PHY 110 Engineering Physics

Lecture 3

UNIT 3 – Fiber optics

Numerical aperture

Light gathering ability of the fiber depends on the numerical aperture , NA and is defined as the sine of the acceptance angle θ_{imax}

$$NA = sin\theta_{imax}$$

$$\theta_{\mathrm{imax}} = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$$

$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2}$$ -------- Eq.11

NA is also related to the relative refractive index Δ

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

Numerical aperture

Numerical aperture can also be expressed in terms of relative refractive , Δ

$$(NA)^2 = n_1^2 - n_2^2 = (n_1 - n_2)(n_1 + n_2)$$

Multiply and divide with $2n_1$

$$= \left(\frac{n_1 + n_2}{2}\right)\left(\frac{n_1 - n_2}{n_1}\right) 2n_1$$

Approximating $(n_1+n_2)/2 \sim n_1$

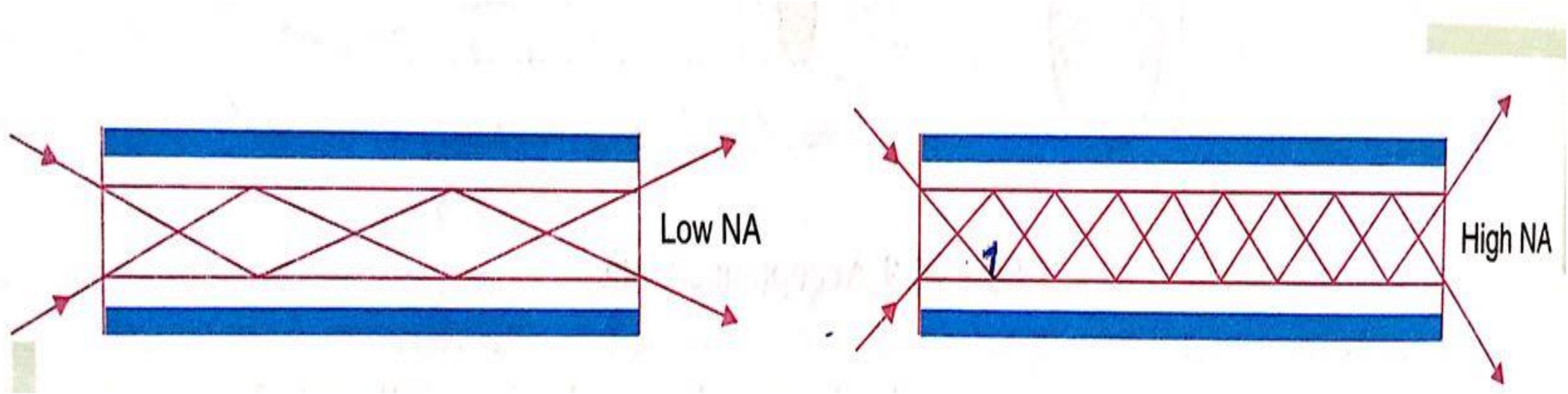
$$= 2\, n_1^2 \Delta$$

That is $$NA = n_1 \sqrt{2\Delta}$$

- Depends only on the refractive indices of the core and cladding.
- Independent of the dimension of the fiber

Numerical aperture

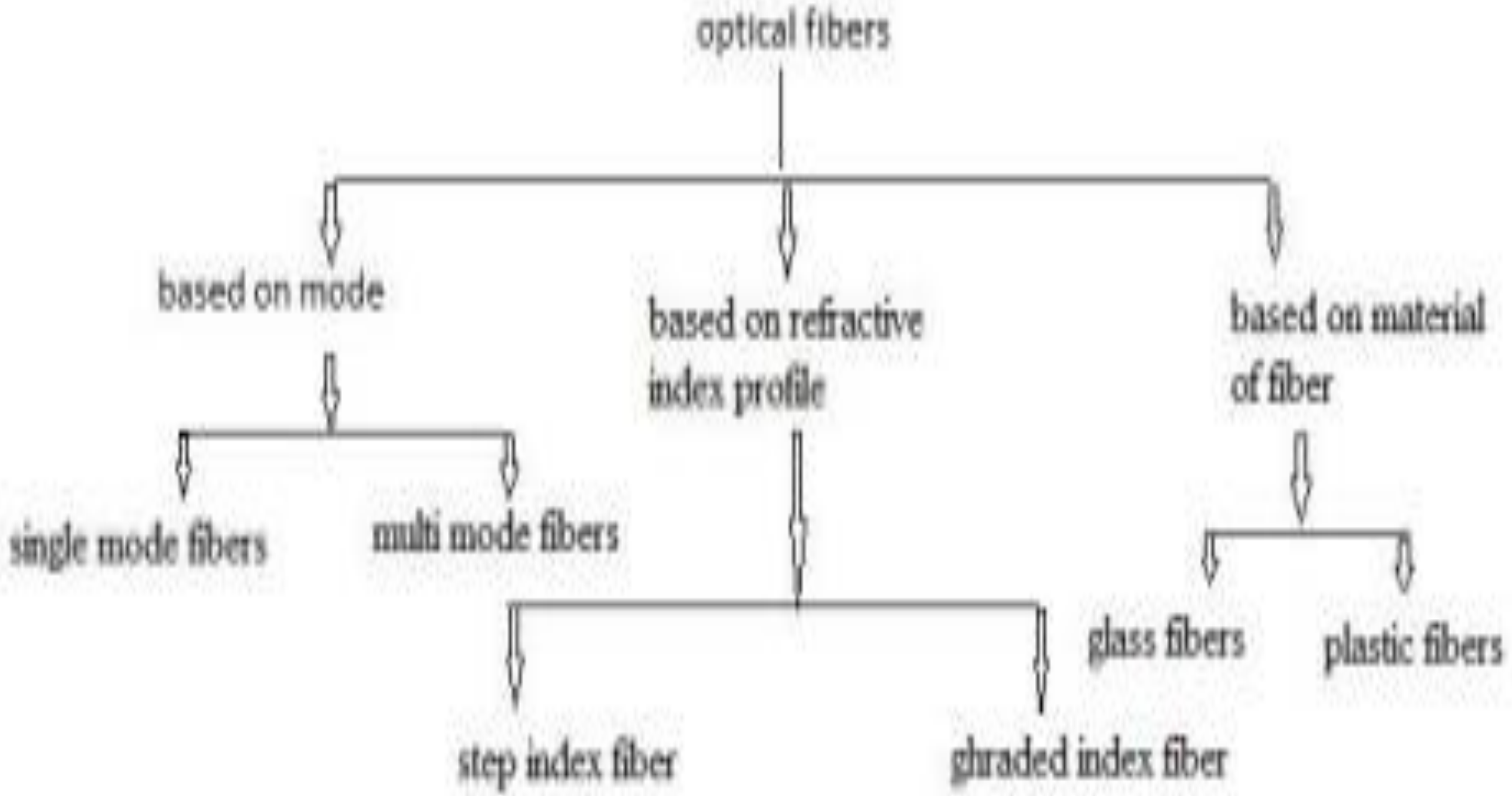
- Measure of the light gathering ability of the fiber
- Depends only on the refractive indices of the core and cladding.
- Independent of the dimension of the fiber
- Typical values are in the range 0.13 to 0.50



High NA means fiber accept large amount of light from the source and allows it to propagate through the fiber

The numerical aperture of a fiber if the angle of acceptance is 15°, is

a. 0.17
b. 0.26
c. 0.50
d. 0.75


optical fibers
based on mode
based on refractive index profile
based on material of fiber
single mode fibers
multi mode fibers
step index fiber
ghraded index fiber
glass fibers
plastic fibers

Based on mode:

- The rays travelling in the fiber by total internal reflection are called modes

1) SINGLE MODE OPTICAL FIBER

✓ Only one path for light to pass

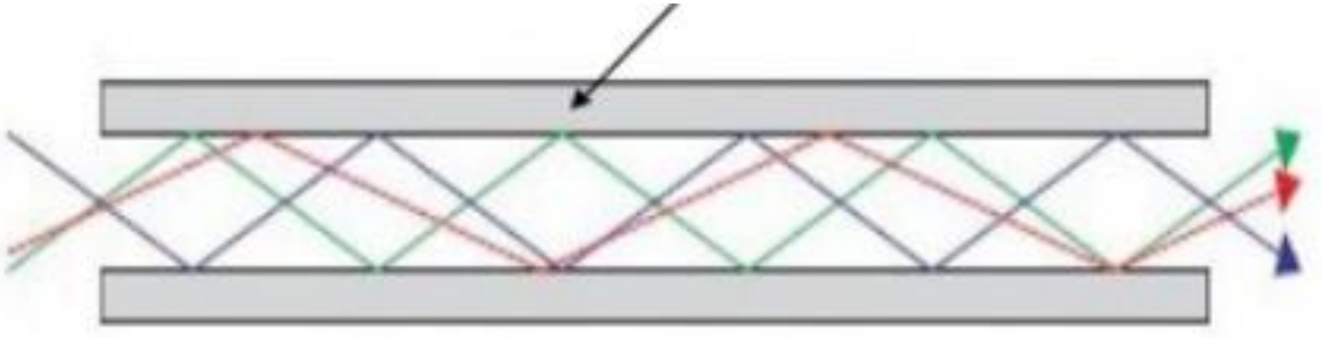
✓ Very small core diameter (~10 µm)

✓ Low band width 40 GHz

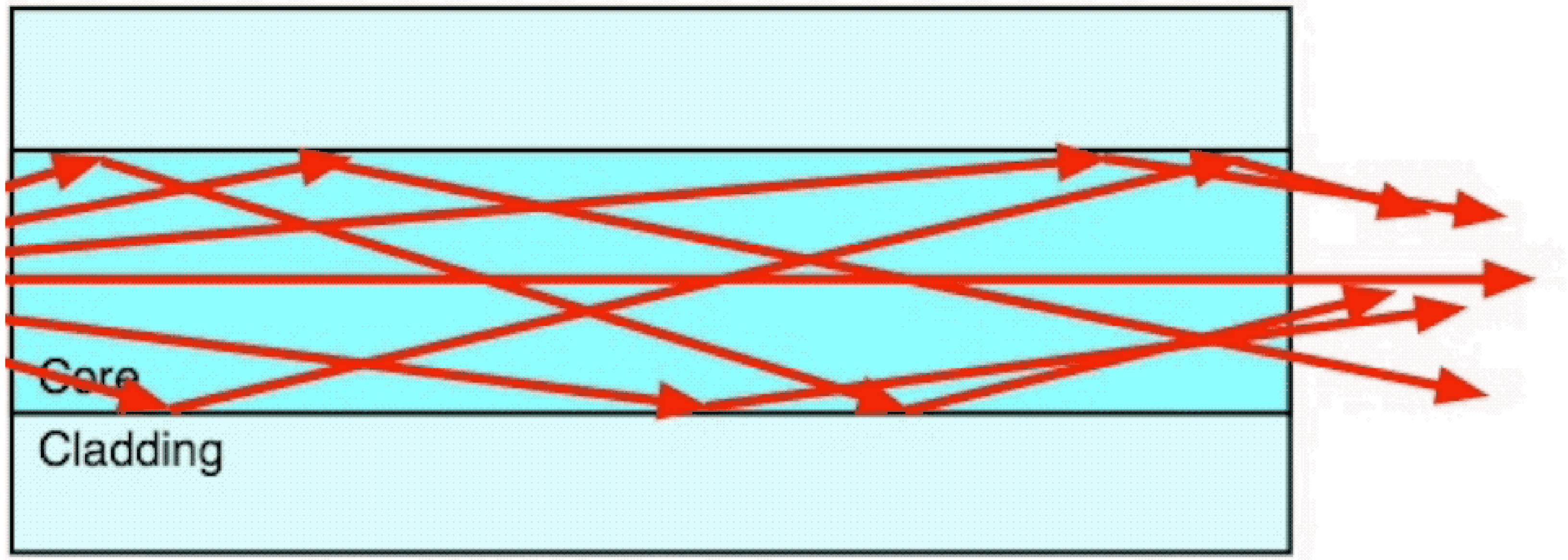
✓ Mostly used in long distance and low cost circuits, like T.V. cable

2)MULTI MODE FIBERS:

- If the thickness of the fiber is very large that it supports more than one mode then the fiber is called multi mode fiber.
- The core diameter of this fiber is about 50 to 200µm and the outer diameter of cladding is 100 to 250µm

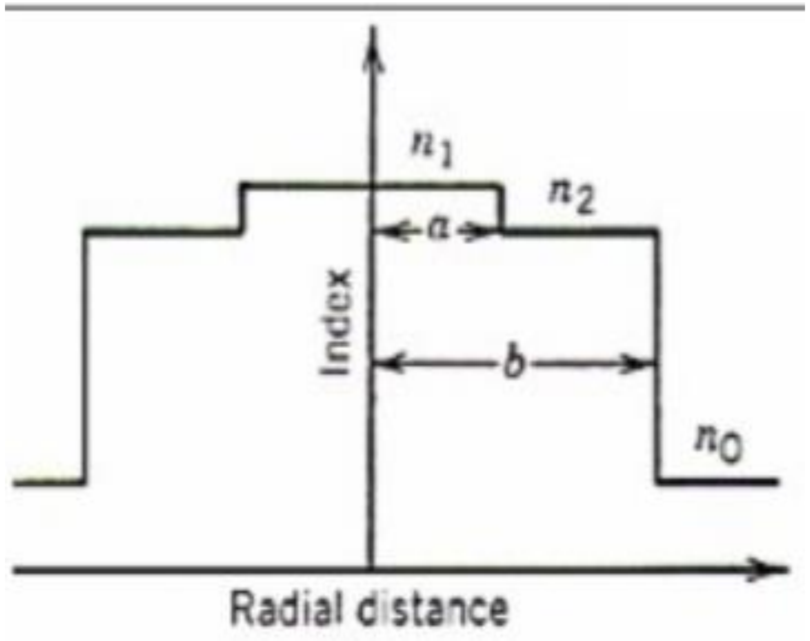


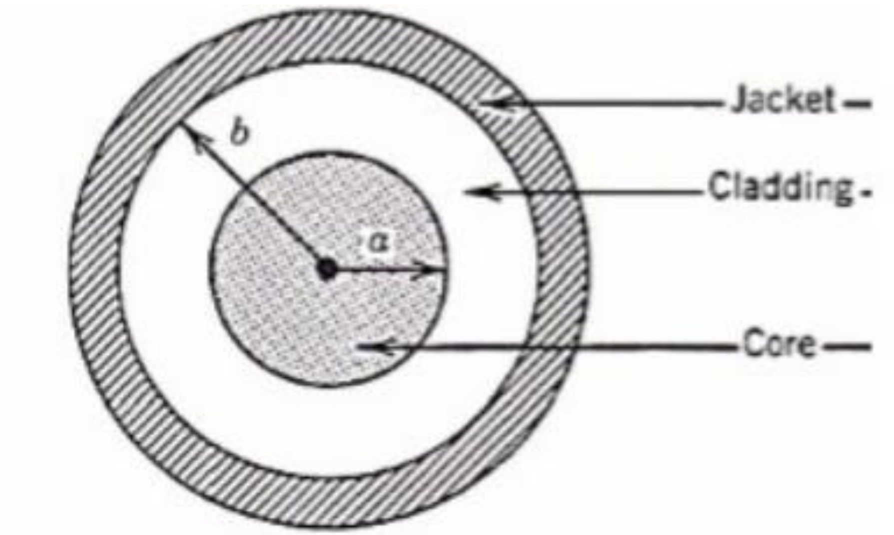
Multimode Fiber


Core
Cladding

Based on refractive index profile:

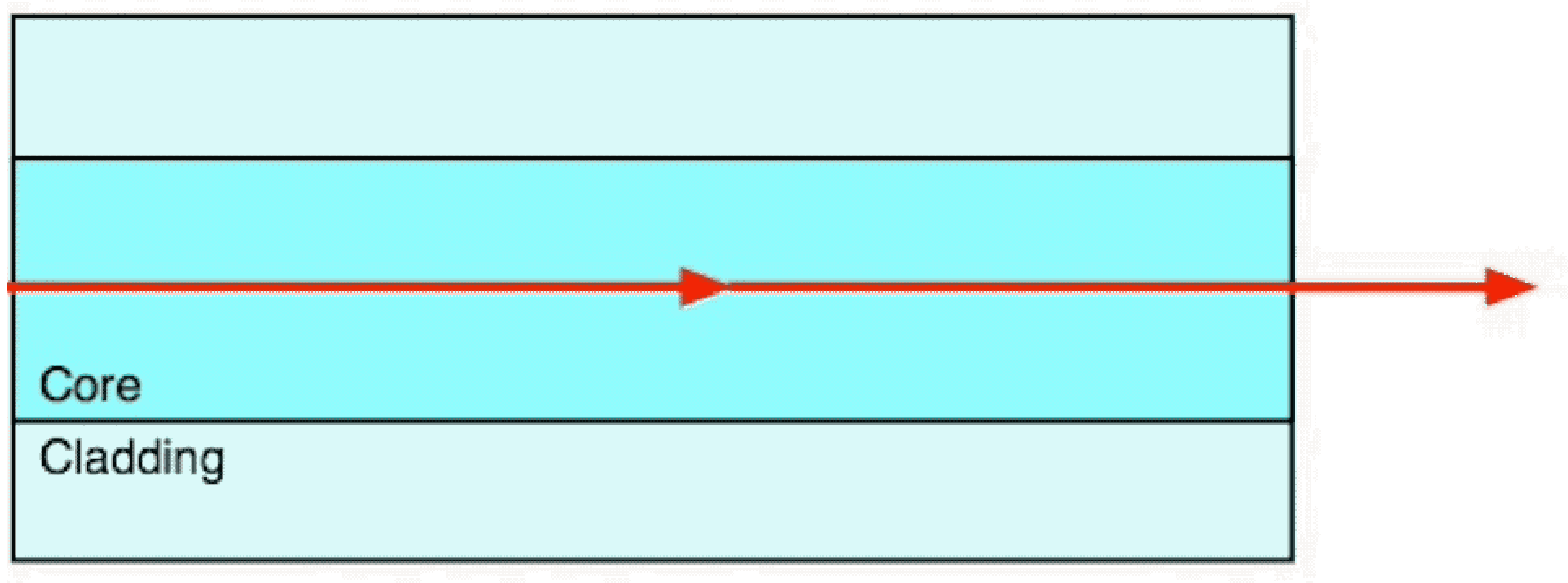
1) STEP-INDEX OPTICAL FIBER





- ✓ Uniform/constant refractive index of the core
- ✓ Core have higher refractive index than cladding
- ✓ Abrupt change in ‘n’ at the interface
- ✓ Graph of radial distance vs. refractive index seems like a step
- ✓ The transmission of information will be in the form of signals or pulses

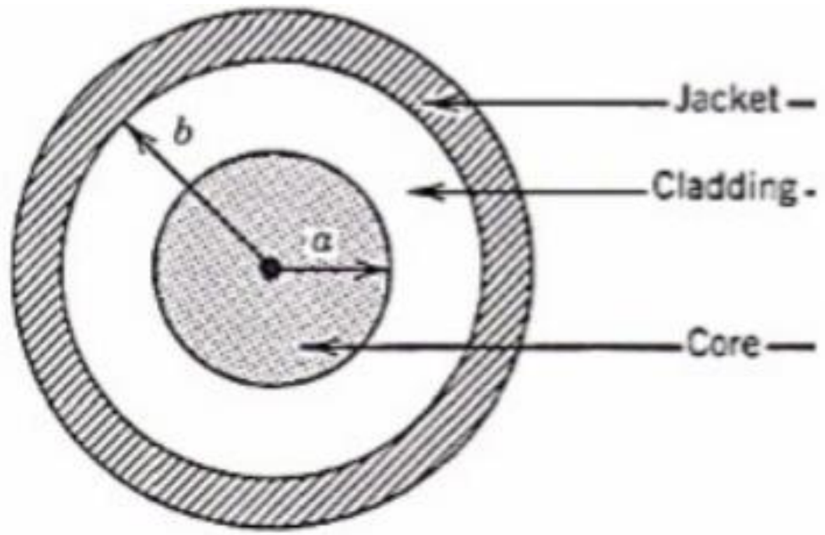
STEP-INDEX OPTICAL FIBER

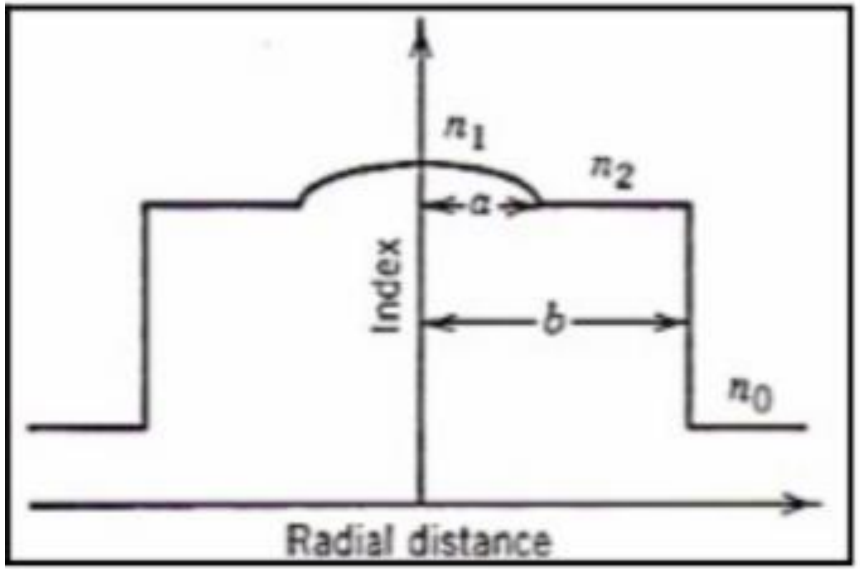


Transmission / propagation of signal in Step-index fibers:

- Generally the signal is sent through the fiber in digital form i.e. in the form of pulses.
- The same pulsed signal travels in different paths.
- Let us now consider a signal pulse travelling through step index fiber in two different paths (1) and (2).
- The pulse (1) travelling along the axis of the fiber and pulse (2) travelling away from the axis.
- At the receiving end only the pulse (1)which travels along the fiber axis reaches first while the pulse(2) reaches after some time delay.
- Hence the pulsed signal received at the other end is broadened. This is called internal dispersion.
- This reduces transmission rate capacity of the signal.
- This difficulty is overcome by graded index fibers.

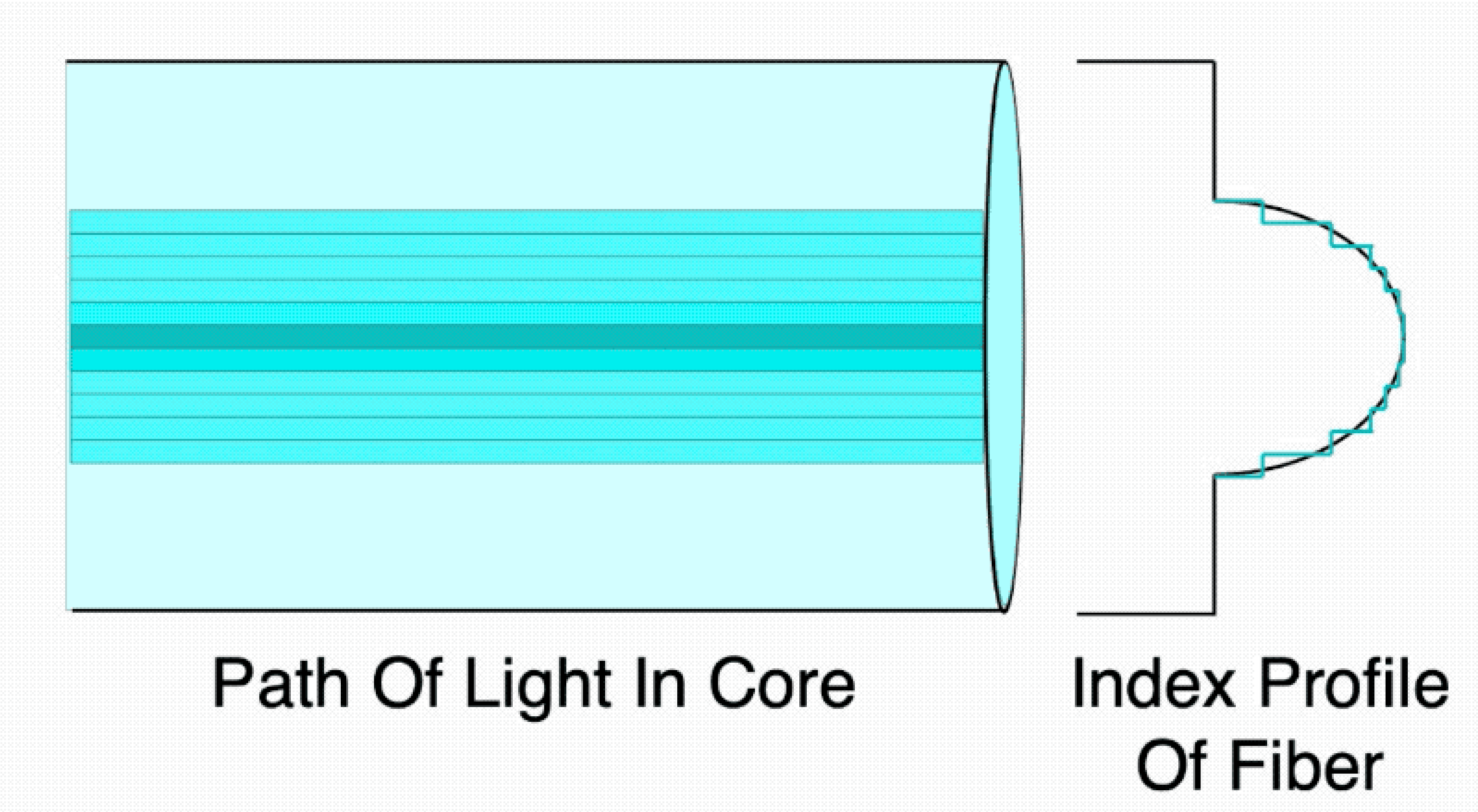
2) GRADED-INDEX OPTICAL FIBER





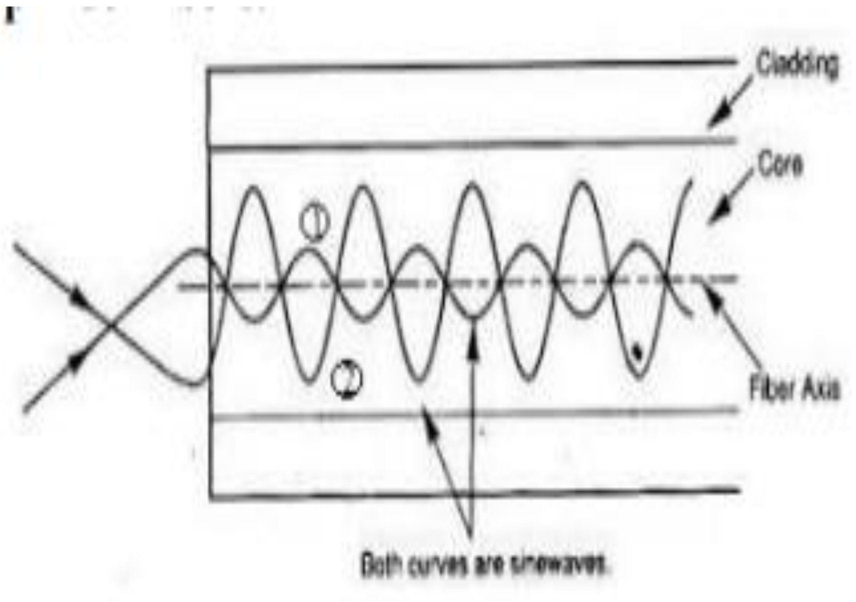
- ✓ Refractive index is highest at the center and decrease towards core-cladding **interface**- n varies gradually with radial distance
- ✓ Symmetric distribution along the diameter- **concentric circles**
- ✓ Same ‘n’ at the interface- **core material and cladding material have nearly same n**
- ✓ Coaxial tube of material with different n

GRADED-INDEX OPTICAL FIBER



Transmission / propagation of signal in Graded-index fibers

- Let us now consider a signal pulse travelling through graded index fiber in two different paths (1) and (2).
- The pulse (1) travelling along the axis of the fiber though travels along shorter route it travels through higher refractive index.
- The pulse (2) travelling away from the axis undergo refraction and bend as shown in fig. though it travels longer distance, it travels along lesser refractive index medium.
- Hence both the pulses reach the other end simultaneously.
- Thus the problem of inter model dispersion can be overcome by using graded index fibers.



Based on types of materials:

- glass-glass optical fiber
- glass-plastic optical fiber
- plastic-plastic optical fiber

How does the refractive index of the core vary in Graded Index fiber?

a) Tangentially

b) Radially

c) Longitudinally

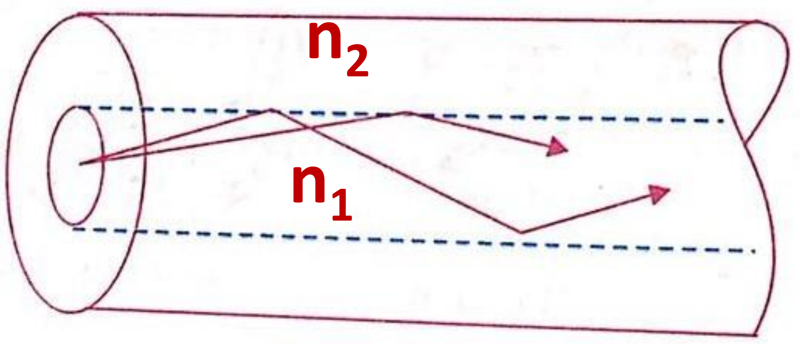
d) Transversely

V-number

V-number sets the upper limit of the number of modes (N_m) that can be transmitted in a multi mode optical fiber, given by the relation

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

$$V = \frac{\pi d}{\lambda} (NA) = \frac{\pi d}{\lambda} n_1 \sqrt{2\Delta}$$



d - the diameter of the core and λ- wavelength of the light

Maximum number of modes N_m supported by

Step index fiber

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

Graded Index fiber

$$N_m \cong \frac{1}{4}V^2$$

For a fiber to be single mode $V \leq 2.4$ for graded index fiber. and the wavelength with which the fiber becomes single mode is called cutoff wavelength λ_c

$$\lambda_c = \frac{\pi d}{2.4}(NA) \longleftarrow V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}$$

Single mode transmission in a multimode fiber can be realized by reducing the diameter or decreasing the Δ

Possible number of allowed paths of the light of wavelength λ in the optical fiber is called modes of propagation. State true or false

a) True
b) False

In single mode fibre the diameter of the core is nearly equal to

a) 10 μm
b) 100 μm
c) 250 μm
d) 125 μm

Ans: A

Losses and Dispersion in optical fibers

When the optical signal is made to propagate through the optical fiber, signal strength reduces and shape of the wave changes due to

1a. Attenuation

- ***a) Absorption***
- ***b) Scattering***

→ ***Intrinsic loss/attenuation***

1b. Radiative loss

Bending of optical fib → ***Extrinsic loss/attenuation***

2. Dispersion

- **a) Intermode**
- **b) Intramode**
  - **i. Material dispersion**
  - **ii. Waveguide dispersion**

- ❑ Loss of amplitude of the signal: attenuation
- ❑ Change in shape of the signal: Distortion/dispersion

LOSSES IN OPTICAL FIBERS

ATTENUATION

The loss of signal amplitude is known as attenuation

The loss of optical power as light travels down the fiber exponentially depends on the distance

$$P_0 = P_i e^{-\alpha L}$$

$$\alpha = \frac{1}{L} ln \frac{P_i}{P_0}$$

P_o is the power at distance L, P_i input power and α is the **fiber attenuation constant expressed in /km**

In unit of dB/km, is defined as,

$$\alpha_{dB/km} = \frac{10}{L} log \frac{P_i}{P_0}$$

In ideal case, P_i = P_o and attenuation is zero

LOSSES IN OPTICAL FIBERS

1. Losses due to Attenuation

a) Material absorption

- Imperfection and impurities in the fiber account for **3-5 %** loss
    - ✓ OH- common impurity-
    - ✓ Due to water trapped during the manufacturing process or Humidity from the atmosphere
    - ✓ Cu, Ni,Cr,V, Mn impurities in glass absorb visible wavelength

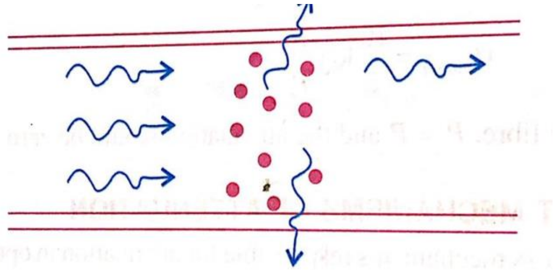
- Electronic absorption at UV and vibrational absorption at IR wavelengths are un avoidable
- Absorption found to be minimum around the wavelength 1.3 µm (1300 nm)
- Propagation of light with wavelength above 1.7 µm or **1700nm** is not possible due to infrared (IR) absorption

LOSSES IN OPTICAL FIBERS

1. Losses due to Attenuation

b) Rayleigh scattering

- Account for the **96%** of attenuation in the fiber
- Microscopic density variation causes changes in refractive index locally in the fiber
- These obstructions act as scattering centers and scatter light in all direction- Rayleigh scattering
- It varies as $1/\lambda^4$ – high at lower wavelength
- Lower wavelength limit is **800 nm** (**0**.8 μm)



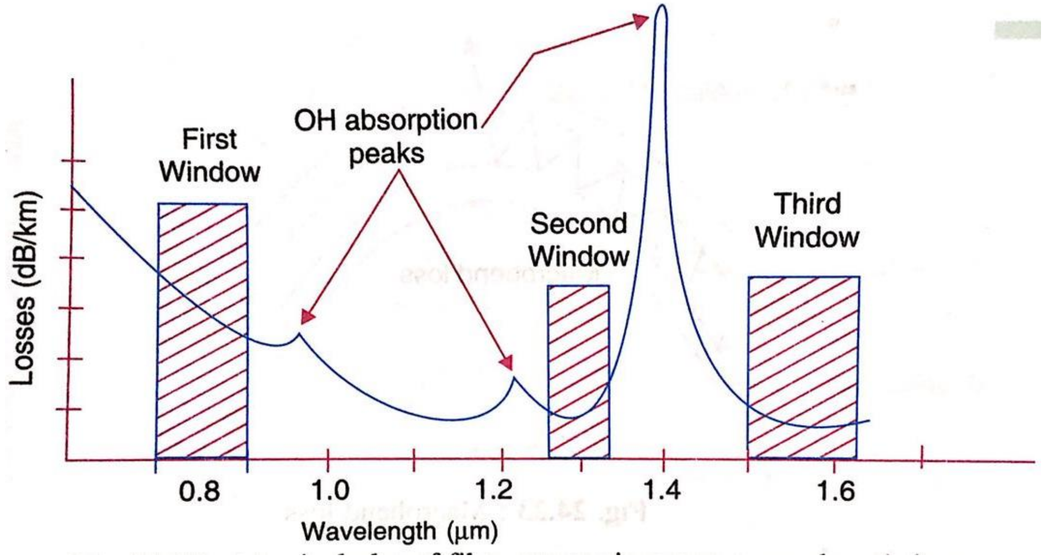
Material absorption set the upper wavelength limit at 1700 nm and Rayleigh scattering set the lower wavelength limit at 800 nm. So light having wavelength in the range **800-1700 nm** is used in optical communication!

LOSSES IN OPTICAL FIBERS

800-1700nm is used in optical communication

1. Losses due to Attenuation

λ nm	loss dB/km
820-880	2.2
1220-1320	0.6
1550-1610	0.2



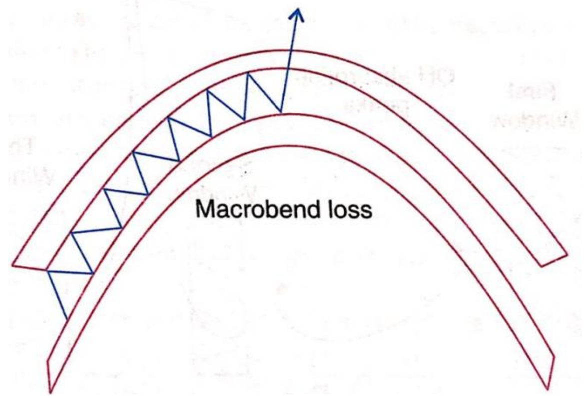
- ✓ The band of wavelength at which the attenuation is a minimum is called optical window or transmission window or low-loss window
- ✓ The range 1550-1610 is most preferable
- ✓ 1300 nm is suitable as the dispersion is minimum

LOSSES IN OPTICAL FIBERS

2. Losses due to bending of Optical fiber

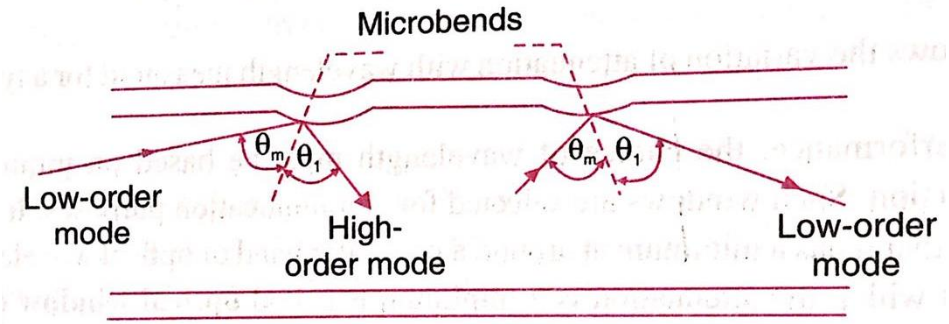
a) Macrobend

Fiber is bend in noticeable way and strain induced ‘n’ change TIR conditions and light escape



b) Microbend

- Small scale local bend on the fiber
- Not clearly visible
- Indicative of pressure on the fiber
- Light refracted into the cladding as TIR condition get changed



What causes microscopic bend?

a) Uniform pressure
b) Non-uniform volume
c) Uniform volume
d) Non-uniform pressure

Ans: D

The loss in signal power as light travels down a fiber is called

a. Dispersion
b. Scattering
c. Absorption
d. Attenuation

Ans: D

Which range of wavelength is most preferable for the transmission light through optical fiber with minimum loss **??**

a) 820-880 nm
b) 1220-1320 nm
c) 1550-1610 nm
d) None of the above

Ans: C

Which range of wavelength used in optical communication?

a) 800-1700 nm
b) 1700-2500 nm
c) 200-800 nm
d) None of the above

Ans: A

Which of the following has more distortion?

a) Single mode step-index fiber
b) Graded index fiber
c) Multimode step-index fiber
d) Glass fiber

Ans: C

In which of the following there is no distortion?

a) Graded index fiber
b) Multimode step-index fiber
c) Single step-index fiber
d) Glass fiber

Ans: A