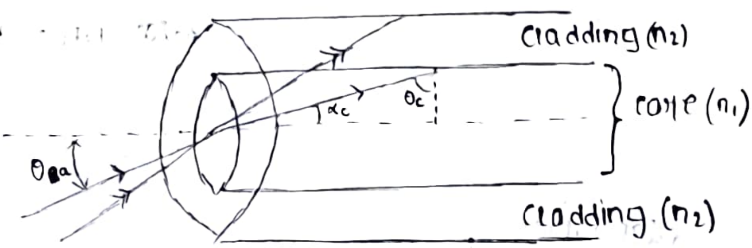
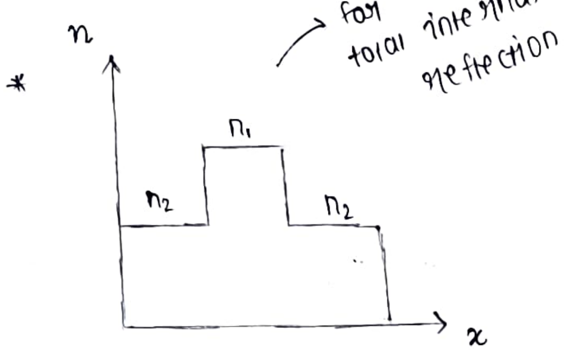
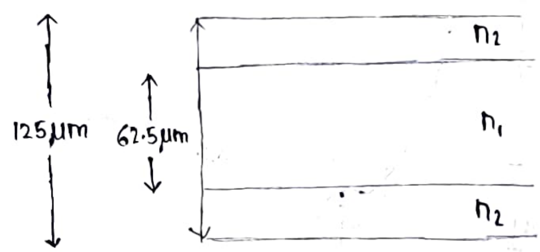
CONDITION FOR LIGHT PROPAGATION IN OPTICAL FIBRE :







(Step index fibre)

* Applying snell's law in the core - cladding boundary we get :

$$n_1 \sin \theta_c = n_2 \sin 90^\circ$$

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

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

* α_c is the "critical propagation angle"

$$\theta_c = 90^\circ - \alpha_c$$

$$\sin \theta_c = \cos \alpha_c$$

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

* Applying snells law at the gap fibre interference

$n_a \sin \theta_a = n_1 \sin \alpha_c$, $\theta_a \rightarrow$ acceptence angle.

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

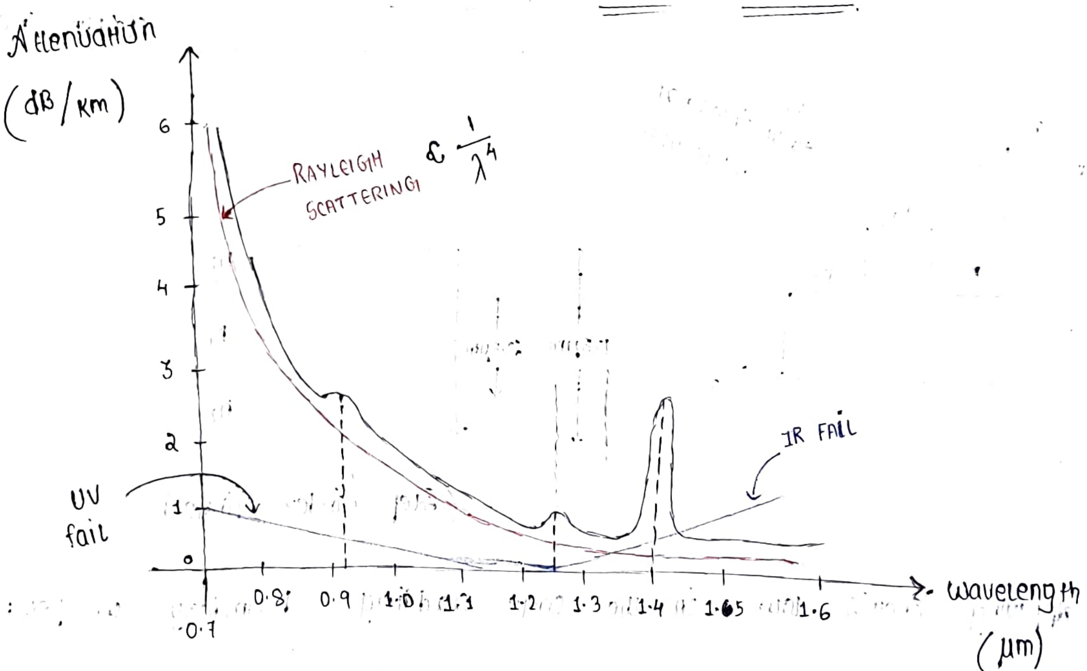
if outside medium is air : $n_a \simeq 1$

then $\sin\theta_a = \sqrt{n_1^2 - n_2^2}$

numeric aperture $\rightarrow$ $\boxed{NA = \sqrt{n_1^2 - n_2^2}}$

$NA = n_1\sqrt{2\Delta}$, $\Delta = \frac{n_1 - n_2}{n}$

Losses in fiber optics



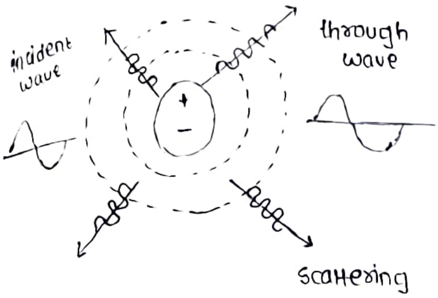
(Silica gel loss spectrum)

→ Three types of loses :

* Absorption loss : It is the process of conversion of EM waves energy into other forms of energy.

Intrinsic silica glass absorption occurs in both UV & IR while UV loses increase at lower wavelength, IR losses increases at higher wavelength

* Rayleigh scattering loss : It is a wavelength dependent process, that depends on material inhomogeneitis smaller than wavelength. It is inversely proportional to λ^4.



This strong dependence of loss due to Reyleigh scattering on wavelength, restricts the operation of silica optic fibre at lower wavelengths. The loss peaks occur at points of wavelength :

Peaks.

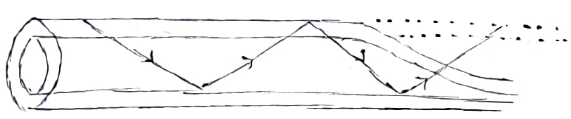
① - 0.93 pm
② - 1.25 pm
③ - 1.40 pm

} ~~for~~ silica gel from left graph.

* Bending loss :

Bending the fibre also causes attenuation. This is not strongly dependent on wavelength. It is classified as micro & macro bending.

- Micro bends are small microscopic bends of fibre axis, that occur mainly, when a fibre is scabled. ~~and~~



micro

- Macrobends are bends that have large radius of curvature ~~bends~~ relative to the fibre diameter.

Module - 6

Module:6	Propagation of EM waves in optical fibers	6 hours
Introduction to optical fiber communication system - light propagation through fibers - Acceptance angle - Numerical aperture - V-parameter - Types of fibers – Attenuation - Dispersion-intermodal and intramodal. Application of fiber in medicine - Endoscopy.		

- **Introduction to optical fiber communication**
- **Light propagation through fibers**
- **Acceptance angle, numerical aperture**
- **V-parameter, Types of fibers**
- **Attenuation, dispersion, intermodal and intramodal**
- **Application of fiber in medicine, endoscopy**

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Fibre Optics

- **Prerequisites :**

(refractive index of a material, Snell's law)

- **Fibre optics:**
  - Numerical Aperture for step index fibre, critical angle, angle of acceptance
  - V number, number of modes of propagation, types of optical fibres,
  - Fibre optic communication system

FIBER OPTICS

Optics is the branch of physics which involves the behavior and properties of light, including its interactions with matter and the construction of instruments that use or detect it.

God is great engineer – any image seen by human eyes connected to the brain by optical nerves

1870 – British Physicist – John Tyndall

- showed to Royal society that light could be guided along a curved glass stream.

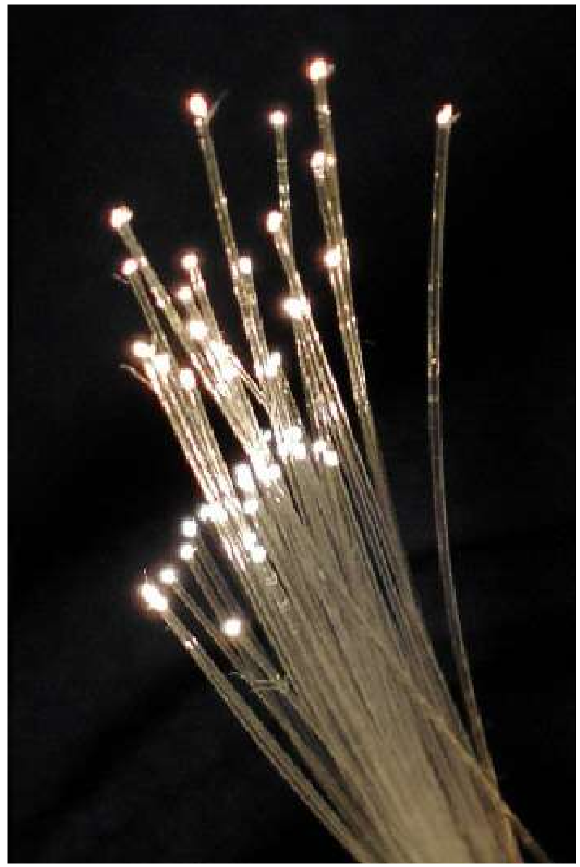
1880 - Alexander Graham Bell : demonstrated - role of optical fiber communication by transmitting speech in the form of light waves.

1960 – next era – development of an optical fiber started with the use of optical fiber as a wave guide for light.

Heavy transmission lossess restricted its further development.

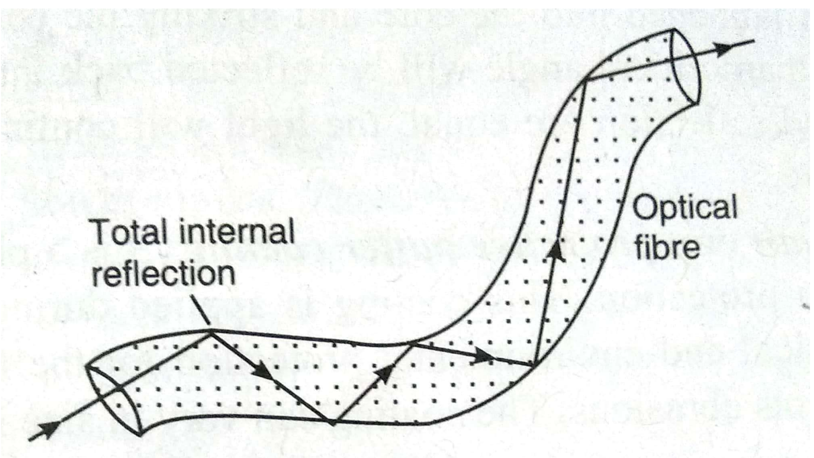
1970 – An industry named “Corning glass works” fabricated low loss fibres.

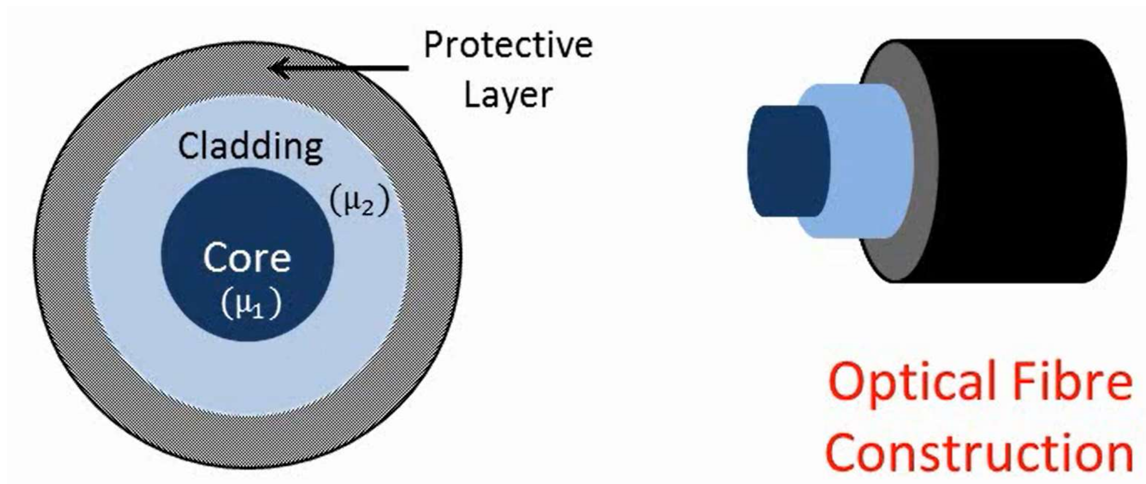
Solid state laser diode was used to avoid losses.



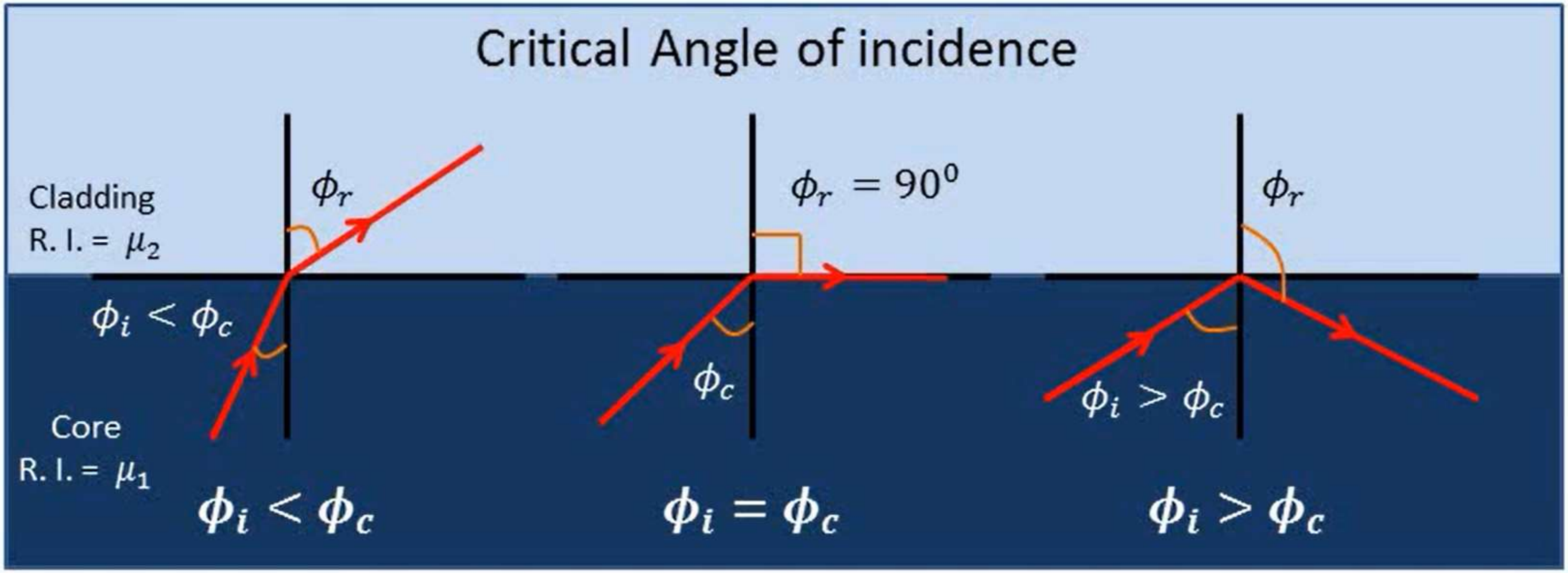
Optical Fibre

- An optical fibre is a **cylindrical wave guide** made of transparent dielectric (glass or clear plastic), which guides light waves along its length by **total internal reflection**
- Typical diameter of optical fibre is **9 µm to 62.5 µm**





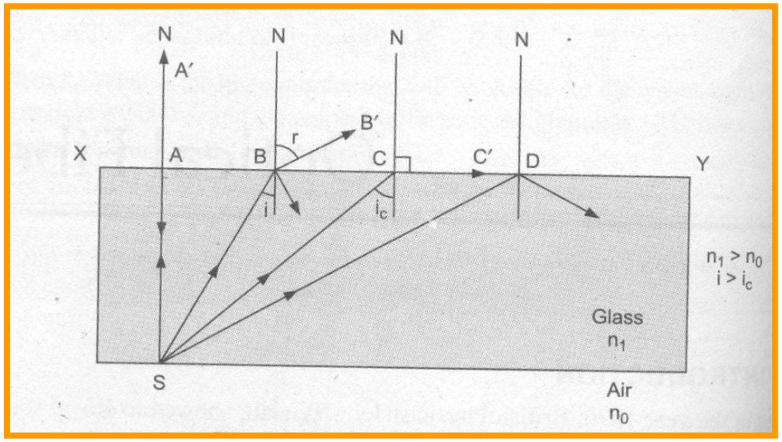
Total Internal Reflection

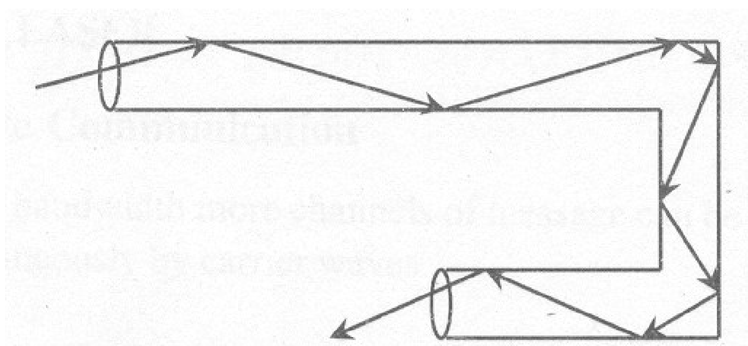


1. Refractive index of core (μ_1) must be greater than refractive index of cladding (μ_2).

2. The angle of incidence of light rays at core cladding boundary must be greater than critical angle of incidence

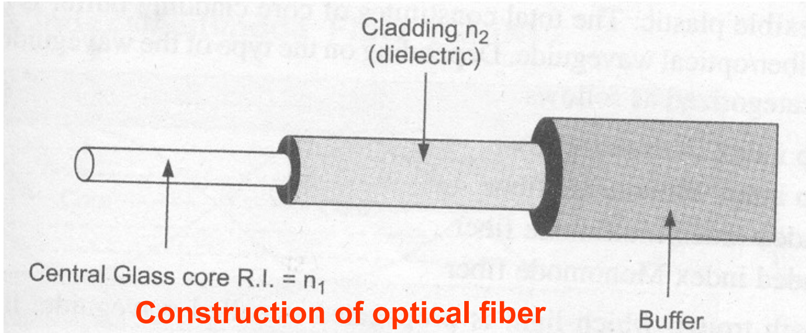
Total internal reflection – principle of optical fiber



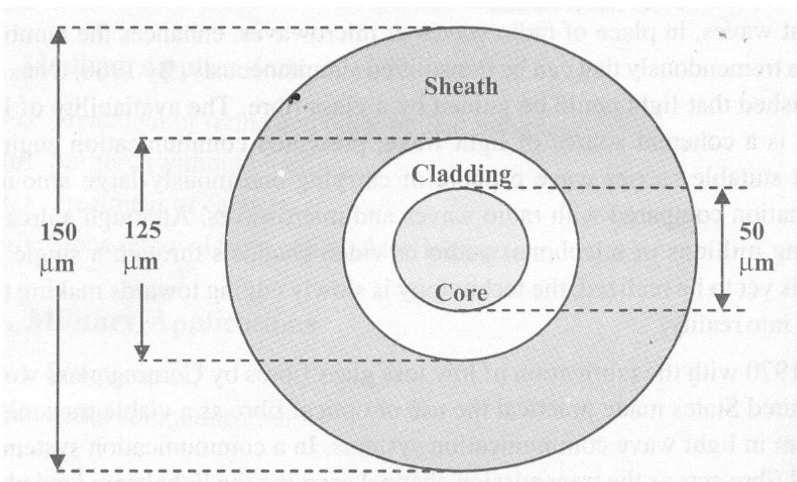


Propagation of light wave inside a fiber optic cable

- The refracted ray bends away from the normal as the light travels from denser to the rarer medium.
- As the angle of incidence increases, the angle of refraction also increases.
- At a particular angle i_c no light penetrates into the second medium. The angle at which the 'r' equals 90° is called critical incident angle.
- Increasing further the angle of incidence 'i' so that $i > i_c$, all light is reflected back to the same medium. This phenomenon is said to be **Total Internal Reflection (TIR)**.
- ***Principle of TIR enables to keep the light inside the fiber***



Construction of optical fiber

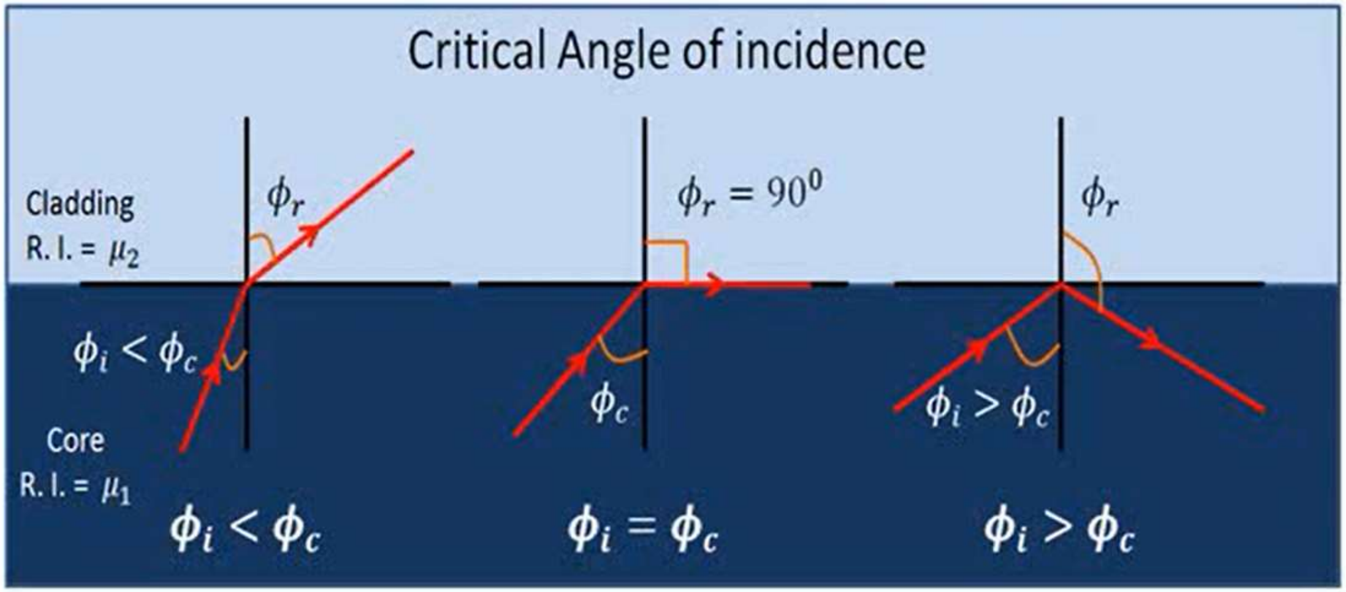


Cross-sectional view of the fiber optic cable

Core	Cladding
1. Doped silica	Silica
2. Silica	Polymer

- It has in general three co-axial regions.
- The inner most region is the light guided region, known as core.
- It is surrounded by another co-axial region known as cladding.
- The outer most layer is known as sheath or jacket or buffer.

- **Core :** R.I be n_1. Made from silica or doped silica.
- **Cladding :** R.I be n_2. slightly less than n1. Made from silica or polymer with one or more layer. Cladding reduces the scattering loss at the core surfaces.
- **Buffer :** It encapsulates the fiber For mechanical strength and flexibility. Protection of the fiber. Made of elastic plastic material.



Critical angle of incidence (ϕ_c) is defined as angle of incidence at core-cladding boundary for which light ray travels along the core-cladding boundary after refraction.

According to Snell's Law –

$$\frac{\sin\phi_i}{\sin\phi_r} = \frac{\mu_2}{\mu_1}$$

When $\phi_i = \phi_c, \phi_r = 90^0$

$$\therefore \frac{\sin\phi_c}{\sin 90} = \sin\phi_c = \frac{\mu_2}{\mu_1}$$

Thus For Total Internal Reflection,

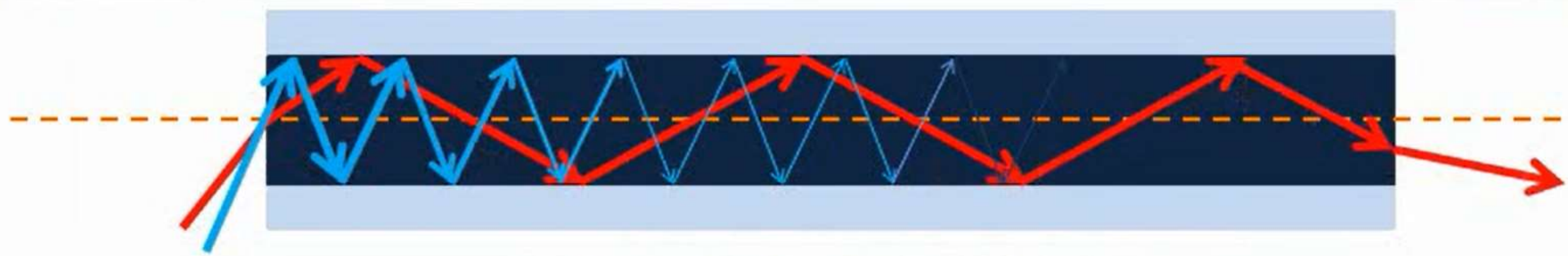
$$\boxed{\sin\phi_i > \frac{\mu_2}{\mu_1}}$$

Modes of Propagation

The light ray paths along which the waves are in phase inside the fibre are known as modes.

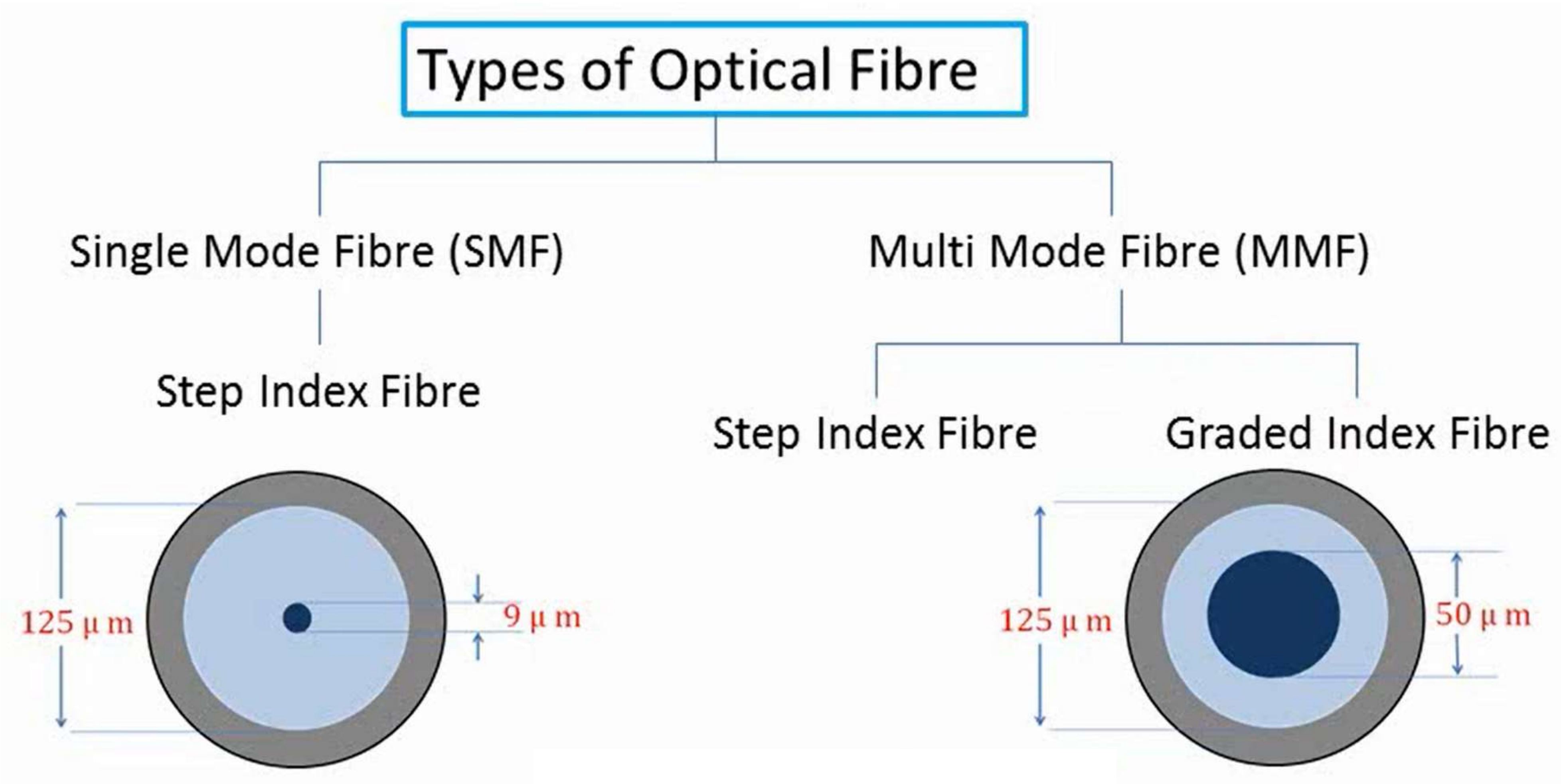
In simple words the allowed paths for the light ray inside the fibre are known as modes of propagation.

$$\text{Number of modes} \propto \frac{d}{\lambda}$$

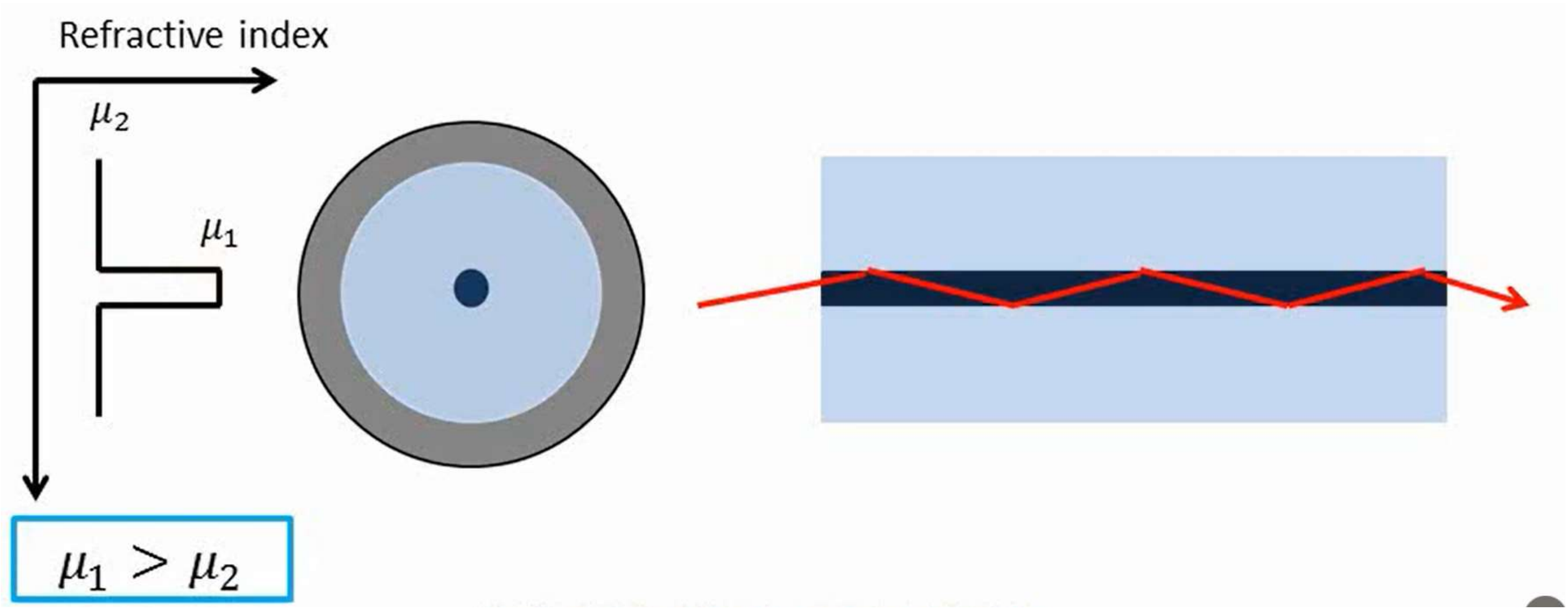


Higher Order Modes: The modes that propagate at angles close to the critical angle ϕ_c. In this, fields are distributed more towards the edge of the wave-guide and tend to send light energy into the cladding

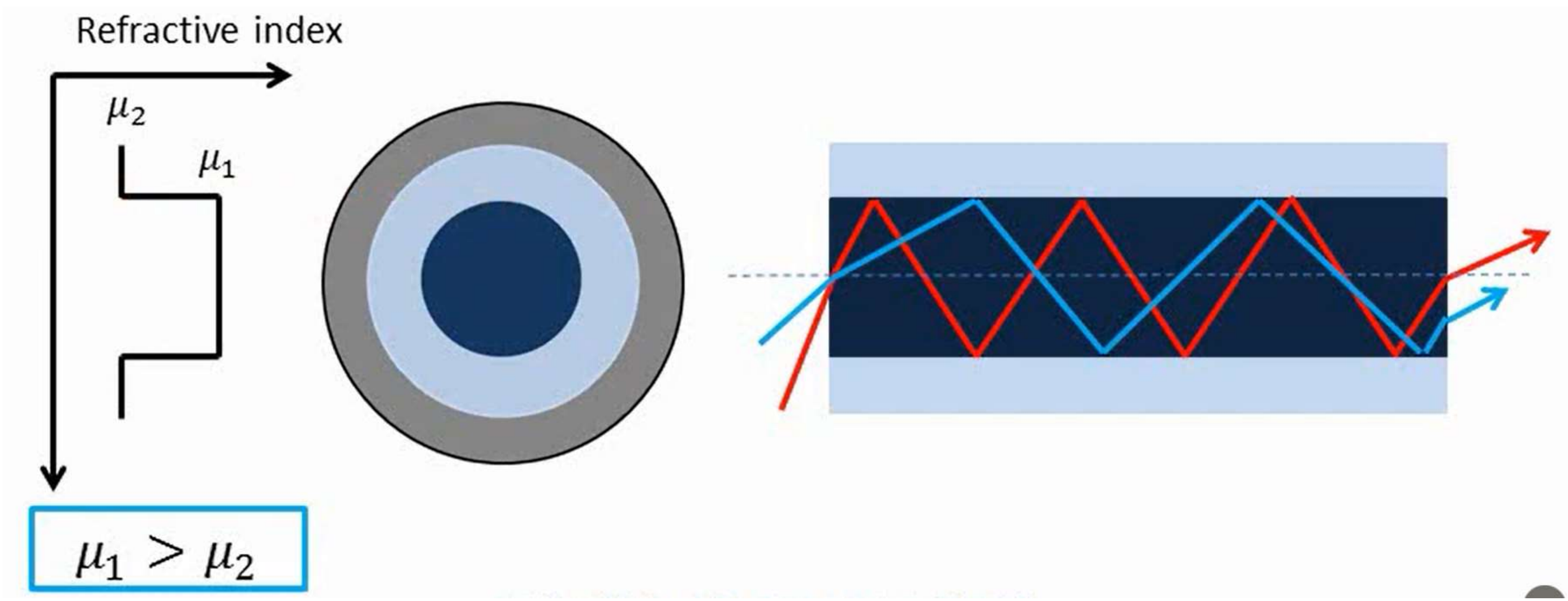
Lower Order Modes: The modes that propagate at angles larger than the critical angle ϕ_c. In this, fields are concentrated near the centre of the fibre


Types of Optical Fibre
Single Mode Fibre (SMF)
Multi Mode Fibre (MMF)
Step Index Fibre
Step Index Fibre
Graded Index Fibre
125 μ m
9 μ m
125 μ m
50 μ m

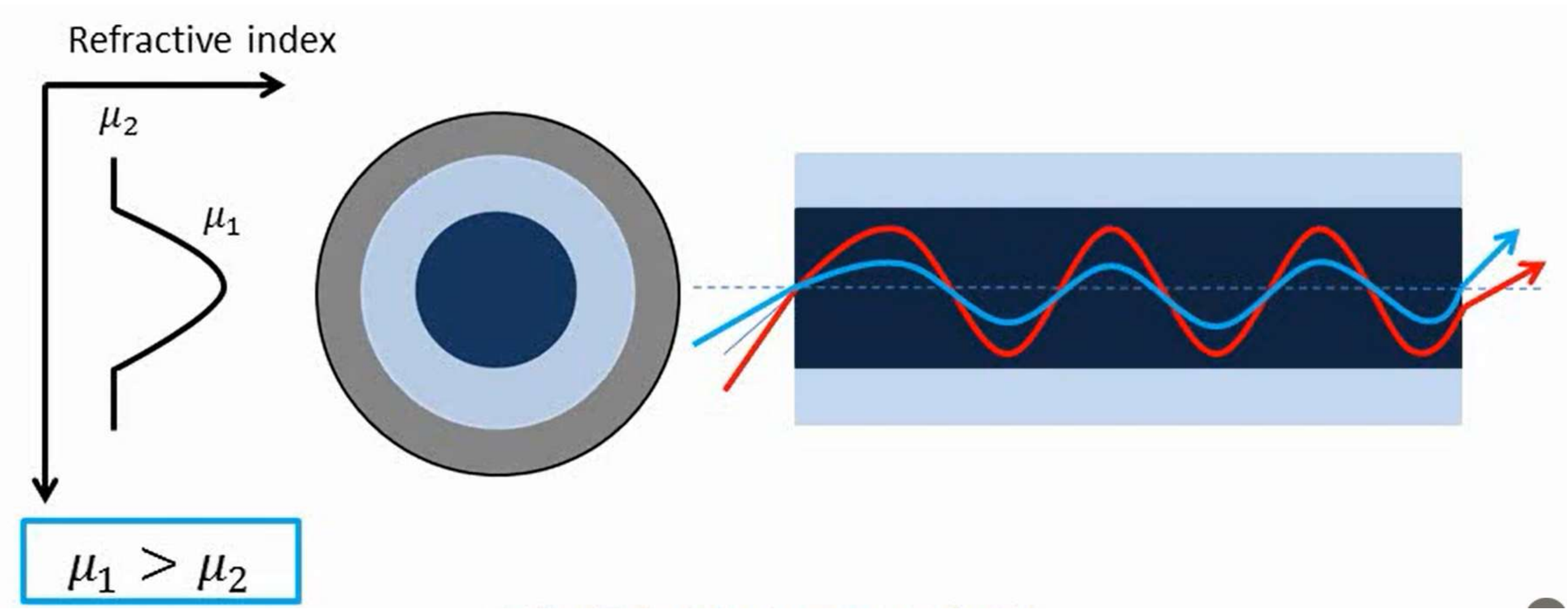
Single Mode Fibre (SMF)



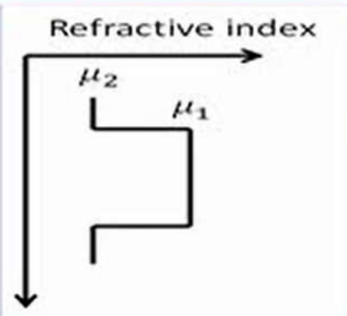
Multi Mode Fibre (MMF) – Step Index Fibre

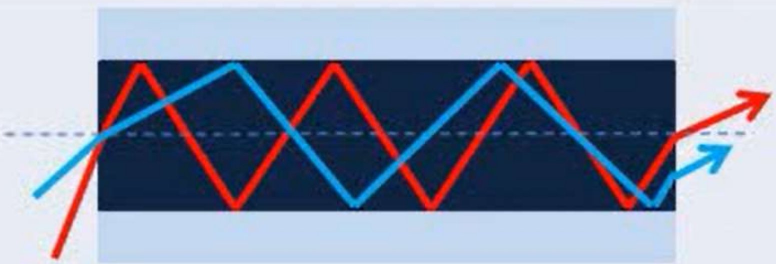


Multi Mode Fibre (MMF) – Graded Index Fibre



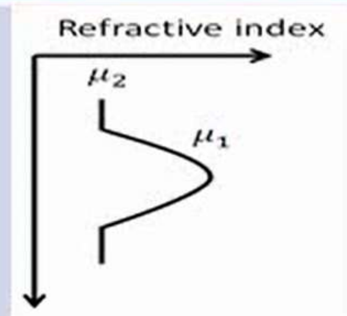
Step Index Fibre

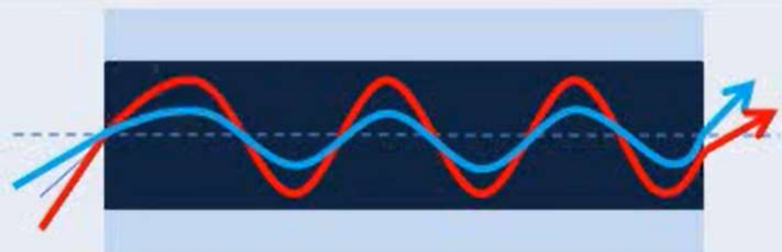




Light rays entering at different angles will take different time to arrive at the other end.

Graded Index Fibre





Light rays take almost same time to reach other end irrespective of angle of entrance.

Types of optical fiber

Comparison of single mode and multimode fibers.

Single mode fiber	Multimode fiber
1. These fibers support only one mode of propagation.	These fibers support the propagation by many modes.
2. Traveling signal inside the fiber has only one group velocity.	The different modes have different group velocities and each mode will follow its own path between the transmitter and receiver.
3. The amount of dispersion introduced is less than that introduced as compare to the multimode fiber.	The intermodal dispersion exists due to different group velocities of various modes.
4. These fibers have step index profile. (but rare grade index profile).	These fibers can also have either step index or graded index profile.
5. These are very high quality fibers for wide band transmission and are fabricated from doped silica for reducing the attenuation.	These are fabricated using multicomponent glass or doped silica.
6. Light has to be launched in these fibers only using laser diodes	Light can be launched in these fibers using LED sources.

Note : Mode is the path taken by the light rays while entering into the fiber.

Dispersion:

Dispersion is the spreading of light pulse as it travels along the length of the optical fibre.

It limits the information carrying capacity of the fiber.

1. ***Intermodal***: happens in multimode step index fiber.

   Can be avoided using graded index fiber

2. ***Intramodal*** – happens in single mode step index fiber.

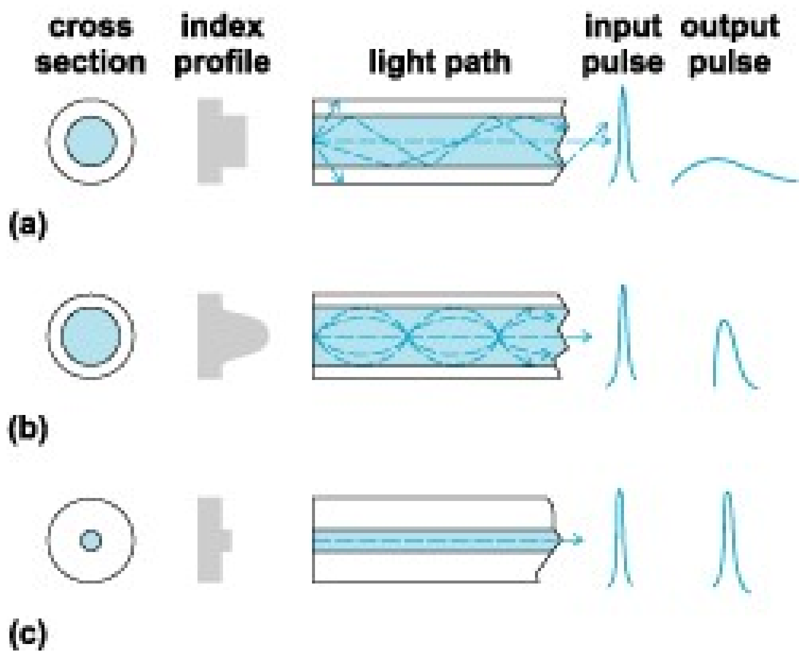
   The dispersion arises within the mode of the pulse.

   The intramodal dispersion is classifed into

a) Material dispersion

b) Waveguide dispersion.

Its only single mode step index fiber does not suffer from intermodal dispersion, but however suffers from chromatic dispersion



Schematic diagram for pulse broadening due to intermodal dispersion in the three types of fibres

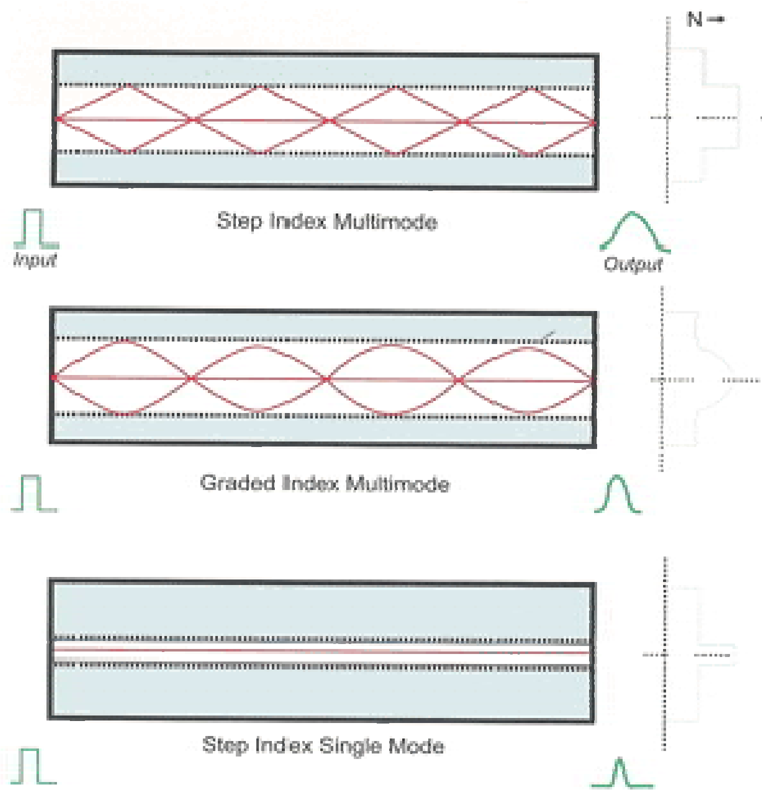


Figure 2-15 Optical Fiber Modes

Measuring intermodal dispersion

- The modes take different routes but travels with same velocity and hence arrive at different time at the receiver end of the FO Cable.
- This ultimately causes the pulse widening and is called intermodal dispersion or simply modal dispersion.

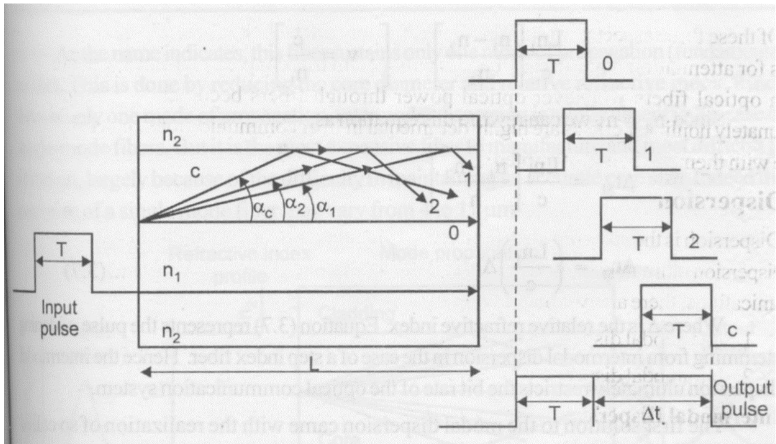


Figure 3.6: Modes in an optical fiber

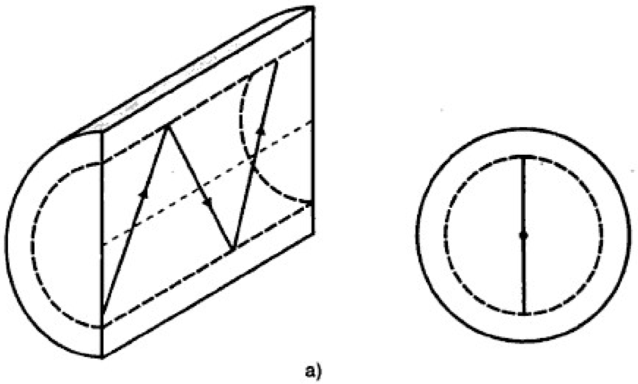
- For digital transmission : logic 1 – light pulse; logic 0 – no light pulse.
- Light pulse enters a fibre, each pulse breaks down to a set of small pulses carried by a individual mode.
- At the fibre end, individual pulses recombine and overlaps resulting in a long pulse.

Meridional and Skew beams

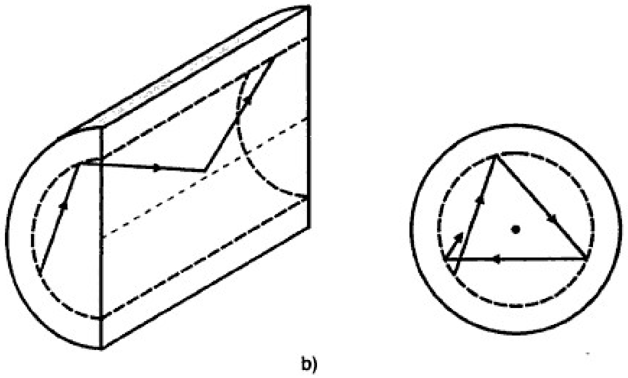
Beams propagating in a optical fibre are divided into two categories.

Meridional beams: During propagation they intersect the centre line of the fibre.

Skew beams: Propagate without intersecting the central axis. They are not confined to a single plane but tend to follow a helical path along the fibre.



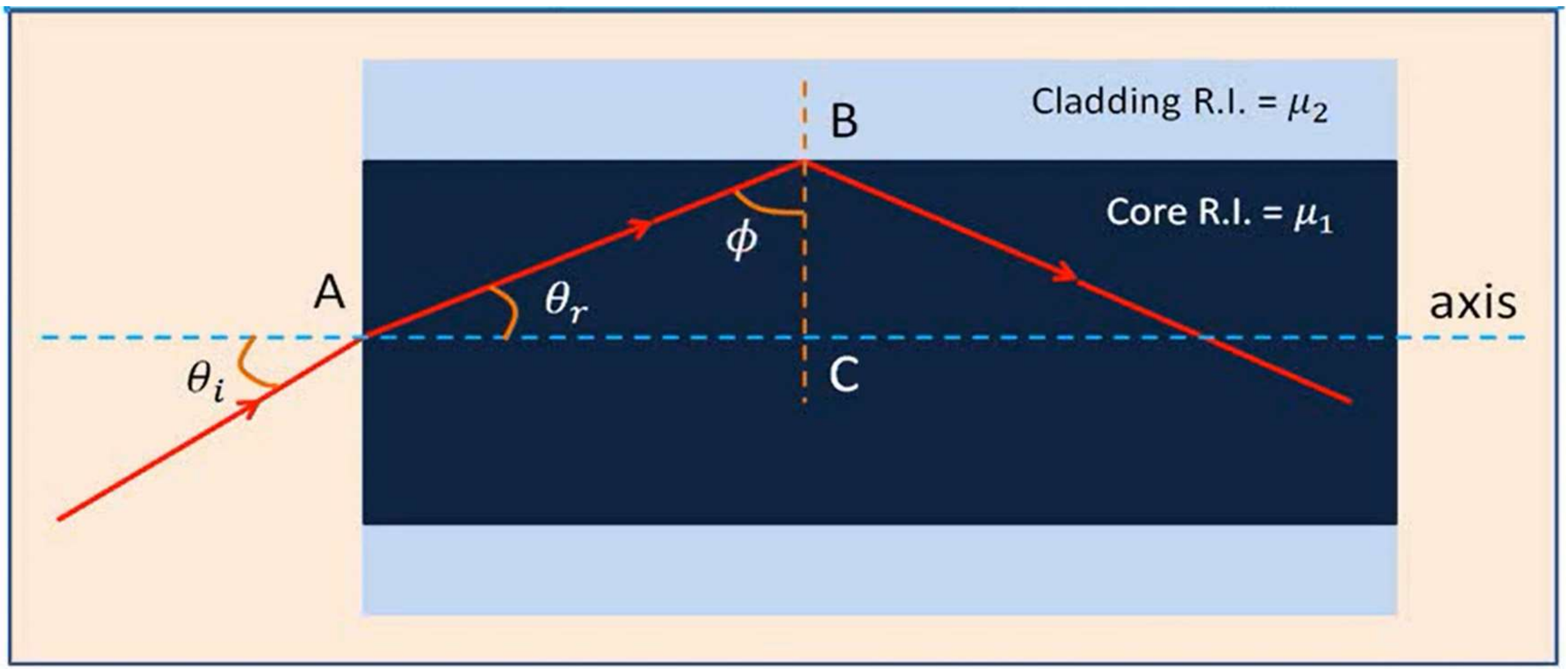
Meridional (longitudinal & cross section)



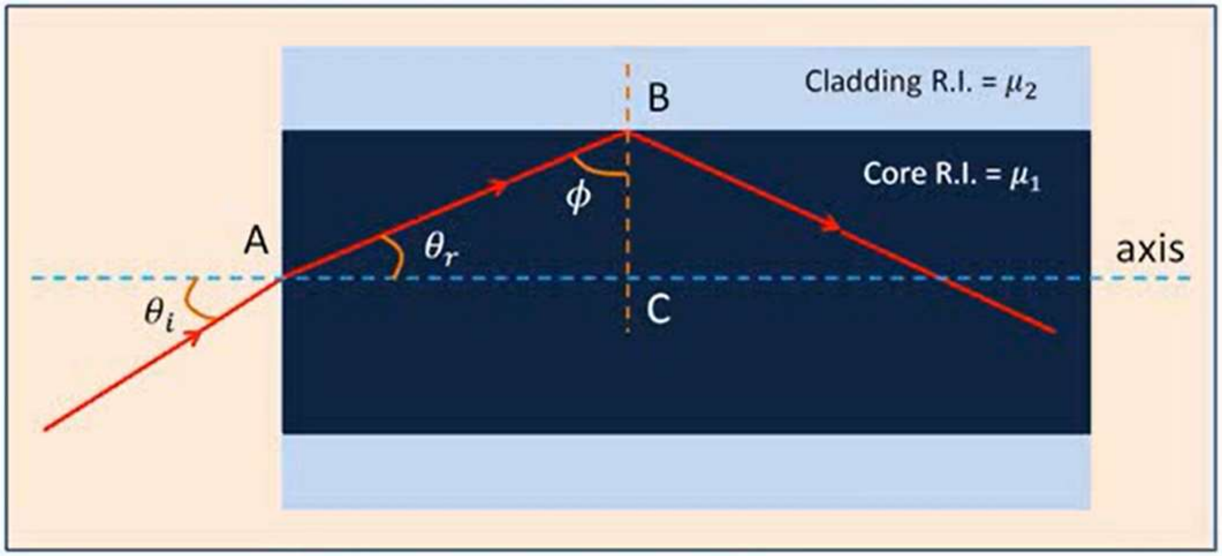
Skew (longitudinal & cross section)

- Skew beams are more difficult to track.
- Constitute a major portion of the total number of guided rays.
- Their analysis is not necessary to obtain general picture of rays propagating in fibre.
- Sufficient to consider meridional rays for practical purposes.

Numerical Aperture and Acceptance Angle



Numerical Aperture and Acceptance Angle



$$\boxed{\frac{\sin\theta_i}{\sin\theta_r} = \mu_1} \quad (1)$$

In Δ ABC,

$$\sin\theta_r = \sin(90 - \phi)$$

$$\boxed{\sin\theta_r = \cos\phi} \quad (2)$$

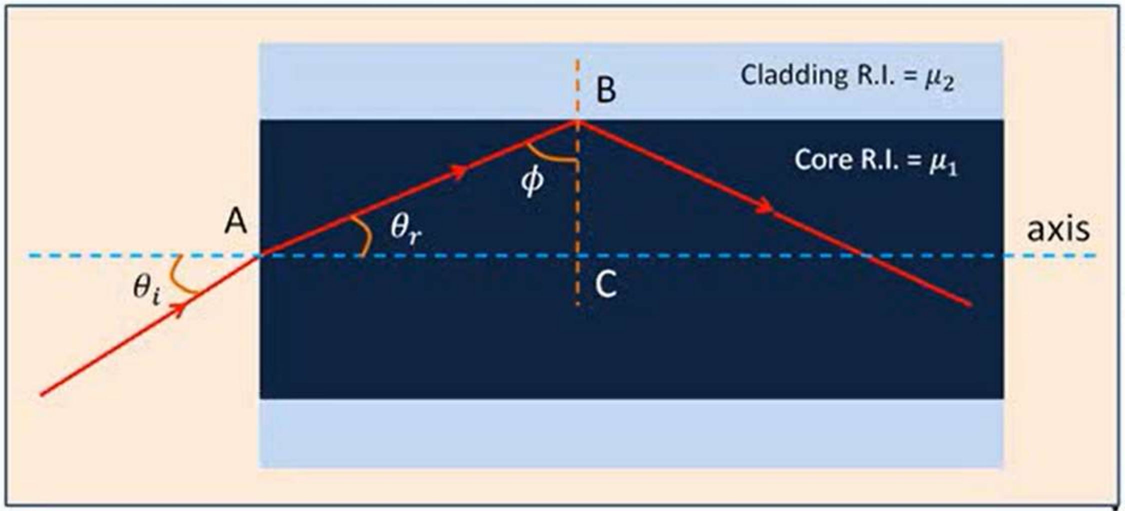
From (1) and (2)

$$\boxed{\sin\theta_i = \mu_1 \cos\phi}$$

When $\theta_i = \theta_{i(max)}$, then $\phi = \phi_c$

$$\boxed{\therefore \sin\theta_{i(max)} = \mu_1 \cos\phi_c} \quad (3)$$

Numerical Aperture and Acceptance Angle



As $\cos\phi_c = \sqrt{1-\sin^2\phi_c}$

$$\therefore \sin\theta_{i(max)} = \mu_1\sqrt{1-\sin^2\phi_c}$$

We know $\sin\phi_c = \dfrac{\mu_2}{\mu_1}$

$$\therefore \sin\theta_{i(max)} = \mu_1\sqrt{1-\left(\frac{\mu_2}{\mu_1}\right)^2}$$

$$\therefore \sin\theta_{i(max)} = \mu_1\sqrt{\frac{(\mu_1)^2-(\mu_2)^2}{(\mu_1)^2}}$$

$$\boxed{\frac{\sin\theta_i}{\sin\theta_r} = \mu_1} \quad (1)$$

$$\boxed{\sin\theta_r = \cos\phi} \quad (2)$$

$$\boxed{\therefore \sin\theta_{i(max)} = \sqrt{(\mu_1)^2-(\mu_2)^2}} \quad (4)$$

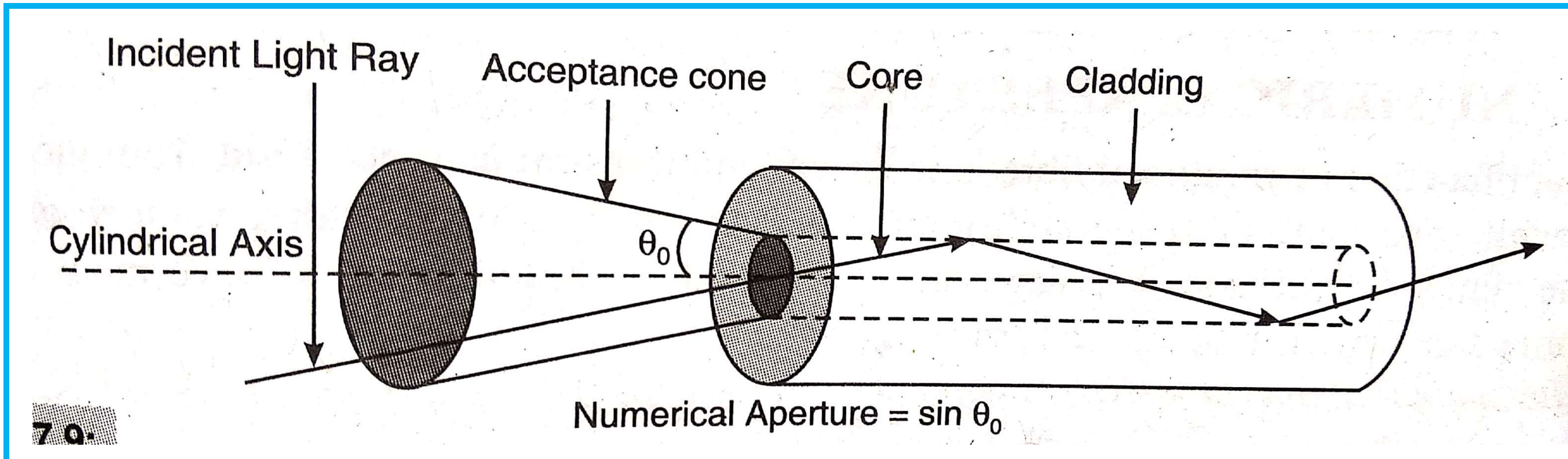
$$\boxed{\therefore \sin\theta_{i(max)} = \mu_1\cos\phi_c} \quad (3)$$

$\theta_{i(max)} = \sin^{-1}\left(\sqrt{(\mu_1)^2-(\mu_2)^2}\right)$
is called as Acceptance Angle

Acceptance angle is the maximum angle that a light ray can have relative to the axis of the fibre and propagate down the fibre

Acceptance Cone:

- In three dimensions, the light rays contained with in the cone having a full angle **$2\theta_0$** are accepted and transmitted along the fibre.
- Light incident beyond this cone, refracts through the cladding and the corresponding optical energy is lost.



Numerical Aperture is defined as sine of the acceptance angle

$$\boxed{\mathrm{N.A.} = \sqrt{(\mu_1)^2 - (\mu_2)^2}} \quad 5$$

$$(\mu_1)^2 - (\mu_2)^2 = (\mu_1 + \mu_2)(\mu_1 - \mu_2)$$

$$\therefore (\mu_1)^2 - (\mu_2)^2 = \left(\frac{\mu_1+\mu_2}{2}\right)\left(\frac{\mu_1-\mu_2}{\mu_1}\right) 2\,\mu_1$$

As $\left(\frac{\mu_1+\mu_2}{2}\right) \approx \mu_1$

$$\therefore (\mu_1)^2 - (\mu_2)^2 = \left(\frac{\mu_1 - \mu_2}{\mu_1}\right) 2\,(\mu_1)^2$$

$$\therefore (\mu_1)^2 - (\mu_2)^2 = 2\,(\mu_1)^2\,\Delta$$

$\Delta = \frac{\mu_1 - \mu_2}{\mu_1}$ is called as fractional index difference

$$\boxed{\therefore\ \mathrm{N.A.} = \mu_1 \sqrt{2\,\Delta}}$$

N.A. determines the light gathering ability of the fibre

V-number and Number of modes

An optical fibre is characterized by one important parameter known as **V- number**

It is also called as **normalized frequency**. It is given by -

$$V = \frac{2\pi a}{\lambda}\sqrt{(\mu_1)^2 - (\mu_2)^2} = \frac{2\pi a}{\lambda}\, N.A.$$

a = radius of core

λ = wavelength of light being transmitted

μ_1 = refractive index of core

μ_2 = refractive index of cladding

For Step Index fibre,

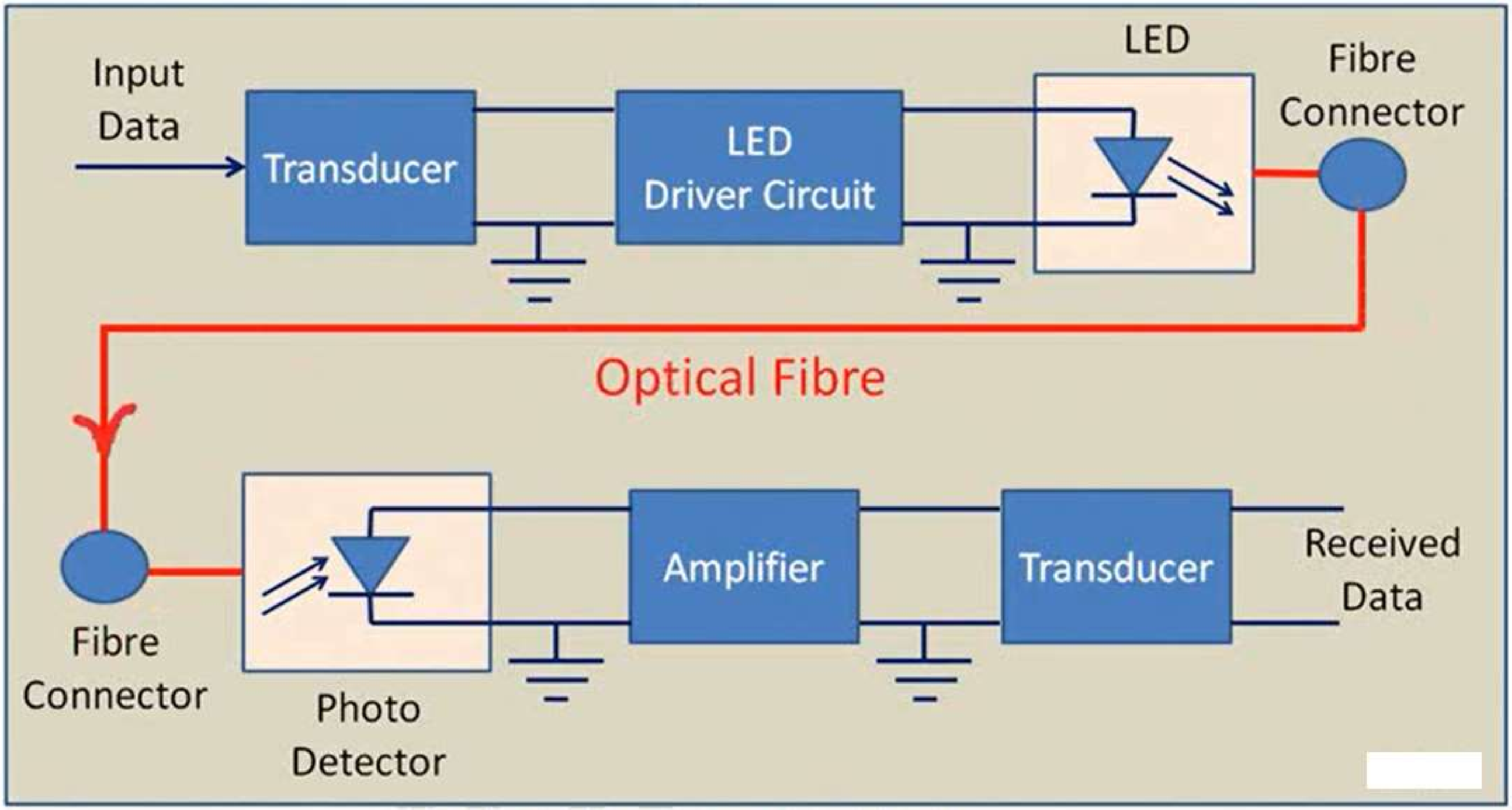
maximum no. of modes Nm supported by a step index optical fibre is $N_m \approx \frac{1}{2} V^2$

For V < 2.405 the fibre can support only one mode and is called Single Mode Fibre.

Multi Mode Fibres have V > 2.405 and support many modes simultaneously.

- **Each mode has a definite value of V-number below which the mode is cut off**

Fibre Optics Communication System

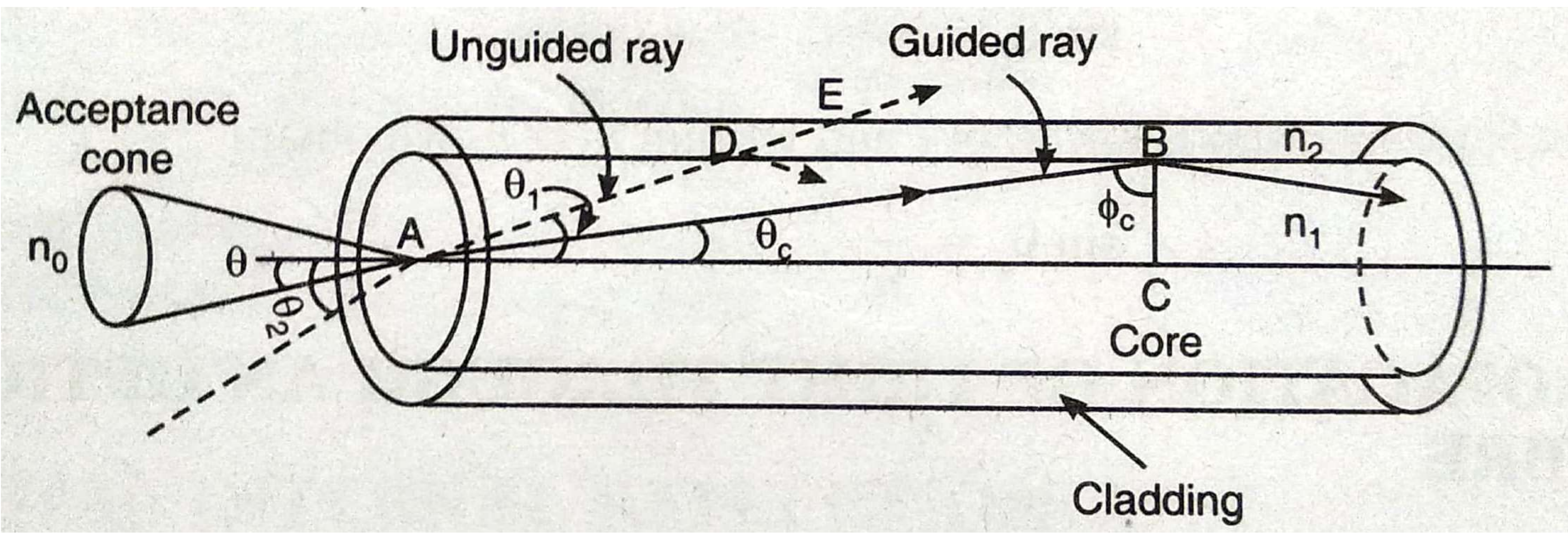


Advantages of using Optical Fibre Communication network

1. The data is transmitted in the form of light. Due to high frequency of light, large bandwidth is available. So the data transfer speed increases and more channels are available.
2. As the optical fibres are very thin and can accommodate more channels, they need less space as compared to cable network.
3. Transmission losses are low.
4. Fibre optic communication system is not affected by electromagnetic disturbances.
5. Optical fibres are not affected by corrosion and atmospheric conditions. So optical fibre network has longer life.
6. There is good electrical isolation between transmitter and receiver.

Critical Angle of Propagation

- Let two rays entre the fibre at two different angles of incidence θ and θ_2
- The dotted ray incident at an angle θ_2 undergo refraction at point A giving an angle θ_1 with respect to the axis of fibre. further this ray transmitted out of the fibre and does not propagate through fibre
- The solid ray with an angle of incidence θ_1 undergo refraction at point A and propagates at an angle θ_c in the fibre and makes an angle ϕ_c at point B (core-cladding boundary) and undergo total internal reflection
- Here $\boldsymbol{\theta_c}$ is called as **critical propagation angle**

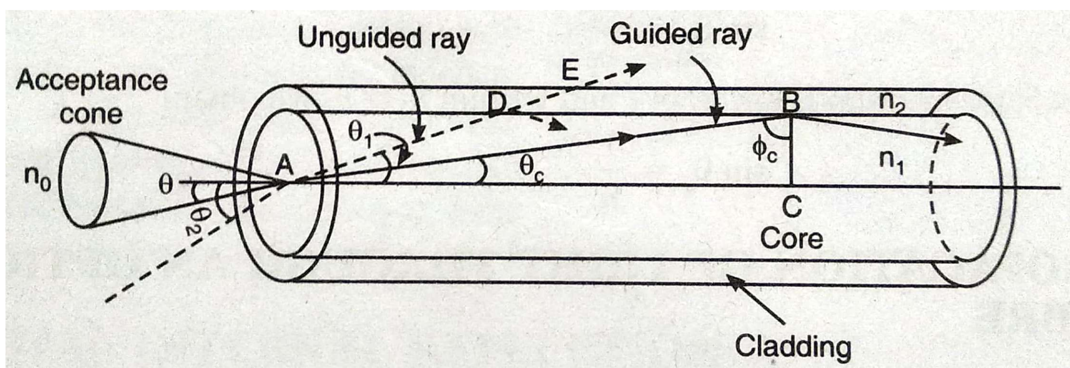


From Δ ABC, $\frac{AC}{AB} = sin\emptyset_c$ and , $\frac{AC}{AB} = \cos\theta_c$

$$\therefore\ cos\theta_c = sin\emptyset_c = \frac{n_2}{n_1}$$

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

Those rays which are refracted into the cable at angles θ_r < θ_c will propagate in the optical fibre



Endoscopy

- **Endoscopy** means *looking inside* and typically refers to looking inside the body
- For medical reasons using an **endoscope**, an instrument used to examine the interior of a hollow organ or cavity of the body.

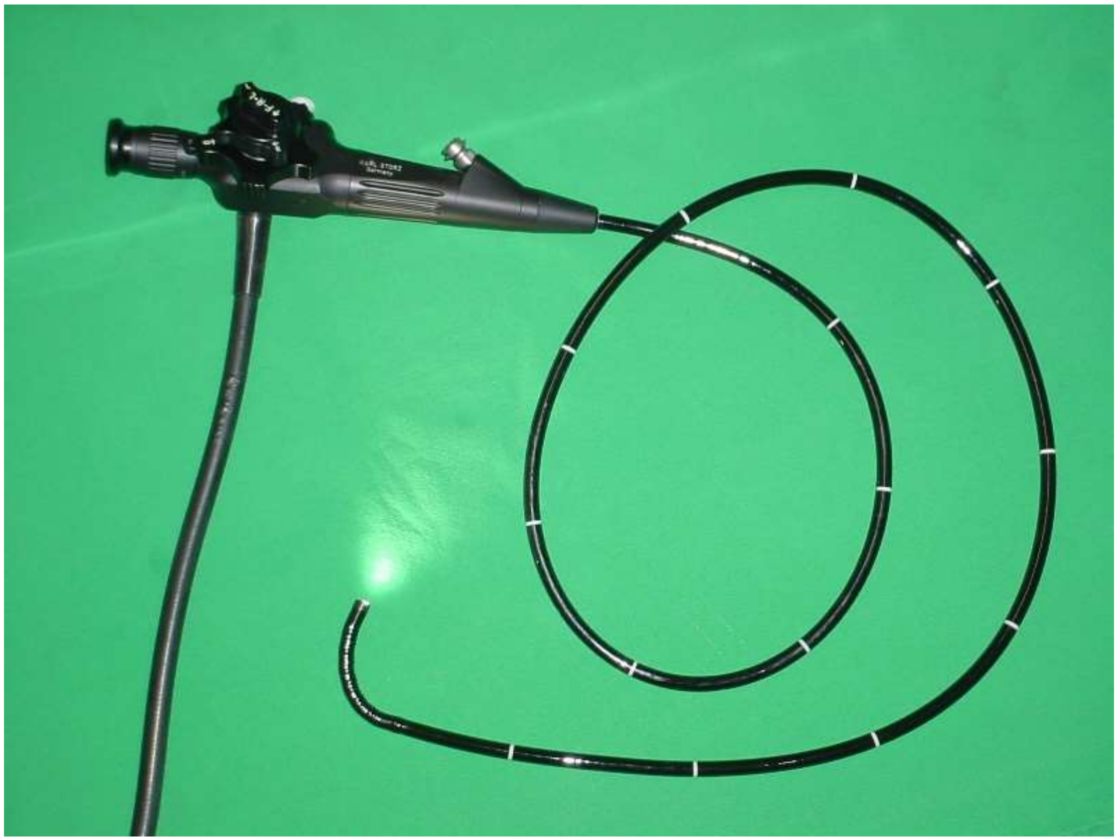
Endoscopy Cont..

- An Endoscopy is a simple procedure which allows a doctor to look inside human bodies using an instrument called an endoscope.
- A cutting tool can be attached to the end of the endoscope, and the apparatus can then be used to perform surgery.
- This type of surgery is called Key hole surgery, and usually leaves only a tiny scar externally.
- Unlike most other medical imaging devices, endoscopes are inserted directly into the organ.
- Endoscope can also refer to using a borescope in technical situations where direct line of-sight observation is not feasible

Endoscopy Cont..

- Non-surgical endoscopes are marketed in hardware and building supply stores under the name **snake camera** or **inspection camera**.
- Naturally these endoscopes are not as well made as surgical endoscopes and relay inspection images that are lower quality.

Flexible Endoscope



- Endoscopy is a **non-ionising imaging technique** used in medical physics to examine the interior of the human body.
- The difference between other imaging techniques and endoscopy is that endoscopy uses a device called an **endoscope,** which is inserted directly into the human body.
- This classifies it as an **invasive medical procedure**, unlike other imaging techniques based on radiation or sound.

- Fiber optics is used in endoscopy. Optical fibers are flexible and transparent fibers with a diameter just a little bigger than a human hair. They are primarily used for **transmitting light**.
- In fiber optics, a core is usually surrounded by a transparent cladding material with **a lower index of refraction**. The way light is transmitted in fiber optics, which allows doctors to use endoscopes to see the body's interior, depends on the **total internal reflection principle**

Endoscope

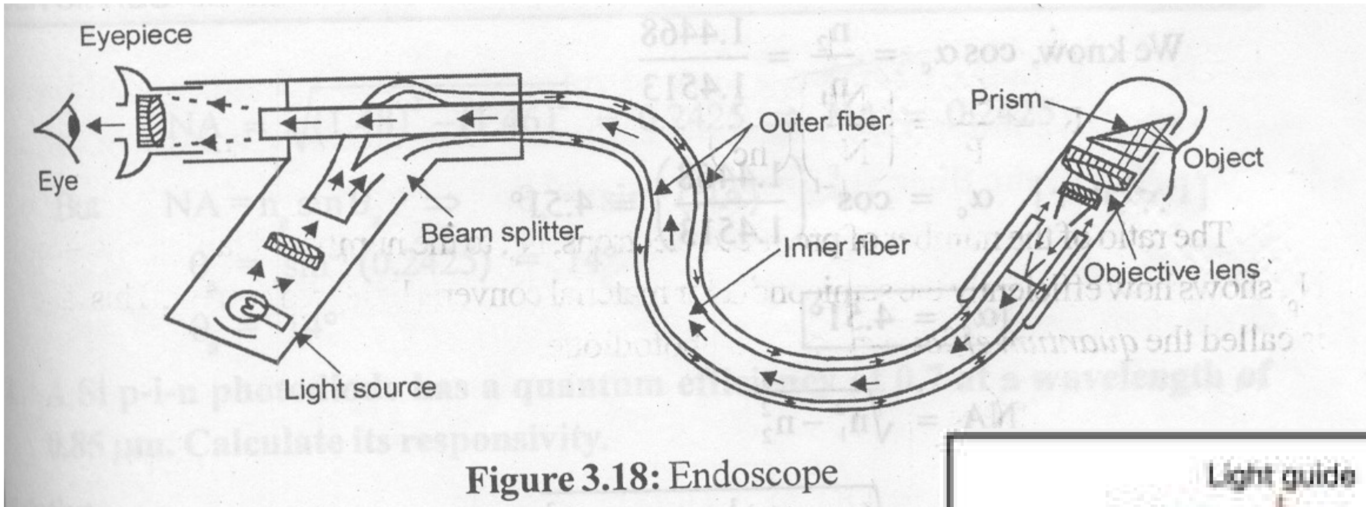
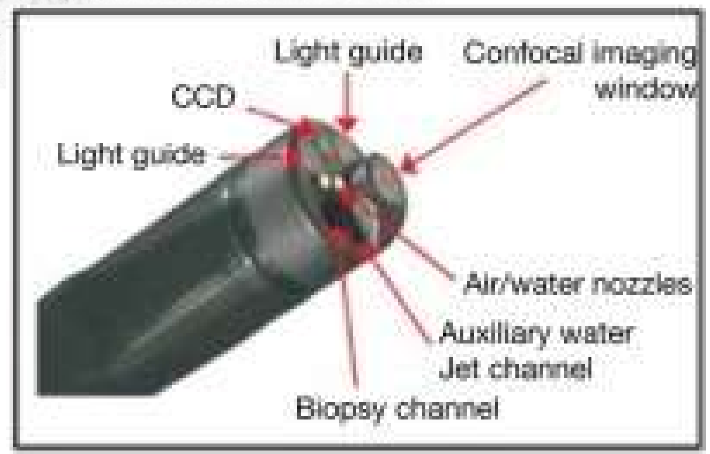


Figure 3.18: Endoscope



Endo - inside ; scope – device to look

Coherent bundles are combination of different fibers where their terminations occupy the same relative positions in both of the bound ends.

The coherent bundles are capable of transmitting images and are the flexible image carriers.

Fibre optic endoscopy procedure

- When using endoscopes with fibre optics, a light source in the tip of the endoscope illuminates the passageways. The light is reflected from the passageways back into this tip. Light is guided by a step-index structure inside the optical fibre that induces total internal reflection and directs coupled light from one end to the other without loss. For this to happen, the **refractive index of the fibre core material** (n_1) **must be greater than that of the fibre cladding material** (n_2).

What are the applications of endoscopy?

- Endoscopy is currently used in a variety of applications in medical physics. While endoscopy is mainly used in **surgeries** to allow surgeons to visualize the interior of the human body while operating, other uses include **looking into the passageways** of the human body to determine any abnormalities.

  - ✓ The gastrointestinal tract (GI tract)
  - ✓ The respiratory tract
  - ✓ Normally closed body cavities (through a small incision)
  - ✓ Nuclear reactor cores and jet engines etc..,