6 to E'_3 energy level gives out the stimulated emission nothing but the laser of wavelength **6328 A°**, which is in visible region & **red** in color .

Merits:

i) It has continuous output.
ii) The laser beam is highly monochromatic.
iii) Ne-Ne laser is highly stable.
iv) No separate cooling is required for it.
v) As gases are found in pure form their optical properties are well define.

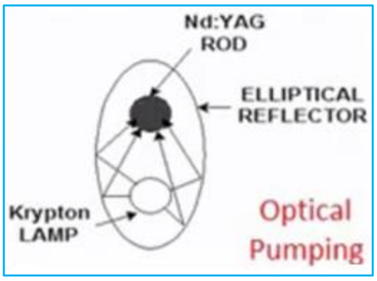
Demerits:

It has very low output power.

Applications:

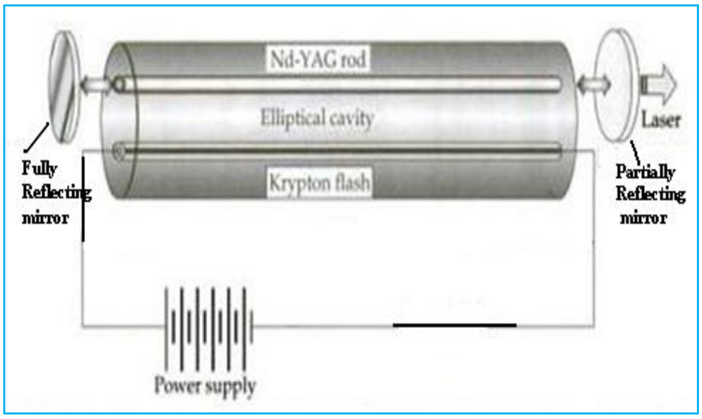
i) It is used as source in construction and reconstruction of holography.
ii) It is used in different research activities and laboratory purpose.
iii) It is also used in optical fiber communication.

Nd: YAG Laser:



It is a high power solid state laser; Nd stands for Neodymium (Nd^{+3} ions) and YAG stands for Yttrium Aluminum Garnet ($Y_3Al_5O_{12}$). Here some of Y^{+3} ions are replacing by Nd^{+3} ions. Here laser action occurring inside Nd. YAG is act as host or supporting atom, it cannot take part in lasing action.

Construction:



It consist of elliptically cylindrical reflector in which Nd:YAG rod and Krypton flash lamp are kept parallel to each other. The inner side of the cylinder is reflecting, the reflecting arrangement is adjusted such that all the light radiations are focus on Nd:YAG rod. Both end of the cylinder are closed with reflecting mirror, one side is fully reflecting and another is partially reflecting as shown in fig.

Working:

Figure represents the energy level diagram of Nd: YAG laser. E_3 is the metastable state & E_1 is the ground state of Nd atom.

When krypton flash lamp is switch on it emits the light of wavelength between 5000 A° to 8000 A° which is sufficient to excite the Nd^{+3} ions to higher energy level (pump band) as shown in fig. the upper laser level (E_3) is rapidly get populated due to downward transition from higher energy level. As E_3 is the metastable state population inversion is carried out in it. The transition from E_3 metastable state to lower laser level (E_2) gives stimulated emission of wavelength 10600 A° which is in **infrared** region generally use for machine operation.

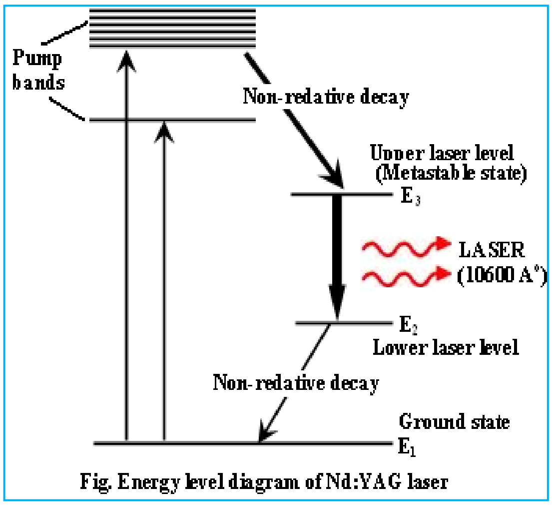


Fig. Energy level diagram of Nd:YAG laser

Application of laser:

- He-Ne laser is generally use as the bar code reader.
- Laser is used as light source in optical fiber communication system.
- They used in medical field for different purposes i.e. for surgery, treatment of detached retina etc.
- High power laser is used for cutting, drilling, welding of hard metals.
- Laser is used in 3-D photography i.e. Holography.
- They are used in automatic control of rocket and missile.
- They are used in computer printer, CD-ROM to read and write data.
- Laser are used to develop the hidden finger prints and also used to clean the delicate instruments.

Module2

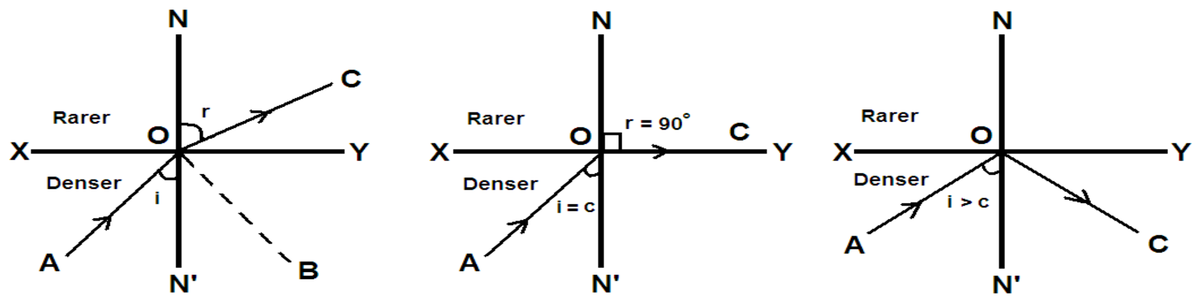
FIBER OPTICS

Introduction:

Fiber optics is the very important invention due to which entire sinario of telecommunication is change. Fiber optics is the technology related with transfer of light energy through a guided media like a optical fiber. They can transmit the laser and other light from one end to another as a result of **repeated total internal reflection**. The light is used to carry information in optical fiber. The information carrying capacity of light is thousand times greater than radio waves and microwaves due to its large bandwidth frequency.

Total Internal Reflection of Light (TIR):

When ray of light traveling from denser to rare medium and when angle of incidence greater than critical angle of incidence the ray of light reflected into same medium known as total internal reflection.



Condition for total internal reflection:

i) The ray must be **incident from denser medium to rarer medium**, therefore core must have larger refractive index (n_1) than cladding material (n_2). i.e. $\mathbf{n_1 > n_2}$

ii) The light should be incident by an angle of ‘θ’ which is greater than critical angle ‘θc’ **i.e.** $\boldsymbol{\theta_i > \theta_c}$**,**

Advantages of optical fiber over the metallic cable:

Optical fibers have many advantageous features which are not found in metallic cables

- It has high information carrying capacity typically 140 Mbps.
- It is free from noise those occurring due to electrical interference.
- A large signals can be pass thorough optical fiber in particular time without any interference hence the cross talk between two adjacent fibers is negligible.
- It offers greater security to the user.
- Optical fiber is flexible, lighter & smaller so it is easy to handle.
- Optical fiber cable is cheaper & safer.
- Transmission loss of signal in optical fiber is much lower than that of metallic cables.
- Fiber are made out of glass, hence they are perfectly insulator, also in signal being transmitted is in the optical form, so there is no danger of sparking due to short circuit.

Optical fiber:

Def^{n}: It is a thin, flexible thread of glass or plastic design to guide light along their length. Its diameter is about 125μm.

Principle:

It is worked on the principle of the Total internal reflection of light. When the light enters one end of fiber it undergoes successive total internal reflections from side wall and travel along the length of fiber.

Construction:

It consist of three parts,

i) Core: it is the central cylindrical region through which light is transmitted. The refractive index of core is denoted by 'n_1' which is **larger** as compare to cladding. The size of the core is in the range of 25μm.

ii) Cladding: the core is surrounded by a coaxial middle region called cladding. The refractive index of cladding is denoted by 'n_2' is always less than core. The purpose of cladding is to keep the light within the core by total internal reflection and avoid to leakage of light from one fiber to another. It also provides strength to the cable. The core as well as cladding is made up of the same material like glass or plastic. e.g. Silica, Phosphate, Fluoride, Chalcogenide etc.

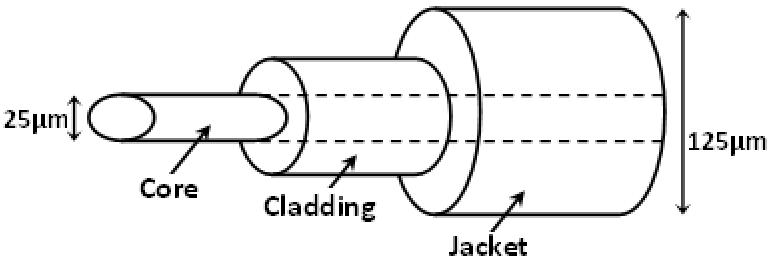


Fig. Structure of fiber optics.

iii) Jacket: The outer most cover of the optical fiber is known as jacket. It is protects the fiber from moisture and abreaction. It is generally made of the Plastic or rubber.

Working:

When the ray of light launch from the launching zone (generally air) by an appropriate launching angle then angle of incidence at core cladding boundary will be greater than critical angle and total internal reflection takes place. In this way multiple total internal reflection takes place at core cladding boundary and light is transfer to another end.

The total internal reflection is occur only when the incident ray follow the following condition.

i) The ray must be **incident from denser medium to rarer medium**, therefore core must have larger refractive index (n_1) than cladding material (n_2). i.e. $\mathbf{n_1 > n_2}$

ii) The light should be incident by an angle of 'θ' which is greater than critical angle 'θc'
i.e. $\theta_i > \theta_c$,

Basic Terms:

Critical angle (θc):

Critical angle is defined as the angle of incidence for which angle of refraction is 90° (**$\theta_r = 90°$**).

$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$

Acceptance angle (θo):

Def^n: The acceptance angle of incidence is defined as the maximum angle at which the ray of light propagating through the optical fiber.

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

For air the refractive index $n_0 = 1$

$$\therefore \theta_0 = \sin^{-1}\sqrt{{n_1}^2 - {n_2}^2}$$

$$\therefore \theta_0 = \sin^{-1}(N.A.)$$

Acceptance cone (2θo):

The twice of acceptance angle is Acceptance cone.

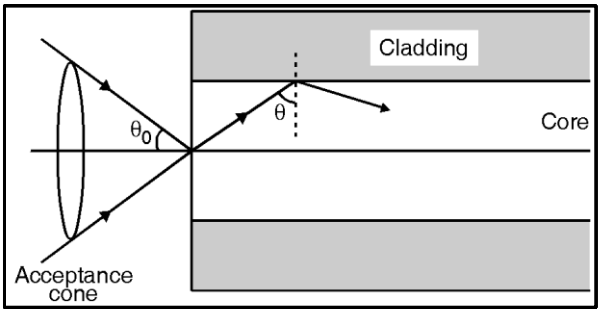
Acceptance cone = 2 x Acceptance angle = 2θo

Numerical Aperture (N.A.):

Que: Define numerical aperture of optical fiber. Derive an expression for numerical aperture of step index fiber.

Def^n: The light gathering ability of an optical fiber is known as the numerical aperture. The numerical aperture is (N.A.) is measured as the sine of the acceptance angle.

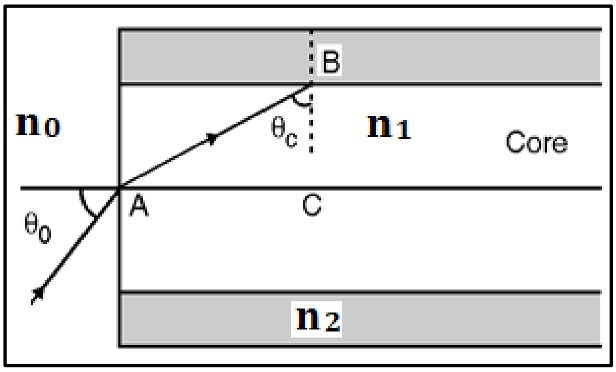
The numerical aperture sometimes called as the **figure of merit for optical fibers.**



$$\mathbf{N.A.} = \boldsymbol{Sin\ \theta o}$$

To calculate numerical aperture, consider the light wave which travels along the core and meets the cladding, with $\theta > \theta_c$, will be totally reflected.

Any light wave incident on the core within this maximum external incident angle θ_0 is coupled into the fibre and will propagate. This angle is called as angle of acceptance.



Let us now derive a mathematical relation for the numerical aperture.

Now from Figs. b) and c) and applying Snell's law of refraction at A and B we get,

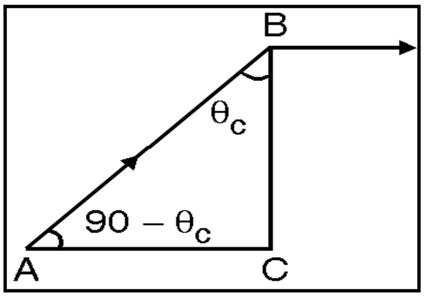
$$n_0 \sin\theta_0 = n_1 \sin\theta_r \text{ (at point A)}$$

$$n_0 \sin\theta_0 = n_1 \sin(90-\theta_c) \dots\dots (1) \text{ (at point A)}$$

$$n_1 \sin\theta_c = n_2 \sin 90 \dots\dots (2) \quad \text{(at point B)}$$

$$n_1 \sin\theta_c = n_2$$

$$\mathbf{\sin\theta_c} = \frac{\mathbf{n_2}}{\mathbf{n_1}} \quad \dots\dots \ (\mathbf{3})$$



But, $\sin(90-\theta_c) = \cos\theta_c$ therefore equation (1) becomes

$$n_0 \sin\theta_0 = n_1 \cos\theta_c$$

$$n_0 \sin\theta_0 = n_1\sqrt{1-\sin^2\theta_c}$$

Put $\sin\theta_c$ from equation (3), we get

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

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

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

$$\mathbf{N.A.} = \frac{\sqrt{\mathbf{n_1}^2-\mathbf{n_2}^2}}{\mathbf{n_0}}$$

For air refractive index (no) = 1

$$\mathbf{N.A.} = \sqrt{\mathbf{n_1^2}-\mathbf{n_2^2}}$$

$$\mathbf{N.A.} = \mathbf{n_1}\sqrt{\mathbf{2}\,\Delta}$$

It is used to describe the light collecting ability of an optical fiber. The larger is the magnitude of numerical aperture a fiber, the greater will be the amount of light collected by the fiber from the external source of light.

N.A. is the parameter which provides information about the acceptance angle i.e. the angle at which if the light ray enters the fiber it is sure to have Total Internal Reflection occur.

It has been observed that N.A. for the fibers used in short distance communication are in range of 0.4 to 0.5, whereas for long distance communications N.A. are in the range of 0.1 to 0.3.

Fractional refractive index change (Δ):

The fractional difference (Δ) between the refractive indices of the core and the cladding is known as fractional refractive index change.

It is expressed as

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

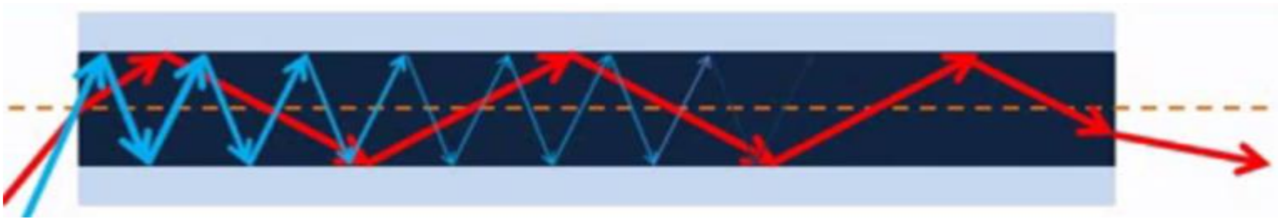
This parameter is always positive because for optical fiber $n_1 > n_2$. Typically (Δ) is of the order of 0.01

Mode of propagation and Number of modes:

The light ray paths along with the waves are in phase inside the optical fiber is known as modes. In simple words the allowed paths for the light ray inside the optical fiber is known as mode of propagation.

$$\textbf{Number modes} \propto \frac{d}{\lambda}$$

$$N_m \propto \frac{1}{2} V^2$$



V-number:

An optical fiber is characterized by one important parameter known as V-number. The number of modes supported by a fiber is determined by an important parameter known as **V-number or cut off parameter**. It is also called as **normalized frequency**. It is given by

$$V = \frac{\pi d}{\lambda}\sqrt{n_1{}^2 - n_2{}^2} = \frac{\pi d}{\lambda}(N.A.)$$

$$V = \frac{\pi d}{\lambda}(N.A.)$$

$$V = \frac{\pi d}{\lambda} n_1 \sqrt{2\,\Delta}$$

Where,
d = diameter of core
λ = wavelength of light being transmitted
n_1 = refractive index of core
n_2 = refractive index of cladding

The maximum number of modes Nm supported by a step index fiber is

$$N_m \propto \frac{1}{2} V^2$$

Significance:

- Each of the mode mentioned above has a particular value of V-number parameter, below which the mode will be cut off.
- For **V < 2.405 the fiber can support only one mode** and hence it is single mode fiber (SMF), for **V > 2.405 the fiber can support multimode** and hence it is multimode fiber (MMF).

Losses in fiber:

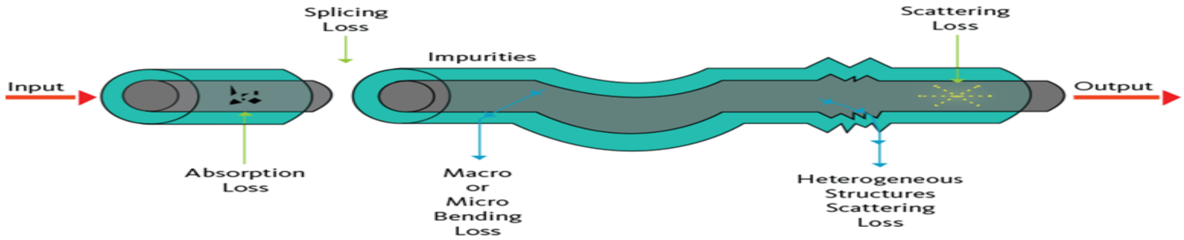
Attenuation:

Attenuation means **"loss of optical power"** in the fiber itself. It is defined as ratio of optical input power (P_{in}) to the optical output power (P_{out}) along its length (L).

$$\alpha = \frac{10}{L}\log\frac{P_{in}}{P_{out}}$$

The band of the wavelengths at which attenuation is minimum is called an **"Optical Window"**. Such window are selected for data transmission through fiber.
Grain fiber tends to have generally lower attenuation than SI fiber.

There are some **extrinsic fiber core attenuation (EFA) losses** such as **bending and splicing losses** cause due to incorrect handling, manufacturing defects, environmental factors like change in temperature, humidity and pressure etc.
There are some **intrinsic fiber core attenuation (IFA) losses** such as **light absorption and scattering loss**.



Classification of Optical Fiber based on Number of Mode of Propagation:

1) Single-mode optical fiber
2) Multimode optical fiber

Single-mode optical fiber:

The single mode optical fiber is design to carry only one signal of light (mode). This signals or ray of light often contains a range of different wavelengths. The typical single mode optical fiber has core diameter of 8-10 µm and cladding diameter of 125 µm. It is designed such that only a small refractive index difference exists between the core and the cladding. Only laser light can be used for the signal propagation through single mode optical fiber.

Multimode optical fiber:

In multimode optical fiber, more than one signal can be propagated. Multimode fibers have several advantages over single mode fibers. The multimode optical fiber has large core diameter. Multimode optical fibers are mostly used for shorter distance communication, such as within the building or inside a campus. Typical multimode fiber have data rates of 10 Mbit/s to 10 Gbit/s over the length of upto 600 m, which is sufficient for the majority of applications within the premises.

Difference between Single mode and Multimode:

Sr. No.	Single-mode optical fiber	Sr. No.	Multimode optical fiber
1)	It design to carry only one signal of light (mode)	**1)**	It design to carry more than one signal of light (mode)
2)	It has small core diameter.	**2)**	It has large core diameter.
3)	It has small refractive index difference between the core and the cladding.	**3)**	It has large refractive index difference between the core and the cladding.
4)	It mostly used for longer distance communication.	**4)**	It mostly used for shorter distance communication.
5)	Only laser light can be used for the signal propagation.	**5)**	Both laser and LED light can be used for the signal propagation.
6)	It has small optical losses.	**6)**	It has large optical losses.

Classification of Optical Fiber based on Refractive Index Profile:

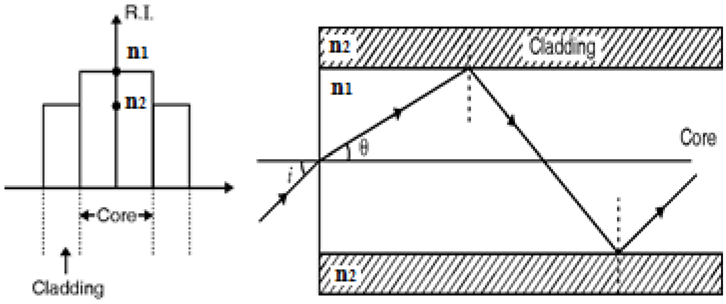
1) Single Mode Step Index Fibers (SMF)
2) Multi-Mode Step Index Fibers (MMF)
3) Multi-Mode Graded Index Fibers (GRIN)

The classification of optical fiber is based upon the index profile of an optical fiber this defines how the index of refraction varies as a function of radial distance from the center of the fibers.

Single Mode Step Index Fibers (SMF):

It is simplest type of an optical fiber consists of transparent glossy material of uniform refractive index $\mathbf{n_1}$, surrounded by cladding of uniform refractive index ($\mathbf{n_2}$) slightly less than core.

These fiber are known as step index due to discontinuity of profile at core cladding interface.



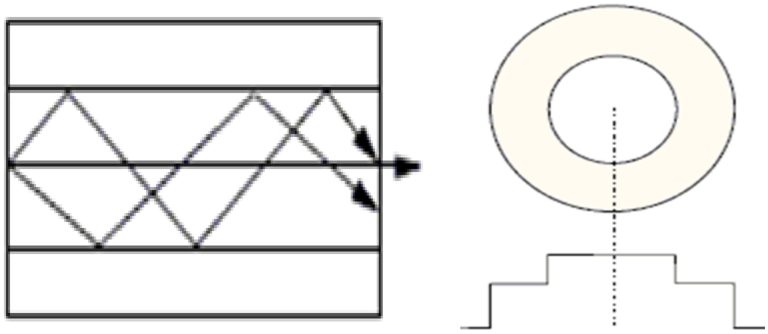
It is a low loss optical fiber with a very small diameter compared with the wavelength of the light source. Their radius is of the order of 1 to 16 micrometer.

This fiber required a laser source for the input signal because of extremely small acceptance cone.

Mono mode means it has a single path for light to travel in the fiber.

It is useful for long distance transmission of signal. It is as shown in figure.

Multi-Mode Step Index Fibers (MMF):



In this case the optical fiber has large core radius i.e. 25 to 60 um and large numerical aperture.

Due to large radius and numerical aperture it can couple efficiently to a light source like LED.

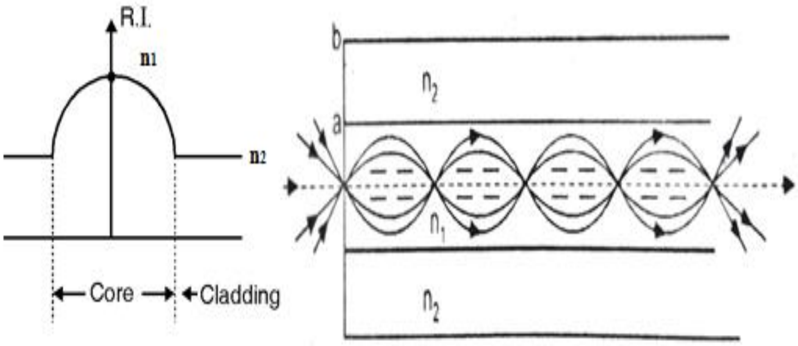
Comparatively large are radius allows many rays to travel down to core.

All these rays striking me cladding at various acceptance angles. Because each ray travels a different distance at the same speed, their arrival times will vary, giving rise to multimode step index type fiber.

Important characteristics of step index fiber:

- Very small core diameter.
- Low numerical aperture.
- High attenuation loss
- Very high bandwidth.

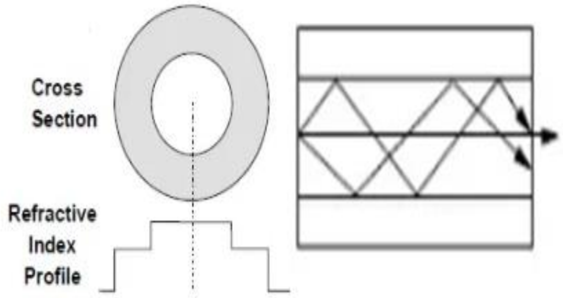
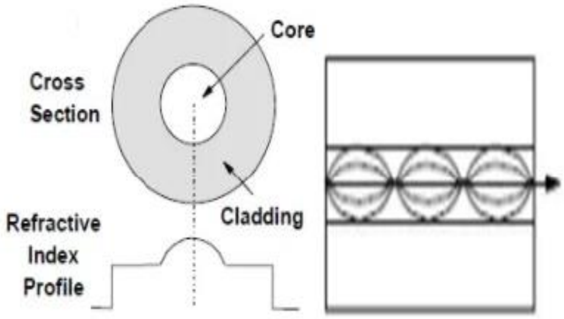
Multi-Mode Graded Index Fibers (GRIN):



The graded index fiber has its core refractive index **gradually decreasing** in a **nearly parabolic** manner. R.I. has maximum value at the center of core and decreases continuously towards cladding as shown in fig. The variation in refractive index is achieved by using concentric layer of different refractive index. In this case the optical fiber has large core radius i.e. 25 to 60 um and large numerical aperture. Due to large radius and numerical aperture it can couple efficiently to a light source like LED. Comparatively large core radius allows many rays to travel down to core. They consist of the axial rays and various other rays. All these rays striking me cladding at various acceptance angles. Because each ray travels a different distance at the same speed, their arrival times will vary, giving rise to multimode step index type fiber Such fiber can causes interference of propagating rays. It is as shows in figure.

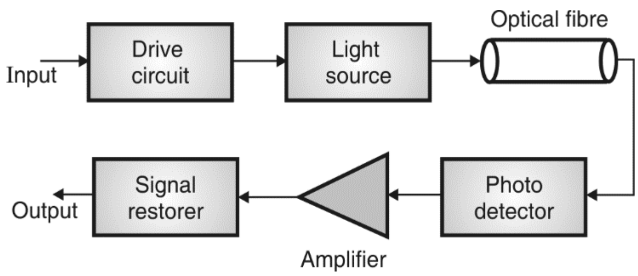
Difference between step index and graded index fiber:

Que: Distinguish between step index and graded index optical fiber with refractive index profile diagram?

Sr. No.	Step index optical fiber	Sr. No.	Graded index optical fiber
1)		**1)**	
2)	R.I of core is constant.	**2)**	R.I of core is gradually decreases from center towards cladding.
3)	It has **uniform** refractive index profile.	**3)**	It has **parabolic** refractive index profile.
4)	Light can travel different distance in different interval of time (zig-zag manner).	**4)**	Light can travel different distance in same interval of time (helical manner).
5)	Lower Numerical aperture (NA) than graded index fiber.	**5)**	Higher Numerical aperture (NA) than step index fiber.
6)	Suitable for short distance communication.	**6)**	Suitable for long distance communication.
7)	Low bandwidth compare to graded index fiber.	**7)**	High bandwidth compare to step index fiber.
8)	Less expensive to manufacture due to simple construction.	**8)**	High expensive to manufacture due to complex construction.
9)	Higher signal attenuation due to more signal loss.	**9)**	Lower signal attenuation due to less signal loss.

Application of optical fiber:

- **Communication system**



In optical fiber communication system light waves which are carrier waves, are generated by a LED or a laser diode as shown in fig.

The intensity of light is proportional to the current passing through it. When the message in electrical form is fed to the optic source, the light output from it follows the variations of message. In order to have efficient transmission through the fiber the frequency of operation is chosen to lie in the optical window region of the fiber.

At the received end, the photo detector converts the light wave into an electric current. The message is contained in the detector output current.

The detector output current is filtered to extract the message and it is amplified if needed. It is then fed to a suitable transducer to convert into an audio or video form.

- **Medicine**
  Optical fiberscope use in endoscopy for visualization of internal portion of the body.
- **In aircrafts cabling**
  They are much smaller in size and weight, hence used in aircraft.
- **Data security**
  The cross talk between neighboring fibers are almost absent, therefore they are very useful in defense communication.

It is used in industry for security alarm system and process control.

It is used in computer networking to exchange information between different terminals in network.

- **Communication network in high voltage region**
  They can be safely used in high voltage environment. Ex. power station.
- **Entertainment applications**
  A coherent optical fiber bundle is used to enlarge the image displayed on a TV screen.
- **Pressure sensors**
  It is used as a temperature sensor (The measurement and calibration of this output power provides the amount of pressure acted over the fiber.)
- **Temperature sensor**
  It is used as a temperature sensor (If the fiber is subjected to heating, the temperature causes a change in the refractive index of the fiber, as the temperature increases refractive indices of core and cladding reduces)
- **Smoke detector**
  A smoke detector and pollution detector can be built using fiber.
- **Level detector**
  A loop of fiber can be used to determine the level of liquid in a container.

Important Formulae:

- **Critical Angle (θc):**

$$\theta c = \sin^{-1}\frac{n_2}{n_1}$$

- **Acceptance Angle (θo):**

$$\theta o = \sin^{-1}\frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0}$$

$$\theta o = \sin^{-1}\sqrt{{n_1}^2 - {n_2}^2} \qquad \text{Since } n_0 = 1 \text{ for air}$$

$$\theta o = \sin^{-1}(N.A.)$$

- **Fractional refractive index change (Δ):**

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

- **Attenuation loss:**

$$\boldsymbol{\alpha = \frac{10}{L}\log\frac{P_{in}}{P_{out}}}$$

- **Numerical Aperture (NA):**

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

$$NA = Sin\,\theta o$$

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

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

- **V-Number:**

$$V = \frac{\pi d}{\lambda}\sqrt{{n_1}^2 - {n_2}^2} = \frac{\pi d}{\lambda}(N.A.)$$

- **Number of modes:**

$$N_m \propto \frac{1}{2}V^2$$

Numerical:

1) Calculate the numerical aperture of a fibre with core index $n_1 = 1.55$ and cladding index, $n_2 = 1.51$.

Soln.:

Given : $n_1 = 1.55$, $n_2 = 1.51$, NA = ?

Formula

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.55^2 - 1.51^2} = \mathbf{0.35}$$

2) An optical glass fibre of R.I. 1.50 is to be clad with another glass to ensure internal reflection that will contain light travelling within 5° of the fibre axis. What minimum index of refraction is allowed for the cladding?

Soln.: $\theta_{max} = 5°$, $n_1 = 1.5$, $n_2 = ?$

Formula : $\theta_m = \sin^{-1}(N.A) = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$

$$\sin\theta_m = \left(\sqrt{n_1^2 - n_2^2}\right)$$

$$\mathbf{n_2 = \left(\sqrt{n_1^2 - \sin^2\theta_m}\right) = 1.4974}$$

3) Calculate the numerical aperture and hence the acceptance angle for an optical fibre given that refractive indices of the core and the cladding are 1.45 and 1.40 respectively.

Soln.: $n_1 = 1.45$, $n_2 = 1.40$, N.A. = ?, $\theta_o = ?$

$$\mathbf{NA} = \left(n_1^2 - n_2^2\right)^{1/2} = (0.1425)^{1/2}$$

$$\mathbf{NA = 0.3775}$$

Acceptance angle

$$\theta_o = \sin^{-1}\sqrt{n_1^2 - n_2^2} = \sin^{-1} 0.3775$$

$$\boldsymbol{\theta_o = 22.18}$$

4) A fibre cable has an acceptance angle of 30° and core index of R.I. 1.4. Calculate R.I. of cladding.

Soln.:

$\theta = 30°$, $n_1 = 1.4$, $n_2 = ?$

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

$$\therefore \quad \sin 30° = \sqrt{n_1^2 - n_2^2}$$

$$0.5^2 = 1.4^2 - n_2^2$$

$$\therefore \quad \mathbf{n_2 = 1.308}$$

5) Compute the NA, acceptance angle, and the critical angle of the fibre having n_1 (core refractive index) = 1.50 and the refractive index of the cladding = 1.45.

Soln. :

$n_1 = 1.50$, $n_2 = 1.45$, N.A. = ?, $\theta_o = ?$, $\theta_c = ?$

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

$$\Delta = \frac{1.5 - 1.45}{1.5} = 0.033$$

$$N.A. = n_1\sqrt{2\Delta} = 1.5\sqrt{2 \times .033}$$

$$\mathbf{N.A. = 0.387}$$

θ_0 = Acceptance angle = $\sin^{-1}$ NA

$\boldsymbol{\theta_0 = 22°}$

$$\theta_c = \sin^{-1}\frac{\mu_2}{\mu_1} = \sin^{-1}\frac{1.45}{1.5}$$

$\boldsymbol{\theta_c = 75.2°}$

6) Calculate the refractive indices of the core and cladding material of a fibre from the following data NA = 0.22, Δ = 0.012

Soln.:

NA = 0.22, Δ = 0.012, n_1 =?, n_2 = ?

$$\Delta = \frac{n_1 - n_2}{n_1} = 0.012$$

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

$$\boldsymbol{n_1 = \frac{NA}{\sqrt{2\,\Delta}} = 1.42}$$

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

$\boldsymbol{n_2 = 1.40}$

7) A glass clad fibre is made with core glass of refractive index 1.5 and the cladding is doped to give a fractional index difference of 0.0005.

Find : (a) The cladding index

(b) The critical internal reflection angle

(c) The external critical acceptance angle

(d) The numerical aperture

Soln. : $n_1 = 1.5$, $\Delta = 0.0005$, n_2 = ?, N.A. = ?, θ_o = ?, θ_c = ?

(a) Let the refractive index cladding be n_2

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

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

$$n_2 = 1.5 - 1.5 \times 0.0005$$

$\boldsymbol{n_2 = 1.499925}$

(b) Let the critical internal reflection angle be ϕ_c

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

$$\theta_c = \left[\frac{n_2}{n_1}\right] = \sin^{-1}\left[\frac{1.4925}{1.5}\right]$$

$$\theta_c = \sin^{-1}(0.9995)$$

$\boldsymbol{\theta_c = 88.2}$

(c) Let the external critical acceptance angle be

$$\theta_0 = \sin^{-1}\sqrt{n_1^2 - n_2^2}$$

$$= \sin^{-1}[(1.5)^2 - (1.49925)^2]^{1/2}$$

$\boldsymbol{\theta_0 = 2.720}$

(d) Numerical Aperture NA = $n_1\sqrt{2\,\Delta}$

$$NA = 1.5\sqrt{2 \times 0.0005} = 1.5\,(0.03162)$$

NA = 0.0474

8) An optical fibre has a NA of 0.20 and a refractive index of cladding is 1.59. Determine the acceptance angle for the fibre in water which has a refractive index of 1.33.

Soln. :

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

When the fibre is in air $n_0 = 1$

$$NA = \sqrt{n_1^2 - n_2^2} = 0.20$$

$$n_1 = \sqrt{(NA)^2 + n_2^2} = \sqrt{(0.20)^2 + (1.59)^2} = 1.6025$$

$\mathbf{n_1 = 1.6025}$

When the fibre is in water $n_0 = 1.33$

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} = \frac{\sqrt{(1.6025)^2 - (1.59)^2}}{1.33}$$

NA = 0.15

$$\theta_0\,(max) = \sin^{-1}(NA) = \sin^{-1}(0.15)$$

$\boldsymbol{\theta_0}$ **(max) = 8.6°**

9) A step index fibre has a numerical aperture of 0.16, a core, a core refractive index of 1.45 and core diameter of 90 mm calculate.

a) The acceptance angle θ_c

b) The refractive index of the cladding.

Soln. : NA = 0.16, $n_1 = 1.45$, $n_2 = ?$ $\theta_c = ?$

(a)
$$\begin{aligned} NA &= \sqrt{n_1^2 - n_2^2} \\ 0.16 &= \sqrt{1.45^2 - n_2^2} \\ 0.0256 &= 1.45^2 - n_2^2 \\ n_2^2 &= 2.0769 \\ \mathbf{n_2} &= \mathbf{1.441} \end{aligned}$$

(b)
$$\sin\theta_c = \frac{NA}{n_0} = \frac{0.16}{1}$$

$$\boldsymbol{\theta_c = 9° \; 12}$$

10) A step index fiber is made with core of index 1.52 and diameter 29 µm and cladding refractive index of 1.5189. If it is operated at wavelength 1.3 µm, find V number of fiber and number of mode it will support.

Soln. :

$n_1 = 1.52$, $n_2 = 1.5189$, $d = 29 \times 10^{-6}$ m, $\lambda = 1.3 \times 10^{-6}$ m, V = ? N_m = ?

$$V = \frac{\pi d}{\lambda}\sqrt{n_1{}^2 - n_2{}^2}$$

$$V = \frac{3.142 \times 29 \times 10^{-6}}{1.3 \times 10^{-6}}\sqrt{(1.52)^2 - (1.5189)^2}$$

$$\mathbf{V = 4.05}$$

As, V > 2.405,

$$N_m \approx \frac{1}{2}V^2 = \frac{(4.05)^2}{2}$$

$\mathbf{N_m = 8.20}$, **Thus the fiber will support 8 modes.**

11) Find the core radius necessary for single mode operation at 850 nm in step index fiber with n_1 = 1.480 and n_2 = 1.47. What is the numerical aperture and maximum acceptance angle of the fiber?

Soln. :

$n_1 = 1.480$, $n_2 = 1.47$, $\lambda = 850 \times 10^{-9}$ m, a = ?, N.A. = ? θ_0 = ?

For single mode operation $V \leq 2.405$

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

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

$$a = \frac{2.405 \times 850 \times 10^{-9}}{2 \times 3.142 \times \sqrt{(1.48)^2 - (1.47)^2}}$$

$$\mathbf{a = 1.894 \times 10^{-6}\, \boldsymbol{m}}$$

$$\mathrm{N.A.} = \sqrt{n_1{}^2 - n_2{}^2} = \sqrt{(1.48)^2 - (1.47)^2}$$

$$\mathbf{N.A. = 0.1717}$$

$$\theta o = \sin^{-1}(\mathrm{N.A.}) = \sin^{-1}(0.1717)$$

$$\boldsymbol{\theta o = 9.887^o = 9^o 53'}$$

12) An optical fiber has core diameter 6 µm and core refractive index is 1.45. The critical angle is 87^0. Calculate i) refractive index of cladding, ii) acceptance angle and iii) number of modes propagating through fiber when wavelength of light is 1 µm.

Soln. :

$n_1 = 1.45$, $d = 6 \times 10^{-6}$ m, $\lambda = 1 \times 10^{-6}$ m, $\theta_c = 87^0$, n_2 = ?, θ_0 = ?, V = ? N_m = ?

$$\theta c = \sin^{-1}\frac{n_2}{n_1}$$

$$n_2 = n_1 \sin\theta_c = 1.45 \times \sin(87)$$

$$\mathbf{n_2 = 1.448}$$

$$\theta o = \sin^{-1}(\mathrm{N.A.}) = \sin^{-1}\sqrt{(1.45)^2 - (1.448)^2}$$

$$\boldsymbol{\theta o = 4.366^0}$$

$$V = \frac{\pi d}{\lambda}\sqrt{n_1{}^2 - n_2{}^2}$$

$$V = \frac{3.142 \times 6 \times 10^{-6}}{1 \times 10^{-6}}\sqrt{(1.45)^2 - (1.448)^2}$$

$$\mathbf{V = 1.435}$$

As, V < 2.405, Number of modes propagating through fiber is 1. It is a single mode fiber.