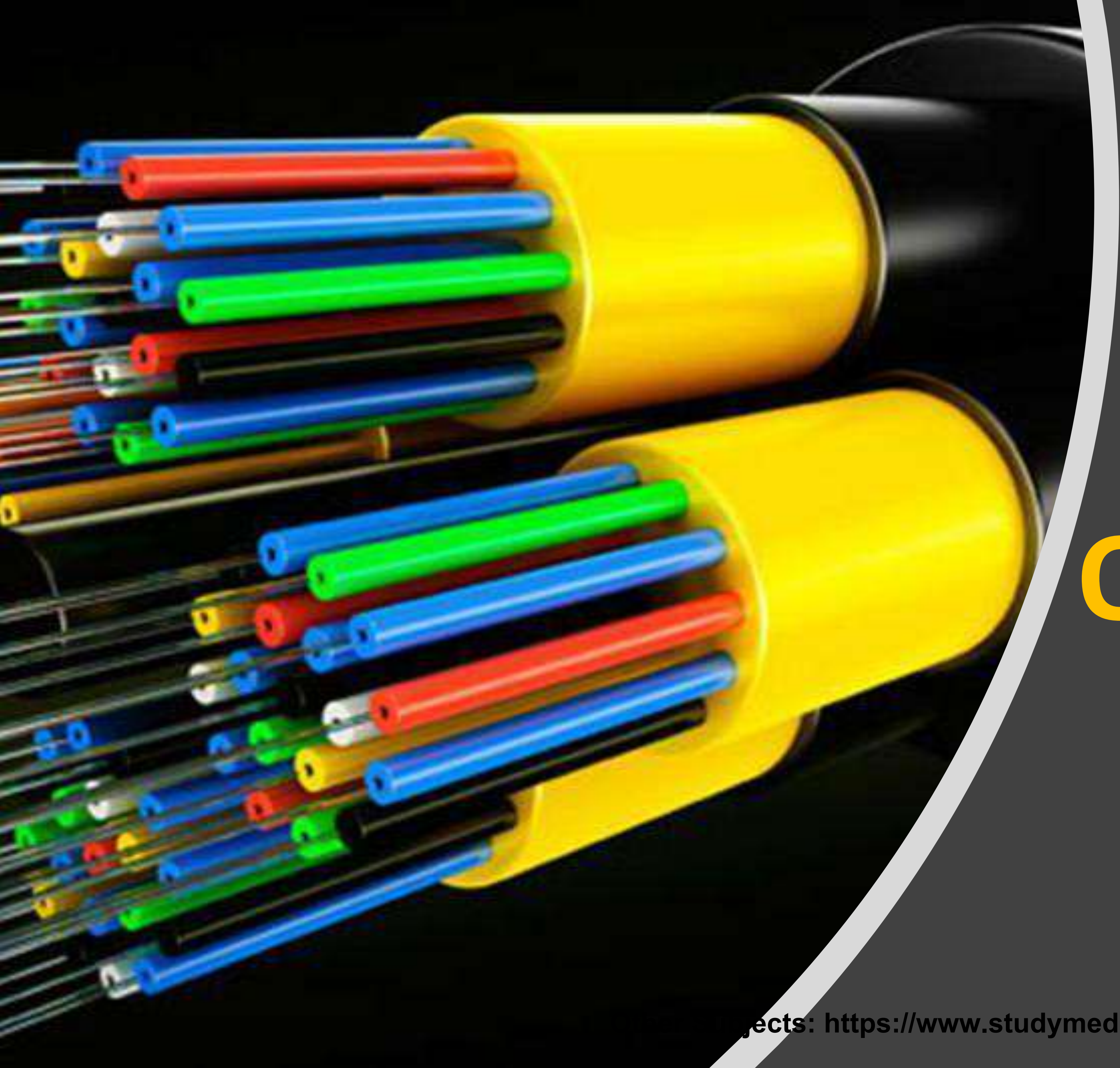
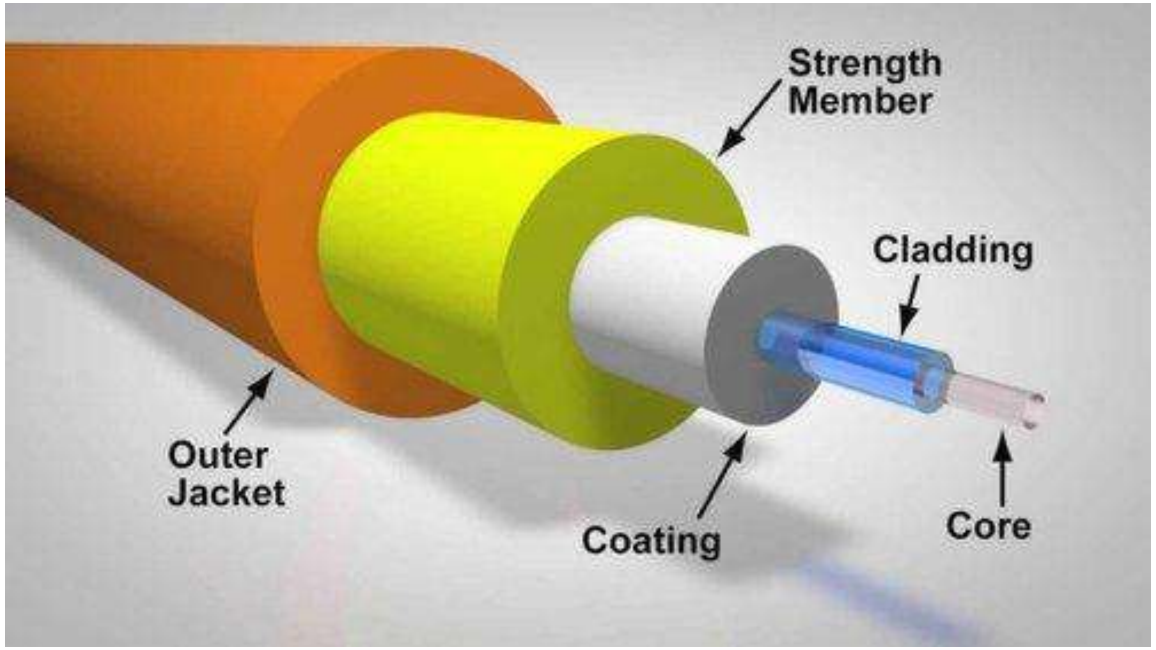
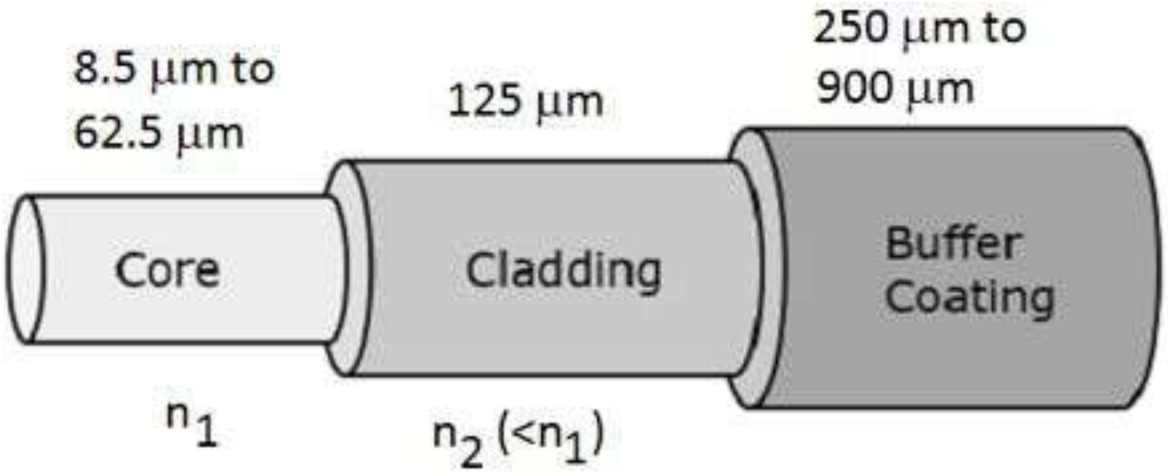


Optic Fibers

Basics of optical fibers

- Critical angle
- Total internal reflection
- Acceptance angle
- Acceptance cone
- Numerical Aperture
- Numerical

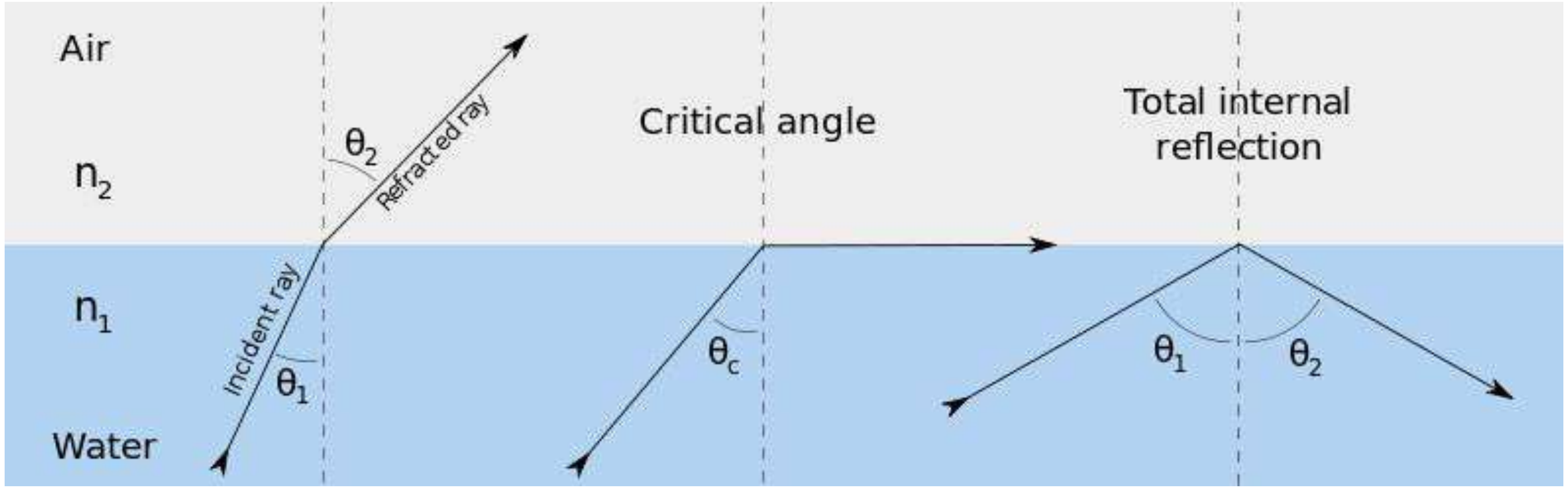




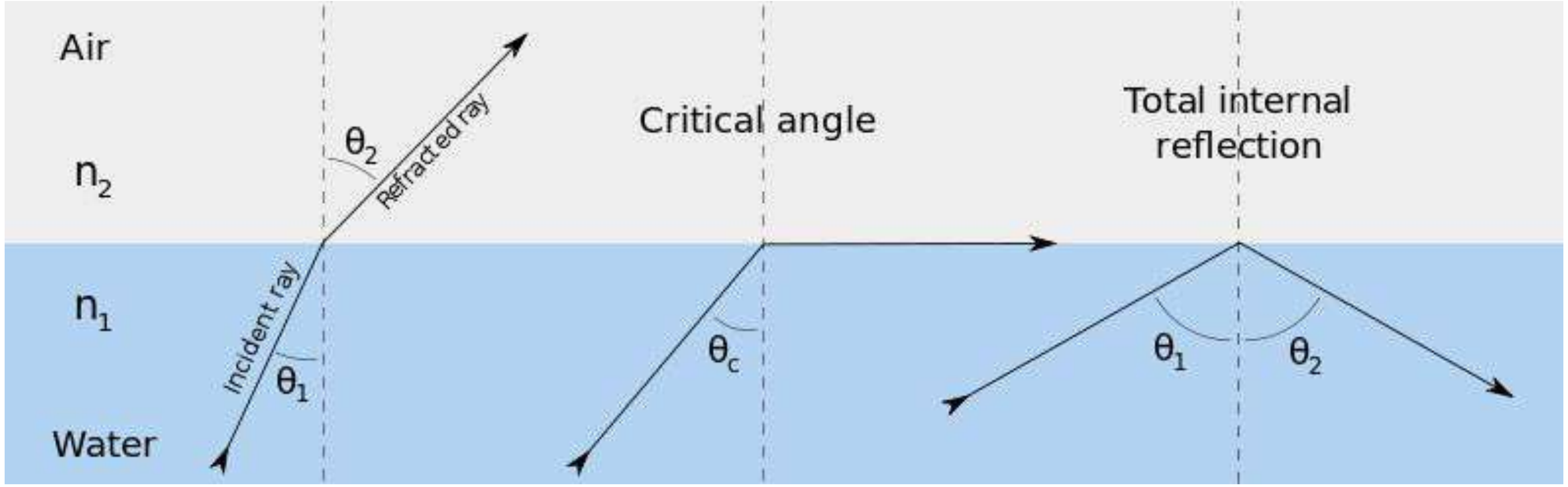
Component	Function
Core	Innermost light guiding region.
Cladding	Coaxial middle region having RI less than core. The purpose of the cladding is to make the light to be confined to the core by the process of total internal reflection.
Buffer Coating	A protective coating to protect from extreme physical and environmental conditions

Critical Angle (θ_c)

- **Critical angle** is the angle of incidence for which the refracted ray grazes the interface between the denser and the rare medium.
- At the angle greater than critical angle rays of light passing through a denser medium to the surface of a less dense medium are no longer refracted but totally reflected.



Critical Angle

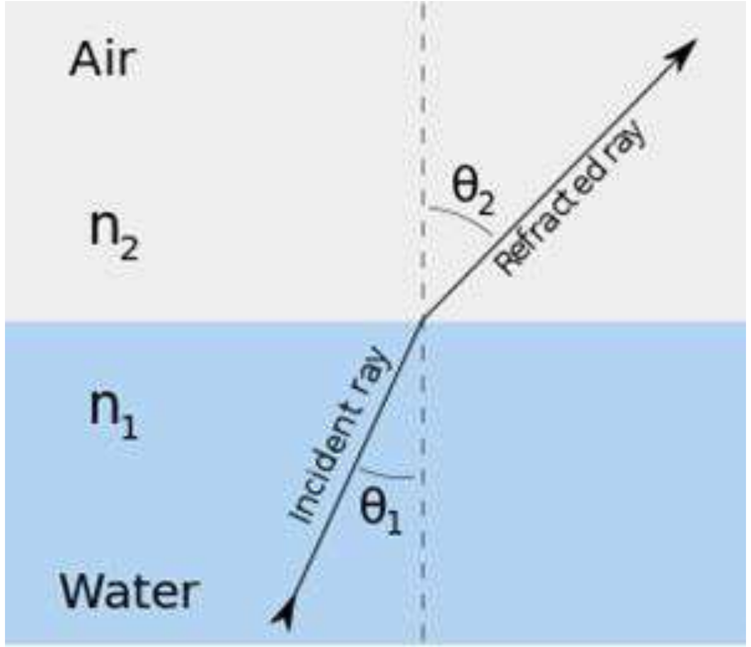


At some particular angle θ_c, the refracted ray grazes the boundary surface so that $\theta_2 = 90^0$. At angles greater than θ_c, there are no refracted rays. The rays are reflected back into the denser medium. Thus,

- If $\theta_1 < \theta_c$, the ray refracts into the rarer medium
- If $\theta_1 = \theta_c$, the ray grazes the interface between the rare and denser medium
- If $\theta_1 > \theta_c$, the ray is reflected back into the denser medium

Let n_1 is refractive index of core and n_2 is refractive index of cladding.
Then according to Snell's law,

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$



At critical angle, $\theta_1 = \theta_c$

As the refracted ray grazes surface, $\theta_2 = 90^0$, $\sin \theta_2 = 1$

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

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

$$\boxed{\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)}$$

The phenomenon in which light is totally reflected from denser to rarer medium boundary is known as **total internal reflection**.

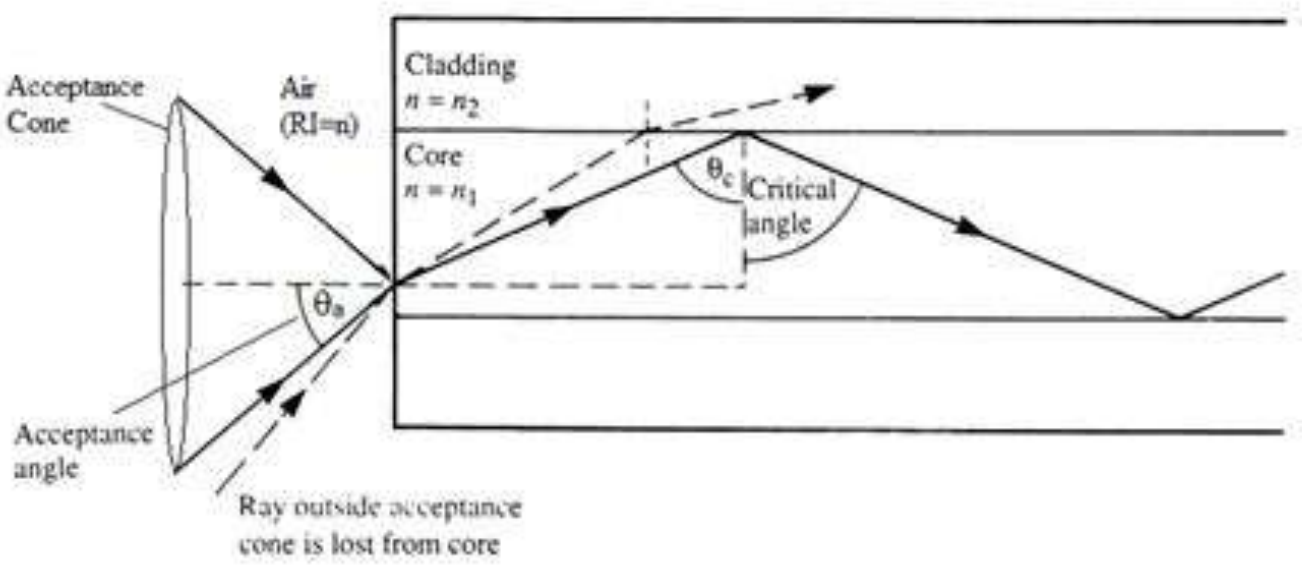
In optical fiber, total internal reflection at the fiber wall can occur and light propagates down the fiber, in following two conditions.

1. The refractive index of the core material, n_1, must be slightly greater than that of the cladding n_2.
2. At the core-cladding interface, the angle of incidence between the rays and the normal to the interface must be greater than critical angle. The rays that are incident at smaller angles are refracted into the cladding and are lost.

Acceptance angle and acceptance cone

Acceptance Angle: The maximum angle of launch of the light beam at its end to enable the entire light to pass through the core is known as acceptance angle

Acceptance Cone: Rotation of acceptance angle across the axis



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

If the medium through which light entering is air, n_0=1 and acceptance angle is given by

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

$$\text{Acceptance Cone} = 2 \times \text{Acceptance Angle} = 2 \times \theta_a$$

Numerical Aperture

- The main function of an optical fiber is to accept and transmit as much light from the source as possible.
- The light gathering ability of a fiber depends on two factors, namely core size and the numerical aperture.
- Numerical Aperture is the measure of the ability of an optical fiber to collect or confine the incident light ray inside it.
- Numerical Aperture is defined as the sine of the acceptance angle.

$$\text{Numerical Aperture (NA)} = \sin\theta_a = \left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$$

For air $n_0=1$

$$\text{Numerical Aperture (NA)} = \sin\theta_a = \sqrt{n_1^2 - n_2^2}$$

Formulae for Numerical

Critical Angle (θ_c)

$\sin\theta_c = \frac{n_2}{n_1}$ Or $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

Acceptance angle and acceptance cone

- $\theta_a = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$
- $Angle\ of\ acceptance\ cone = 2 \times Acceptaance\ angle = \ 2 \times \theta_a$

Numerical Aperture

- $NA = \ \sin(\theta_a) = \sqrt{n_1^2 - n_2^2}$

For an optic fiber placed in air, if acceptance angle is 52.74^0, calculate numerical aperture.

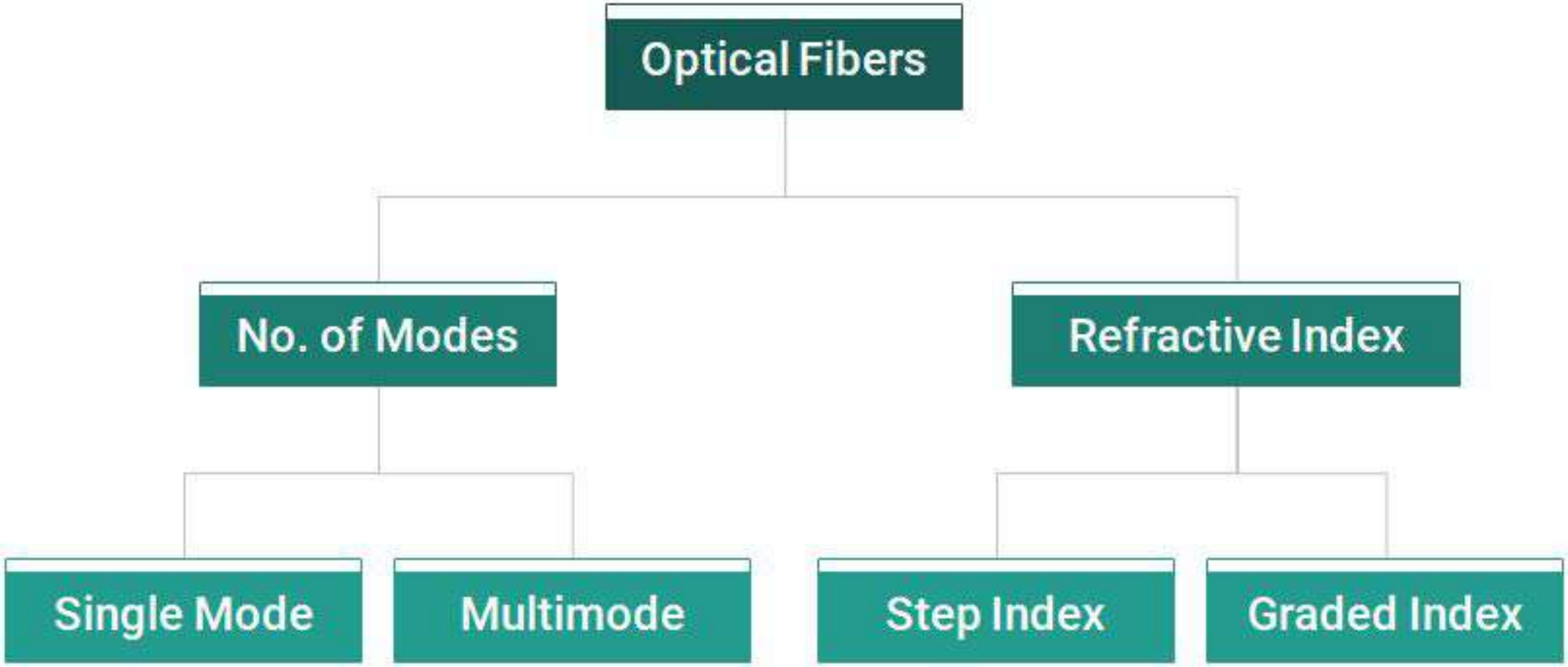
Calculate numerical aperture of an optic fiber with refractive indices of core and cladding 1.546 and 1.378, respectively.

Calculate the maximum value of angle of incidence such that light rays can travel through the fiber. Data given: $n_1 = 1.6$, $n_2 = 1.5$. ***[InSem Mar 20]***

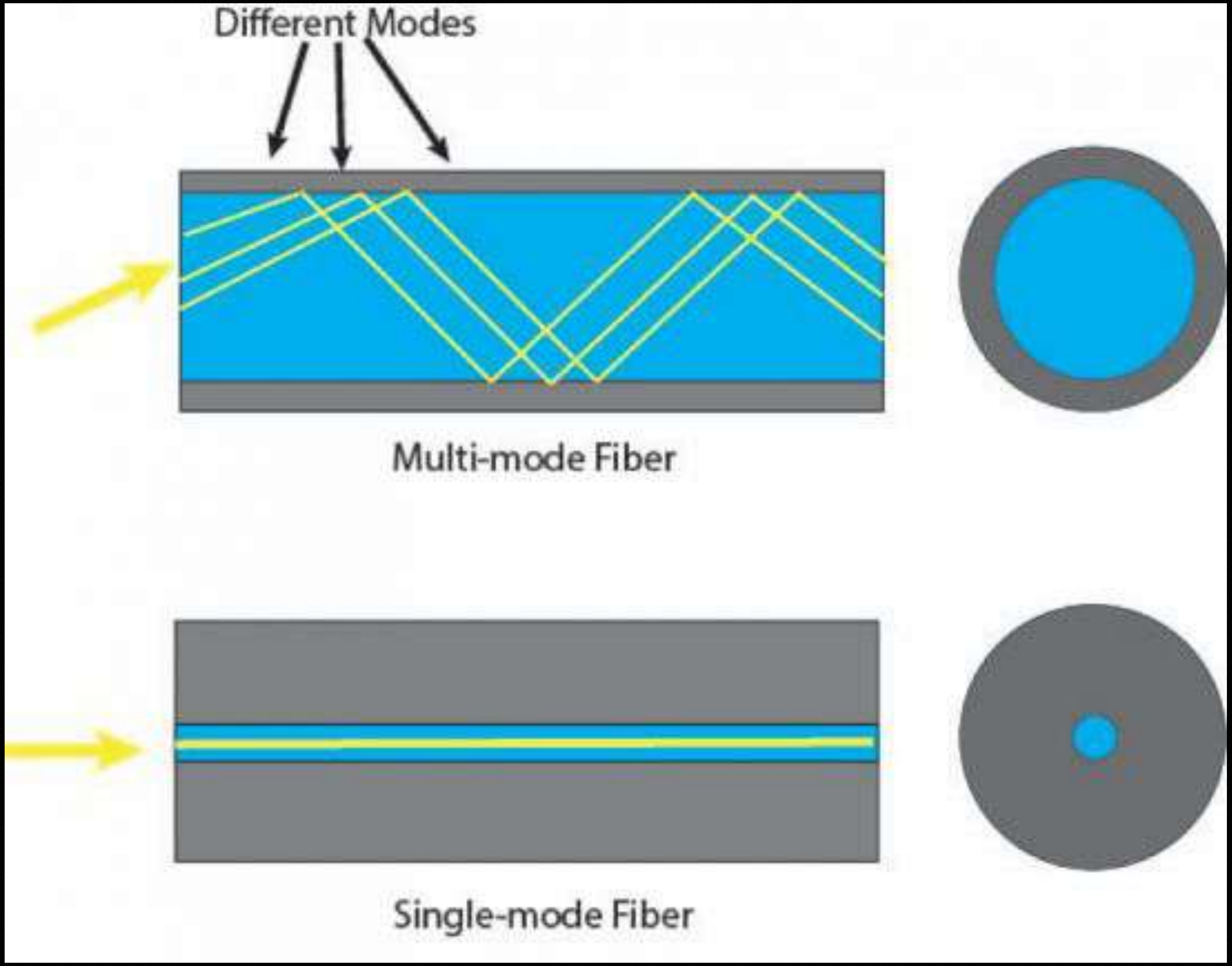
step index fiber has core and cladding refractive indices of 1.65 and 1.48. Calculate values of critical angle, numerical aperture and acceptance angle if it is placed in air.[InSem, Oct 19, 4m]

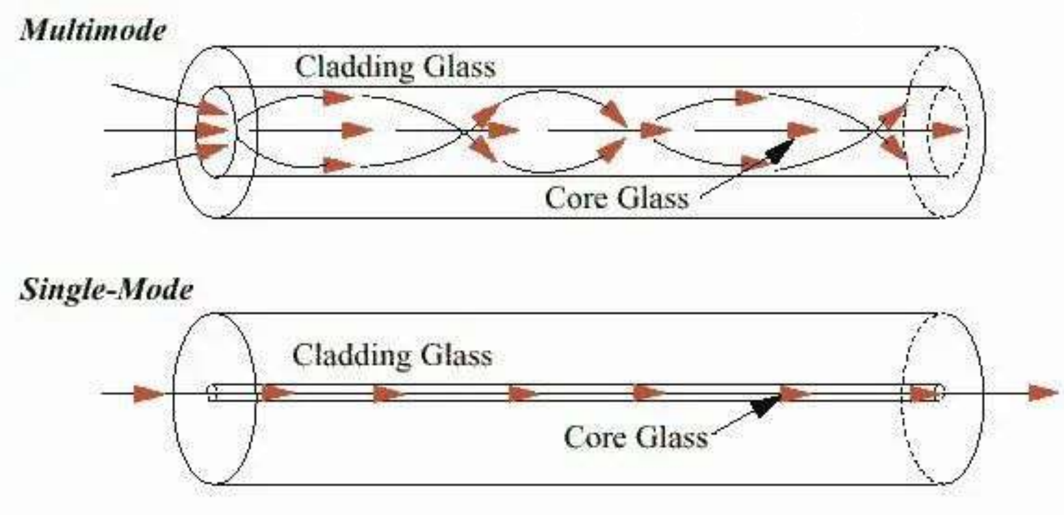
If the angle for acceptance cone of an optical fiber is 68.160, calculate maximum entrance angle and numerical aperture. If the refractive index of cladding is 1.52, calculate refractive index of core.

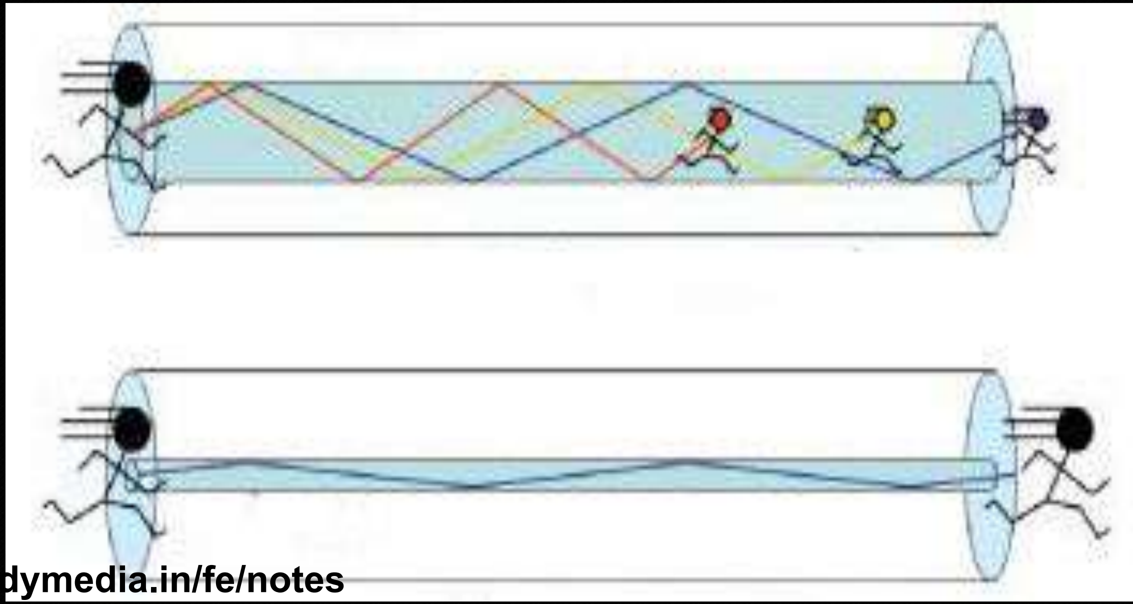
Classification of Optic Fibers


Optical Fibers
No. of Modes
Refractive Index
Single Mode
Multimode
Step Index
Graded Index

Single mode and Multimode Fibers







Single mode and Multimode Fibers

Sr.	Parameters	Single Mode	Multimode
1	Number of modes	Transmit a single mode during transmission	Transmit more than one mode during transmission
2	Diameter of single core	Very small (5 – 10 μm)	Larger (50 μm or more)
3	Difference in refractive index of core and cladding	Very small	Very large
4	End to end connectivity	Easy	Difficulty
5	Intermodal dispersion (time difference between entry and arrival of optical signal)	There is no intermodal dispersion	They suffer from intermodal dispersion
6	Transmission	Long distance	Short distance

Fractional Refractive Index change (Δ)

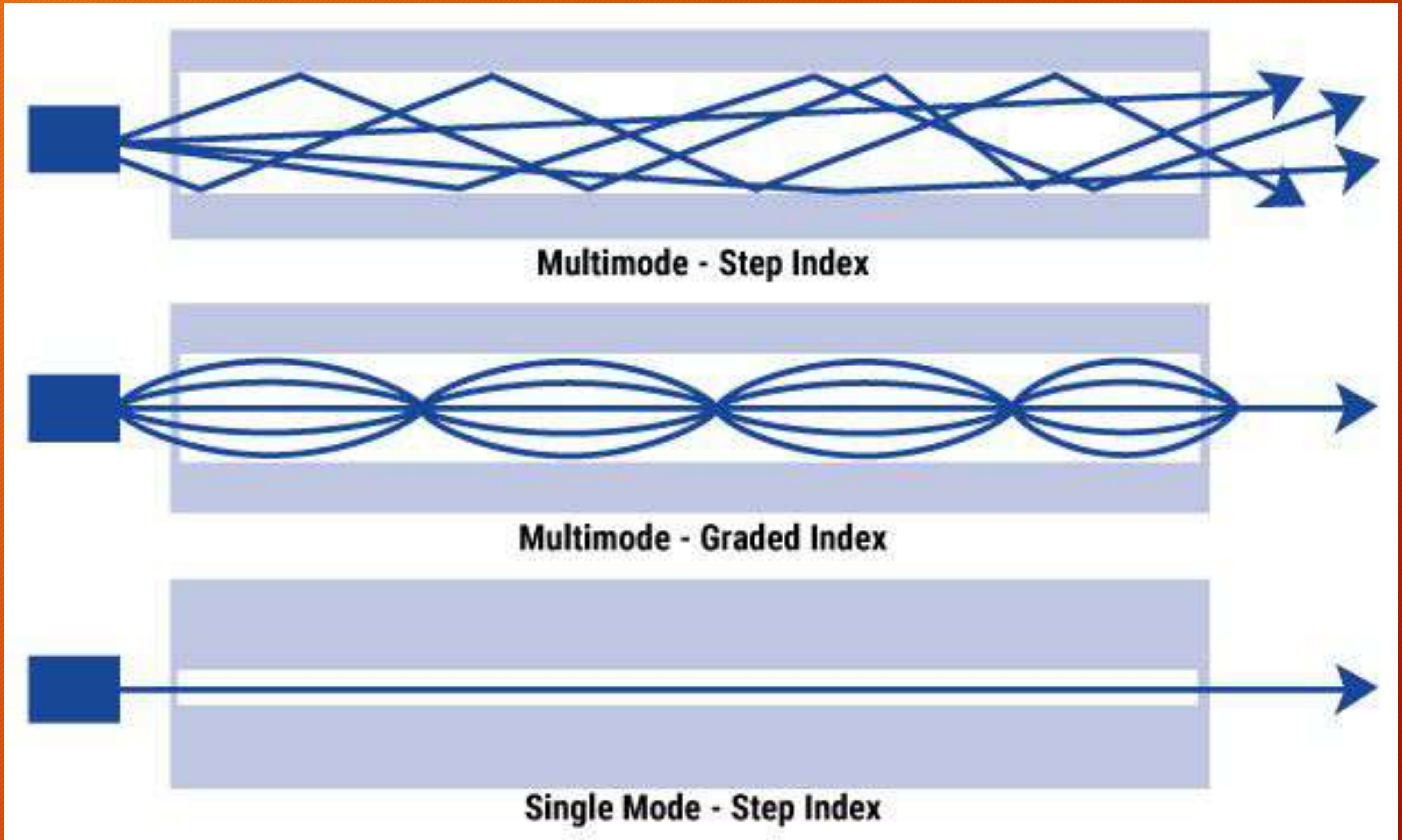
- The fractional difference Δ between the refractive indices of the core and the cladding is known as the fractional refractive index change.

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

$$\because \text{Numerical Aperture (NA)} = \sin\theta_a = \sqrt{n_1^2 - n_2^2}$$

$$\therefore \text{Numerical Aperture (NA)} = n_1\sqrt{2\Delta}$$

Step index and graded index fibers

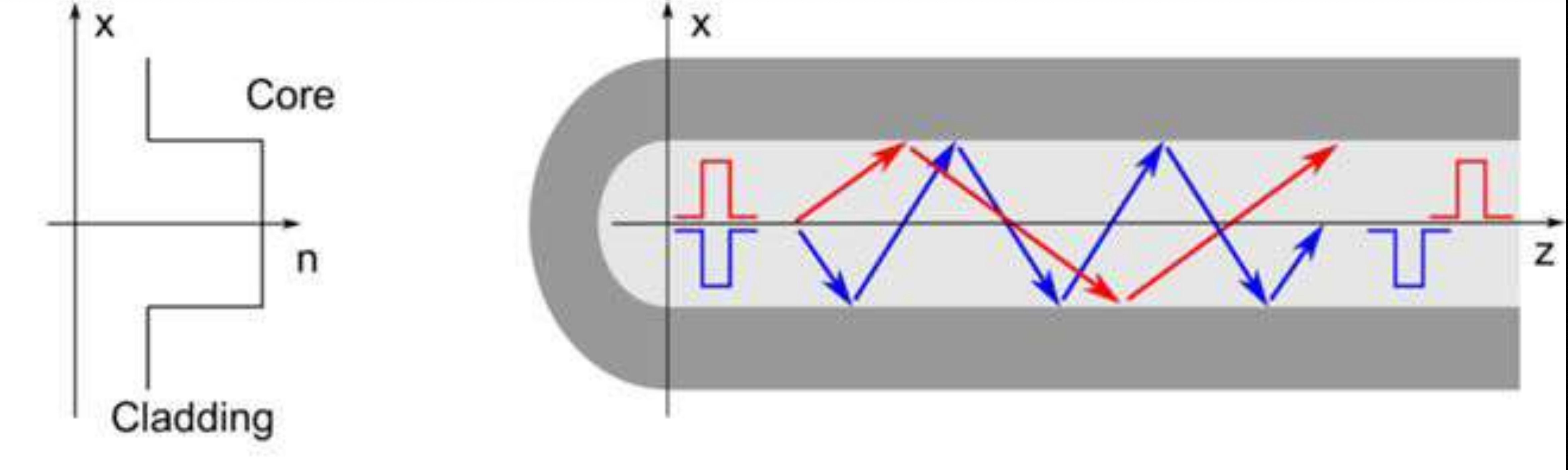


Step Index fibers

The refractive index of core and cladding varies step by step.

It is uniform throughout and undergoes abrupt change at the core cladding boundary.

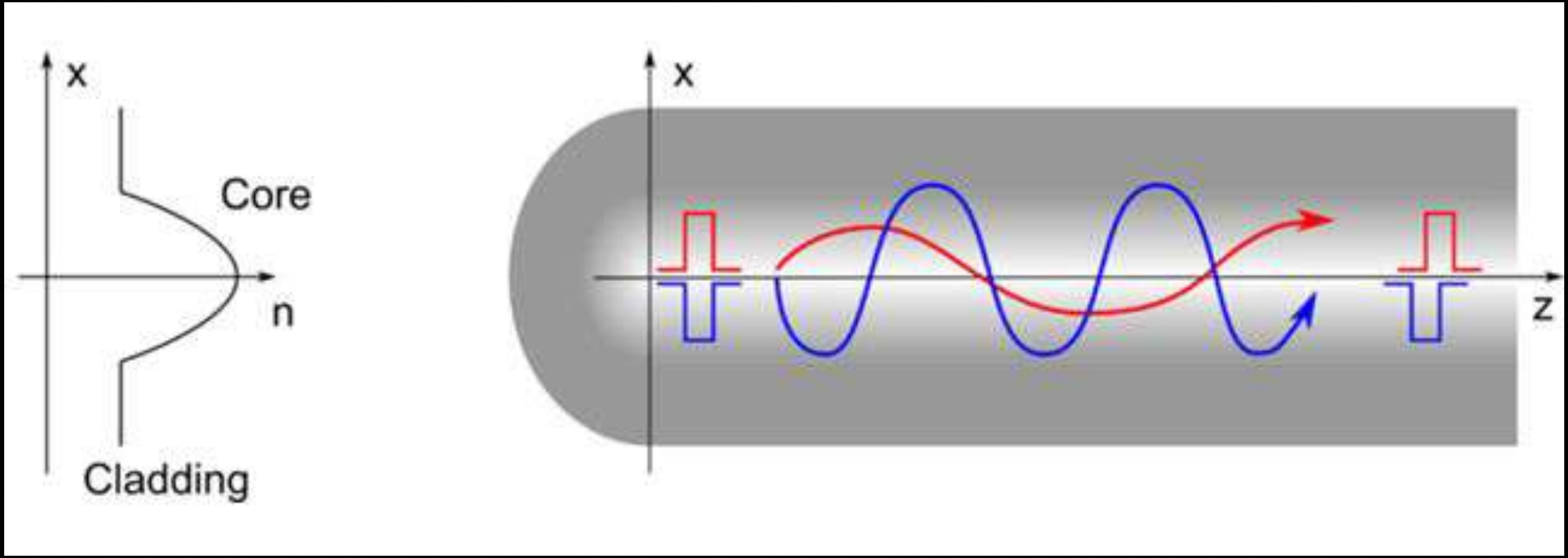
Light travels in zig-zag manner.



Graded Index fibers

The refractive index of core is made to vary gradually, and it is maximum at the center of the core.

Light travels in helical manner. They have higher bandwidth compared to step index fibers



Step Index and Graded Index Fibers

Sr.	Parameters	Step Index	Graded Index
1	Variation in RI of core and cladding	Step-by-step	Radial distance
2	RI difference at core-cladding interface	Larger	Smaller
3	Transmission of modes	Single and multimode signals	Multimode signal
4	Intermodal dispersion	Larger	Less
5	Bandwidth for multimodal transmission	Lower bandwidth due to lower numerical aperture	Higher bandwidth due to high numerical aperture

Step Index and Graded Index Fibers

Sr.	Parameters	Step Index	Graded Index
6	Propagation of rays	Light rays propagate as meridional rays since they cross axis of core	Light rays propagated as skws rays as they do not pass through axis of core
7	Pattern of Propagation of rays	Zigzag manner	Either spherical or helical
8	Applications	Long distance transmission	Short distance transmission

Calculate refractive indices of the core and cladding material of an optical fiber if numerical aperture is 0.22 and fractional index change is 0.012.

Find the fractional refractive index and numerical aperture for an optical fiber with refractive indices of core and cladding as 1.5 and 1.49, respectively.

ATTENUATION / LOSSES IN OPTIC FIBERS

ATTENUATION

- When optical signal propagates through an optical fiber, due to loss of amplitude its power decreases exponentially with the distance. This is called as attenuation.
- The attenuation is defined as the ratio of the optical output power from a fiber of the length L to the input optical power.

If, P_i = power of optical signal at launch

P_0 = power of optical signal emerging at another end

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

Where, α is called the fiber attenuation coefficient expressed in units of km^{-1}.

Taking logarithm of both the sides of the above equations, we get

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

The unit of measurement of attenuation is Bel/km

$$\alpha = \frac{10}{L} \ln \frac{P_i}{P_0}$$

Generally, attenuation measures in dB/km.

LOSSES IN OPTICAL FIBERS

- Losses in optical fibers
  - Intrinsic Losses
    - Absorption
    - Dispersion
    - Scattering
  - Extrinsic Losses
    - Micro bending
    - Macro bending

ATTENUATION: ABSORPTION BY MATERIAL

Absorption by material

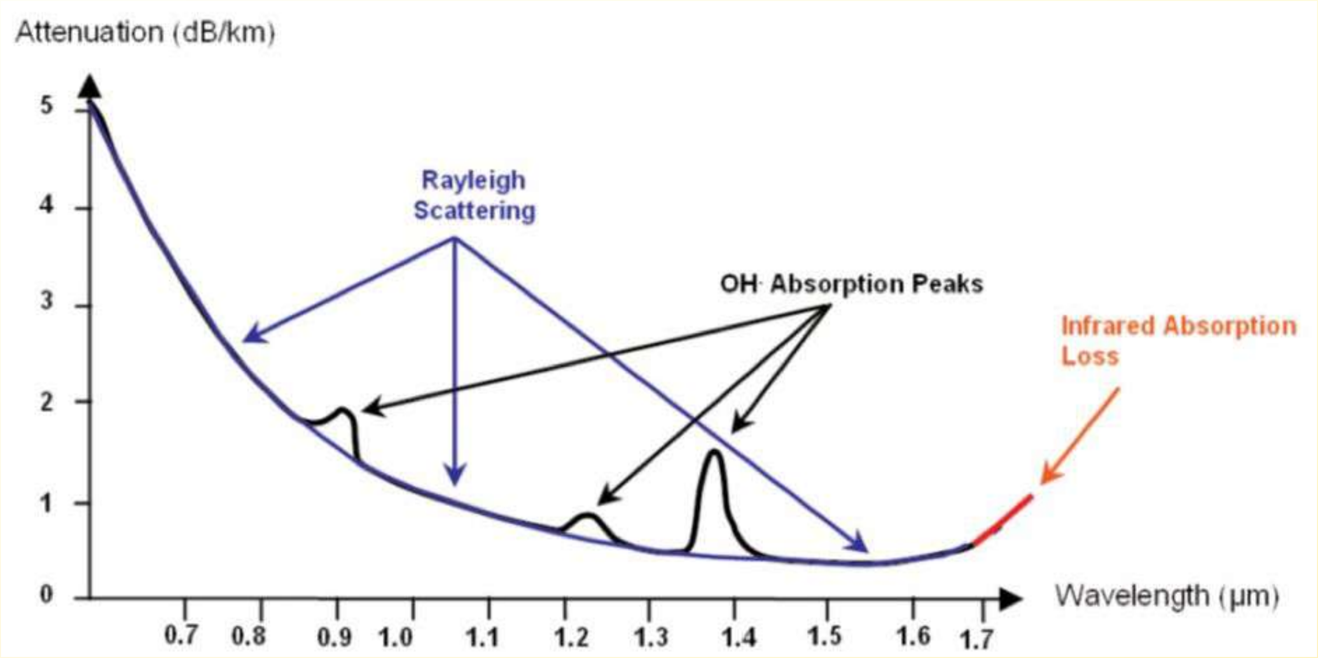
- Absorption by hydroxyl ions (OH)
- Water remnants, 3-5% absorption
- Absorption by natural impurities metals Copper, nickel, etc.

Absorption by pure glass

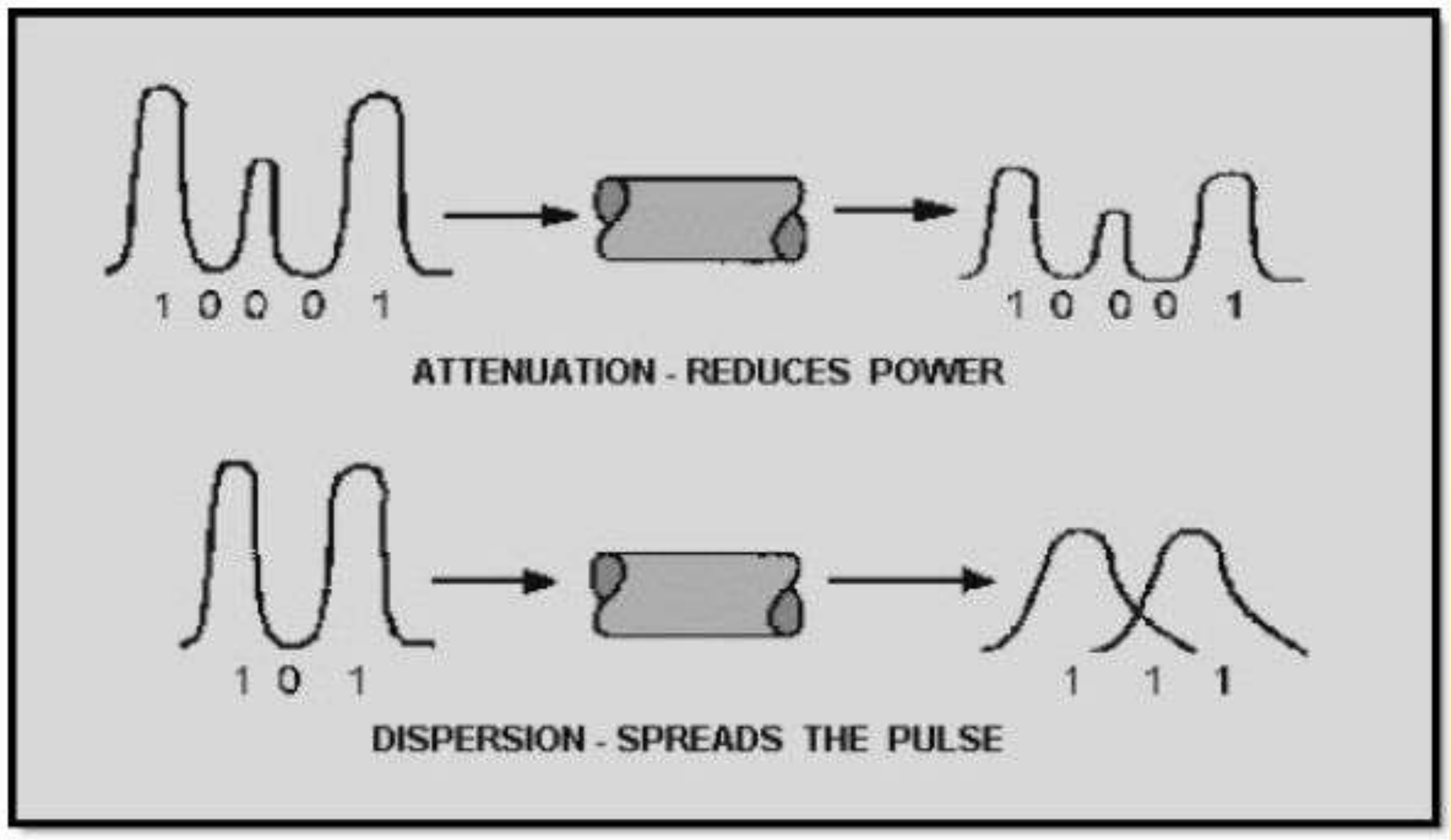
- Strong electronic absorption in UV
- IR absorption is strong at 1700 nm.

Remedy

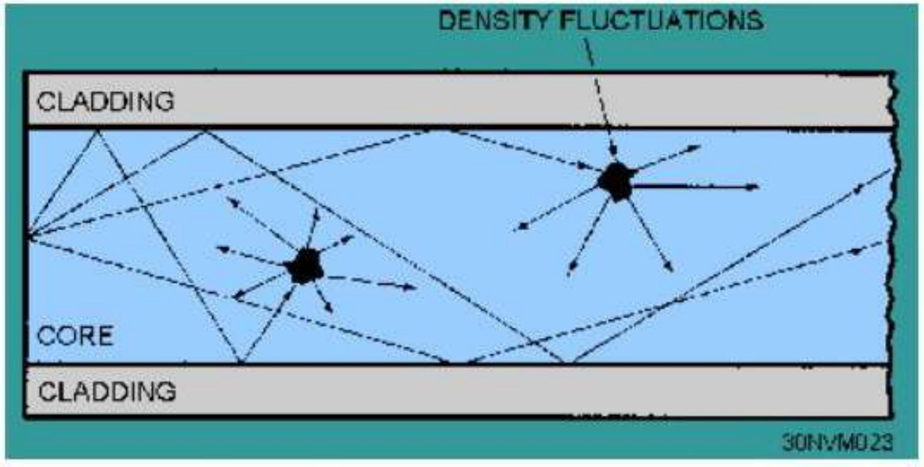
- Material and pure glass absorption cannot be avoided
- Wavelengths range between 800 nm to 1700 nm is preferred



ATTENUATION DUE TO DISPERSION

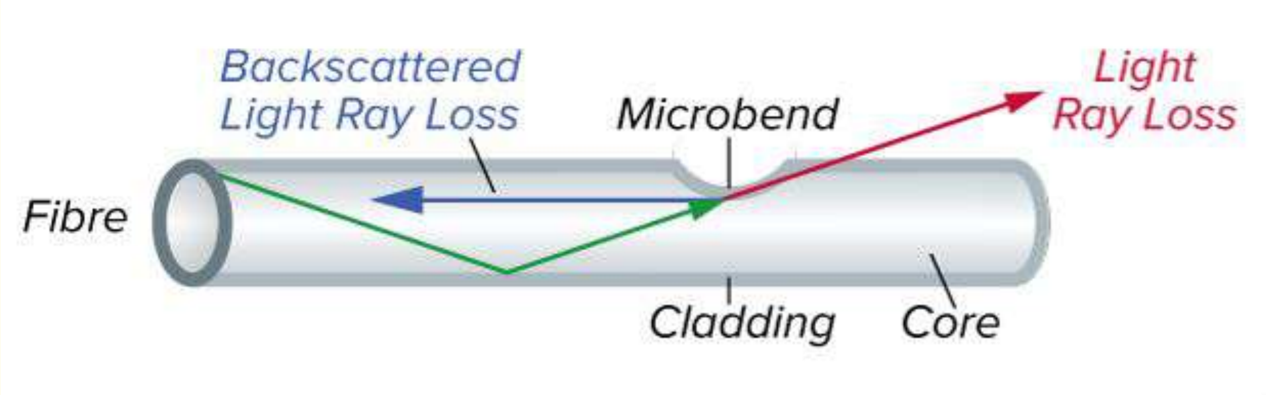


RAYLEIGH SCATTERING



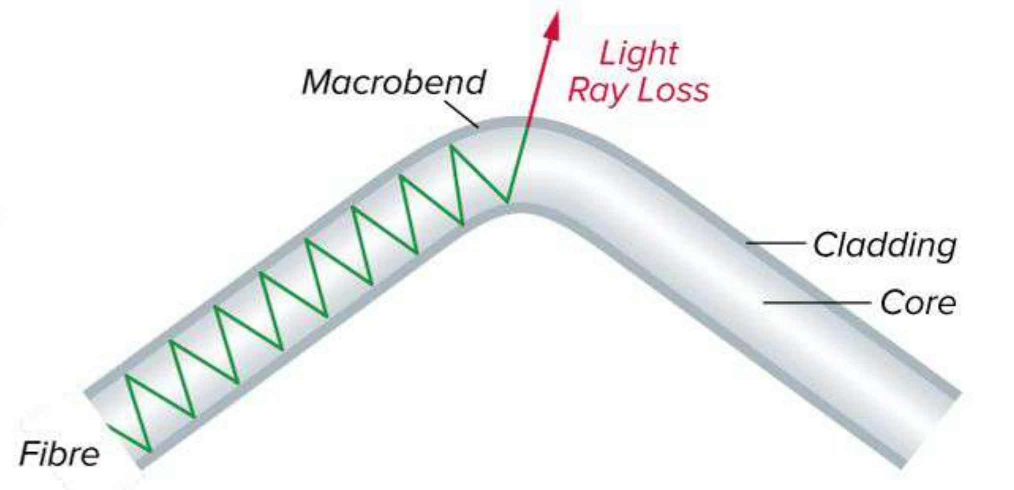
- Rayleigh scattering for majority of attenuation in optical fibers. It account for around 96% losses.
- Rayleigh scattering loss greatly depends on the wavelength chosen for transmission of the signal through the optical fiber.
- It varies as Intensity of scattering $\propto (1/\lambda^4)$
- Thus Rayleigh criterion sets a lower limit on the wavelength for transmission of the signal.
- A minimum wavelength of 800 nm is preferred. Below this scattering losses are too high.

ATTENUATION DUE TO BENDING



- **Micro-bending mainly due to winding**
  - The radiative losses arise when fiber axis is bend during the cabling
  - Light rays propagate into the cladding and hence are lost due to radiation.
  - These losses can be minimized by careful installation and improvement in manufacturing process

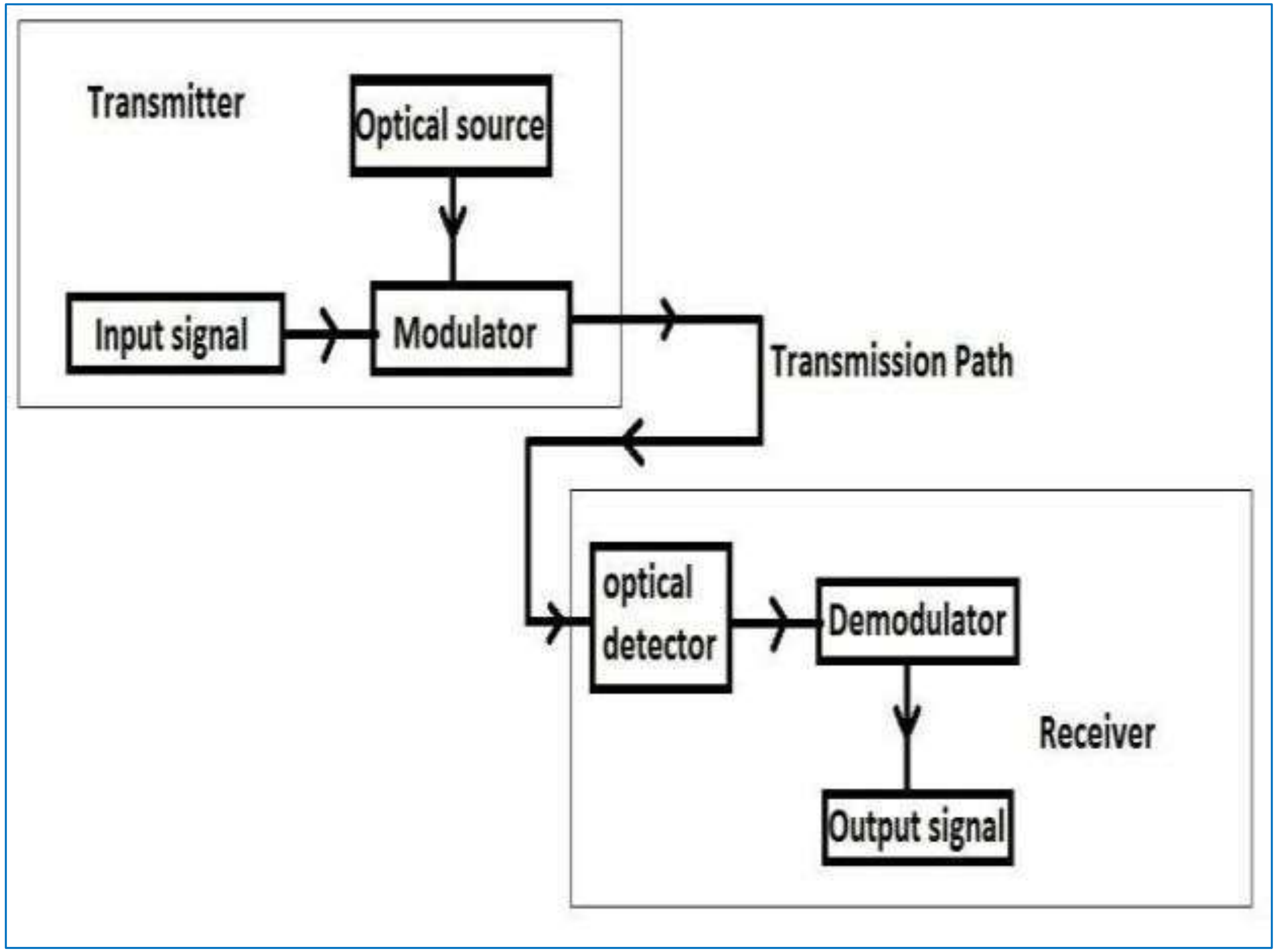
ATTENUATION DUE TO BENDING



- **Macro-bending losses:**
  - A macro-bend refers to the specified minimum bending radius.
  - Improper cabling, bending a fiber optic cable tighter than the specified bending radius, exerting external force may cause deformation in optic fiber and it can cause damage, even break the fiber carried in the cable.
  - The macro-bends result into loss of light radiation.
  - These losses can be minimized by careful handling and installation.

OPTICAL FIBER COMMUNICATION

- The use of optic fiber has tremendously improved the data carrying capacity.
- For example, a typical optical band of 250 MHz can accommodate about 3×10^7 TV programs at a time.
- Similarly, it can carry about 4×10^{10} telephone calls simultaneously.



ADVANTAGES OF OPTICAL FIBER COMMUNICATION

- **High data carrying capacity:**
  - As optical fibers are thinner, more fibers can be bundled together for increasing data carrying capacity.
  - an carry very high frequencies (~ 10^{14} Hz) i.e. more phone lines or more TV programs or more data.
- **High quality signal transmission**
  - Signals from one optic fiber do not interfere with those of other fibers which do not degrade the signal quality. No leakage of information is possible.
  - The signal degradation is negligible as compared to conventional copper wires as there are no I^2R losses.
  - Optic fibers are made from dielectric material which provides isolation between transmitter and receiver.

ADVANTAGES OF OPTICAL FIBER COMMUNICATION

- **No pick up of stray signal i.e. noise**
  - As optic fibers are made up of either glass or plastic, they do not pick up stray signal or noise like copper wire does either due to transmitted signal or due to external factors.
  - Thus the effect of external electromagnetic interference, lightning, external magnetic field, nuclear radiation is minimal.
- **Small size, Lightweight and flexible**
  - Optic fibers are of small size, light weight and are flexible.
  - Helpful in Medical imaging: in bronchoscopes, endoscopes, laparoscopes and mechanical imaging: inspecting mechanical welds in pipes and engines in airplane, rockets, space shuttle, etc

ADVANTAGES OF OPTICAL FIBER COMMUNICATION

- **Cost effective**
  - Optical fibers are typically made from silica. They are very cost effective as they are manufactured in bulk mass production
- **Less power consumption**
  - Optical fiber consumes less power for its operation as compared to metal wires.
- **High Tolerance and corrosion resistant**
  - Optic fibers can tolerate extreme temperature variations (in some cases even upto 800^0C). Corrosion due to water or chemicals is minimal for optic fibers.
- **Idle for carrying digital signal**
  - Optical fibers are very much suitable for carrying digital signals that are ideally suited for computer networks.
  - As large amount of data can be transmitted they are very useful in broadband internet, LAN, etc.

APPLICATIONS OF OPTICAL FIBERS

Sr.	Field	Application
1	Telecommunication	Long distance communication, secure data transmission
2	Video transmission	Cable TV, CCTC, Television broadcast
3	Internet broadband	Hi-speed broadband services: 3G, 4G, 5G, FTTH
4	Networking	LAN, WAN
5	Medical	Guiding laser for surgeries
6	Defense	Hydrophone for seismic waves, radar
7	Sensors	Optical fiber sensors

SHORTCOMINGS OF OPTIC FIBER

- Higher initial cost in installation.
- Higher interfacing cost.
- It requires remote electric power when transmitted through sea water.
- Optic fibers are more expensive for repair/maintain.