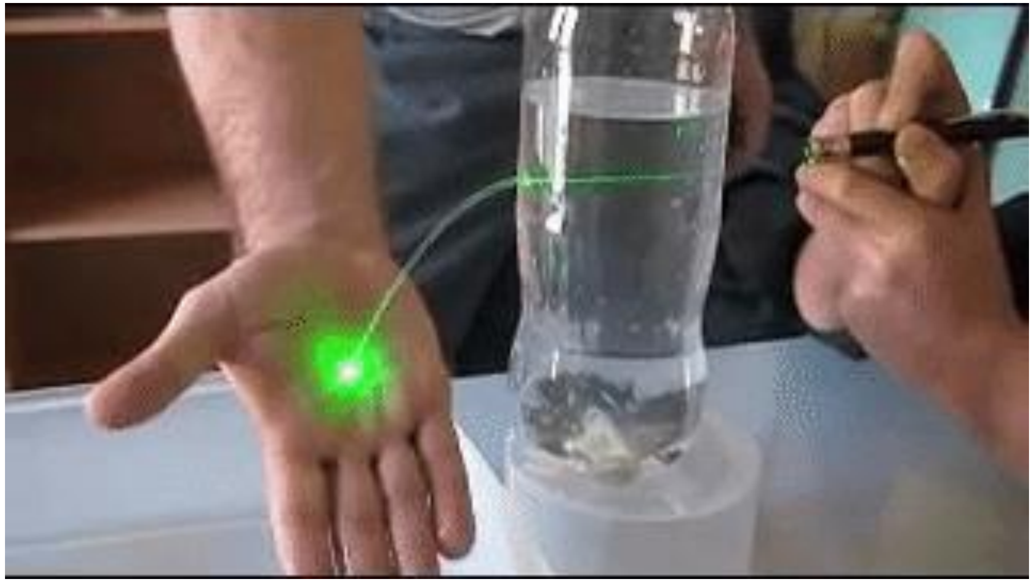
Fibre Optics



Source: Reference given on last slide

Few questions for you

- ***Which of the following is NOT due to total internal reflection of light?***

A. Brilliance of diamond
B. Mirage formation
C. Optical fibre working
D. Rainbow formation

- ***A ray of light will undergo total internal reflection if it***

A. Goes from rarer medium to denser medium
B. Incident at an angle less than the critical angle
C. Strikes the interface normally
D. Incident at an angle greater than the critical angle

- ***Propagation of light through a fiber core depends upon the phenomenon of?***

A. Interference
B. Diffraction
C. Polarization
D. Total internal reflection

- ***What is the principle of fibre optical communication?***

A. Frequency modulation
B. Population inversion
C. Total internal reflection
D. Doppler Effect

Answers

Which of the following is NOT due to total internal reflection of light?

A. Brilliance of diamond

B. Mirage formation

C. Optical fibre working

D. Rainbow formation

A ray of light will undergo total internal reflection if it

A. Goes from rarer medium to denser medium

B. Incident at an angle less than the critical angle

C. Strikes the interface normally

D. Incident at an angle greater than the critical angle

Propagation of light through a fiber core depends upon the phenomenon of?

A. Interference

B. Diffraction

C. Polarization

D. Total internal reflection

What is the principle of fibre optical communication?

A. Frequency modulation

B. Population inversion

C. Total internal reflection

D. Doppler Effect

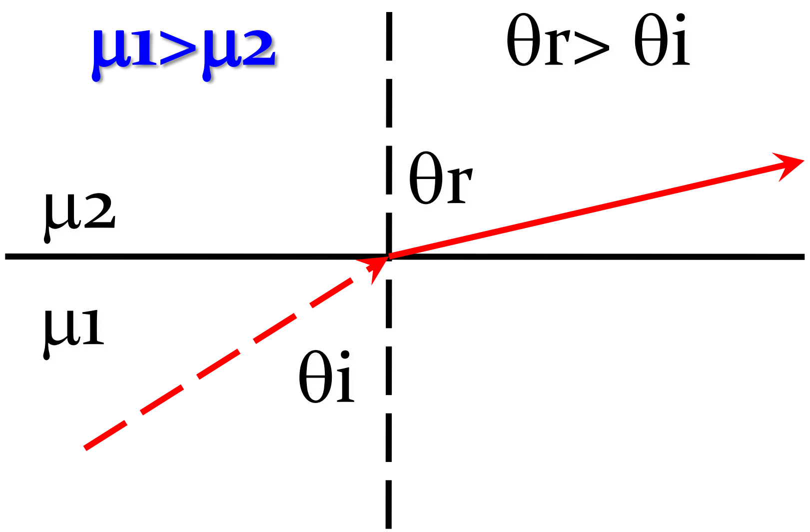
Important term to Know

- ***Refraction***

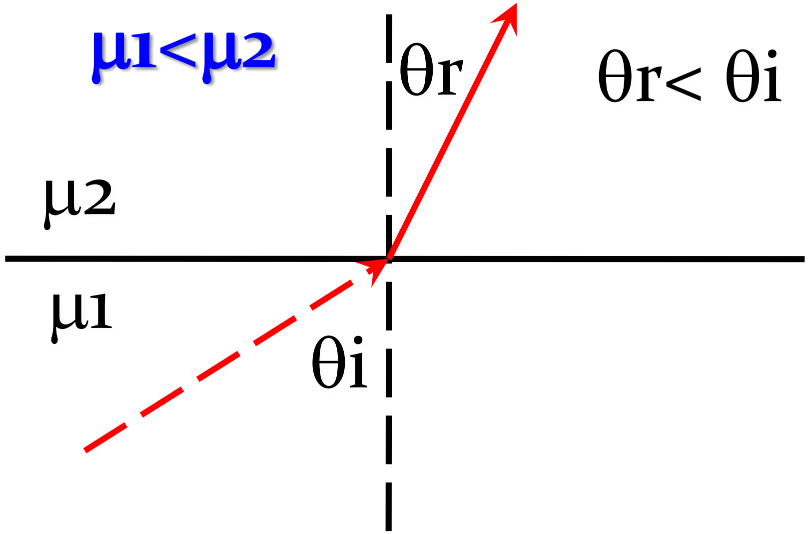
- ***Total Internal Reflection***

Refraction

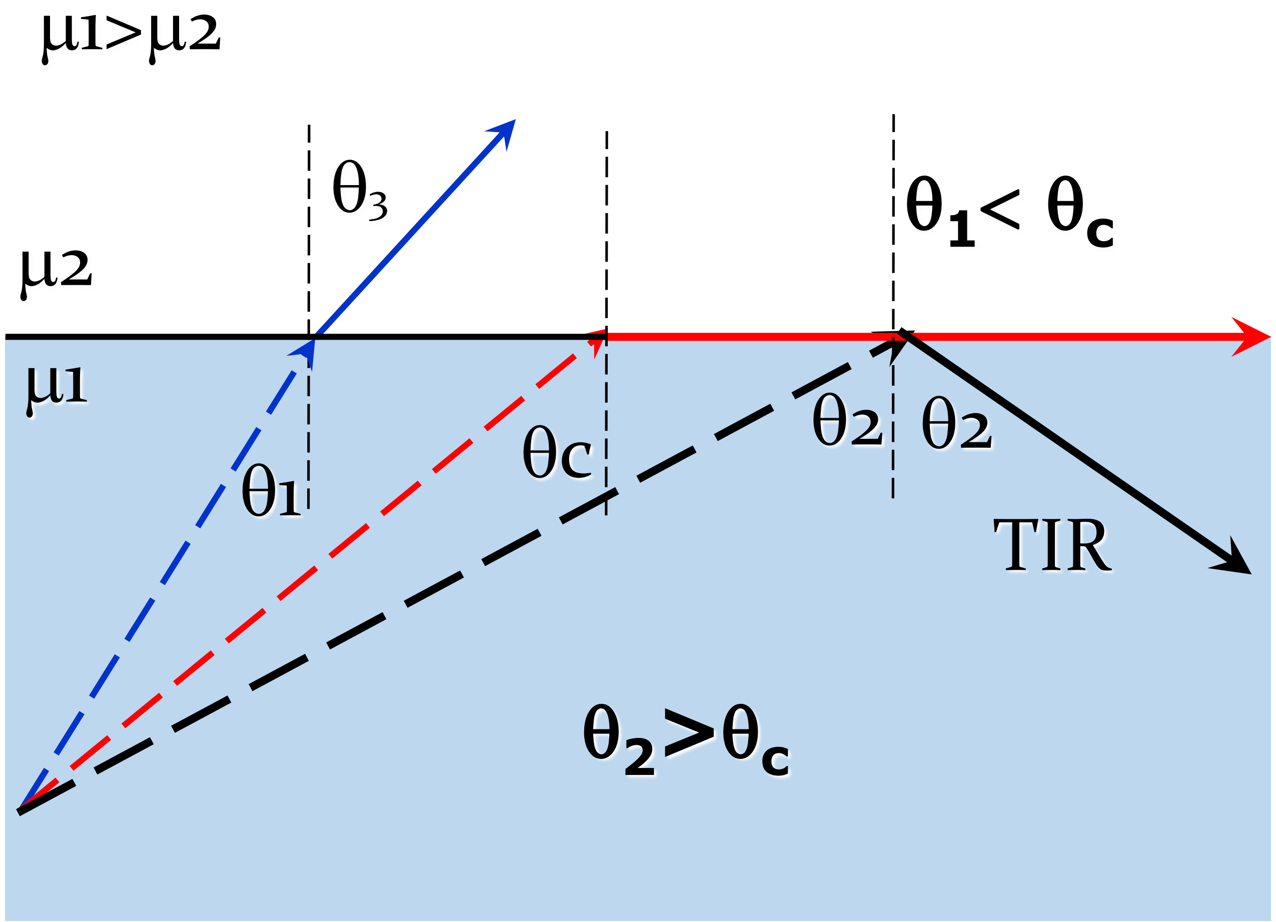
- When light travels from a medium of higher refractive index to a medium of lower refractive index, then the ratio ***μ1/μ2 is greater than 1***. So the angle (sin r) will be greater than angle (sin i) i.e., the refracted ray is ***bent away from the normal***.



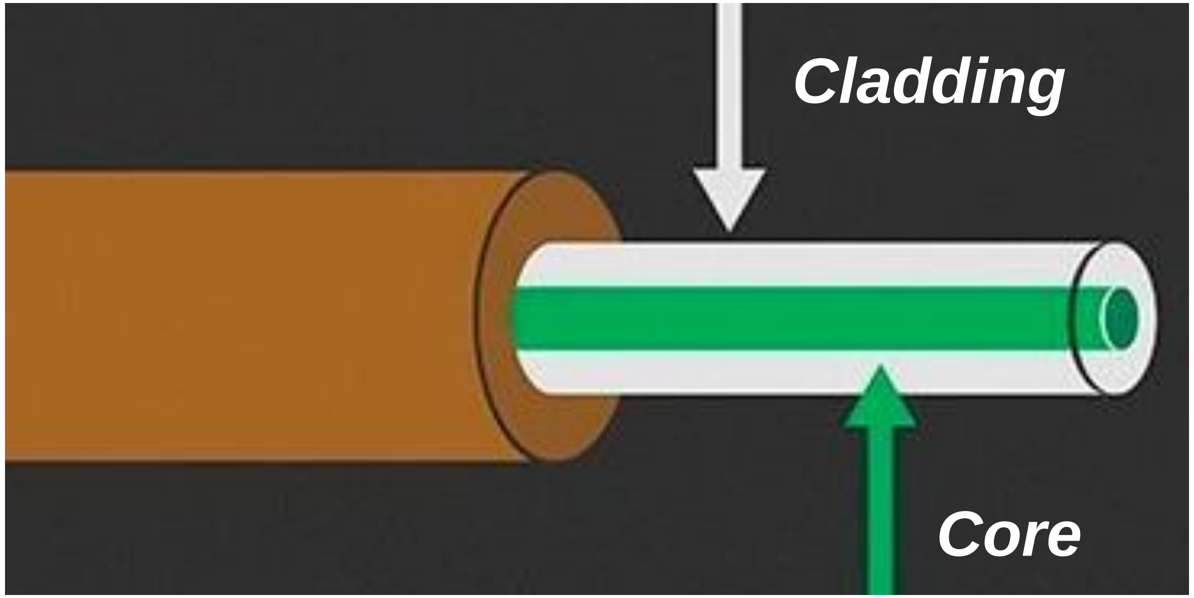
- ***While, when light travels from a medium of lower refractive index to a medium of higher one, then the ratio μ1/μ2 is less than 1. So the angle (sin i) will be greater than angle (sin r) i.e., the refracted ray is bent towards the normal.***



- When the light ray travels from medium with ***higher*** refractive index ***to*** a medium with lower refractive index and strikes the boundary at ***more than critical angle θ_c***, then all light will be ***reflected back in to the incident medium*** i.e. it will not penetrate in to the second medium. This phenomenon is called the ***total internal reflection***.



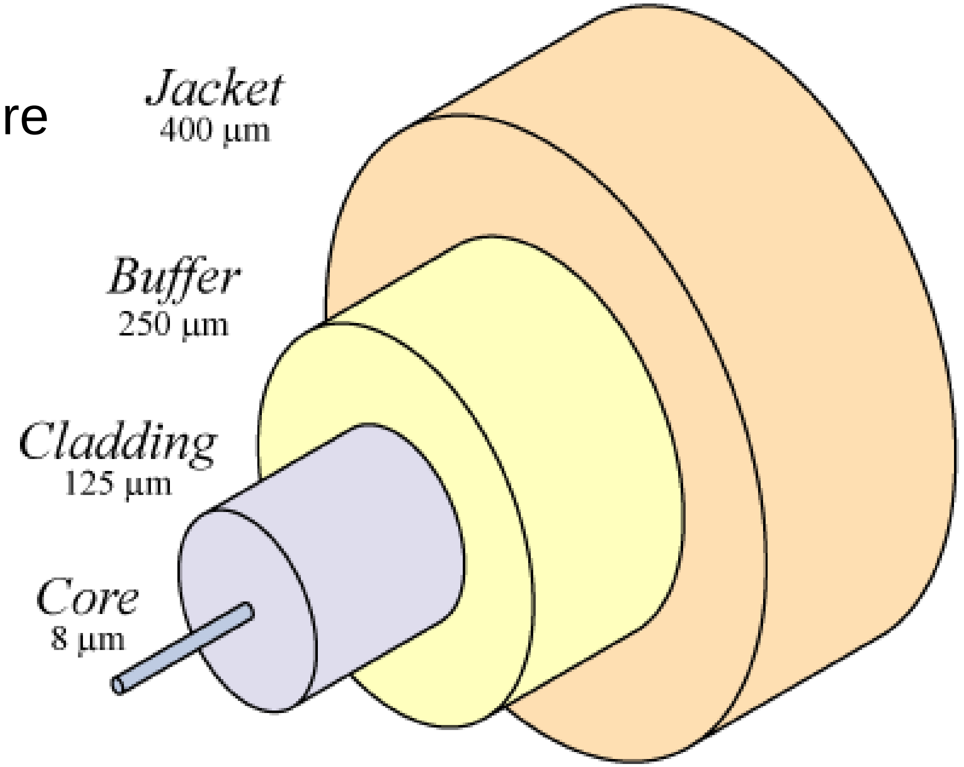
- Optical Fibre is an ***optical transmission*** device which works on the principle of ***total internal reflection***.



- When a light signal is directed at one end of the fibre at a suitable angle, it undergoes repeated ***total internal reflection*** along the length of the fibre and finally comes out at the other end.

Construction of Optical Fibre

- **Core**
  - Glass or plastic with a higher index of refraction than the cladding
  - Carries the signal
- **Cladding**
  - Glass or plastic with a lower index of refraction than the core
- **Buffer**
  - Protects the fiber from damage and moisture
- **Jacket**
  - Holds one or more fibers in a cable



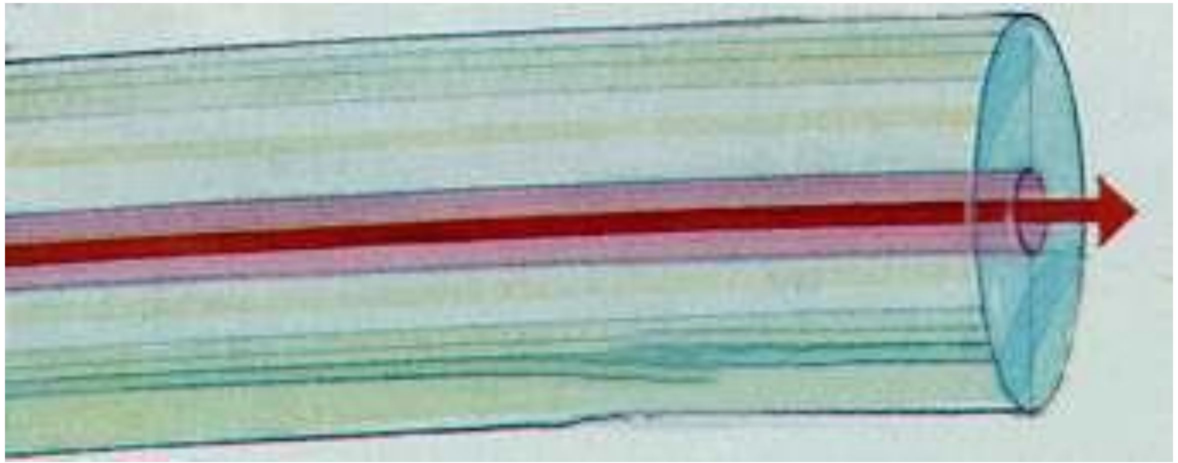
Types of Optical Fibre (Based on core size)

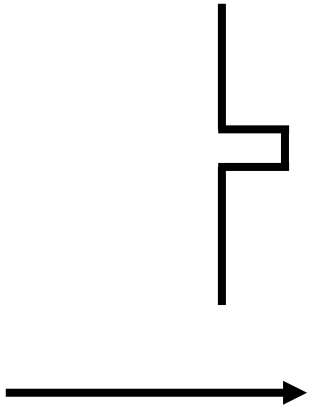
- Single Mode Step Index Fibre
- Multimode Fibre
  - Multimode Step Index Fibres
  - Multimode Graded Index Fibres

Single Mode (Step Index) Optical Fiber

- Single mode step index fiber has a core diameter of ***8 to 9 microns***, which only ***allows one light path or mode***

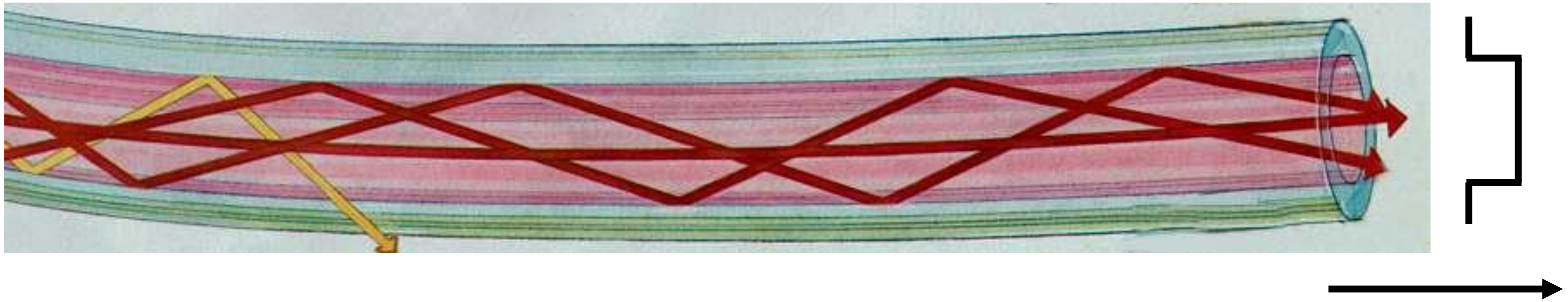
- Single mode fibres have a ***lower signal loss*** and a ***higher information capacity or bandwidth*** than a multimode fibre.





Multimode Step-Index Fiber

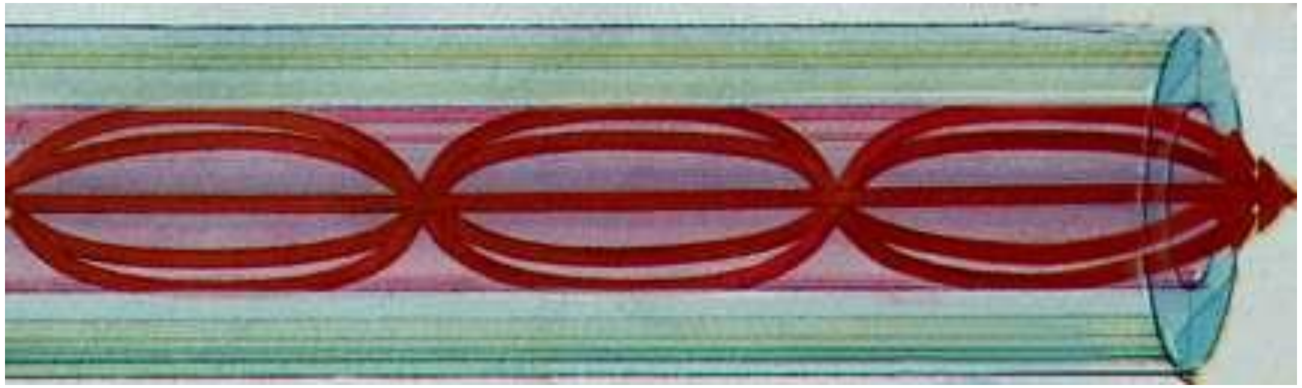
- Multimode fiber has a core diameter of ***50 to 100 microns*** (sometimes even larger)
    - Allows ***several light paths*** (~100) or modes
    - This causes ***modal dispersion*** – some modes take longer to pass through the fiber than others because they travel a longer distance.

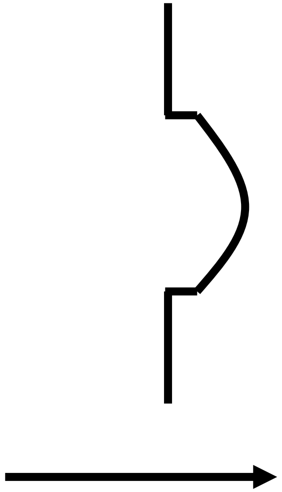


Index of refraction

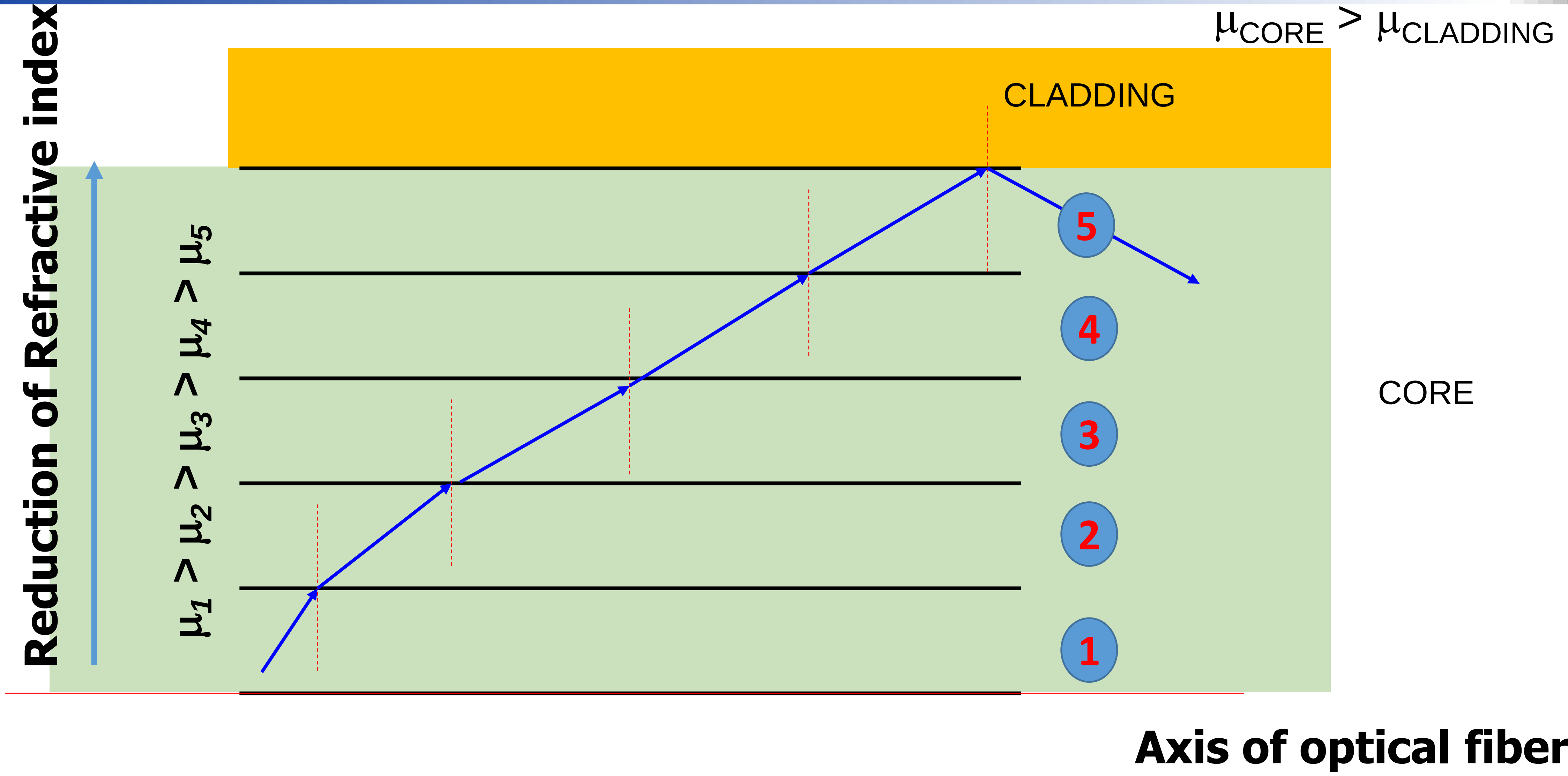
Multimode Graded-Index Fiber

- The index of refraction gradually changes across the core
  - Modes that travel further also move faster
  - This reduces modal dispersion so the bandwidth is greatly increased





To understand the Multimode Graded-Index Fiber



$\mu_1 > \mu_2 > \mu_3 > \mu_4 > \mu_5$

UPES

Step-index and Graded-index

- Step index multimode was developed first, but rare today because it has a low bandwidth (50 MHz-km)
- It has been replaced by graded-index multimode with a bandwidth up to 2 GHz-km

Few questions for you

- ***The fibres not used nowadays for optical fibre communication system are***

A. Single-mode fibre

B. Multimode fibre

C. Coaxial cable

D. Multimode graded-index fibres

- ***How does the refractive index vary in Graded Index fibre?***

A. Tangentially

B. Radially

C. Longitudinally

D. Transversely

- ***Which of the following has more distortion?***

A. Single step-index fibre

B. Graded index fibre

C. Multimode step-index fibre

D. Glass fibre

- ***In which of the following there is no distortion?***

A. Graded index fibre

B. Multimode step-index fibre

C. Single step-index fibre

D. Glass fibre

References

- https://www.wykop.pl/wpis/25189479/wlasciwosci-swiatla-dyfrakcja-dziwniesatysfakcjonu/

Propagation mechanism and communication in optical fiber

Upto now.

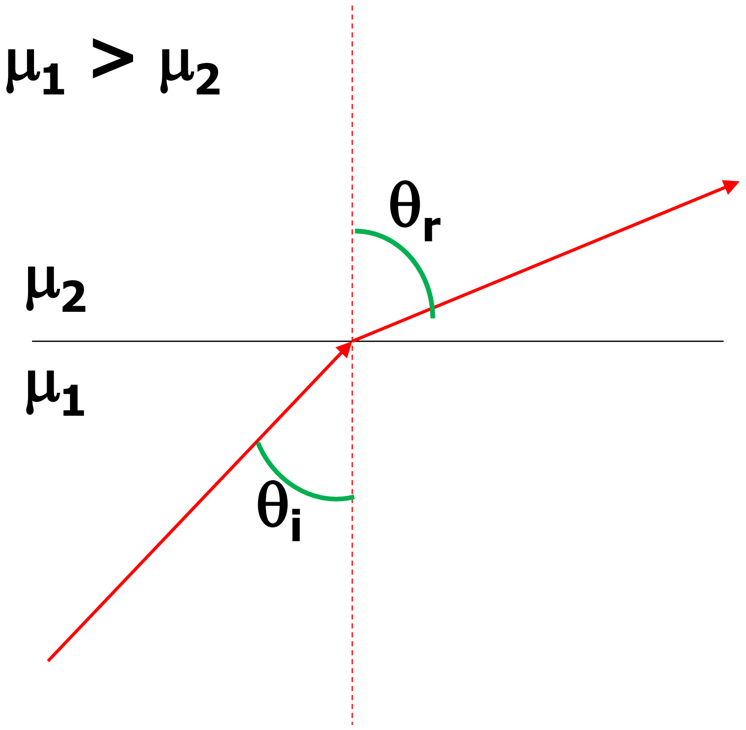
- Refraction (brief of Snell's law.)
- Total Internal Reflection
- What are the Optical Fibers?
- Construction of the Optical Fibers.
- Types of Optical fibers.

- Light Propagation in Optical Fiber
    - Acceptance angle
    - Numerical Aperture
    - Fractional refractive index change

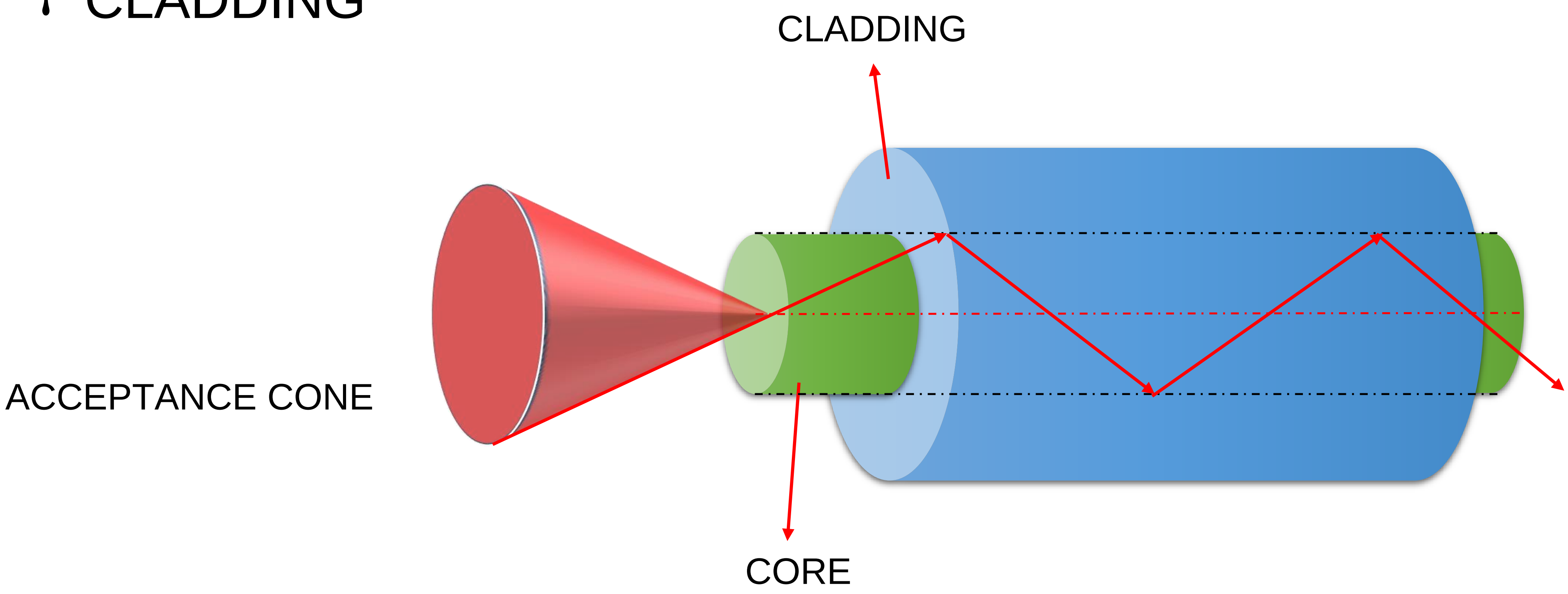
Snell's law

- $$\frac{\sin\theta_i}{\sin\theta_r} = \frac{\mu_2}{\mu_1}$$

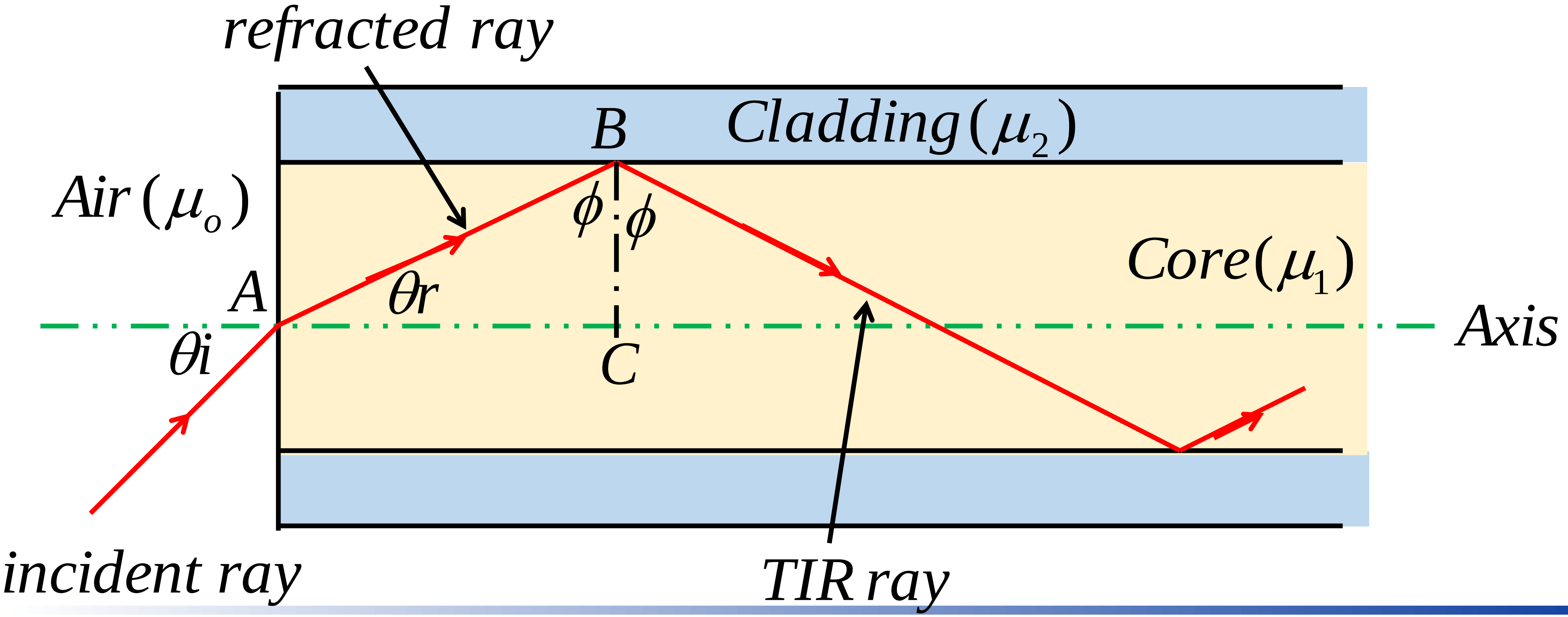
- $$\mu_1 \sin\theta_i = \mu_2 \sin\theta_r$$



$\mu_{CORE} > \mu_{CLADDING}$



- Let us consider the light propagation in an optical fibre.
- The end at which the light enters in the fibre is called launching end.
- Let the refractive index of the fibre core is μ_1 and the refractive index of the fibre cladding is μ_2 (i.e., $\mu_1 > \mu_2$).



Light propagation in fiber: Acceptance Angle

- Let the outside medium through which the light is launched into the fibre has refractive index μ_0. Let the light ray enters the fibre at an angle θ_i to the axis of the fibre and the refracted ray makes and angle θ_r with the axis and strike the core-cladding interface at an angle ϕ (as in fig.).

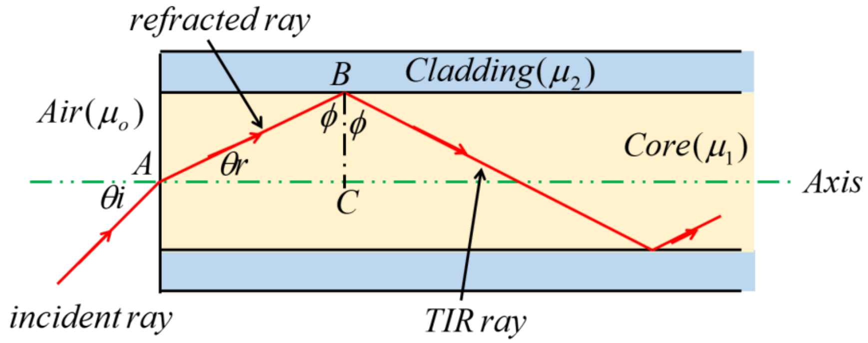
- When the light ray travels from medium with higher refractive index to a medium with lower refractive index and strikes the boundary at more than critical angle θ_c, then all light will be reflected back in to the incident medium i.e. it will not penetrate in to the second medium. This phenomenon is called the ***total internal reflection***.

Light propagation in fiber: Acceptance Angle

- Applying Snell's law at the launching face of the fibre;

we have,

$$\mu_o \sin\theta i = \mu_1 \sin\theta r \qquad (1)$$



Now largest value of θ_i occurs when $\phi = \phi_c$.

- From triangle ABC;

$$\sin\theta r = \sin(90-\phi) = \cos\phi$$

- From eq. (1);

$$\sin\theta i = \sin\theta r \frac{\mu_1}{\mu_o} = \frac{\mu_1}{\mu_o}\cos\phi \qquad (2)$$

- Now when $\phi = \phi_c$ then $\theta_i = \theta_{max}$, So;

$$\sin\theta_{\max} = \frac{\mu_1}{\mu_o}\cos\phi_c \qquad (3)$$

- When $\phi = \phi c$ then according to Snell's law at the interface of core-cladding;

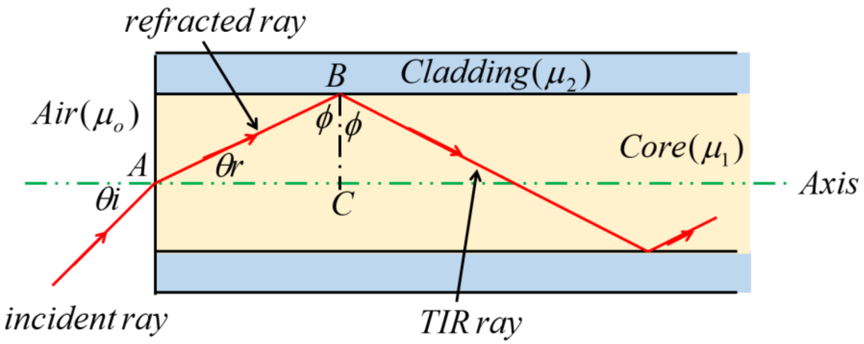
$$\frac{\mu_1}{\mu_2} = \frac{\sin 90^o}{\sin\phi_c}$$

$$\mu_1 \sin\Phi c = \mu_2 \sin 90^0$$

and,

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

$$so,\ \ \cos\phi_c = \sqrt{1-\sin^2\phi_c} = \sqrt{\frac{\mu_1^2-\mu_2^2}{\mu_1^2}} \qquad (4)$$



So, from eqs. (3) and (4)

$$\sin\theta_{\max} = \frac{\mu_1}{\mu_o}\sqrt{\frac{\mu_1^2-\mu_2^2}{\mu_1^2}} = \frac{\sqrt{\mu_1^2-\mu_2^2}}{\mu_o} \qquad (5)$$

- If $(\mu_1^2 - \mu_2^2) >> \mu_0^2$ then for all values of incident angle θ_i, total internal reflection will occur.

Light propagation in fiber: Acceptance Angle

- Assuming μ_0=1 the maximum value of sin θ_i, for a ray to be guided by the optical fibre is given by;

$$\sin\theta_{\max} = \sqrt{\mu_1^2 - \mu_2^2} \qquad (6)$$

and

$$\theta_{\max} = \sin^{-1}\sqrt{\mu_1^2 - \mu_2^2} \qquad (7)$$

This equation gives a relation between the acceptance angle and the refractive indices of the core and the cladding.

- The angle θ_{max} is called the ***acceptance angle*** of the fibre and may be defined as **"maximum angle *that the light ray can have relative to the axis of the fibre*"**
- The light ray contained within the cone having a full angle ***$2\theta_{max}$*** are accepted and transmitted along the fibre. This cone is known as ***acceptance cone***.

Numerical aperture

- It is the measure of the ***light gathering capacity*** of the fiber and is defined as the ***product of sine of the acceptance angle*** and the ***refractive index*** of the medium to which the end faces of the fiber are exposed.

$$NA = \mu_0 sin\theta_{max}$$

- Taking μ_0 =1 for air, we get;

$$NA = sin\vartheta_{max} = \sqrt{\mu_1^2 - \mu_2^2}$$

$$NA = \sin\vartheta_{max} = \sqrt{\mu_1^2 - \mu_2^2}$$

$$NA = \sqrt{\mu_1^2 - \mu_2^2} = \sqrt{(\mu_1 + \mu_2)(\mu_1 - \mu_2)}$$

$$NA = \sqrt{\mu_1^2 - \mu_2^2} = \sqrt{\left(\frac{\mu_1^2 - \mu_2^2}{2}\right)}$$

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

$$= \frac{(\mu_1 + \mu_2)}{2}.(\mu_1 - \mu_2)2$$

$$NA = \sqrt{\mu_1^2 - \mu_2^2} = \mu_1\sqrt{2\Delta}$$

$$let,\ \frac{(\mu_1 + \mu_2)}{2} = \mu_1$$

$$so,\ \mu_1^2 - \mu_2^2 = \mu_1.2\mu_1\Delta = 2\mu_1^2\Delta = \mu_1\sqrt{2\Delta}$$

$$and,\ \Delta = \frac{\mu_1 - \mu_2}{2},\quad or\ \ \mu_1\Delta = \mu_1 - \mu_2$$

Fractional refractive index change

- This parameter is defined as the ratio of the difference between the refractive indices of core and cladding to the refractive index of core and denoted by Δ;

$$\Delta = \frac{\mu_1 - \mu_2}{\mu_1}$$

- Δ is always positive as the refractive index of core is always greater than the refractive index of cladding for the total internal reflection condition.

Modes of fiber: Normalized frequency OR V-number

- The optical fibre is also called an ***optical wave guide***. The energy/signals in the cable is propagated by electric and magnetic field vectors of electromagnetic waves, which can be analyzed by Maxwell's field equations. The Maxwell's equations have discrete sets of solutions called modes.

- The number of modes of multimode fiber cable depends on the wavelength of light, core diameter and material composition. This can be determined by the Normalized frequency parameter (V) given by;

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

Where ,

a = fiber core radius (d is diameter)

λ = wavelength of light

N.A.=numerical aperture

Modes of fiber: Normalized frequency OR V-number

- For a single mode fiber, $V \leq 2.405$ and for multimode fiber, $V \geq 2.405$.

- Mathematically, the number of modes for a multimode fiber is given by;

- The no of modes in a multimode step index fiber is;

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

- The no of modes in a multimode graded index fiber is;

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

- The wavelength corresponding to the value of V=2.405 is known as the cut-off wavelength of the fiber

ATTENUATION

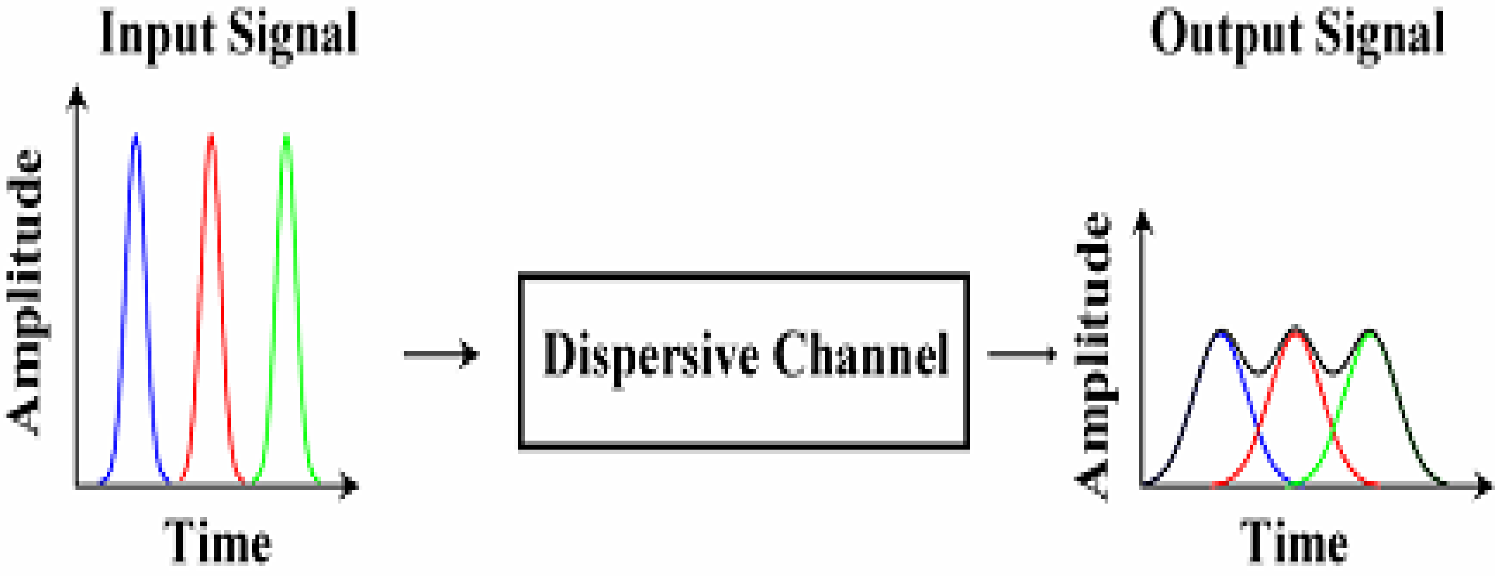
- Attenuation or transmission loss is the loss of optical power as light travels down a fiber. Attenuation controls the distance that an optical signal can travel. The decrease in signal strength along a fiber optic waveguide caused by absorption of light, scattering and bending of fiber.
- ***Attenuation constant:*** Attenuation or transmission loss and dispersion are two most important factors in telecommunication.
- The attenuation of an optical beam is usually expressed in dB/Km or decibel/Km. In general, the attenuation is defined by the formula;

$$\alpha L = 10 \log_{10} \frac{P_{in}}{P_{out}}$$

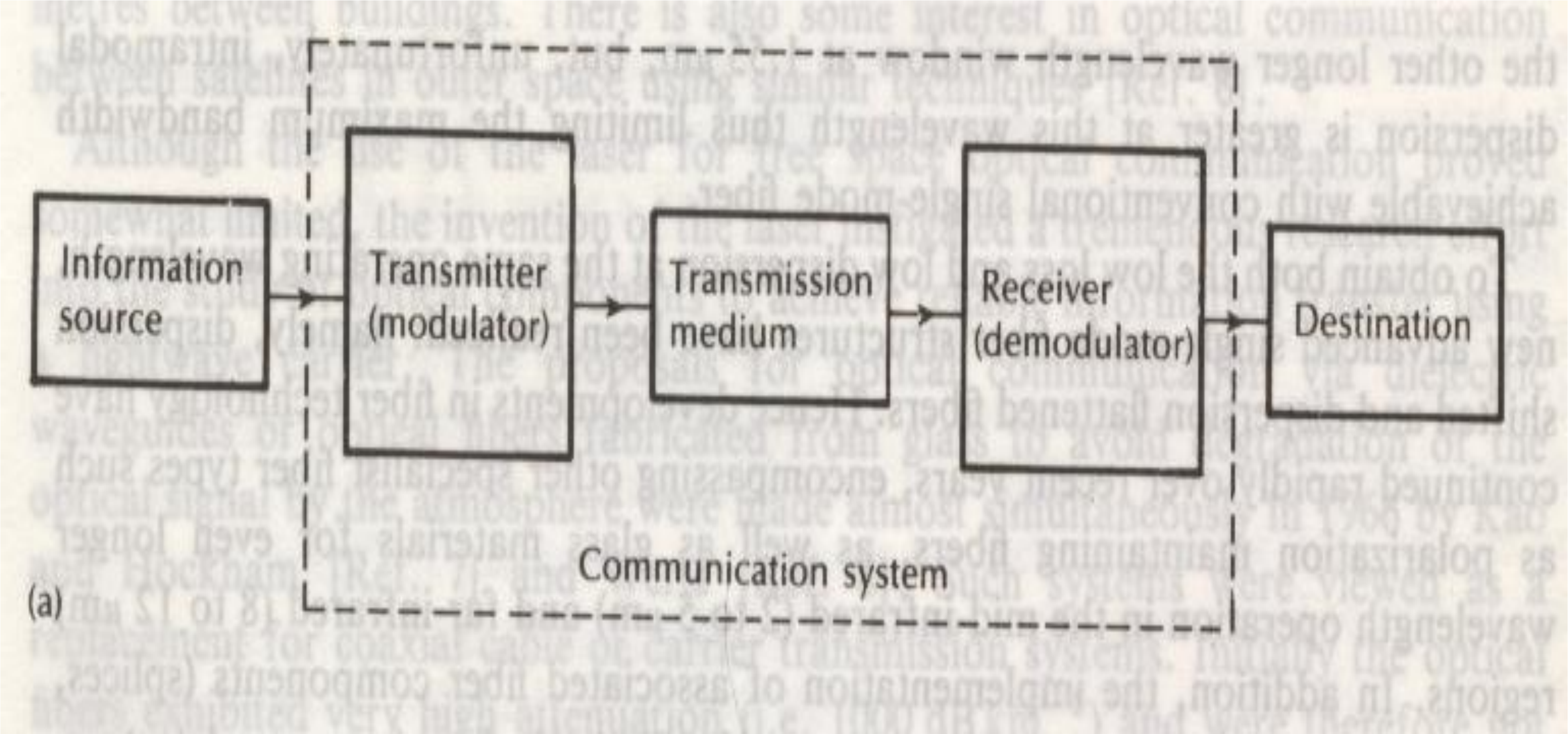
where ***α is the attenuation coefficient*** of the fiber

Dispersion

- Dispersion, expressed in terms of the symbol Δt, is defined as pulse spreading in an optical fiber. As a pulse of light propagates through a fiber, elements such as numerical aperture, core diameter, refractive index profile, wavelength, and laser line width cause the pulse to broaden. This poses a limitation on the overall bandwidth of the fiber.



The General Communication System



The Optical fibre Communication System