OPTICAL FIBER PRINCIPLE (I)

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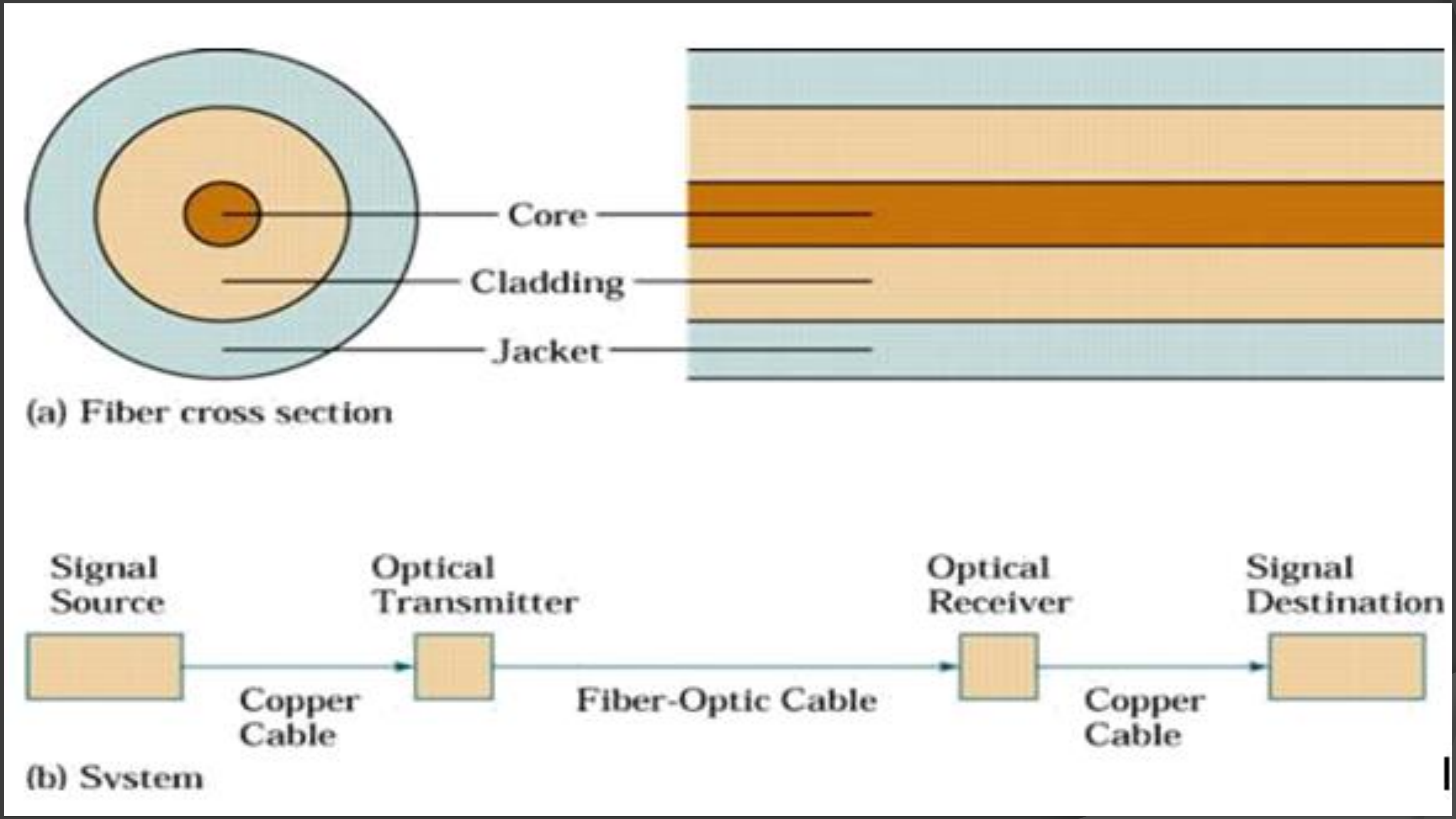
Optical Fiber Principle

- An optical fiber is essentially a waveguide for light
- It consists of a **core** and **cladding** that surrounds the core
- The **index of refraction** of the cladding is less than that of the core, **the refractive index** profile defines the relationship between the refractive index of the core and that of the cladding.
- A light-emitting diode (LED) or **laser diode** (LD) can be used for the source
- Advantages of optical fiber include:
  - Greater bandwidth than copper
  - Lower loss
  - Immunity to **crosstalk**
  - No electrical hazard

Optical Fiber & Communications System



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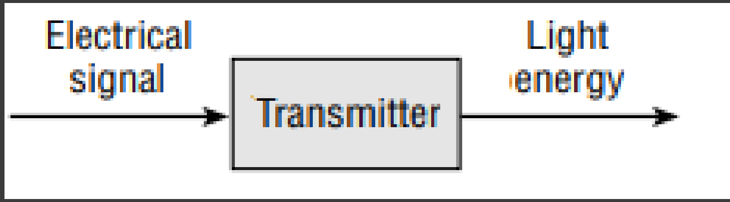
- Transmitter The transmitter converts an electrical signal into light energy to be carried through the fiber optic link. The signal could be generated by a computer, a voice over a telephone, or data from an industrial sensor



- The receiver is an electronic device that collects light energy and converts it into electrical energy, which can then be converted into its original form. The receiver typically consists of a photo detector to convert the received light into electricity, and circuitry to amplify and process the signal.

Optical Fiber

- Optical fiber is made from thin strands of either glass or plastic
- It has little mechanical strength, so it must be enclosed in a protective jacket
- Often, two or more fibers are enclosed in the same cable for increased bandwidth and redundancy in case one of the fibers breaks
- It is also easier to build a full-duplex system using two fibers, one for transmission in each direction

Total Internal Reflection

- Optical fibers work on the principle of **total internal reflection**
- **Total internal reflection** occurs only if light travels from a medium of high index of refraction to a medium of low index of refraction.
- Consider the following situation: A ray of light passes from a medium of water to that of air. Light ray will be refracted at the junction separating the two media. Since it passes from a medium of a higher refractive index to that having a lower refractive index, the refracted light ray bends away from the normal.

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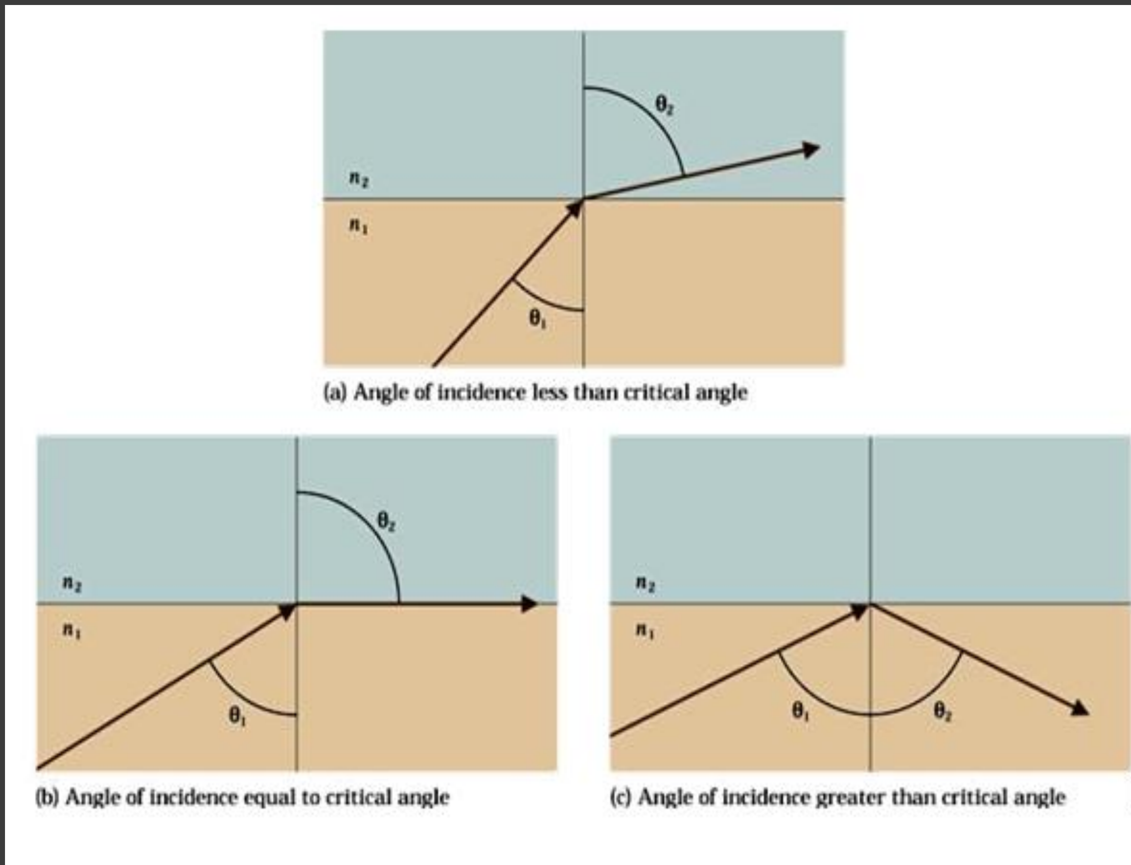
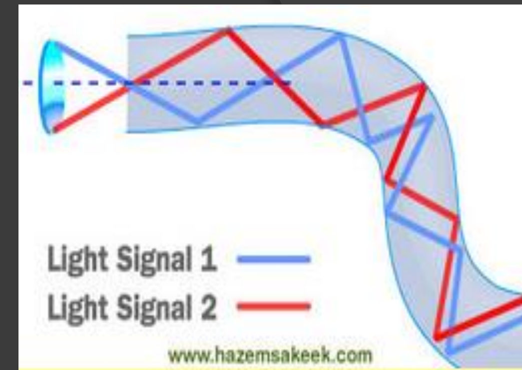


(a) Angle of incidence less than critical angle

(b) Angle of incidence equal to critical angle

(c) Angle of incidence greater than critical angle



Here the angle of refraction is 90 degrees. When the angle of incidence is greater than the critical angle, the incident ray is reflected back to the medium. We call this phenomenon total internal reflection.

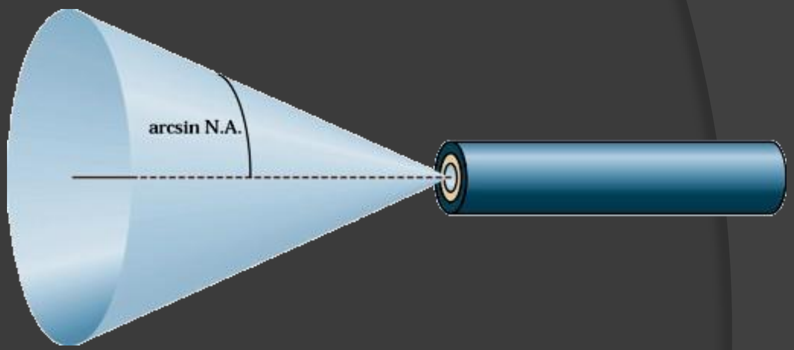
At a specific angle of incidence, the incident ray of light is refracted in such a way that it passes along the surface of the water. This particular angle of incidence is called the critical angle

Numerical Aperture

- The **numerical aperture** of the fiber is closely related to the critical angle and is often used in the specification for optical fiber and the components that work with it
- The numerical aperture is given by the formula:

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

- The **angle of acceptance** is twice that given by the numerical aperture



Optical fibers based on material :

- Optical fibers are made up of materials like silica and plastic. The basic optical fiber material must have the following properties:
- (i) Efficient guide for the light waves
- (ii) Low scattering losses
- (iii) The absorption, attenuation and dispersion of optical energy must be low. Based on the material used for fabrication, they are classified into two types:

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- **Glass fibers :** The glass fibers are generally fabricated by fusing mixtures of metal oxides and silica glasses. Silica has a refractive index of 1.458 at 850 nm.
- **Plastic fibers :** The plastic fibers are typically made of plastics and are of low cost.

• Although they exhibit considerably greater signal attenuation than glass fibers, the plastic fibers can be handled without special care due to its toughness and durability.

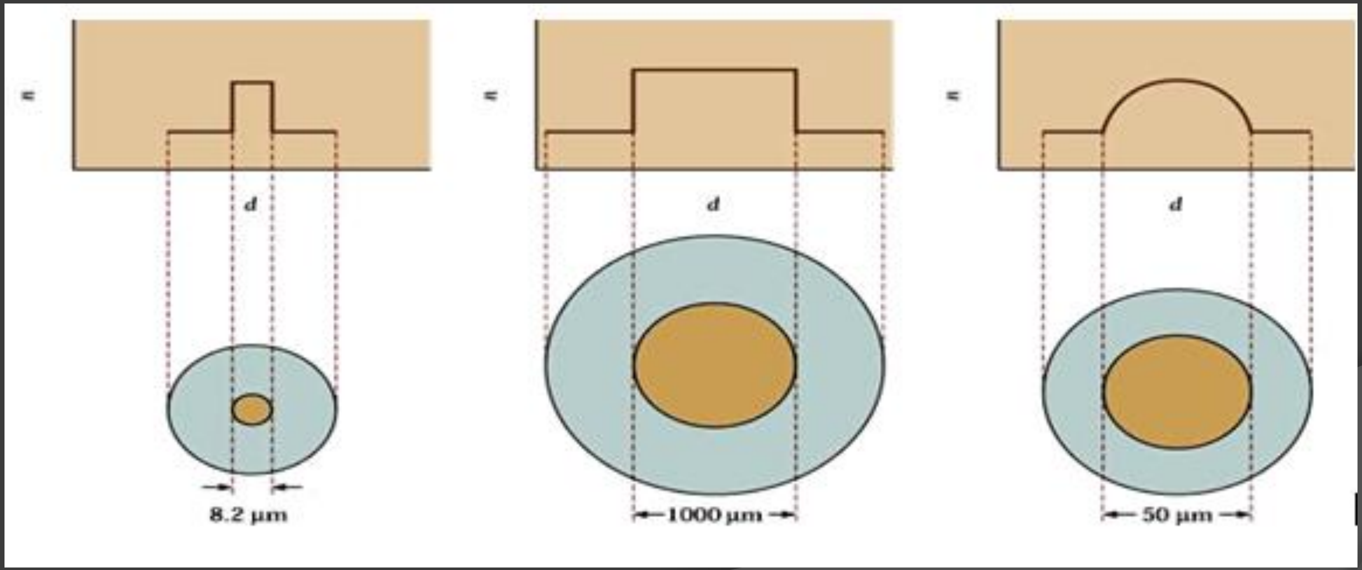
• Due to its high refractive index differences between the core and cladding materials, plastic fibers yield high numerical aperture and large angle of acceptance.

Modes and Materials

- Since optical fiber is a waveguide, light can propagate in a number of modes
- If a fiber is of large diameter, light entering at different angles will excite different modes while narrow fiber may only excite one mode
- Multimode propagation will cause **dispersion**, which results in the spreading of pulses and limits the usable bandwidth
- **Single-mode** fiber has much less dispersion but is more expensive to produce. Its small size, together with the fact that its numerical aperture is smaller than that of **multimode** fiber, makes it more difficult to couple to light sources

Types of Fiber

- Both types of fiber described earlier are known as **step-index** fibers because the index of refraction changes radically between the core and the cladding
- **Graded-index** fiber is a compromise multimode fiber, but the index of refraction gradually decreases away from the center of the core
- Graded-index fiber has less dispersion than a multimode step-index fiber



Optical fibers based on modes or mode types :

- Mode is the one which describes the nature of propagation of electromagnetic waves in a wave guide.
- i.e. it is the allowed direction whose associated angles satisfy the conditions for total internal reflection and constructive interference.
- Based on the number of modes that propagates through the optical fiber, they are classified as:
- Single mode fibers
- Multi mode fibers

Single mode fibers:

- In a fiber, if only one mode is transmitted through it, then it is said to be a single mode fiber.
- A typical single mode fiber may have a core radius of 3 μm and a numerical aperture of 0.1 at a wavelength of 0.8 μm.
- The condition for the single mode operation is given by the V number of the fiber which is defined as such that V ≤ 2.405.
- V – number determines how many modes a fiber can support, It is given by, $V = \frac{2\pi a}{\lambda} N A$, where $NA = \sqrt{n_1^2 - n_2^2}$

- Here, n1 = refractive index of the core; a = radius of the core; λ = wavelength of the light propagating through the fiber.
- If $V \leq 2.405$, then the fibre is single mode fibre (SMF)
- If $V > 2.405$, then the fibre is multimode fibre (MMF)

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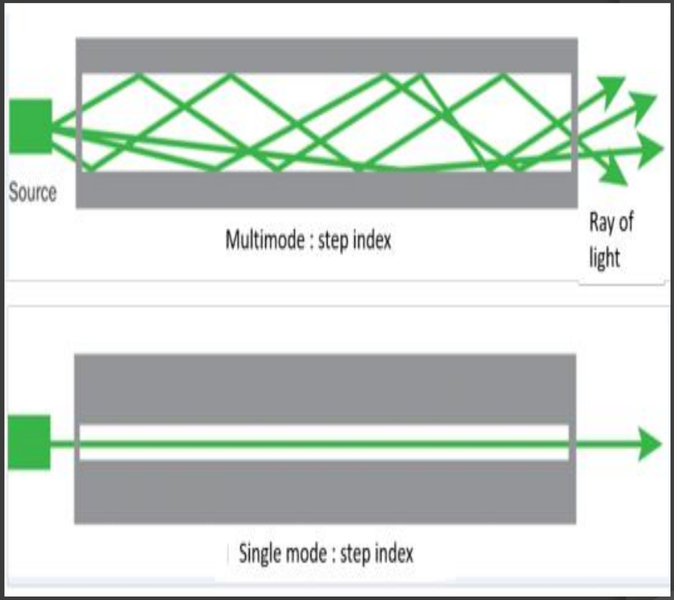
The single mode fiber has the following characteristics:

- Only one path is available.
- V-number is less than 2.405
- Core diameter is small
- No dispersion
- Higher band width (1000 MHz)
- Used for long haul communication
- Fabrication is difficult and costly

Multi mode fibers :

- If more than one mode is transmitted through optical fiber, then it is said to be a multimode fiber.
- The larger core radii of multimode fibers make it easier to launch optical power into the fiber and facilitate the end to end connection of similar powers



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Some of the basic properties of multimode optical fibers are listed below :

- More than one path is available
- V-number is greater than 2.405
- Core diameter is higher
- Higher dispersion
- Lower bandwidth (50MHz)
- Used for short distance communication
- Fabrication is less difficult and not costly

Solved Problem (1) :

- Calculate the V – number and number of modes propagating through the fiber having a = 50 μm,
  n1 = 1. 53, n2 = 1.50 and λ = 1μm.
- The core diameter of the typical multimode fiber varies between 50 μm and about 200 μm, with cladding thickness typically equal to the core radius.

$$\text{V - Number} = \left(\frac{2\pi a}{\lambda}\right) \times \text{N.A} = \left(\frac{2\pi a}{\lambda}\right) \times (n_1^{\,2} - n_2^{2})^{\frac{1}{2}}$$

$$= \frac{2 \times 3.142 \times 50}{1}\left(1.53^2 - 1.50^2\right)^{\frac{1}{2}}$$

$$= 94.72$$

The number of modes propagating through the fiber

V – number = 94.72 ; No. of modes = 4486

Optical fibers based on refractive index profile :

Based on the refractive index profile of the core and cladding, the optical fibers are classified into two types:

- Step index fiber
- Graded index fiber.

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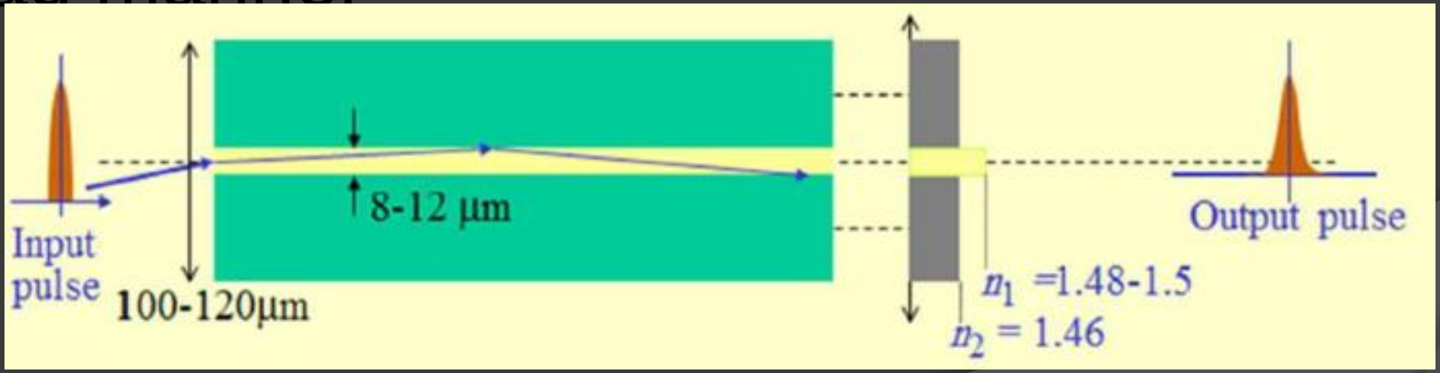
Step index fiber :

- In a step index fiber, the refractive index changes in a step fashion, from the center of the fiber, the core, to the outer shell, the cladding.
- It is high in the core and lower in the cladding. The light in the fiber propagates by bouncing back and forth from core-cladding interface.
- The step index fibers propagate both single and multimode signals within the fiber core.

- The light rays propagating through it are in the form of meridional rays which will cross the fiber core axis during every reflection at the core – cladding boundary and are propagating in a zig – zag manner



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Step index multimode fibers :

- A multimode step index fiber is shown.
  In such fibers light propagates in many modes.
- The total number of modes MN increases with increase in the numerical aperture.
- For a larger number of modes, MN can be approximated by:

$$M_N = \frac{V^2}{2}$$

- The size of the graded-index fiber is about the same as the step-index fiber. The manufacture of graded-index fiber is more complex. It is more difficult to control the refractive index well enough to produce accurately the variations needed for the desired index profile.

- **Graded index fibers :** A graded index fiber is shown in next figure. Here, the refractive index n in the core varies as we move away from the center.
   The refractive index of the core is made to vary in the form of parabolic manner such that the maximum refractive index is present at the center of the core.
- The number of modes in a graded-index fiber is about half that in a similar step-index fiber,

$$M_N = \frac{V^2}{4}$$

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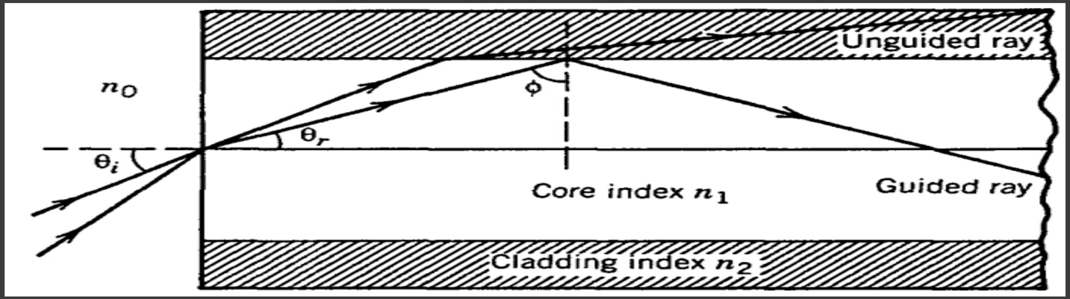
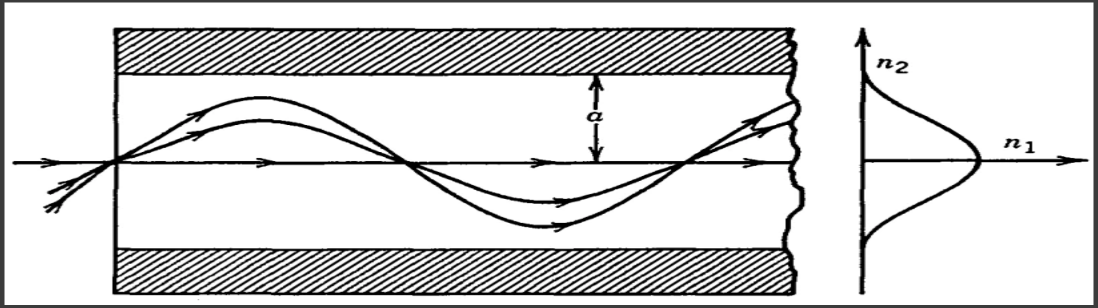
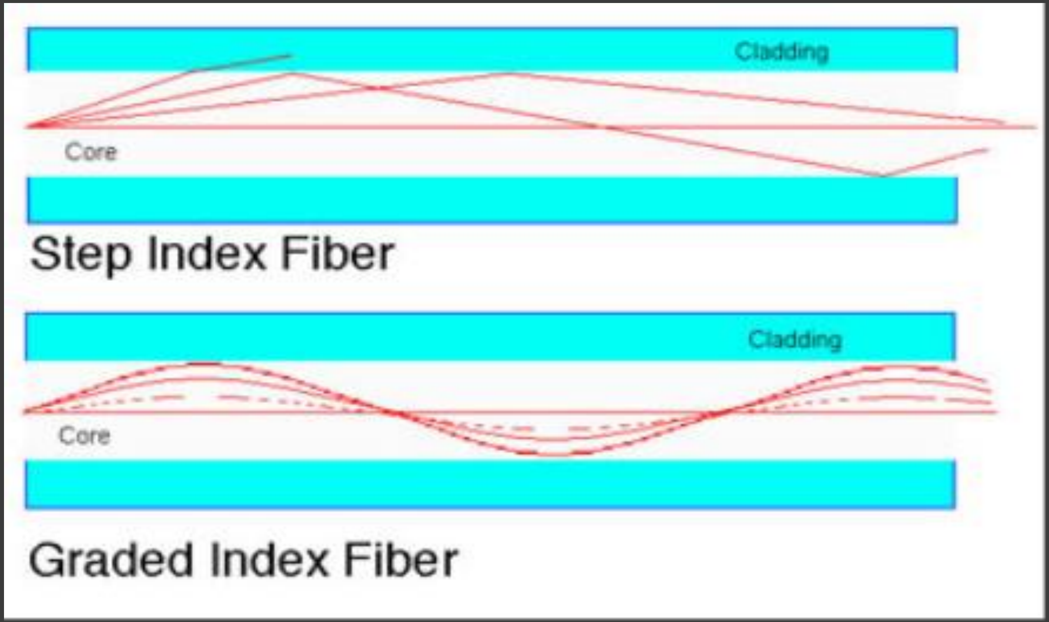
- Step_index fiber



- Graded-index fiber



Step index fiber vs. graded index fiber



Exercise (1) :

- **Find the core radius necessary for single** mode operation at 850 nm of step index fiber with n1 = 1.480 and n2 = 1.465. Hint: V – number = 2.405 (for single mode fiber) a = core radius = 1.554 µm.
- Sol.

$$\text{V - Number} = \left(\frac{2\pi a}{\lambda}\right) \times \text{N.A}$$

- N.A=sqrt((1.48)^2-(1.465)^2)=0.2102
- a= λ* V- number / 2**π*N.A*
- A=850*2.405/2*3.14*0.21=1550 nm=1.55 µm

Exercise (2) :

- A step-index fiber has a normalized frequency V = 26.6 at 1300 nm wavelength. If the core radius is 25 µm. What will be the value of numerical aperture?

- Example: A manufacturer wishes to make a silica-core, step-index fiber with V = 75 and a numerical aperture NA = 0.30 to be used 820 nm. If n1 = 1.458, what should the core size and cladding index be?

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

$$a = \frac{V\lambda}{2\pi \times NA}$$

$$a = \frac{(820\ nm)(75)}{2\pi \times (0.3)} = 3.2627 \times 10^4\ nm$$

$$a = 32.627\ \mu m$$

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

$$n_2 = \sqrt{(1.458)^2 - (0.3)^2}$$

$$n_2 = 1.4268$$

Refrences

1. Electronic communication system 2nd edition. Roy blake

2. Fundamentals of Optical Networks and Components. Partha Pratim Sahu 2020

3. Fiber Optics Installer and Technician Guide. Bill Woodward Emile B. Husson