MODULE - III

LASERS & FIBER OPTICS

Dr. C. R. Kesavulu, Associate Professor, Dept. of Physics

Topics in Module - III

- Characteristics of lasers,
- Spontaneous and stimulated emission of radiation,
- Metastable state, Population inversion, Lasing action,
- Ruby laser,
- He-Ne laser
- Applications of lasers
- Principle and construction of an optical fiber
- Acceptance angle, Numerical aperture,
- Types of optical fibers (Single mode, multimode, step index, graded index)
- Optical fiber communication system with block diagram
- Applications of optical fibers.

LASER

L ight

A mplification by

S timulated

E mission of

R adiation

A laser is a device that can produce a very narrow intense beam of monochromatic coherent light

CHARACTERISTICS OF LASER

- *HIGH MONOCHROMATICITY*
- *HIGH DIRECTIONAL*
- *HIGH INTENSITY*
- *HIGH COHERENT*

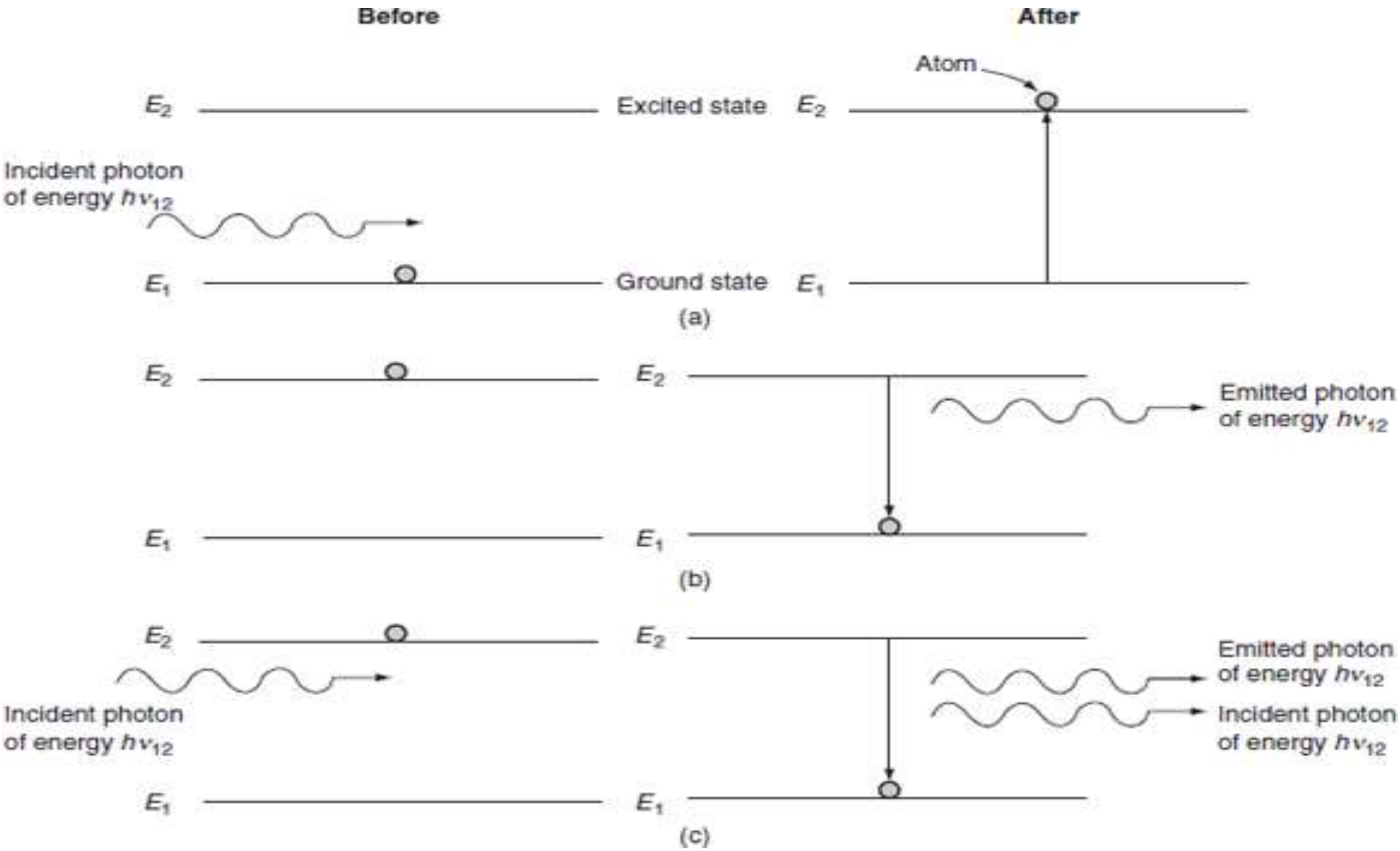
Highly Coherent

- ✓ Spatial Coherence: If two light fields at different points in space maintain constant phase difference over any time t, then they are said to have spatial coherence. The distance up to which same phase or constant phase difference is maintained is called coherence length.

- ✓ Temporal coherence refers to the correlation of phase between the light fields at a point over a period of time.

TRANSITIONS

- Absorption
- Spontaneous Emission
- Stimulative Emission



TRANSITIONS

Spontaneous emission	Stimulated emission
1. Spontaneous emission takes place when excited atoms make a transition to lower energy level voluntarily without any external stimulation	1. Stimulated emission takes place when a photon of energy equal to $h\nu_{12}(=E_2-E_1)$ stimulates an excited atom to make transition to lower energy level
2. Polychromatic radiation	2. Monochromatic radiation
3. Less intensity	3. High intensity
4. Less directionality, more angular spread during propagation	4. High directionality, so less angular spread during propagation
5. Spatially and temporally in coherent radiation	5. Spatially and temporally coherent radiation
6. Example: Light from ordinary source	6. Light from a Laser

Metastable state:

The excited states which have a relatively long lifetime due to slow radiative and non-radiative decay are called metastable states.

The life time of metastable state is 10^{-6} to 10^{-3} s.

Population Inversion:

Usually in a system the number of atoms (N_1) present in the ground state (E_1) is larger than the number of atoms(N_2) present in the higher energy state. The process of making $N_2 > N_1$ is called population inversion. Conditions for population inversion are:

- The system should posses at least a pair of energy levels ($E_2>E_1$), separated by an energy of equal to the energy of a photon ($h\nu$).

- There should be a continuous supply of energy to the system such that the atoms must be raised continuously to the excited state.

There could be no population inversion and hence no laser action, if metastable states do not exist.

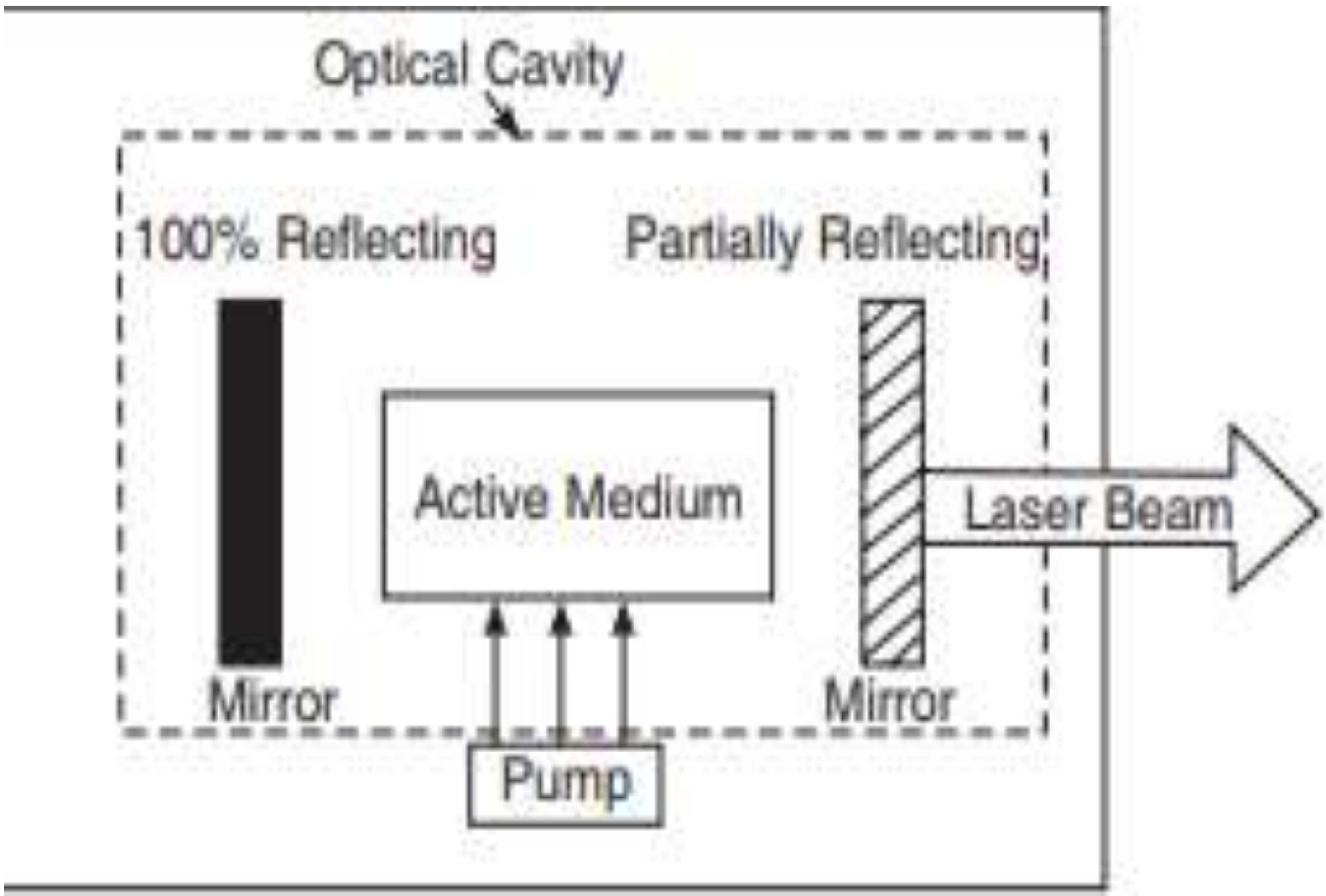
Pumping:

For maintaining a state of population inversion atoms have to be raised continuously to excited state. It requires energy to be supplied to the system. The process of supplying energy to the medium with a view to transfer it into state of population inversion is known as **pumping**. Simply, the process of attaining population inversion is called Pumping

Commonly used pumping types are: —

- Optical pumping:- Exposure to Electromagnetic radiation or Light
- Electric discharge:- By inelastic atom-atom collisions
- Atom:- Atom collision
- Direct conversion
- Chemical reactions
- Injection current

Components of LASER:



Different types of Lasers

Solid Laser : Ruby laser, Nd:YAG laser

Gas Laser : He-Ne, CO_2 laser, Arg-ion laser

Liquid Laser : Europium Chelate laser, $SeOCl_2$ laser

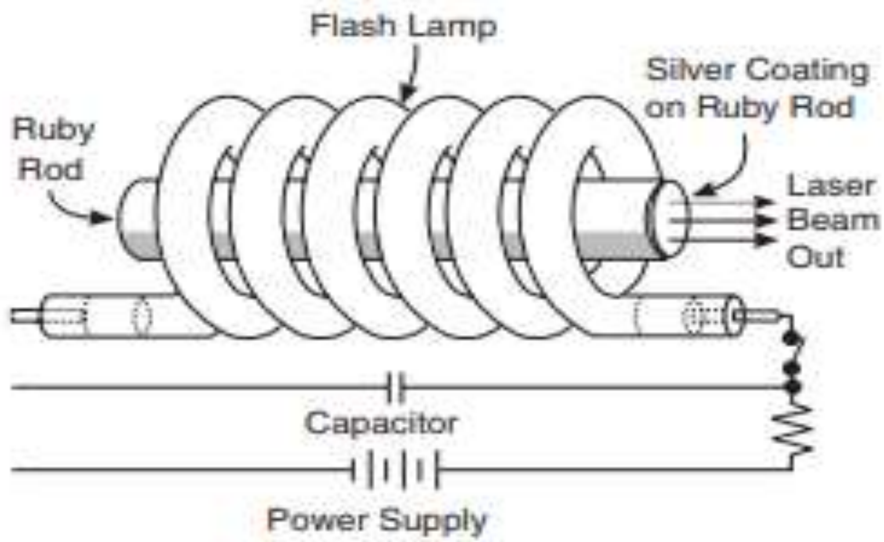
Dye Laser : Rhodamine 6G Dye laser, Courmarin Dye laser

Semiconductor Laser : InP laser, GaAs laser

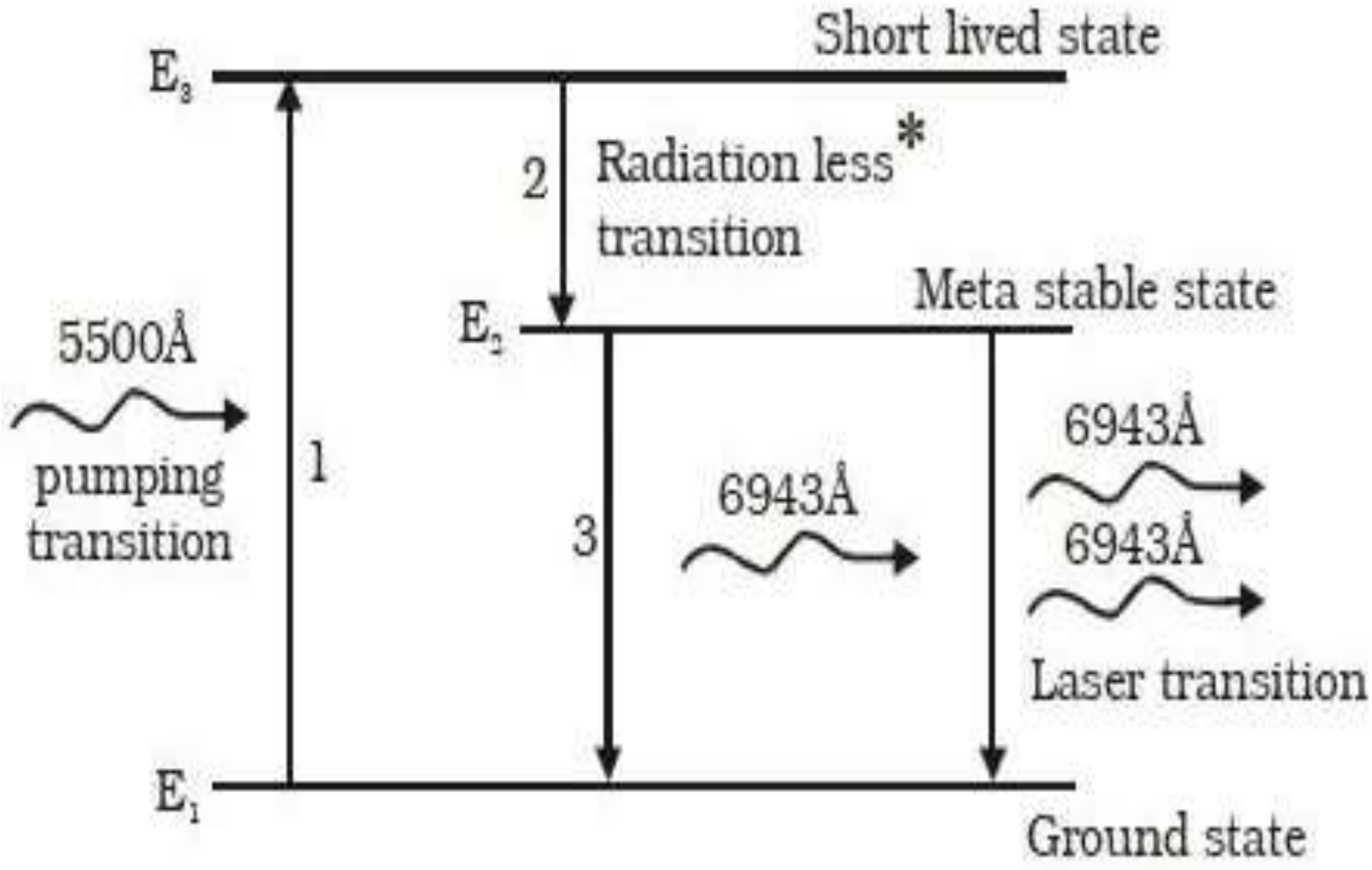
Ruby Laser

- **Active Material:** Ruby crystal in the form of a rod [Al_2O_3+Cr_2O_3]
- **Resonating Cavity:** A fully reflecting surface at the left end of the ruby crystal and partially reflecting end at the right side of the ruby crystal are to be arranged.

  For this, both the ends of the ruby rod are highly polished and painted with silver such that one end is fully reflecting and the other end is partially reflecting. Both the reflecting surfaces are optically flat and are exactly parallel to each other.
- **Pumping System:** Optical Pumping
  For this, a helical Xenon flash lamp with a power supply to pump Cr^{+3} ions to higher levels is used.



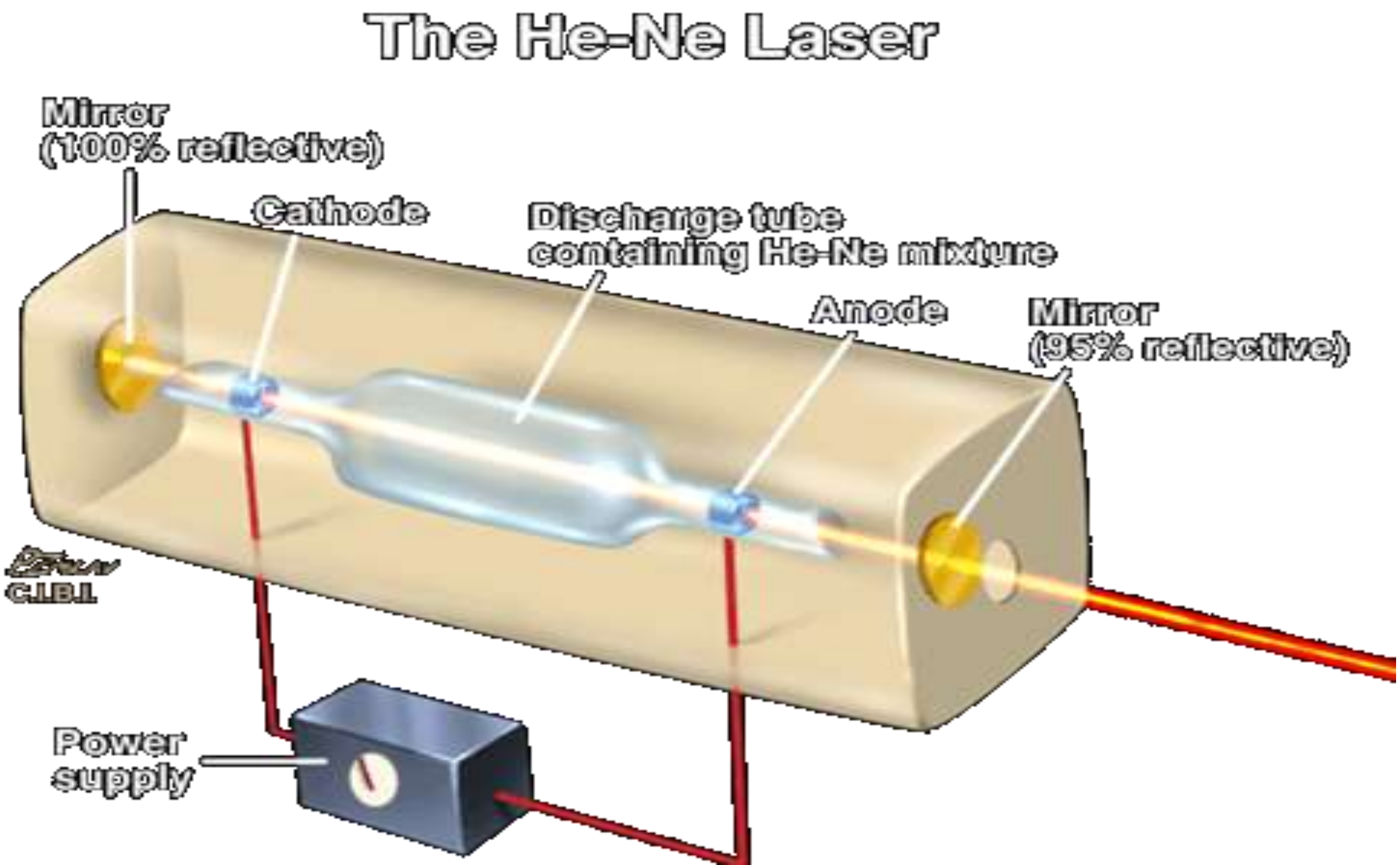
Ruby Laser



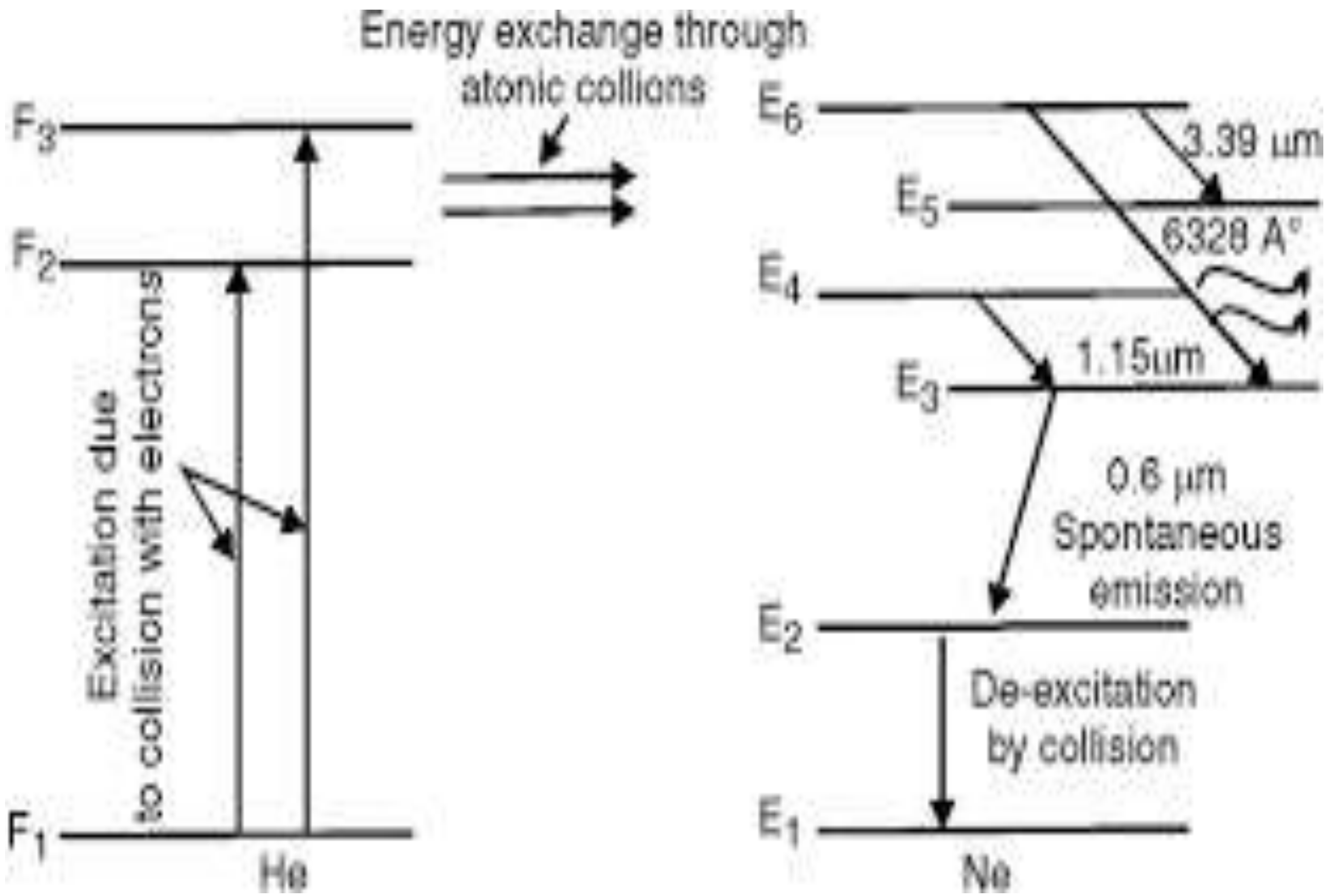
Energy Level Diagram of Ruby Laser

He-Ne Laser

- **Active Material:** He, Ne in the ratio { He-1 mm of Hg, Ne- 0.1 mm of Hg}
- **Resonating Cavity:** one will have two mirrors at ends of discharge tube which are at Brewster's angle (RI = tan θ).
- **Pumping System:** Electrical discharge



He-Ne Laser

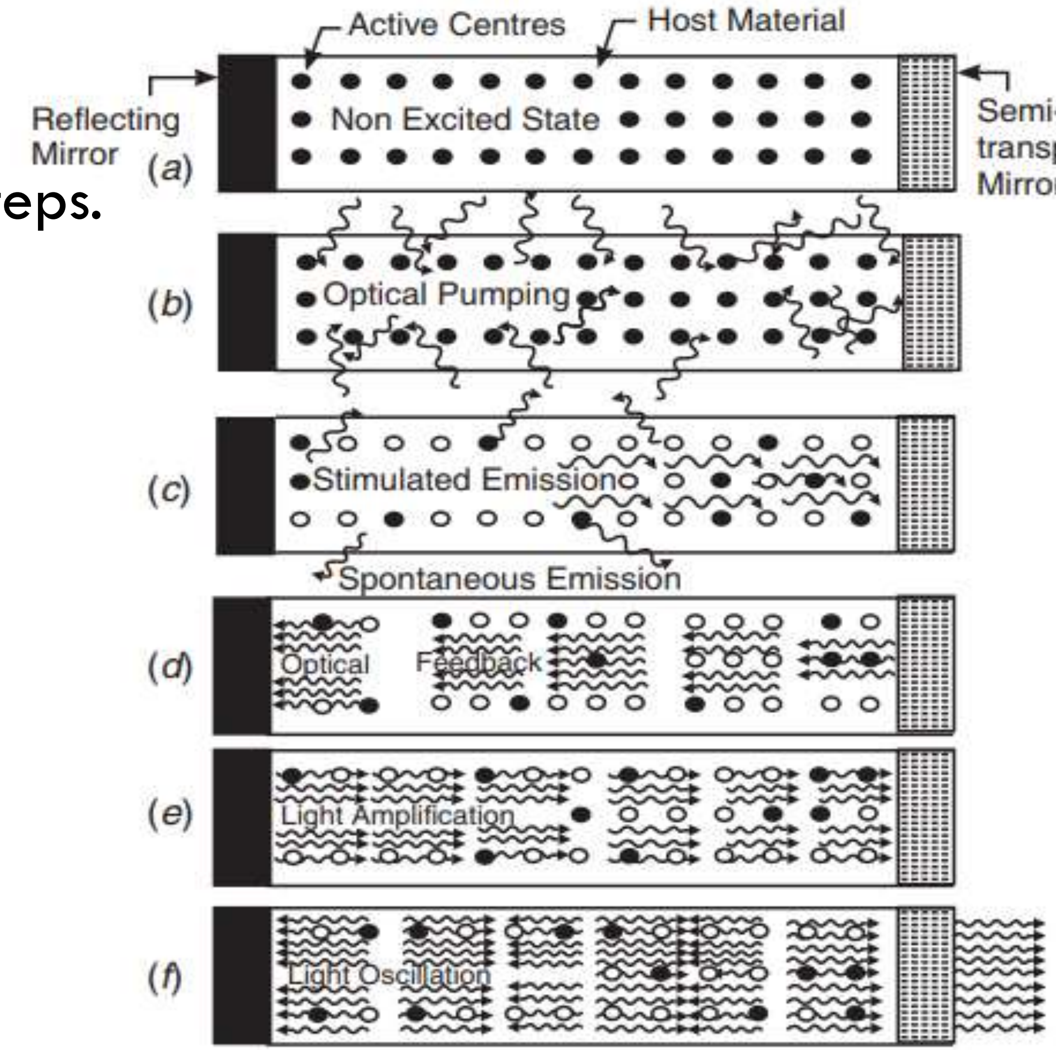


Energy exchange through
atonic collions
F3
F2
F1
Excitation due
to collision with electrons
He
E6
E5
E4
E3
E2
E1
3.39 um
6328 A°
1.15um
0.6 μm
Spontaneous
emission
De-excitation
by collision
Ne

LASING ACTION

Lasing Action involves five steps.

- ✓ Pumping
- ✓ Population inversion
- ✓ Spontaneous Emission
- ✓ Amplification
- ✓ Oscillations.



Light amplification and oscillations due to the action of optical resonator


Thank you!

MODULE - III

LASERS & FIBER OPTICS

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TOPICS TO BE COVERED

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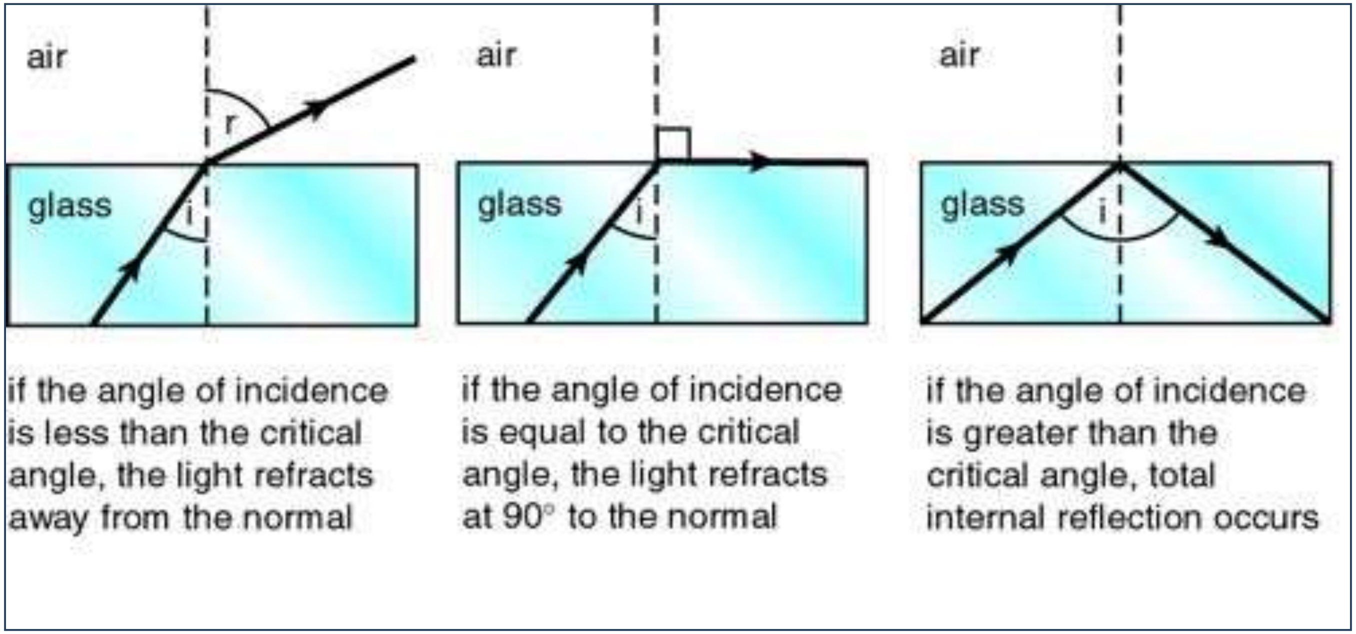
- ❖Metastable state, Population inversion, Lasing action,
- ❖Ruby laser,
- ❖He-Ne laser
- ❖Applications of lasers
- ❖Principle and construction of an optical fiber
- ❖ Acceptance angle, Numerical aperture,
- ❖Types of optical fibers (Single mode, multimode, step index, graded index)
- ❖ Optical fiber communication system with block diagram
- ❖Applications of optical fibers.

PRINCIPLE & CONSTRUCTION OF OPTICAL FIBER

- Fiber optics is a branch of physics based on the transmission of light through transparent filters of glass or plastic.
- Optical fiber is a cylinder of transparent dielectric medium designed to guide visible and infrared light, over long distances.
- Optical fibers work on the principle of total internal reflection.
- When a ray of light travels from a denser medium into a rarer medium and if the angle of incidence is greater than the critical angle then the light gets totally reflected



Core: - A typical cylindrical glass material of diameter 50 μm surrounded by a clad.

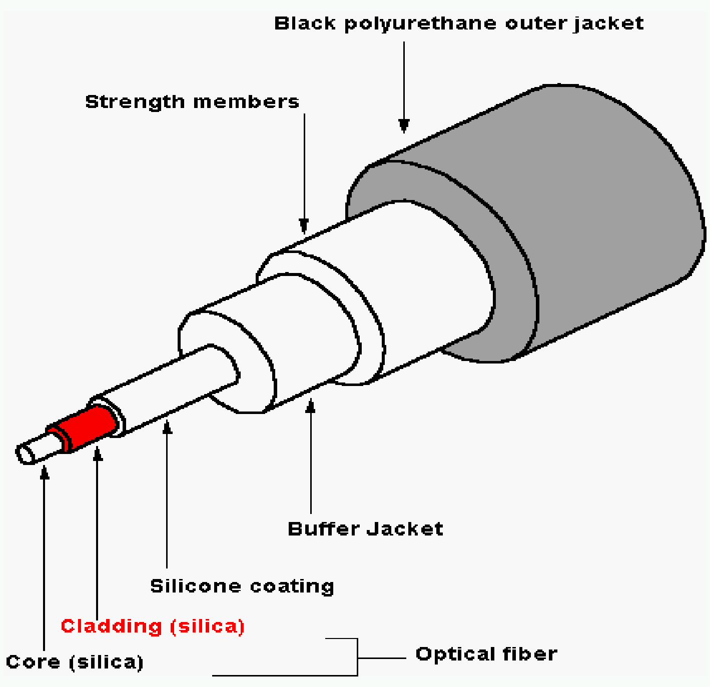
Clad: - A glass material of slightly lower refractive index than core.

Silicon Coating: - It is provided between clad and buffer jacket in order to improve the quality of transmission of light.

Buffer jacket: - It is covered over silicon coating which is made up of plastic material and protects from moisture and abrasion.

Strength members: - This layer is arranged over the buffer jacket to provide necessary toughness and tensile strength to the fiber.

Outer jacket: - Finally a black polyurethane outer jacket to avoid damages during hard pulling, bending, stretching or rolling of the fiber in the real field.



PRINCIPLE & CONSTRUCTION OF OPTICAL FIBER

According to law of refraction

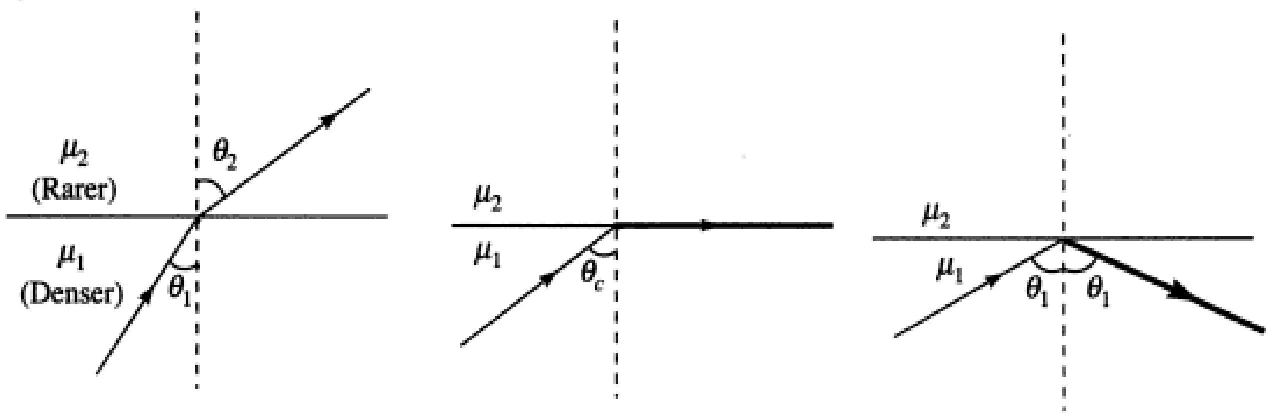
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

If $\theta_1 = \theta_C \Rightarrow \theta_2 = 90^0$

So, $n_1 \sin\theta_C = n_2 \sin 90^0$

$\Rightarrow \sin\theta_C = n_2/n_1 \quad \Rightarrow \theta_C = \sin^{-1}(n_2/n_1)$

As there is no loss of light energy during reflection optical fibers are designed to guide light wave over long distances.



(a) $\theta_1 < \theta_c$ (b) $\theta_1 = \theta_c$ (c) $\theta_1 > \theta_c$

ACCEPTANCE ANGLE AND ACCEPTANCE CONE

- We have to know at what angle called acceptance angle we have to launch the beam. The maximum angle of launch is called 'acceptance angle'.

From Snell's law we have

We have $n_0 \sin \alpha_i = n_1 \sin\alpha_r$

=> $n_0 \sin \alpha_i = n_1 \sin(90-\theta)$ => $n_0 \sin \alpha_i = n_1 \cos\theta$

If θ is less than critical angle θ_C, the ray will be lost by refraction.

When $\theta = \theta_C$; $\alpha_I = \alpha_m$ = maximum α value

Therefore, $\sin \alpha_m = \frac{n_1}{n_0} \cos\theta_C$

And we have $\theta_C = \sin^{-1}(n_2/n_1)$

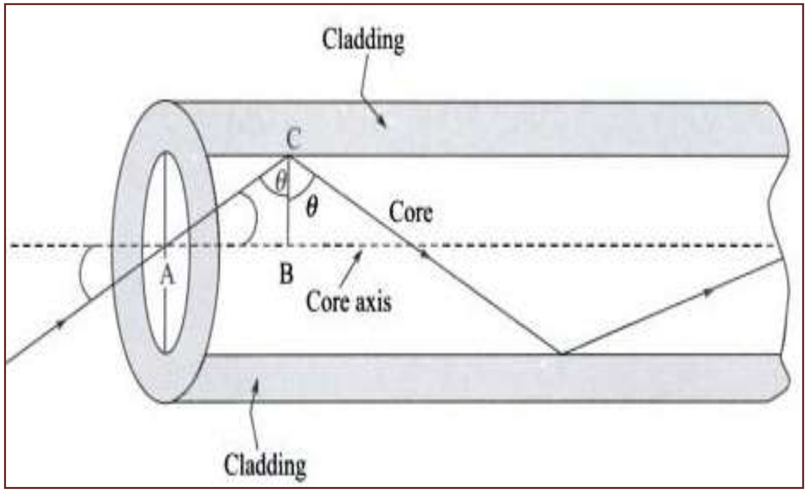
So, $\cos\theta_C = \sqrt{1 - sin^2\theta_C} = \sqrt{1 - \frac{n_2^2}{n_1^2}}$

Therefore,

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

so, $n_0 \sin \alpha_m = \sqrt{n_1^2 - n_2^2}$ if $n_0 = 1$ { medium is air}

$\text{Sin } \alpha_m = \sqrt{n_1^2 - n_2^2}$

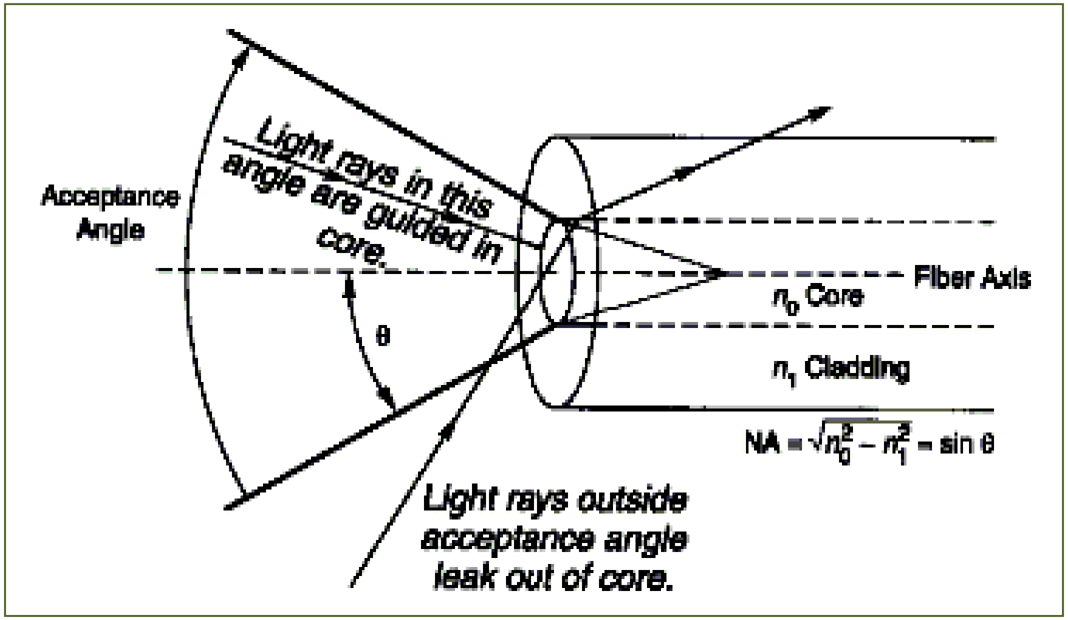


ACCEPTANCE ANGLE AND ACCEPTANCE CONE

This maximum angle α_m is called acceptance angle (or) the acceptance cone half angle of the fiber.

The acceptance angle may be defined as the maximum angle that a light ray can have with axis of the fiber and propagate through the fiber.

Rotating acceptance angle about the fiber axis describes acceptance cone of the fiber.



NUMERICAL APERTURE

- The numerical aperture defines the acceptance angle more clearly.
- The sine of acceptance angle is called **numerical aperture.**

The value of Numerical Aperture, NA is

NA = Sin α_m = $\sqrt{n_1^2 - n_2^2}$ = $\sqrt{(n_1+n_2)(n_1-n_2)}$ = $\sqrt{(n_1+n_2)n_1\Delta)}$ Where $\Delta = \frac{n_1 - n_2}{n_1}$ is fractional difference in Refractive indices, n_1 and n_2 are refractive indices of core and clad respectively.

As $n_1 \sim n_2$ we can take $n_1 + n_2 = 2n_1$ so, NA = $n_1\sqrt{2\Delta)}$

- Numerical aperture is a measure of the amount of light that can be occupied by a fiber.
- NA values ranges from 0.1 to 0.5.

Types of Optical Fibers

- Depending on the relation between refractive indices of core and clad they are divided into two types. Step index fiber and graded index fiber. Additional to these there are also single mode fiber and multimode fiber.

Step-index fiber: -

- In the step-index fiber, the refractive index of core is uniform and undergoes an abrupt change (or step) at the cladding boundary.

The refractive index profile may be defined as

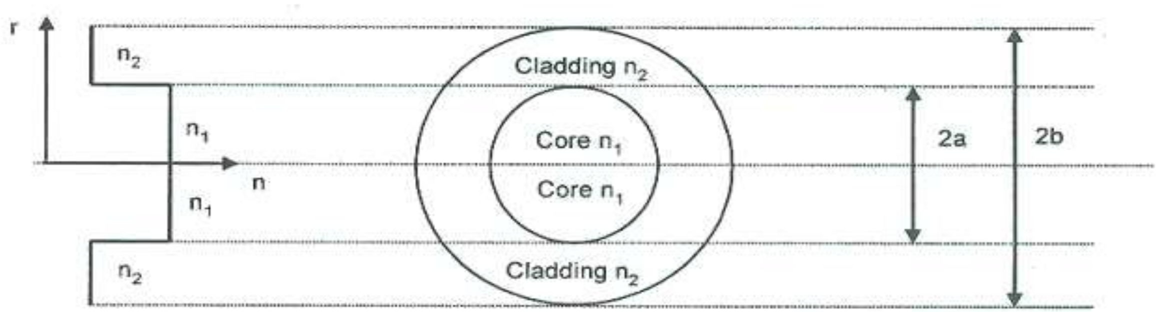
$$n(r)= \begin{cases} n_1 \; for \; r < a \; (core) \\ n_2 \; for \; r \geq a \; (clad) \end{cases}$$

The step-index fibers have a core radius 'a' and $n_2 = n_1(1-\Delta)$

(or) $\Delta \approx \frac{n_1 - n_2}{n_1}$

$n(r) = n_1$ for $r < a$ (core)

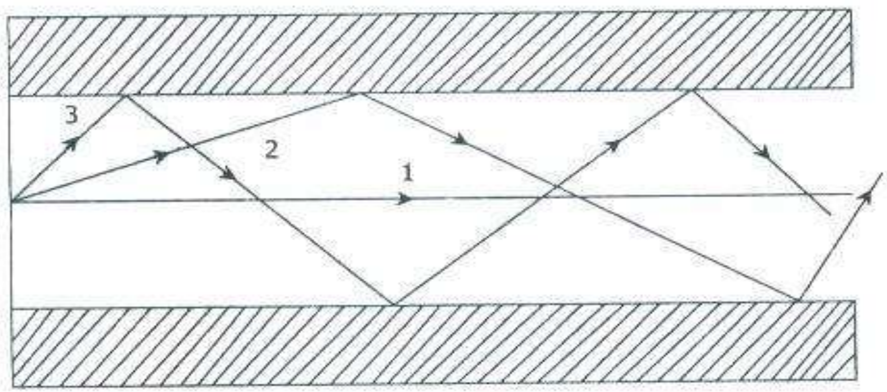
$n(r) = n_2$ for $r > a$ (cladding)



Step index fiber - refractive index profile

Step-index fiber

- Generally the signal sent through the fiber is in digital form i.e., in the form of pulses representing 0's and 1's.
- Let us consider the propagation of one such pulse through the multimode step index fiber.
- The same pulsed signal travels in different paths.
- If we see the diagram it is clear that ray '1' travels shorter distance and ray '3' travels longer distance.
- Hence the three rays reach the received end at different times. Therefore, the pulsed signal received at the other end gets broadened. This is called intermodal dispersion.



Signal Transmission in step-index fiber

Grad-index fiber

- In graded-index fiber, the core refractive index varies as a function of radial distance from the centre of the fiber.
- In the graded index fiber the core refractive index decreases continuously with increasing radial distance 'r' from the centre of the fiber, but is generally constant in the cladding.

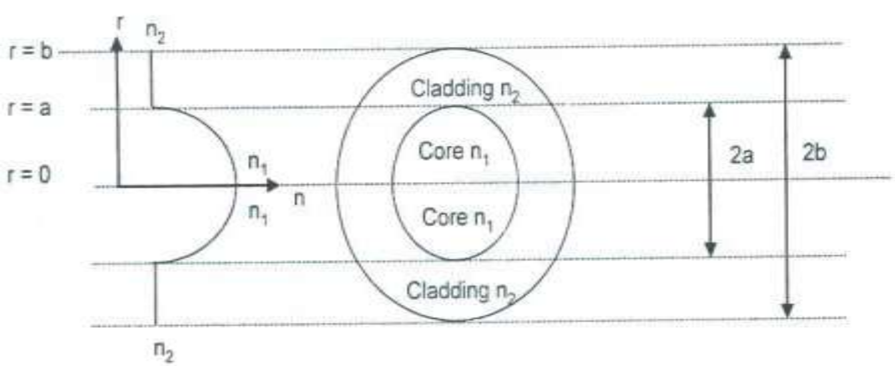
The most commonly used construction for the RI variation in the core is given by n(r)=

$$n(r) = \begin{cases} n_1[1 - 2\Delta(r/a)^{\alpha}]^{1/2} \; for\; r < a\; (core) \\ n_1[1 - 2\Delta]^{1/2} \approx n_1(1 - \Delta) = n_2 \; for\; r \geq a\; (clad) \end{cases}$$

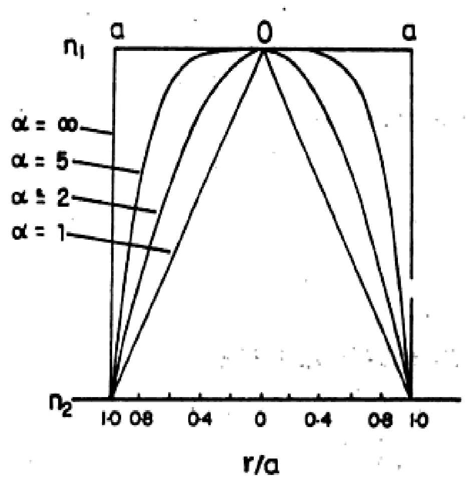
Where n_1 = RI of the core at the centre

a = radius of core, α = Grading profile of RI in the core material

$\Delta = \frac{n_{1-n_2}}{n_1}$ = fractional total change of the core RI, α = 2

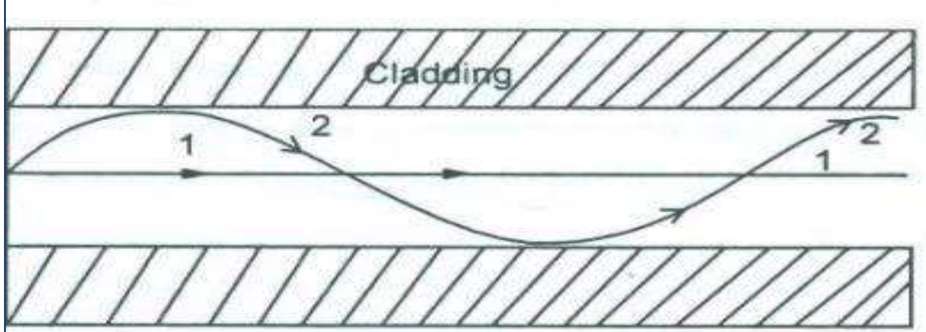


Graded Index fiber - refractive index profile



Grad-index fiber

- The pulse represented by 1, travelling along the axis of the fiber, though travels along shorter route it travels through a medium of higher refractive index.
- The other pulse represented by 2, travelling away from axis and undergoes reflection.
- Though it travels longer distance, it travels along a trajectory possessing relatively less refractive index and hence both pulses reach the other end simultaneously.
- So, the problem of intermodal dispersion is reduced to minimum.



Propagation of different model rays in G.I Fiber

Difference between Step-Index and Grad-Index Fiber

S. N	Step-Index fiber	Grad-Index fiber
1	The RI of the core is uniform throughout and undergoes sudden change at cladding boundary.	The RI of the core is made to vary in parabolic manner such that the maximum RI is present at the centre of core.
2	The diameter of core is about 100 µm for multimode fiber and 10µm for single mode fiber.	The diameter of the core is about 50µm in case of multimode fiber.
3	The light rays propagating through it are in the form of meridional rays.	The light rays propagating are mainly skew rays, which follow a helical path.
4	Signal distortion is more in multimode step-index fiber	Signal distortion is low because of self-focusing effect.
5	Bandwidth of fiber is about 50MHz Km for multimode step-index fibers, but for single mode, the bandwidth is more than 1000 MHz Km.	Bandwidth of fiber is from 200 MHz Km to 600 MHz Km even though theoretically it has infinite bandwidth.
6	Attenuation is more for multimode step index fiber	Attenuation is less.
7	Numerical aperture is more for multimode SI fiber but for single mode it is very less.	Numerical Aperture is less.

Difference between Single Mode and Multi Fiber

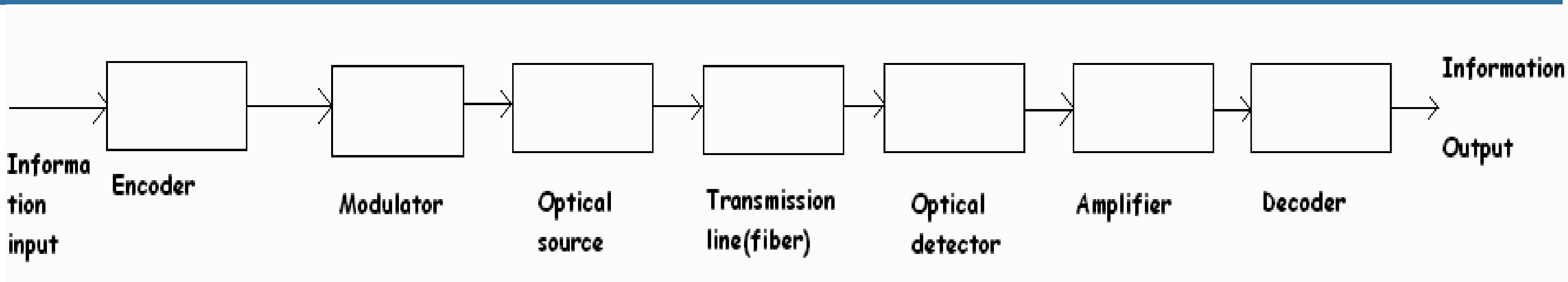
S.NO	Single mode fiber	Multimode fiber
1	In single mode fiber only one mode (HE_{11}) can propagate through the fiber.	Multimode fiber allows a large number of paths or modes for the light rays travelling through it.
2	The condition for single mode operation is given by V-number, given as $V = 2\pi/\lambda \, n_1 \, a\sqrt{2\Delta}$: $V \leq 2.405$	Here $V > 2.405$
3	The single mode fiber has smaller core diameter < 10 µm and the difference between RI of core and cladding is very small.	In multimode fiber the core diameter and the relative refractive index difference are more than the single mode fiber.
4	There is no dispersion.	There will be some dispersion.
5	The single mode fibers are more suitable for long distance communication.	These fibers are used in local area networks.
6	Launching of light into single mode fiber and splicing of two fibers is very difficult.	Launching of light into fiber and splicing of two fibers is easy.
7	Fabrication is very difficult and fiber is costly.	Fabrication is easy and the fiber is cheaper.

Attenuation

- The main specification of a fiber optic cable is its attenuation.
- Different mechanisms are responsible for the signal attenuation in the fiber.
- The attenuation of the signal is measured in Decibel/KM.
- Signal attenuation is defined as ratio of input optical power P_i into fiber to the output received optical power P_O from the fiber.
- The attenuation coefficient of the signal per unit length is given as
  - $$\alpha = \frac{10}{L} \log \frac{P_i}{P_o} \text{ dB/Km}$$

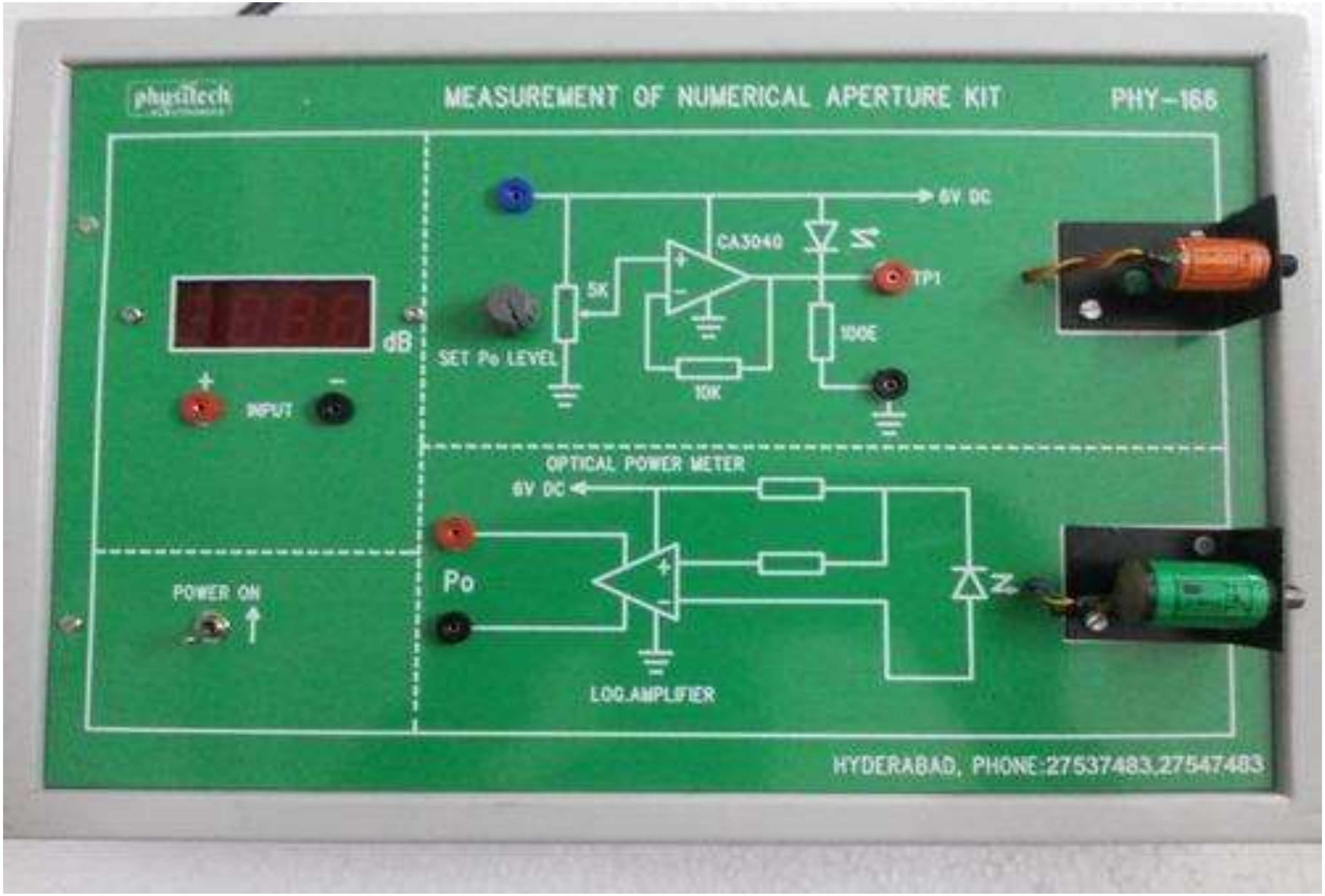
- ❑ Absorption Loss
- ❑ Scattering Loss
- ❑ Bending Loss
- ❑ Transmission Loss

Optical fiber communication system



- The above figure shows the important components of an optical fiber communication system.
- Transmitter consists of information encoder which converts the information signal into coded pulses. Then there is modulator which controls the operation of optical source.
- The emitted light from the source is coupled to the fiber optic cable which constitutes the transmission medium.
- The light emerging from the other end of the optical fiber cable is given to the optical detector which converts light into electrical signal.
- The optical detector, amplifier and decoder or demodulator constitutes the receiver.
- Amplifier amplifies the detected electrical signal and then the amplified signals are decoded to original information.
- The optical sources are semiconductor laser diodes and LED.
- The optical detectors are PIN photodiodes and avalanche Photodiodes.

Optical fiber communication system



Consider an optical fiber of core refractive index 1.48 and fractional index difference 0.05. Obtain the clad RI and Numerical Aperture.

$$\Delta = \frac{n_1 - n_2}{n_1} = 0.05$$

A step-index fibre is made with a core of refractive index 1.52, a diameter of 29 μm and a fractional difference index of 0.0007. It is operated at a wavelength of 1.3 μm. Find the V-number and the number of modes that the fibre will support

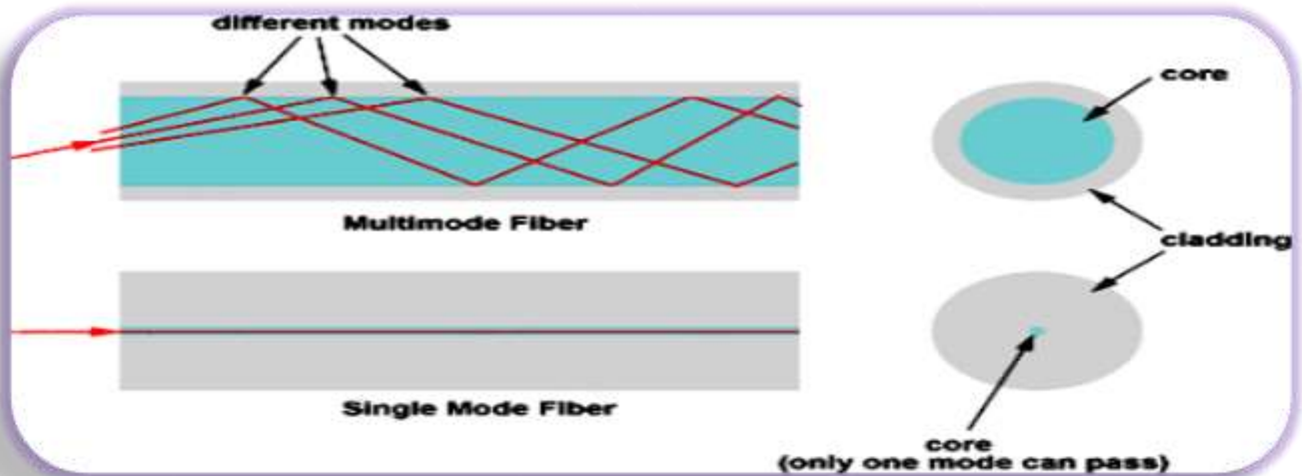

Thank you!

FIBER OPTICS

Types of Optical Fibres

- Based on the mode of propagation, all the fibers are divided into:

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



Single mode and Multi mode propagation of light

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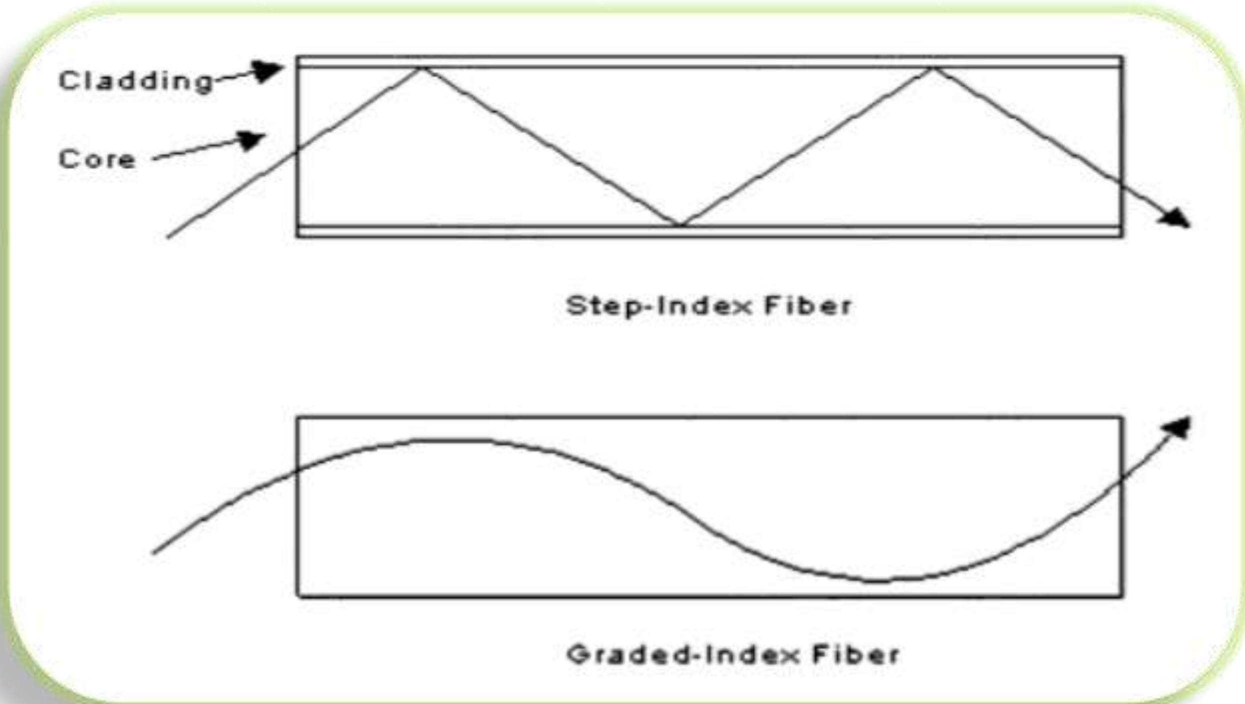
Types of Optical Fibres

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



Light path through Step- index and Graded index Fibre

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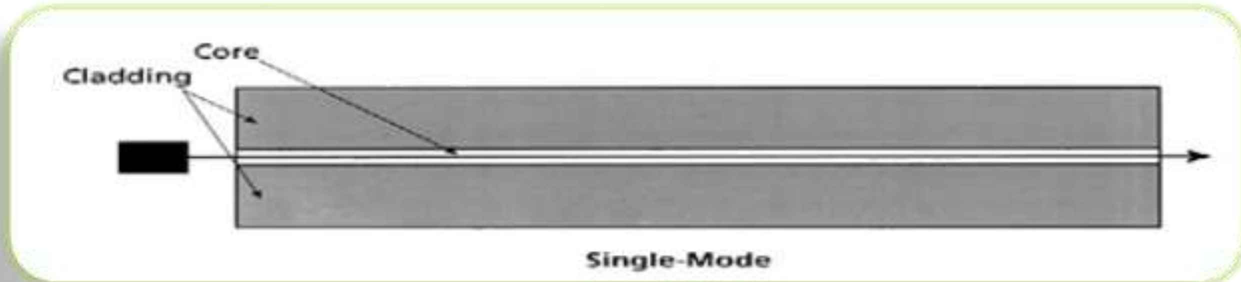
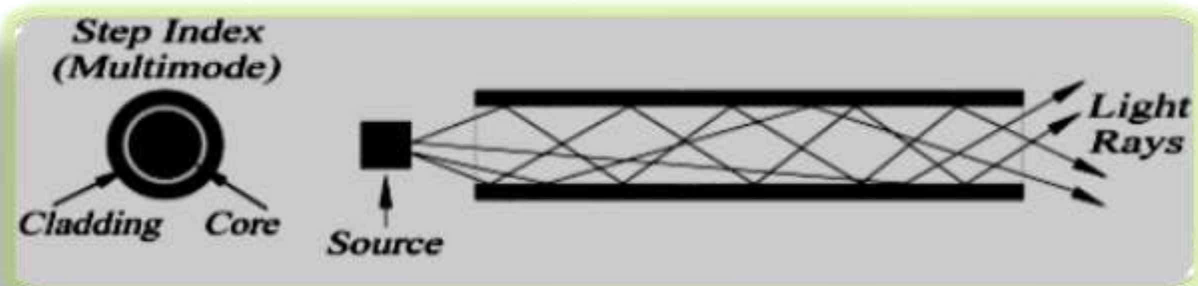
Step index optical fibre

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



Single mode Step index optical Fibre



Multi mode Step index optical Fibre

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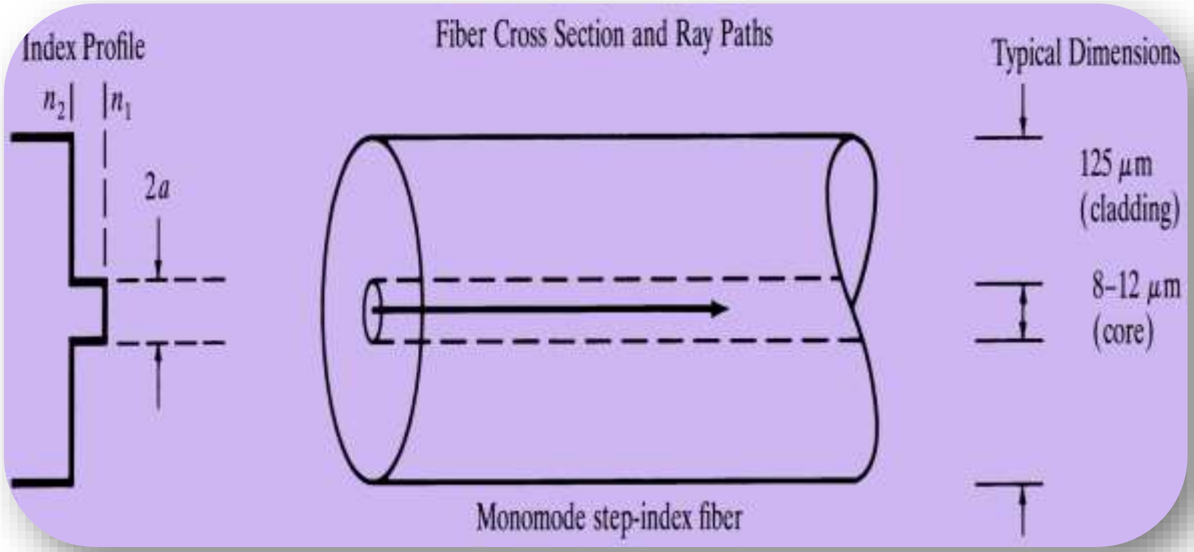
Refractive index profile in Single mode Step index fibre

- The refractive index is uniform throughout the core of this fibre.
- As we go radially in this fibre, the refractive index undergoes a step change at the core-cladding interface.
- The core diameter of this fibre is about 8 to 12 μm and outer diameter of cladding is 60 to 125 μm.
- In this fibre, the transmission of light is by successive total internal reflections i.e. it is a reflective type fiber.
- These fibres are mainly used in submarine cable system.



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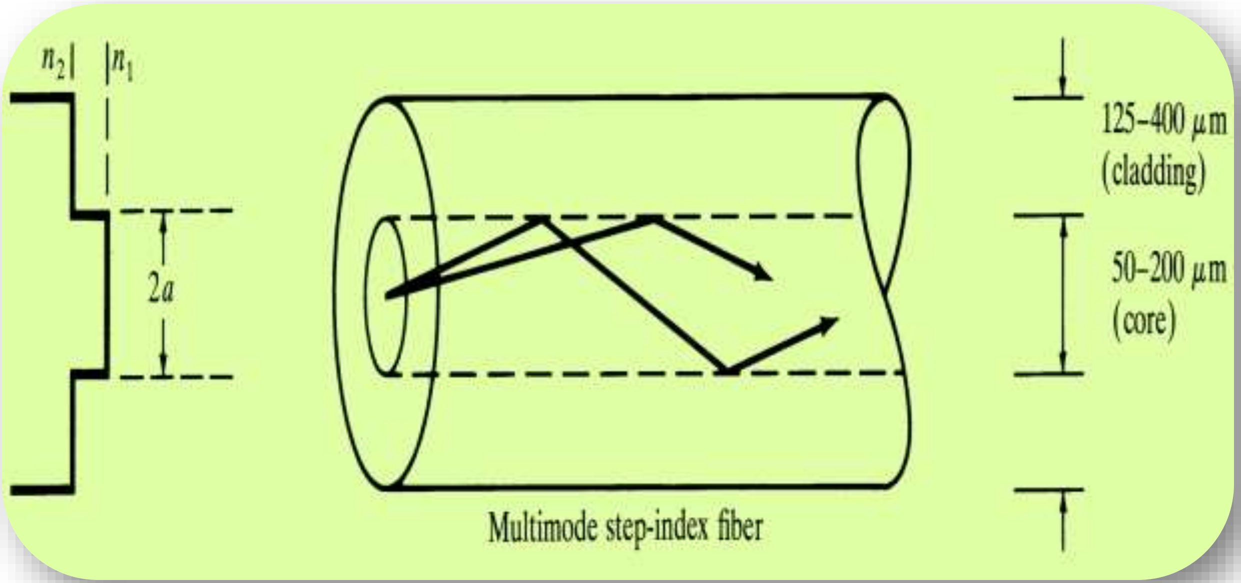
Refractive index profile in Multimode Step index fibre

- Its core and cladding diameters are much larger to have many paths for light propagation.
- The core diameter of this fiber varies from 50 to 200 μm and the outer diameter of cladding varies from 125 to 400 μm.
- Light propagation in this fiber is by multiple total internal reflections i.e., it is a reflective type fiber.
- It is used in data links, which have lower band width requirements.



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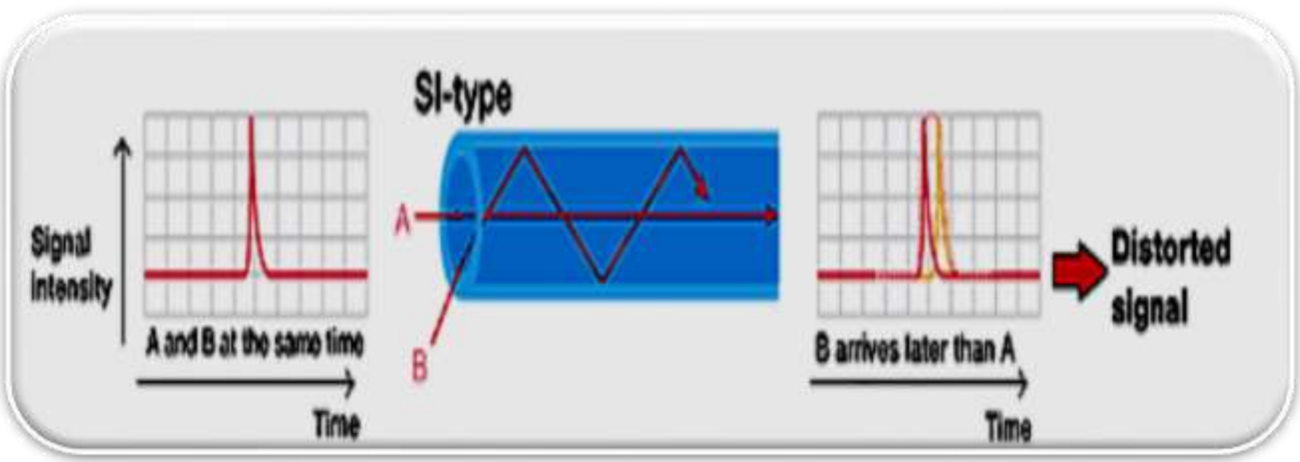
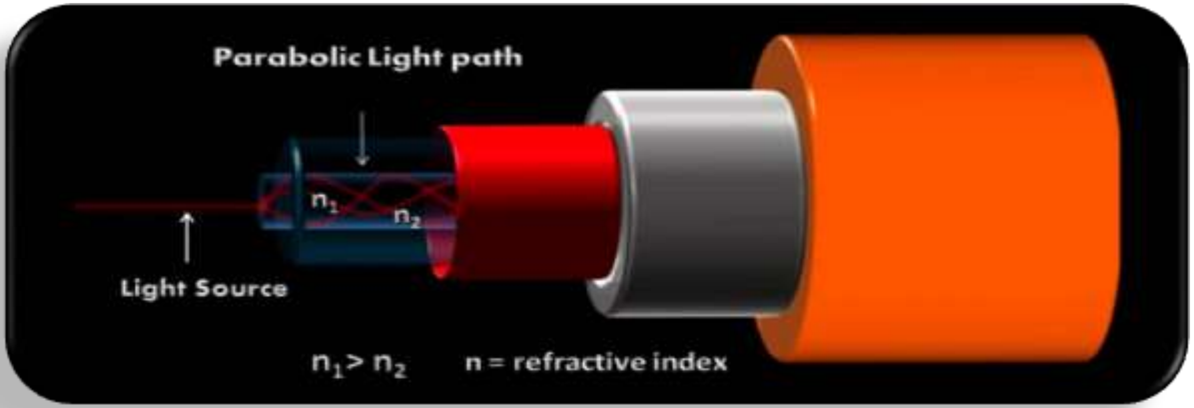
Transmission of signal in step index fibre

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



Graded index optical fibre

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



Multimode Graded index optical fibre

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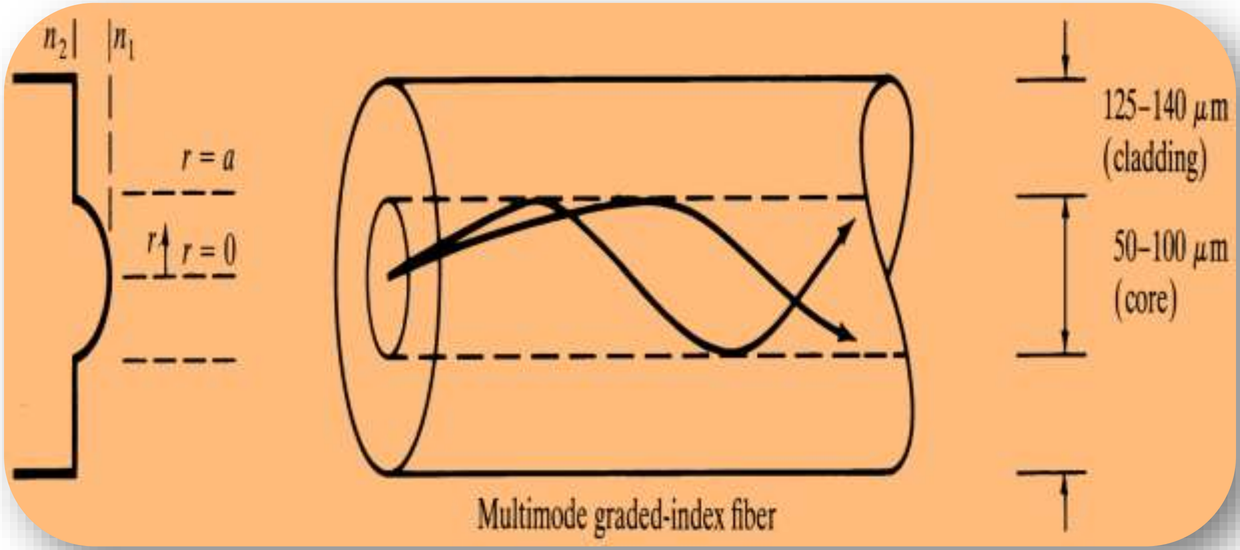
Refractive index profile in Multimode graded index fibre

- In this fiber, the refractive index decreases continuously from center radially to the surface of the core.
- The refractive index is maximum at the center and minimum at the surface of core.
- The diameter of the core varies from 50 to 100μm and the outer diameter of the cladding varies from 100 to 140 μm.
- The refractive index profile is circularly symmetric.



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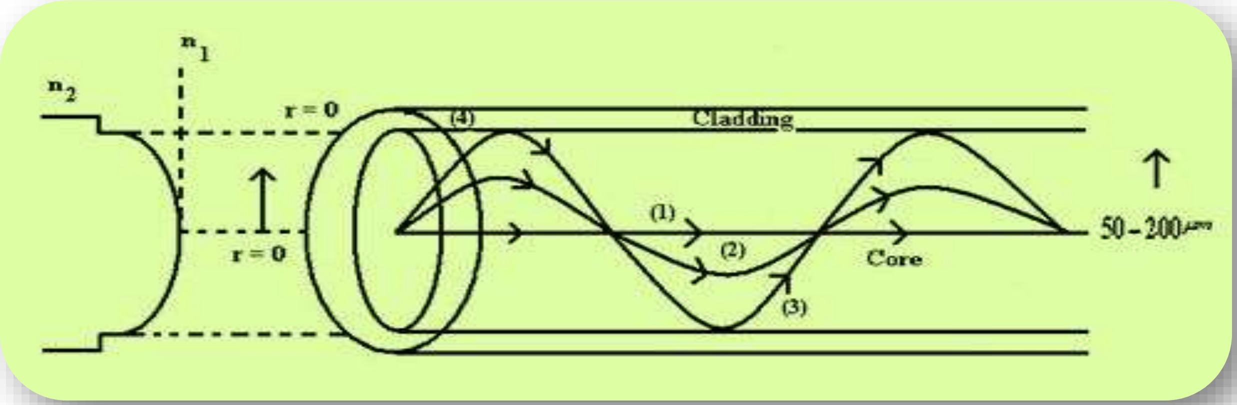
Refractive index profile in Multimode graded index fibre

Explanation:

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

Transmission of signal in graded index fibre

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



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Attenuation in Optical Fibers

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

$$\alpha = 10/L \log (Pi/Po) \text{ dB/km}$$

Where, L is the length of the fiber.

The mechanisms through which attenuation takes place are

1.Absorption losses.

2.Scattering losses.

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3. Bending losses.

4.Microbending and Wave guide losses.

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