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FIBRE OPTICS

Syllabus

- Basic principle of optical fibre, step index and graded index fibers
- parameters of optical fibers, acceptance angle, acceptance cone, numerical aperture, normalized frequency, No. of modes,
- Attenuation in optical fibers, intermodal and intramodal dispersion (no derivation), optical fibers in communication.

Introduction

An optical fiber is essentially a waveguide for light

- An optical fiber (or fibre) is a glass or plastic fiber designed to guide light along its length by confining as much light as possible in a propagating form.
- They are arranged in bundles called optical cables and used to transmit light signals over long distances.
- Based on the principle of "Total Internal Reflection"
- Optical fibers are widely used in fiber-optic communication, which permits transmission over longer distances and at higher data rates than other forms of wired and wireless communications.

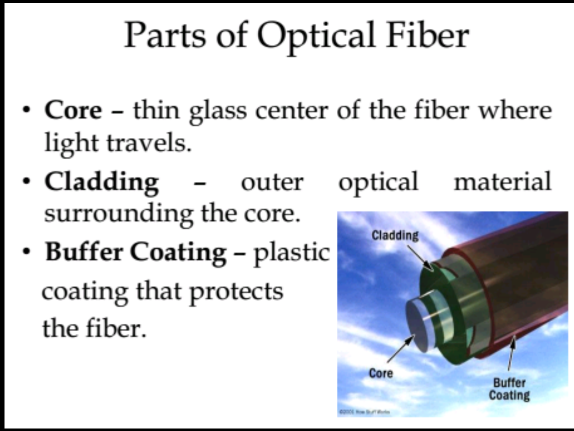
The light-guiding principle behind optical fibers was first demonstrated

in by Daniel Colladon and Jaques Babinet in the 1840s,

with Irish inventor John Tyndall offering public displays using water-fountains .

A fibre optic cable consists of glass or plastic threads, which are protected by the thin polyvinyl chloride (PVC) or metal sheath. The central part of optical fibe is known as core, which is surrounded by cladding. These layers are further protected by PVC sheath

1. **Core** is made up of thin glass or plastic layer through which light travels.

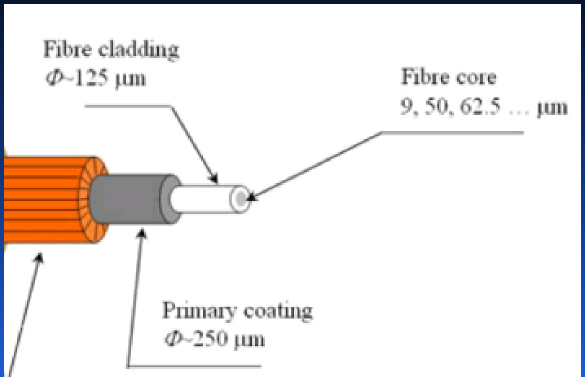


2. **Cladding** is outer optical material surrounding the core and reflects back the light into the core.

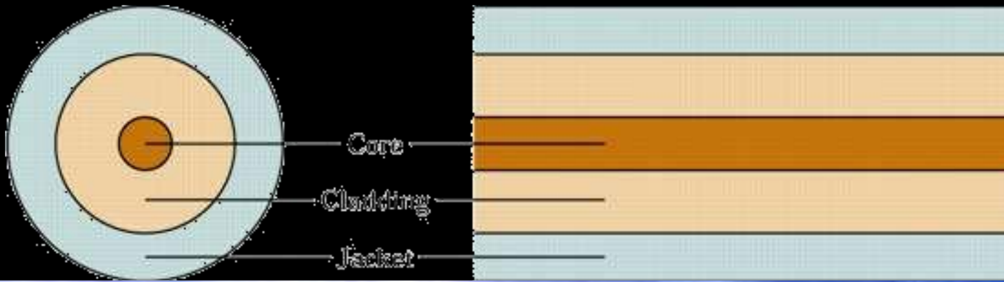
3. **Sheath** is plastic coating that protects fibre from any damage or other environmental conditions.

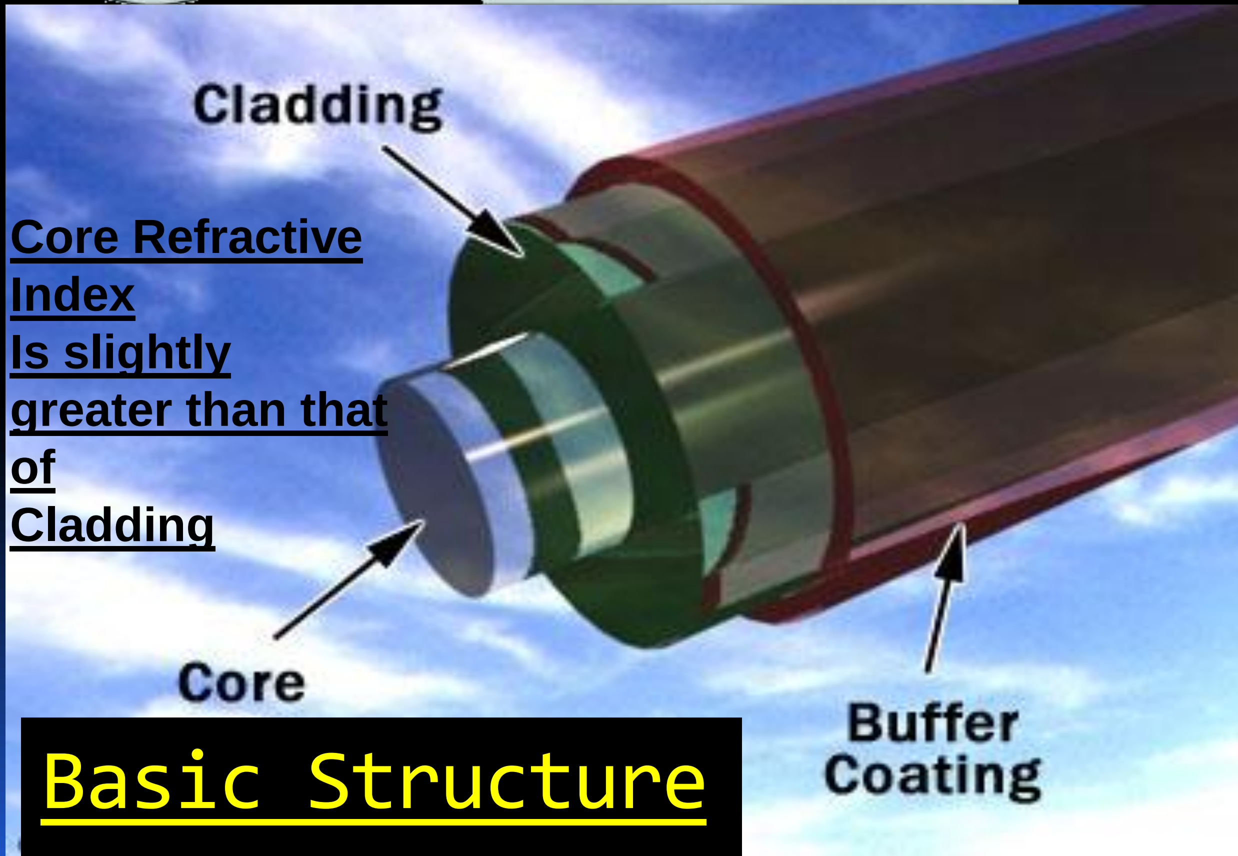
Core Refractive Index Is slightly greater than that of Cladding

The range of the core diameter is 5-100 micrometer. The cladding diameter isusually 125 um and sheath diameter is about 250 um.



Optical fibers are very fine fibers of glass. They consist of a glass core, roughly fifty micrometres in diameter, surrounded by a glass "optical cladding" giving an outside diameter of about 125 Micrometres.





Core Refractive Index Is slightly greater than that of Cladding

Basic Structure

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

Protective Sheath/Buffer Coating
- Protects the fiber from damage and moisture

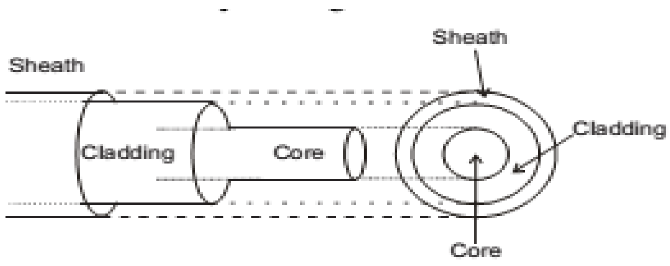
Jacket
- Holds one or more fibers in a cable

Optical fibres are fabricated from glass or plastic material which are transparent to optical frequencies. Therefore, based on the nature of core and cladding the optical fibres are of three types :

(i) plastic core with plastic cladding

(ii) glass core with plastic cladding and

(iii) glass core with glass cladding.



- In case of plastics, the core is made up of polystyrene or polymethyl metha acrylate (PMMA) and cladding is made from silicon or teflon.
- On the other hand in case of glass, it is made of silica (SiO_2) with refractive index 1.458.
  1. The refractive index of pure silica can be increased by doping with germania (GeO_2) or phosphorous pentaoxide (P_2O_5).
  2. Likewise, the refractive index of pure silica can be decreased by doping with Boria (B_2O_3) or fluorene.

Hence the doped silica can be used as both core or cladding materials.

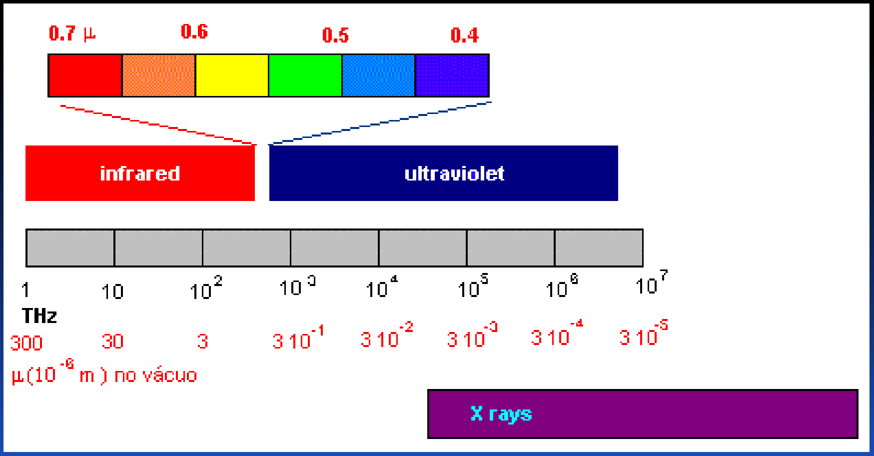
Advantages of optical fiber :

- Greater bandwidth
- Lower loss
- Immunity to **crosstalk**
- No electrical hazard
- Free from electromagnetic interferences

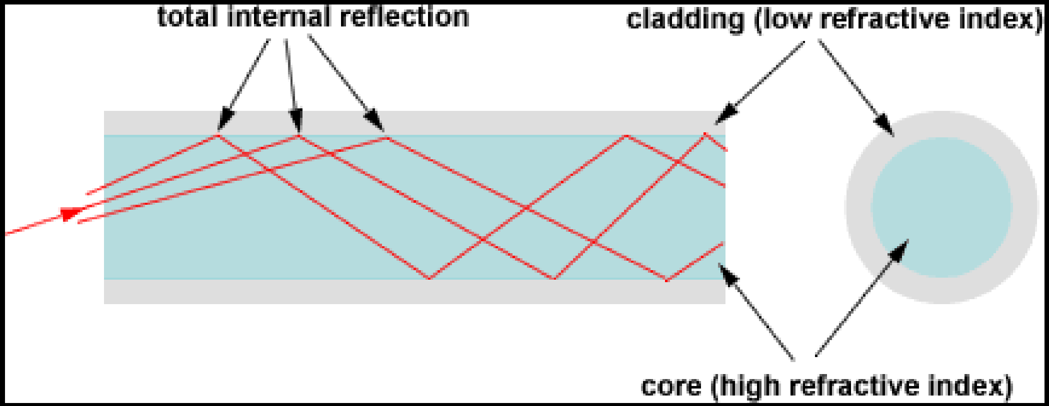
Light Propagation

- Visible light extends from 380 nm (violet) to 780 nm (red).
  - For smaller wavelengths ultra-violet radiation (UV) occurs. Longer wavelengths correspond to the infrared region (IR).

- Optical Fibres communication elements operate in the micrometer wavelength zone of the frequency spectrum (frequencies between 10^{14} Hz to 10^{15} Hz).



Transmission of Light in Optical Fibre

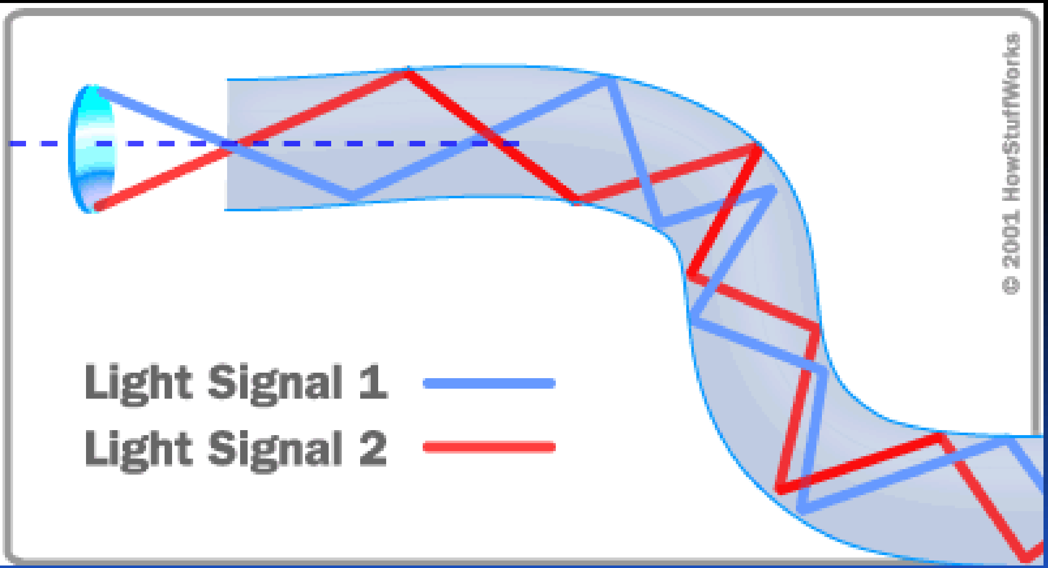


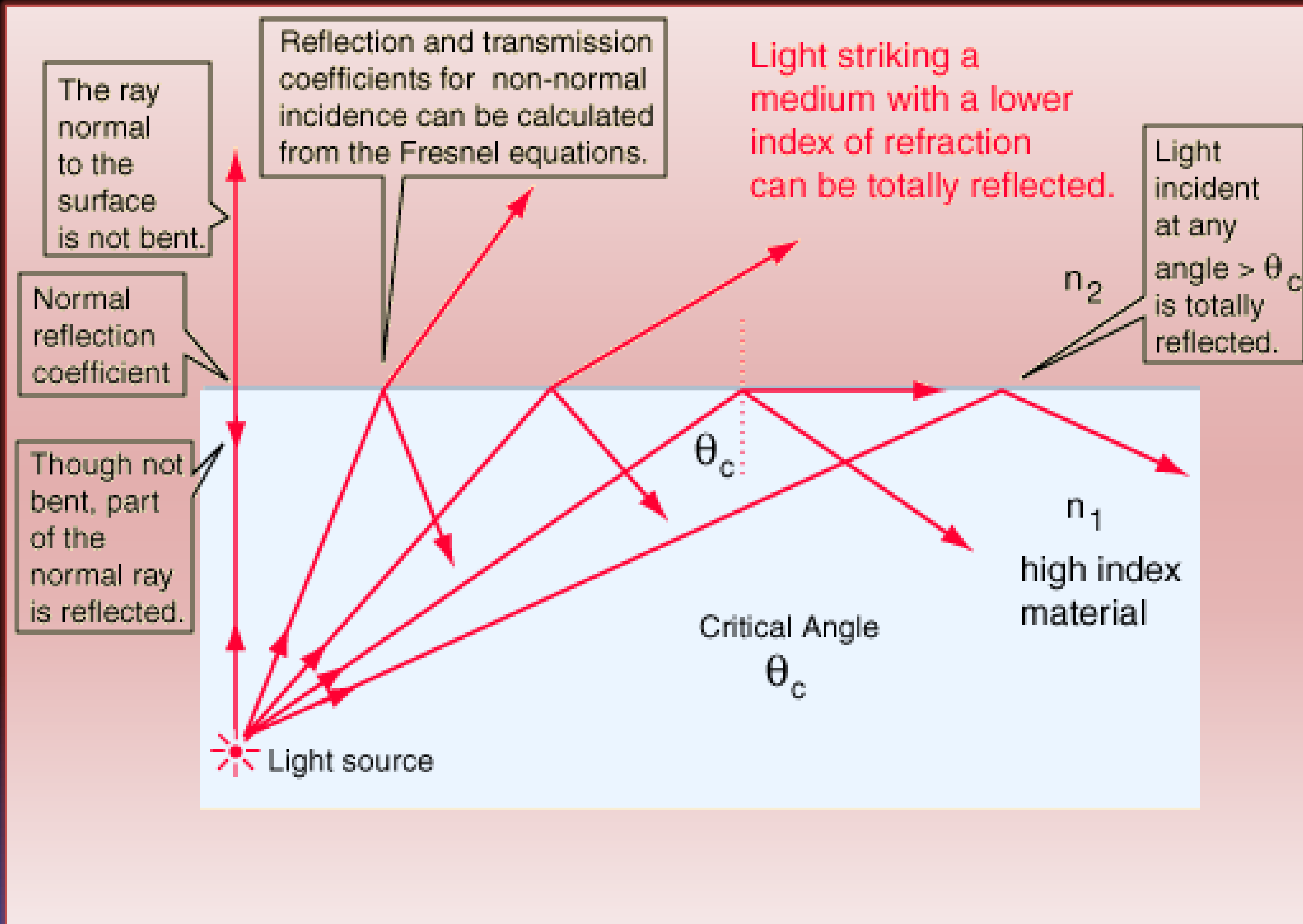
An optical fiber guides light waves in distinct patterns called *modes*.

Mode describes the distribution of light energy across the fiber.

The precise patterns depend on the wavelength of light transmitted and on the variation in refractive index that shapes the core.

Total Internal Reflection




The ray normal to the surface is not bent.
Reflection and transmission coefficients for non-normal incidence can be calculated from the Fresnel equations.
Light striking a medium with a lower index of refraction can be totally reflected.
Light incident at any angle > θc is totally reflected.
Normal reflection coefficient
Though not bent, part of the normal ray is reflected.
n2
θc
n1
high index material
Critical Angle θc
Light source

Total Internal Reflection & Critical Angle

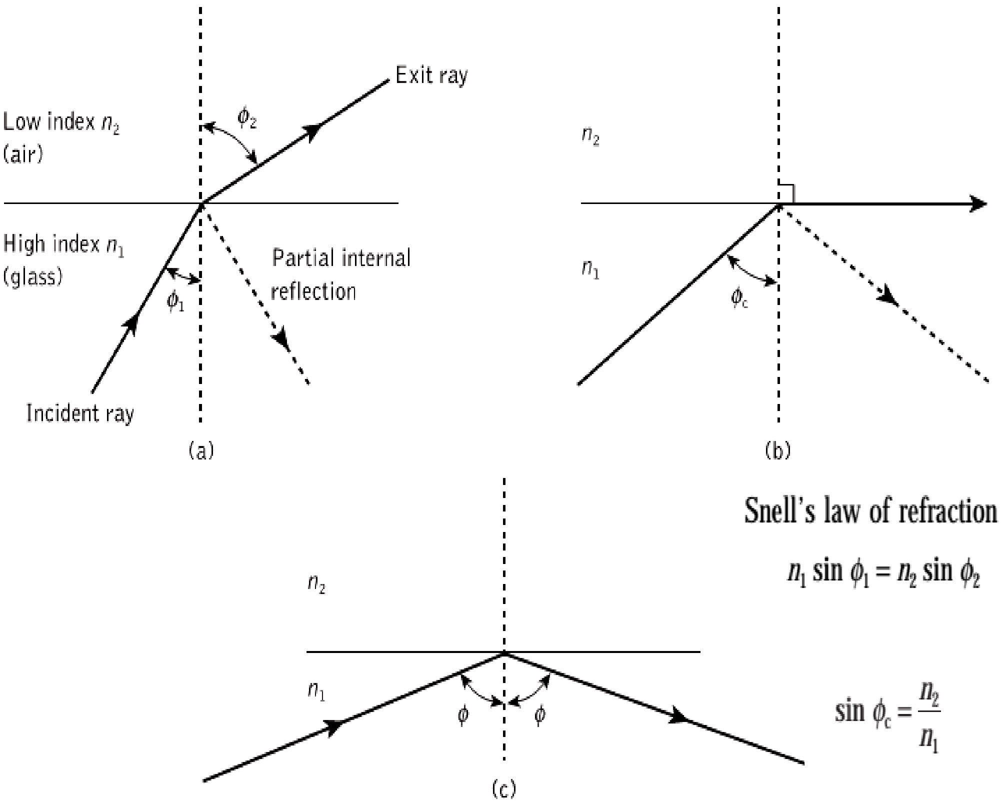


Figure: Light rays incident on a high to low refractive index interface (e.g. glass–air): (a) refraction; (b) the limiting case of refraction showing the critical ray at an angle ϕ_c; (c) total internal reflection where $\phi > \phi_c$

Expression for Critical Angle :

According to Snell's Law,

$$n_1 \sin\phi_1 = n_2 \sin\phi_1$$

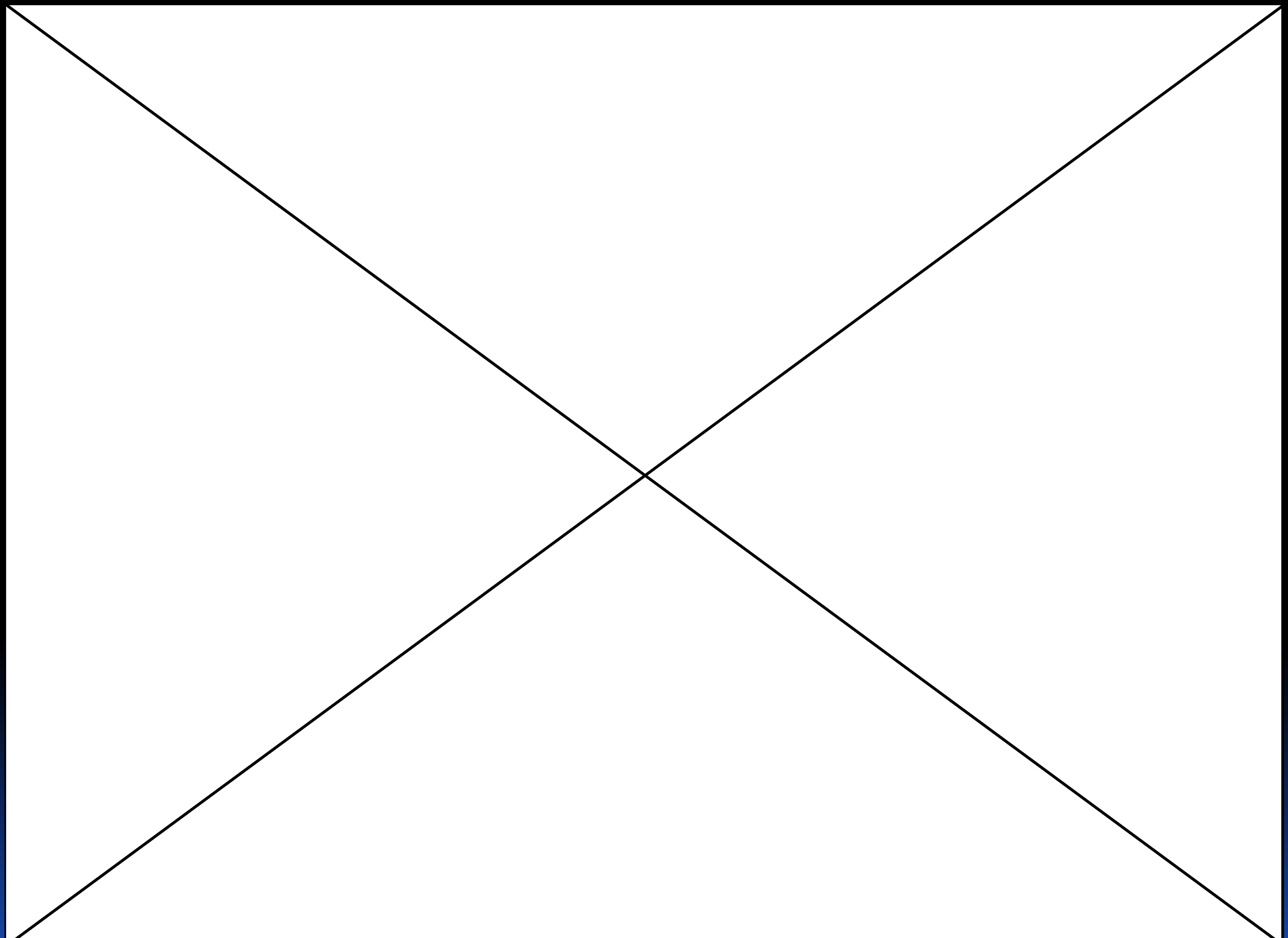
If angle of incidence = Critical Angle ($\phi_1 = \phi_c$),

Then, $\phi_2 = 90^o$

$$n_1 \sin\phi_c = n_2 \sin 90$$

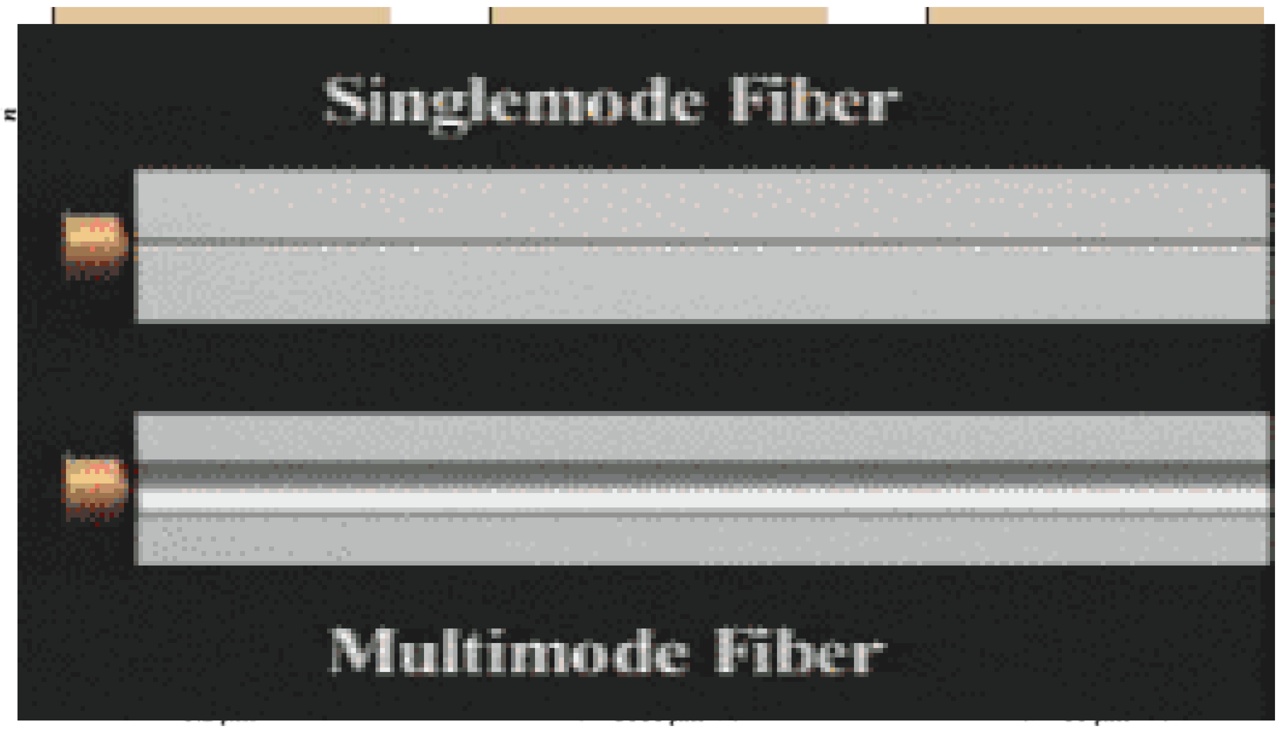
$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

In case of optical fibre, the refrective index of core (n_1) is slightly greater than the refrative index of cladding (n_2). Then light signal is totally internally reflected. As a result, light ray undergoes multiple total internal reflections at core cladding interface until it emerges out of the other end of the fibre even if the fibre is bent.



Types of Fiber

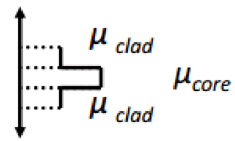
1. Step Index Single Mode
2. Multi-Mode
   1. Step Index
   2. Graded Index



- Step-index fibers → because the index of refraction changes radically (in step) between the core and the cladding
- Graded-index fiber is a compromise multimode fiber, here 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

Single (Mono) Mode :

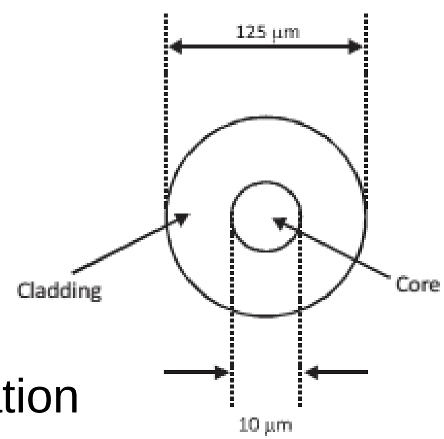
This is called so because the refractive index of the fibre '**step**' up as we move from the cladding to the core and this type of fibre allows single mode to propagate at a time due to very small diameter of its core.

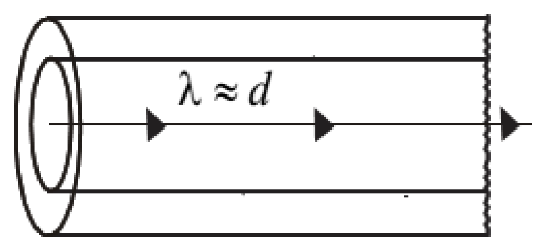


ADVANTAGE:
1. Best for high speeds
2. Long distances
3. High bandwidth

- In this fibre, the refractive indices of the cladding and the core remain constant

- In this fibre, the size of its core (diameter) is typically around 9-10 μm.





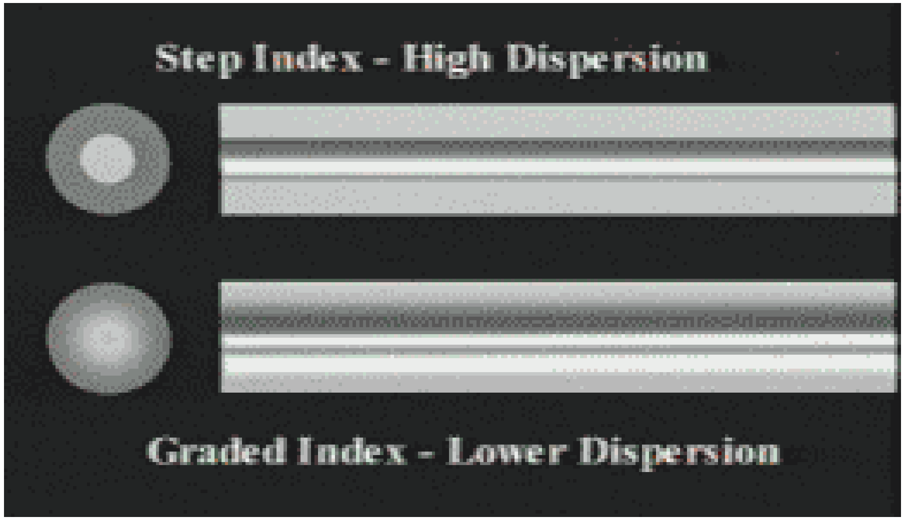
Allows only one mode of propagation

Multimode fibre :

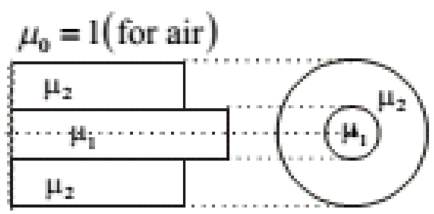
This is called so because it allow more than one mode to propagate. Over more than 100 modes can propagate through multimode fibres at a time. The size of its core is typically around 50 μm or 62.5 μm.

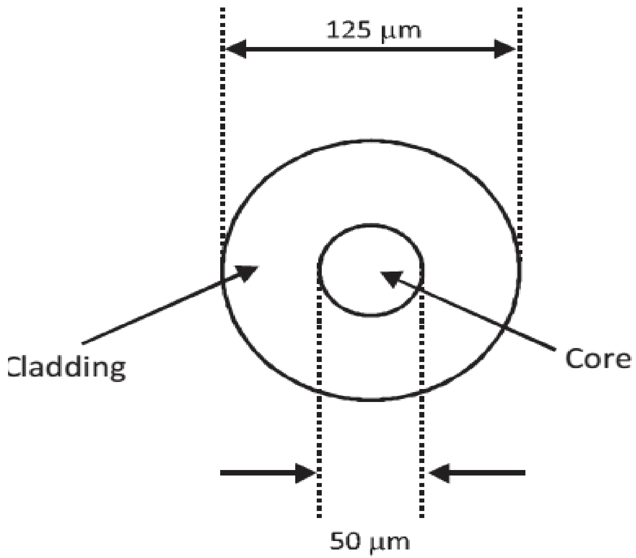
Two Types

- Step Index Fibres
- Graded Index Fibres



- **Multi Mode Optical Fibre(Step-Index)** : Allows many modes of propagation





- Numerical Aperture (NA) varies from 0.20 to 0.29 respectively.
- Typically the core diameter is 50 µm to 100 µm
- Due to higher value of NA , and larger core size in this case, fibre connections and launching of light is very easy
- Due to several modes, the effect of dispersion gets increased, i.e. the modes arrive at the fibre end slightly different times and so spreading of pulses takes place.

Features:

Large core size, so source power can be efficiently coupled to the fiber

High attenuation (4-6 dB / km), Low bandwidth (50 MHz-km)

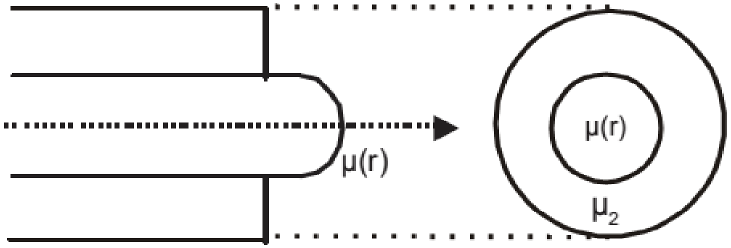
Used in short, low-speed data links

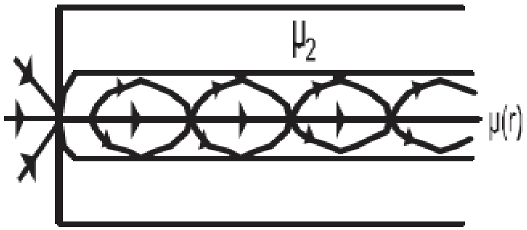
Also useful in high-radiation environments, because it can be made with pure silica core

Graded index Multimode Fibre

The profile of the refractive index is nearly parabolic that results in continual refocusing of the ray in the core, and minimizing the modal dispersion.

Standard graded index fibres typically have a core diameter of 50 µm or 62.5 µm and the cladding diameter of 125 µm.





The refractive index of graded index fibre is given by

$$\mu(r) = \mu_1 \sqrt{1 - 2\Delta\left(\frac{2r}{d}\right)^{\alpha}}$$

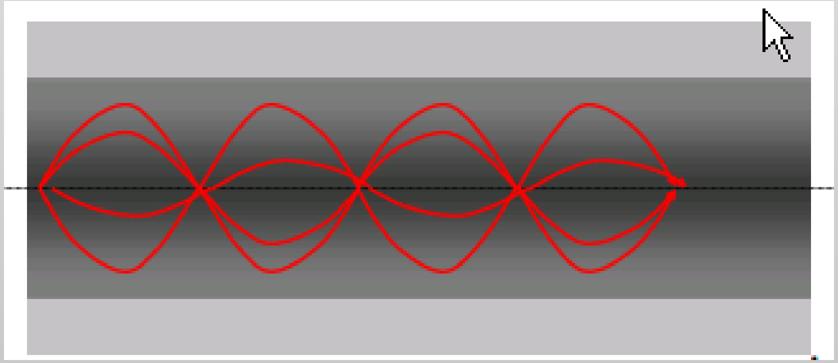
$\mu(r)$ is the core index at radial distance ‘r’ from the core axis, μ_1 is refractive index at core axis, Δ is fractional refractive index difference, d is core diameter and α is grading profile index number.

<u>Please Note that in this figure Core and Cladding are marked wrong: Core should be marked as Cladding and vice versa</u>

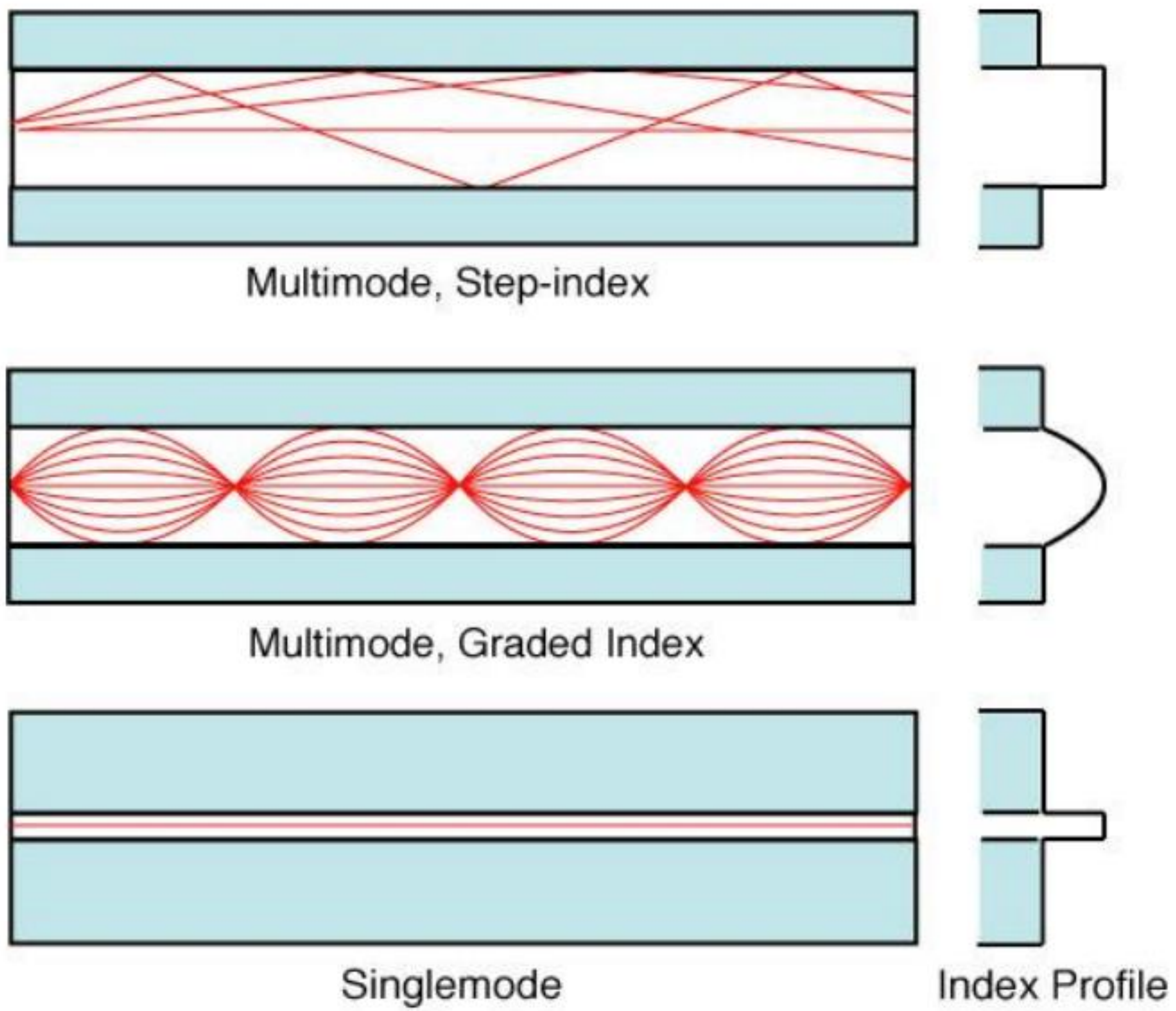
Features of Graded Index Fibre

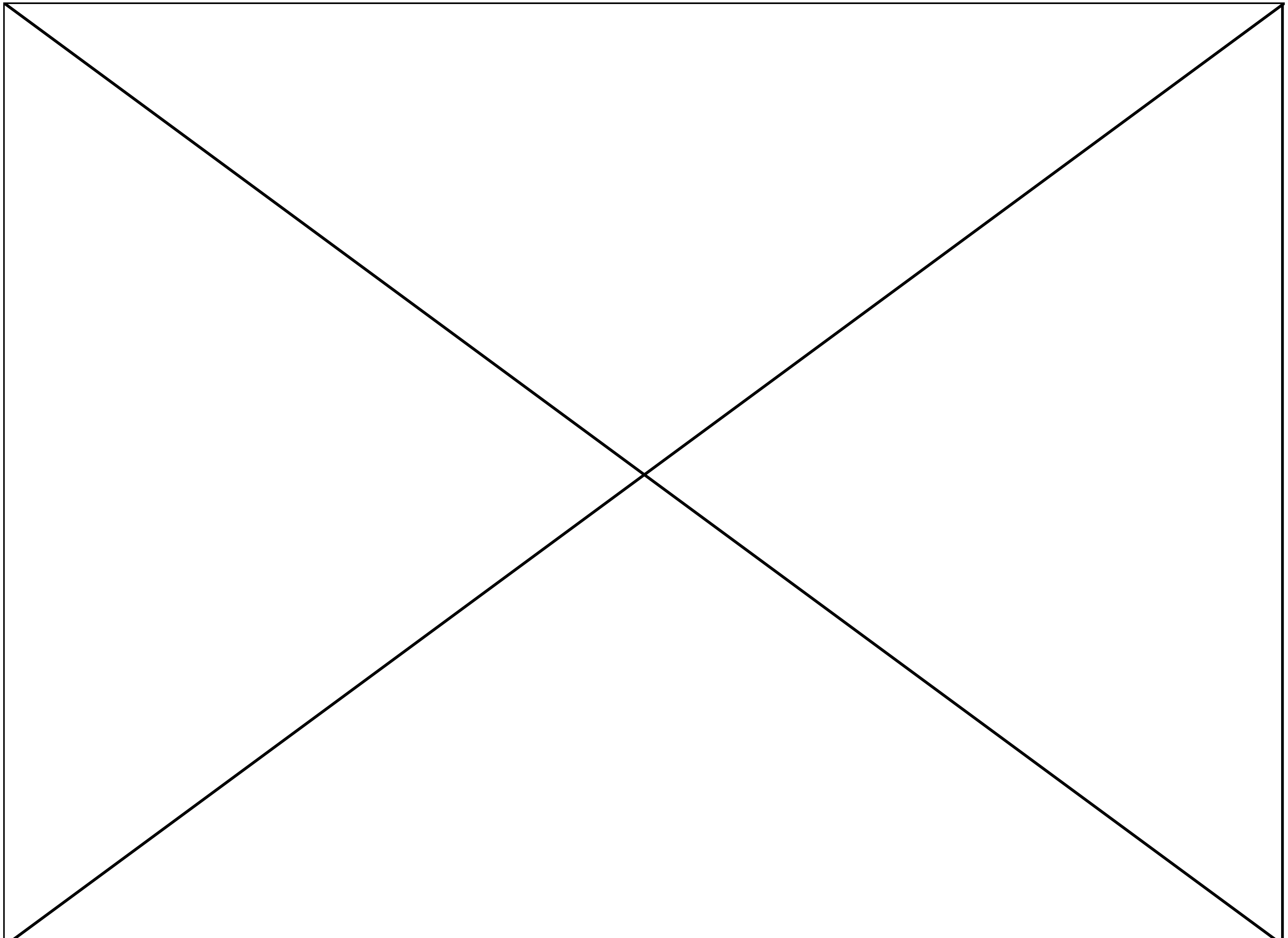
1. The light wave <u>follow sinusoidal</u> paths along the fibre.
2. In this fibre, the refractive index of the core decreases with increasing radial distance from the fibre axis.
3. The value of the refractive index is highest at the centre of the core and decreases to a value at the edge of the core that equal the refractive index of the cladding.
4. Useful for "premises networks" like LANs, security systems, etc.
   1. 62.5/125 micron has been most widely used
   2. Works well with LEDs, but cannot be used for Gigabit Ethernet

- Low modal Dispersion
  - Longer path is now located in lower index region; the larger time taken is compensated by faster travel leading to less pulse broadening



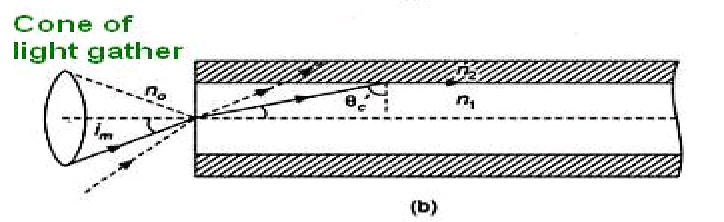
Types/index profile



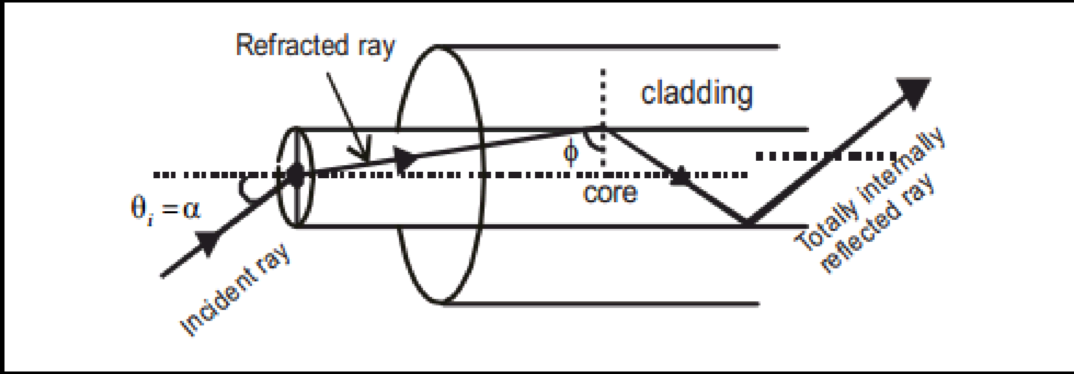


IMPORTANT DEFINITIONS & PARAMETERS OF OPTICAL FIBRE

Acceptance Angle



- **Acceptance angle:-** The acceptance angle is the maximum angle made by incident ray of light with the axis of core at core-outside medium, so that it gets totally internally reflected at core cladding interface.



Let α be the acceptance angle.

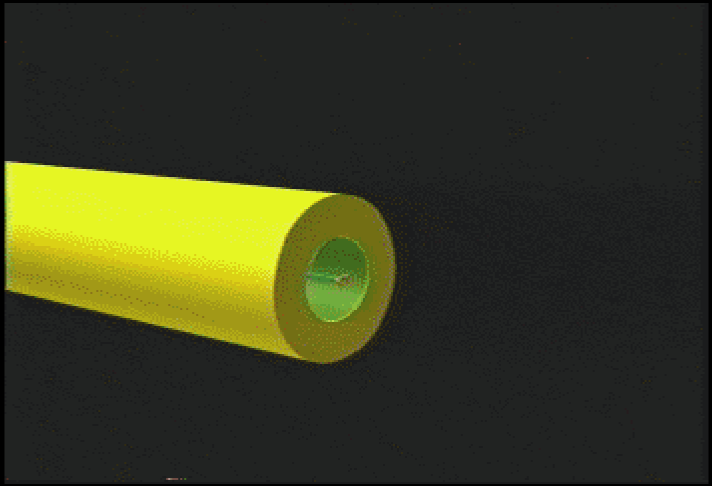
Then for $\theta_i = \alpha_{max}$, $\phi = \theta_c$ (Criticle angle)

For $\theta_i < \alpha_{max}$, $\phi > \theta_c$, total internal reflection takes place

For $\theta_i > \alpha_{max}$, $\phi < \theta_c$, signal transmisson does not takes place.

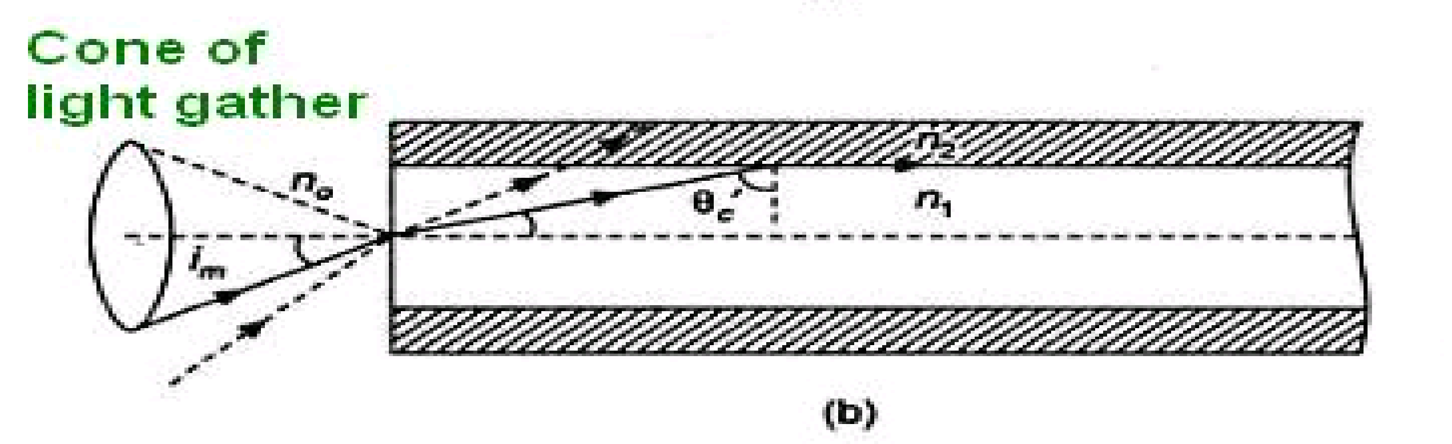
The **acceptance angle** of an optical fiber is **defined** based on a purely geometrical consideration (ray optics): it is the maximum **angle** of a ray (against the fiber axis) hitting the fiber core which allows the incident light to be guided by the core.

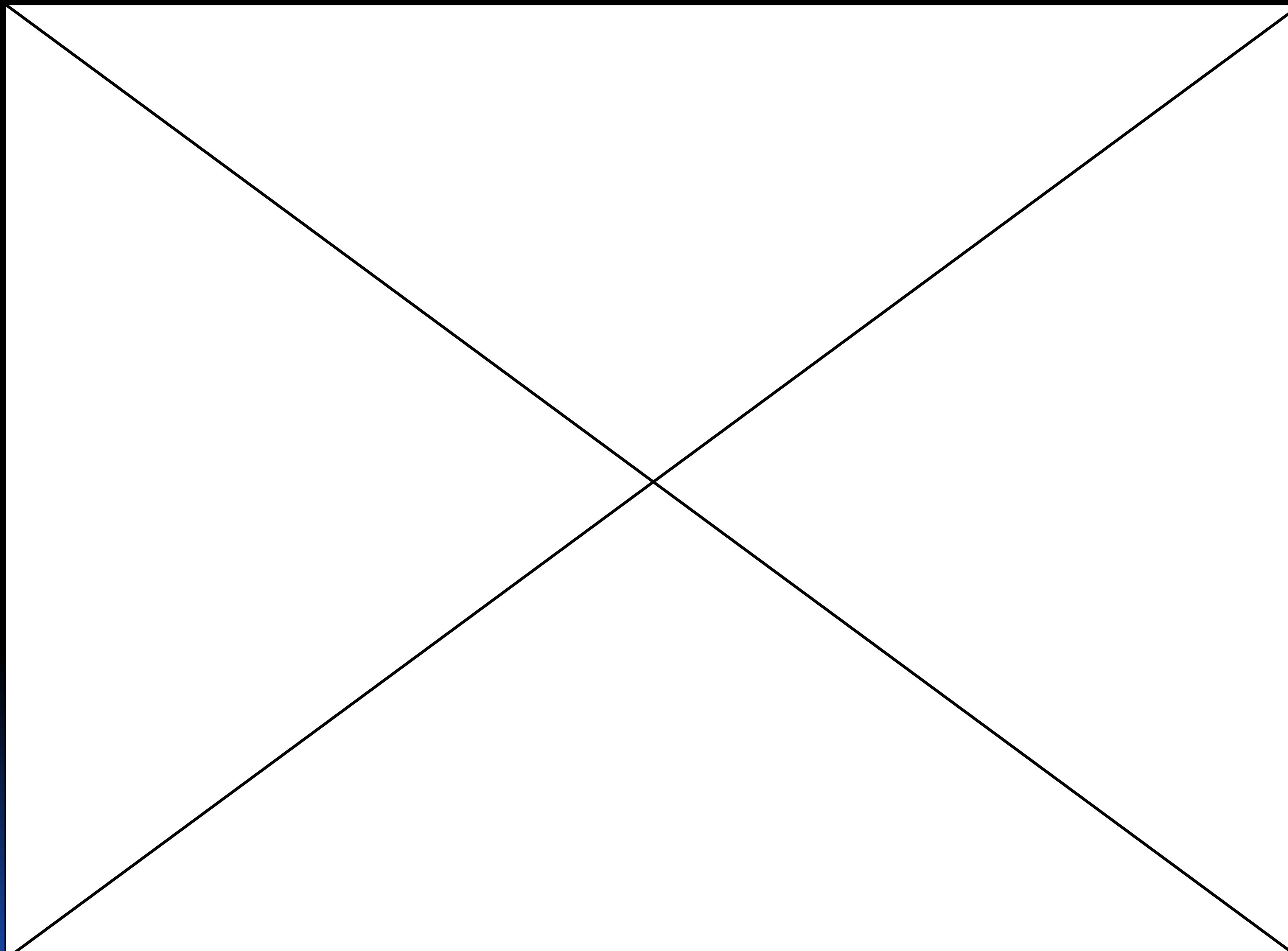
Acceptance Cone



(ii) **Acceptance cone**

Acceptance cone is a cone around core axis having angle 2 α_{max} = maximum acceptance angle. Therefore only those rays get totally internal reflected and able to travel through optical fibre, which enter the optical fibre through acceptance cone.





(iii) **Numerical aperture**

Numerical aperture is most important parameter of an optical fibre. It measure the amount of light collected by an optical fibre at core-cladding outside medium interface .

The numerical aperture (N.A) is defiend as the sine of acceptance angle.

$$\therefore \quad \text{Numerical aperture (N.A)} = \mu_0 \sin \alpha_{max} = \sqrt{\mu_1^2 - \mu_2^2}$$

Where μ_1 = refractive index of core, μ_2 = refractive index of cladding medium and μ_0 is the refractive index of outer medium.

In presence of air $\mu_o = 1$

$$\therefore \quad N.A = \sin \alpha_{max} = \sqrt{\mu_1^2 - \mu_2^2} \qquad \text{..... (3.3)}$$

also known as figure of merit of the optical fibre

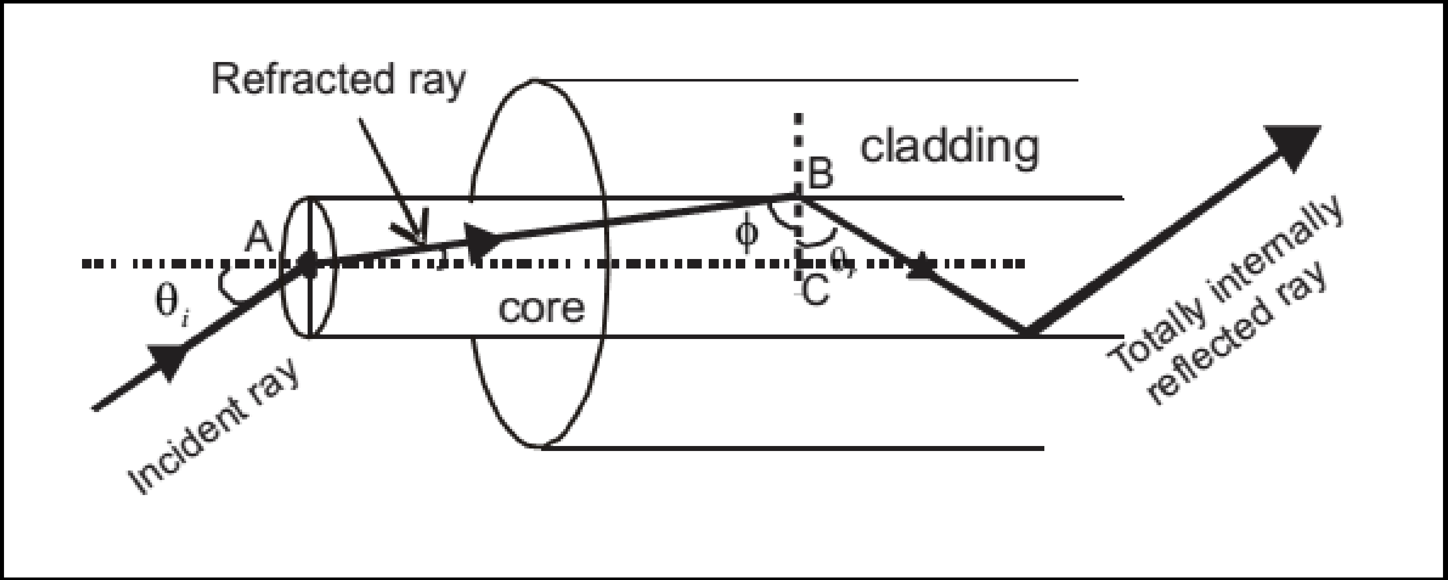
(iv) **Fractional Refraction index/Relative refractive index**

Fractional refrective index difference is defiend as the ratio of the difference between the refrective indices of core and the cladding to the refractive index of core .It is denoted by Δ ,

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

The value Δ is always positive. For effective transmission of optical signal $\Delta \approx 0.01$.

Relationships



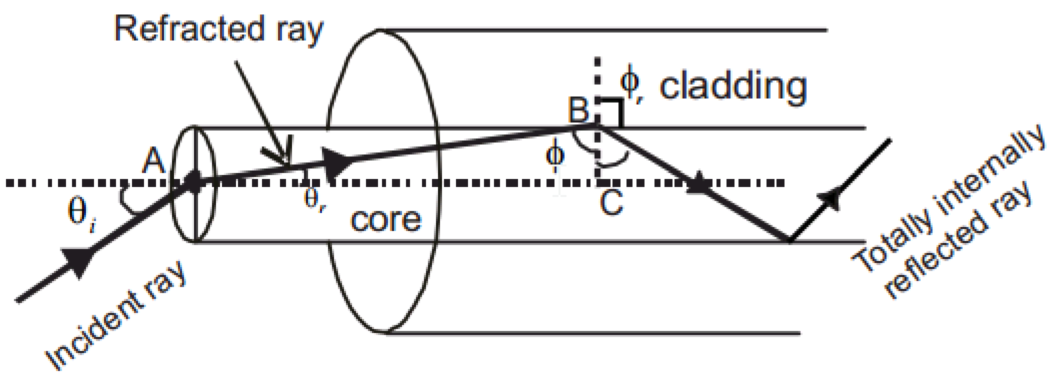
$$\alpha_{max} = \text{Acceptane angle} = \sin^{-1}(N.A)$$

For air, $n_o \sim 1$

$$\sin \alpha_{max} = \mu_1 \sqrt{2\Delta}$$

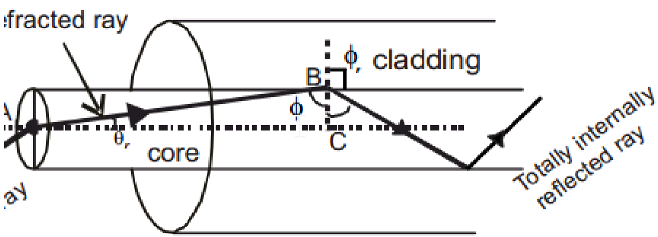
Relationship between acceptance angle and numerical aperture

Let us consider the light propagation in an optical fibre. Here, μ_1 is the refractive index of core, μ_2 is refractive index of cladding and μ_o is the refractive index of outer medium. Let a light ray enter the fibre at an angle θ_i and θ_r is the angle of refraction. The refracted ray strikes the core-cladding interface at an angle ϕ.



If $\phi > \theta_c$ (critical angle), the ray undergoes total internal reflection at core-cladding interface. As long as $\phi > \theta_c$, the light remains within the fibre by multiple total internal reflections.

Apply Snell's law for incident ray at point 'A'



$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{\mu_1}{\mu_0}$$

From Δ ABC

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

$$\sin\theta_i = \sin\theta_r \frac{\mu_1}{\mu_0}$$

When $\phi = \phi_c$, $\theta_i = \alpha_{max}$

$$\therefore \quad \sin\alpha_{max} = \frac{\mu_1}{\mu_0} \cos\phi_c$$

$$\cos\phi_c = \frac{\mu_0}{\mu_1} \sin\alpha_{max}$$

Apply Snell's law at point B

$$\mu_1 \sin\phi = \mu_2 \sin\phi_r$$

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

When $\phi = \phi_c$, $\phi_r = 90^\circ$

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

$$\sin^2\phi_c + \cos^2\phi_c = \frac{\mu_2^{\,2}}{\mu_1^{\,2}} + \frac{\mu_0^{\,2}}{\mu_1^{\,2}} \sin^2\alpha_{max}$$

$$\therefore \quad \frac{\mu_1^{\,2} - \mu_2^{\,2}}{\mu_1^{\,2}} = \frac{\mu_0^{\,2}}{\mu_1^{\,2}} \sin^2 \alpha_{max} \quad \therefore \quad \sin^2 \alpha_{max} = \frac{\mu_1^{\,2} - \mu_2^{\,2}}{\mu_0^{\,2}}$$

$$\sin \alpha_{max} = \frac{\sqrt{\mu_1^{\,2} - \mu_2^{\,2}}}{\mu_0} \text{ or } \alpha_{max} = \sin^{-1}\left[\frac{\sqrt{\mu_1^{\,2} - \mu_2^{\,2}}}{\mu_0}\right]$$

$$\alpha_{max} = \text{Acceptane angle} = \sin^{-1} (\text{N.A})$$

$$\text{N.A} = \sqrt{\mu_1^{\,2} - \mu_2^{\,2}}$$

V-number (normalized frequency) : measure of the number of supported modes

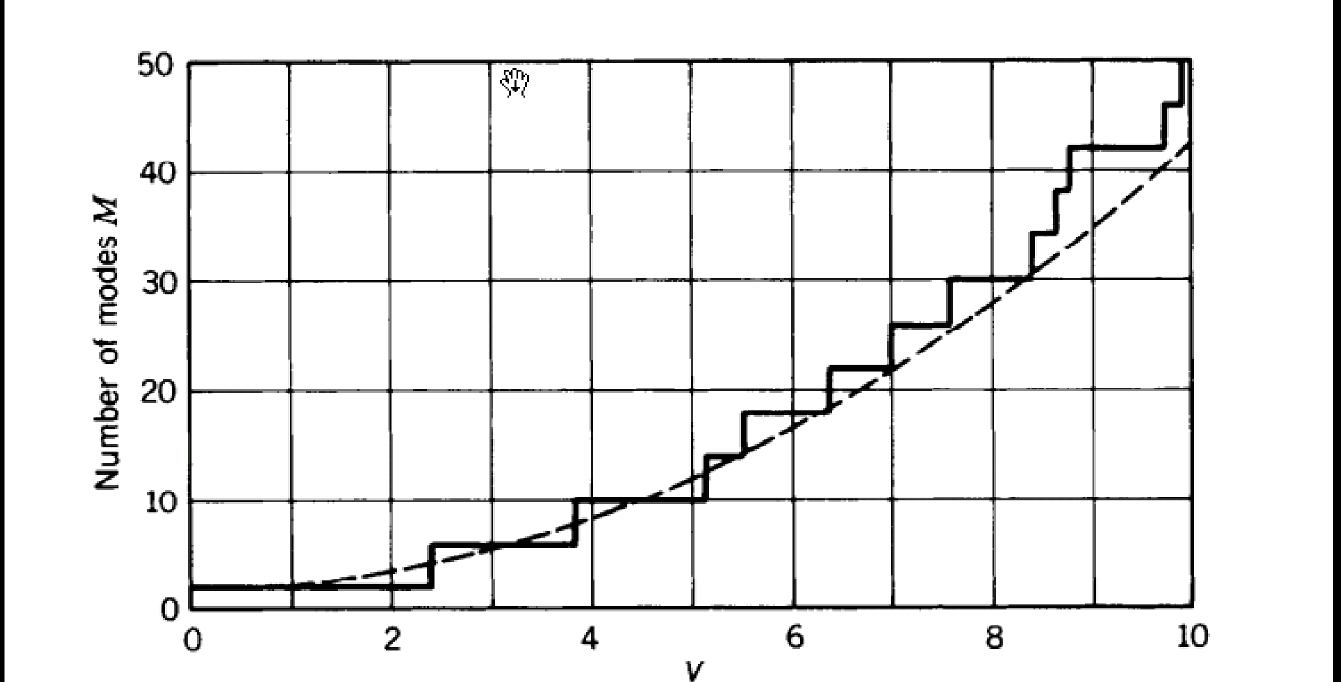
$$V = \frac{2\pi a}{\lambda}\sqrt{\mu_1^2 - \mu_2^2}$$

$$V = \frac{2\pi a}{\lambda}\,(N.A)$$

'a' is the radius of core

λ is the wavelength of optical signal

V-number & Number of Modes



When (i) V< 2.405, the optical fibre can support only one mode.

(ii) V > 2.405, the optical fibre can support more than one mode and known as multi mode optical fibre.

(iii) V = 2.405, the wavelength corresponding to V = 2.405 is known as cut off wavelength (λ_c).

$$\therefore \quad \lambda_c = \frac{2\pi a}{2.405} \sqrt{\mu_1^2 - \mu_2^2}$$

Cutoff Wavelength - this is the minimum wavelength at which the fiber will support only one mode. Wavelengths that are shorter than the cutoff wavelength, can actually allow higher-order modes to propagate.

Cut-off Wavelength

Definition: the wavelength below which multiple modes of light can be propagated along a particular fiber, i.e., $\lambda >= \lambda_c$, single mode, $\lambda < \lambda_c$, multi-mode

$$\boxed{\lambda_c = \frac{\pi d}{2.405} \times NA}$$

d: diameter of the core

Number of Modes (for large V-number)

For optical fibres with large V-number, the possible number of supported modes is approximately given by

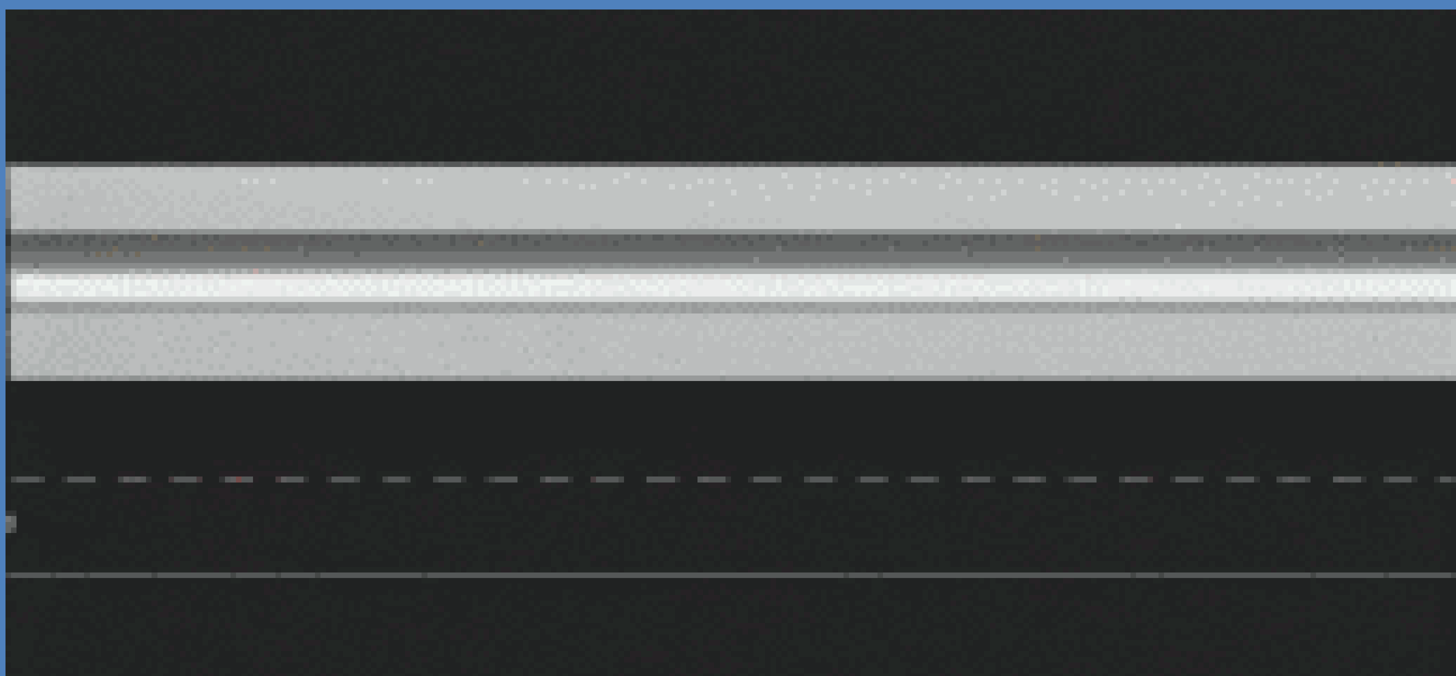
$$N \approx \frac{1}{2} V^2 \quad \Rightarrow$$

Only an Approximate formula
Valid for Large V-Numbers Only

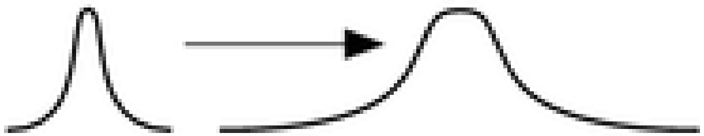
Note : This is a approximate formula and should not be used for fibre carrying only a few modes i.e. small V-number.

DISPERSION

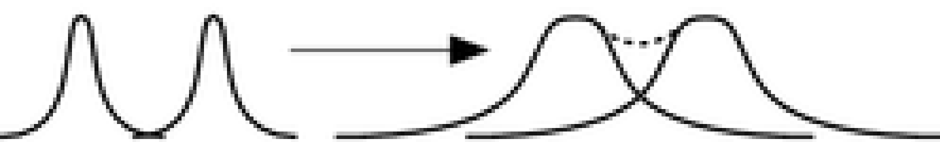
The light signals propagate through any optical fibre suffer with various dispersion effects. As a result the shape of the output signal change relative to the input signal. **This spreading of output pulse in the time domain known as dispersion or distortion in optical fibre.**

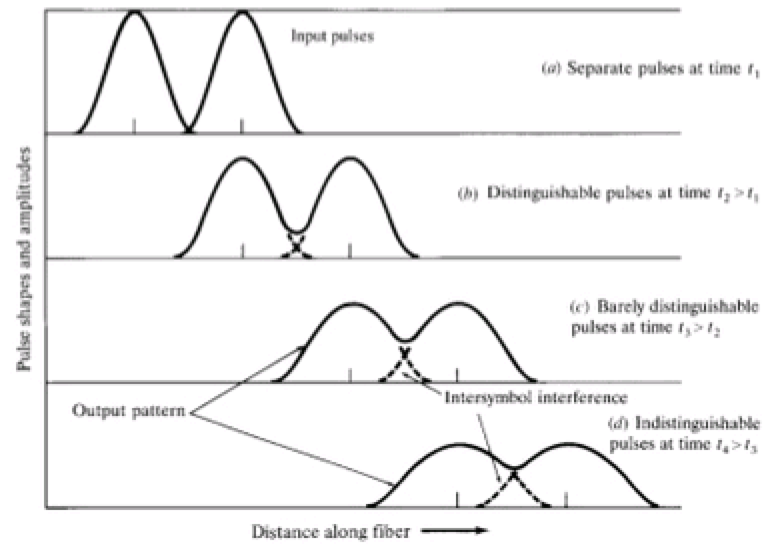


Dispersion



As a pulse travels down a fiber, dispersion causes pulse spreading. This limits the distance and the bit rate of data on an optical fiber.





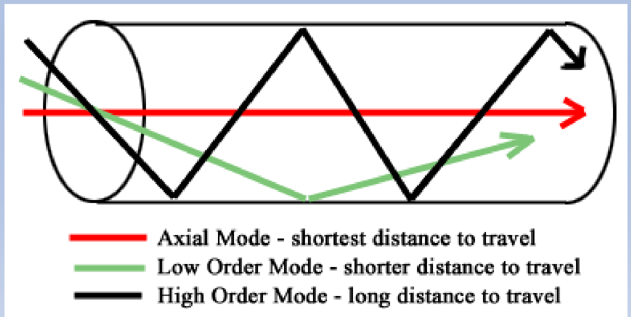
TYPES OF DISPERSION

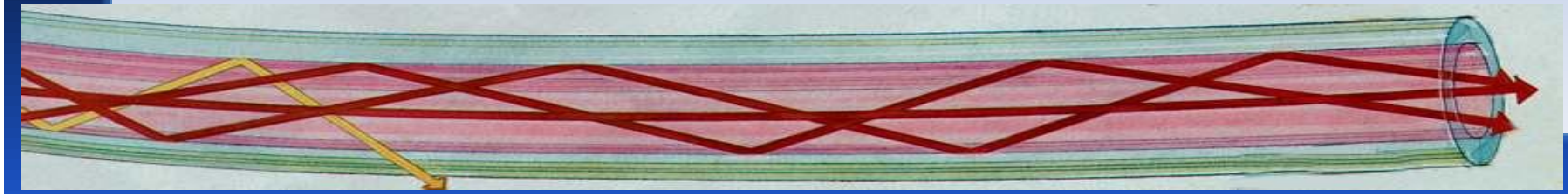
Intermodal Dispersion : Different rays take different times to propagate through a given length of the fibre.
<u>Or</u> Different modes travel with different speeds

Intramodal Dispersion Any given source emits over a range of wavelength and because of the intrinsic property of the material of the fibre, different wavelength takes different amount of time to propagate along the same path.

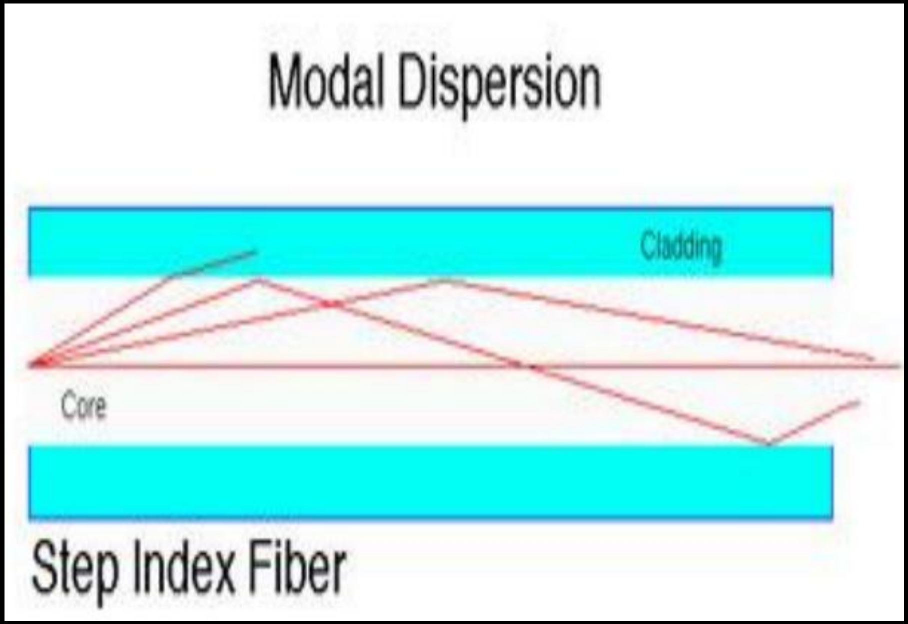
Intermodal Dispersion: Affects only Multimode

- Also known as Modal Dispersion
  - Spreading of a pulse because different modes (paths) through the fiber take different times
  - Only happens in multimode fiber
  - Reduced, but not eliminated, with graded-index fiber





Intermodal Dispersion

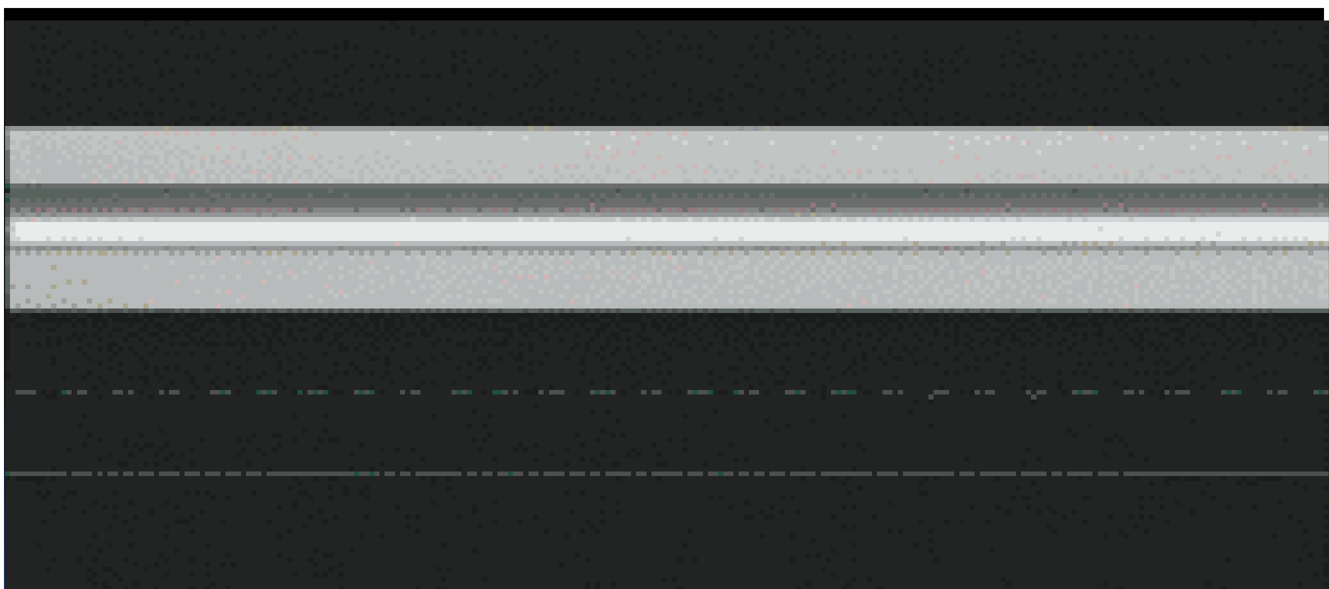


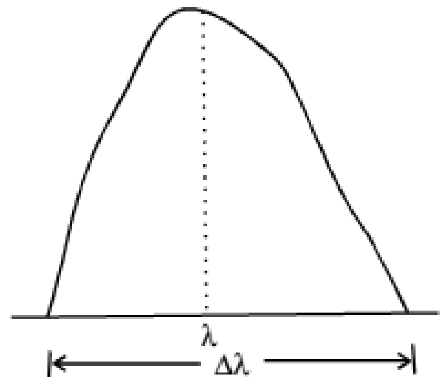
Different rays take different times to propagate through a given length of the fibre.
In the language of wave optics, this is known as intermodal dispersion because it arises due to the different modes travelling with different speeds.

The distortion in which the pulse spreading of the optical signal is due to result of multiple modes having different value of the group velocity at a single frequency is called intermodal distortion.

Intramodal dispersion/chromatic disp.

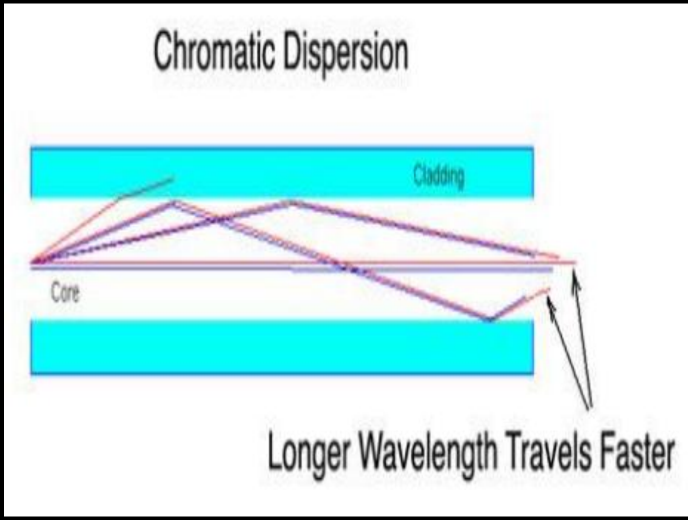
The dispersion or distortion in which pulse spreading occurs within a single mode is known as intramodal dispersion. It is also known as chromatic dispersion. The magnitude of intramodal distortion depends upon wavelength of the optical signal and it increases with increase in the spectral width of optical signal, where $\Delta\lambda$ - spectral width.





Chromatic Dispersion

- Different wavelengths travel at different speeds through the fiber
- This spreads a pulse in an effect named *chromatic dispersion*



✓Chromatic dispersion

- ✓occurs in both singlemode and multimode fiber
- ✓A far smaller effect than modal dispersion

Chromatic Dispersion

Material Dispersion

Arises from the variation of refractive index with wavelength

+

Waveguide Dispersion

Arises from the dependence of the fibre's waveguide properties on wavelength

=

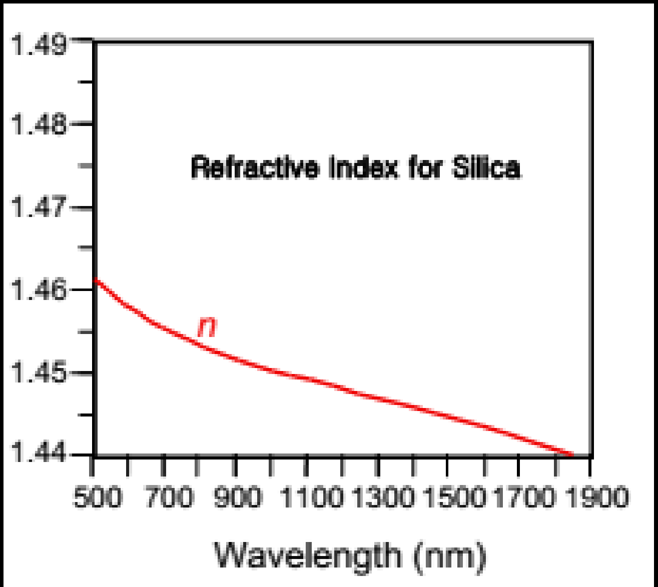
Chromatic Dispersion

Material Dispersion

This is caused by the fact that the refractive index varies (slightly) with the wavelength.

- Some wavelengths therefore have higher group velocities and so travel faster than others. Since every pulse consists of a range of wavelengths it will spread out to some degree during its travel.

- *All optical signals consist of a range of wavelengths*.



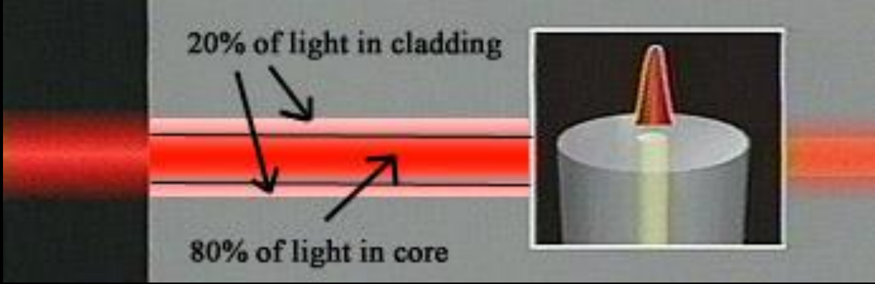
a) Material dispersion: Any guided mode of optical signal consists of well modulated pattern of the groups of waves. In case of material dispersion the core material of the optical fibre offers different refractive index at different angles to the different wavelengths of the optical signal. As a result different spectral components of an optical pulse have different transit time and therefore the spectral components of the pulse combine to produce broadened pulse with a lower peak amplitude at the fibre end. This type of dispersion or distortion is analogous to the dispersion phenomena exhibit by which light travels in prism.

Waveguide dispersion

(Affects mainly single mode)

In a single mode,

- 20% signal is travelling through the cladding and remaining 80% signal travels through the core by multiple total internal reflections.
- As the refractive index of the cladding is less as compare to the refractive index of core, therefore light signal propagation through the cladding is faster as compare to light signal propagation through core.
- Hence, the shape of output signal distorted due to overlapping of core and cladding signals. Such type of dispersion is known as waveguide dispersion.



✓The shape (profile) of the fibre has a very significant effect on the group velocity.

- This is because the electric and magnetic fields that constitute the pulse of light extend outside of the core into the cladding.

✓The amount that the fields overlap between core and cladding depends strongly on the wavelength. The longer the wavelength the further the the electromagnetic wave extends into the cladding.

Waveguide dispersion???

Caused by the wavelength dependence of distribution of energy for the fundamental mode in the fibre

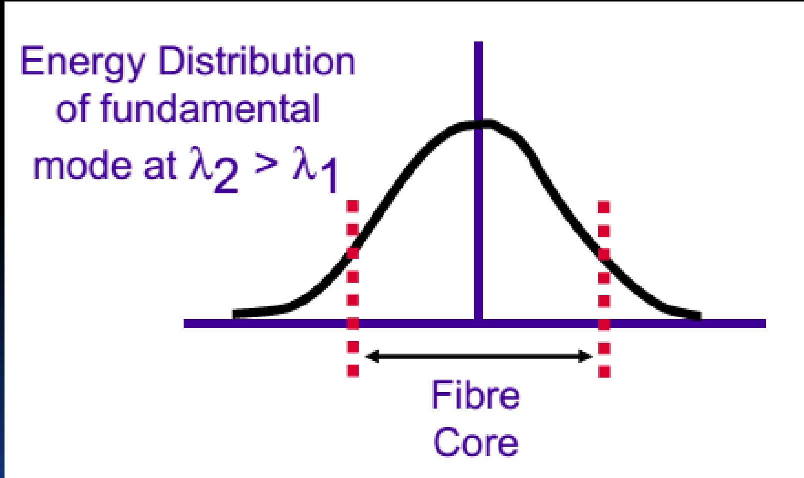
Mainly a problem for singlemode, in multimode mode penetration into the cladding is very small relatively.

As wavelength increases an increasing proportion of the mode energy propagates in the cladding.

But the cladding refractive index is lower thus faster propagation

Waveguide dispersion

Even if refractive index does not change, v_g depends on frequency (wavelength)



Attenuation

- When light travels along the fibre, there is a loss of optical power, which is called attenuation.

Absorption losses over a length L of fiber can be described by the usual exponential law for light intensity (or irradiance) I

$$I = I_0 e^{-\alpha L}$$

I_0 is the initial intensity or the irradiance of the light

α:Attenuation coefficient

$$\alpha = \frac{10}{L} \log_{10} \frac{I_o}{I} \quad \text{(in dB/km)}$$

OR

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

P_i → Input power

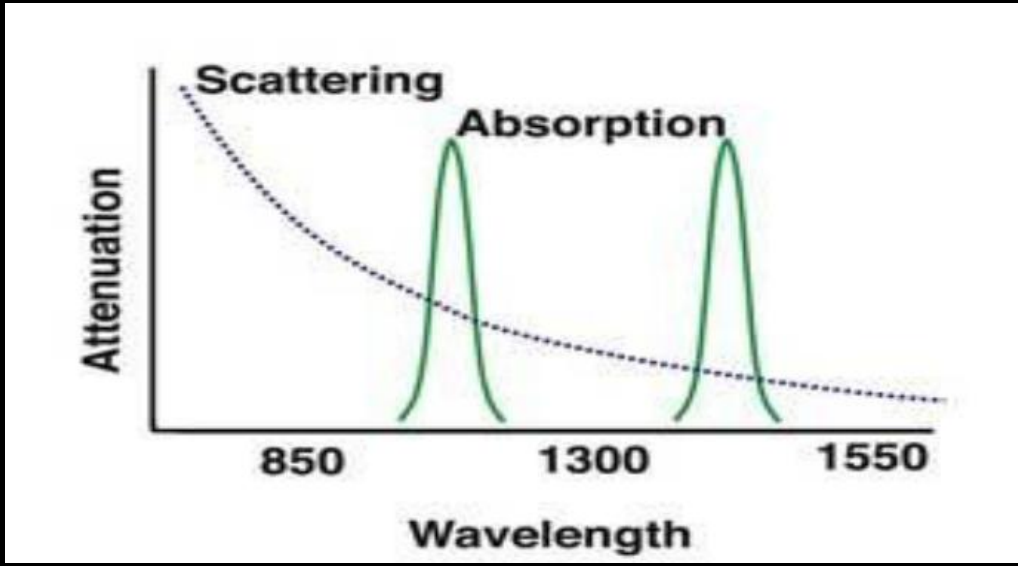
P_o → Output power

Length **L** of the fibre is expressed in **kilometers**

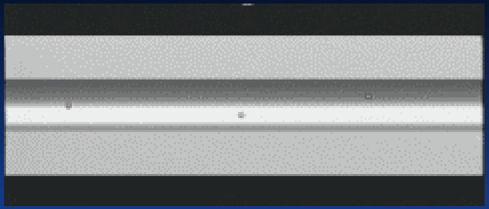
unit of Attenuation is decibels/kilometer i.e. **dB/km**

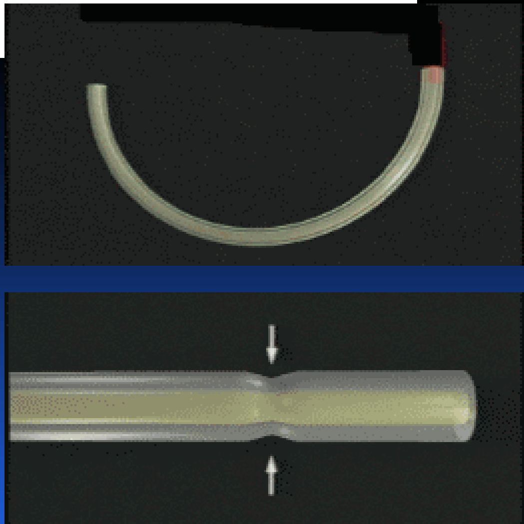
Cause/Reasons:

- Absorption
- Scattering
- Bending losses



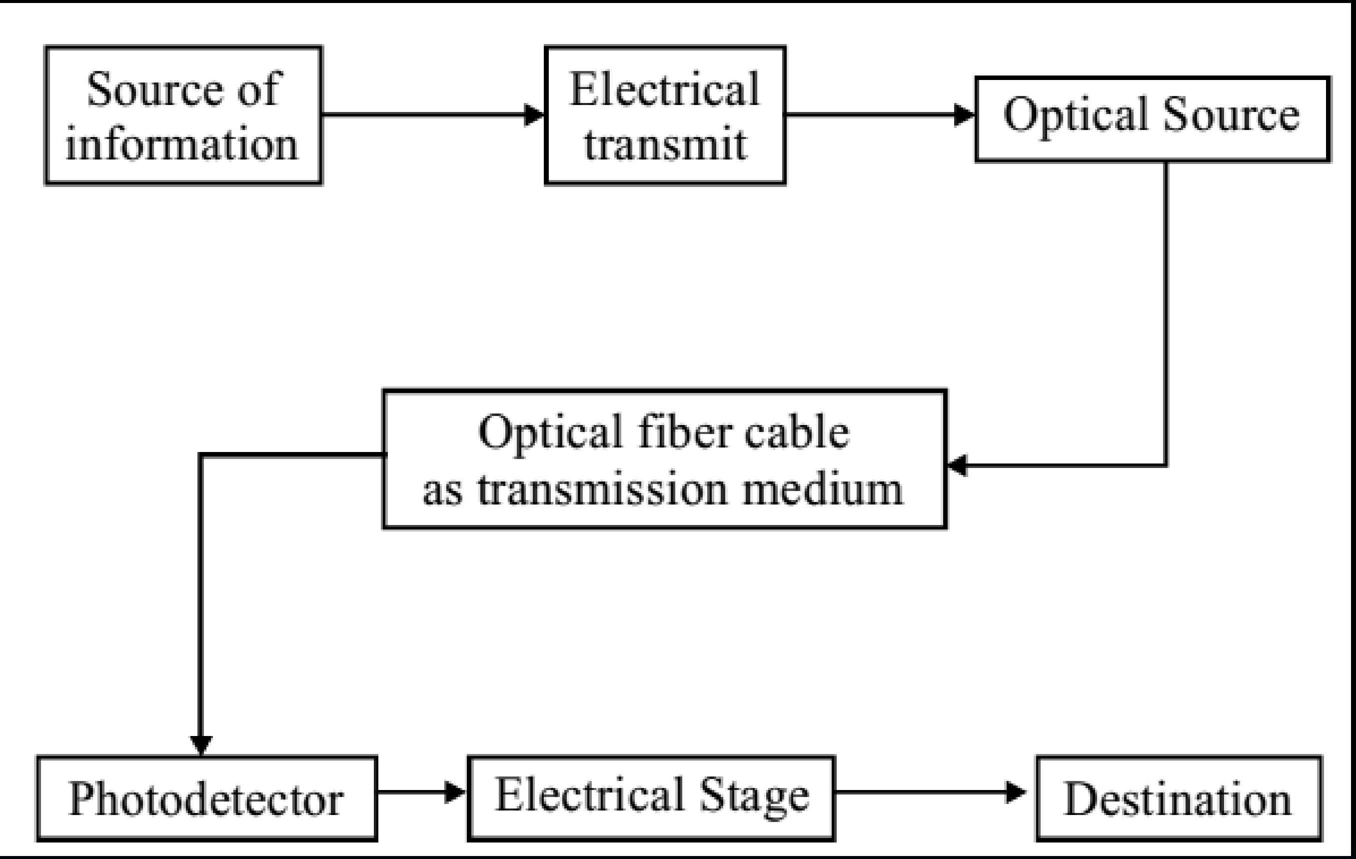
Each mechanism of loss is influenced by the properties of fibre Material and fibre structure.



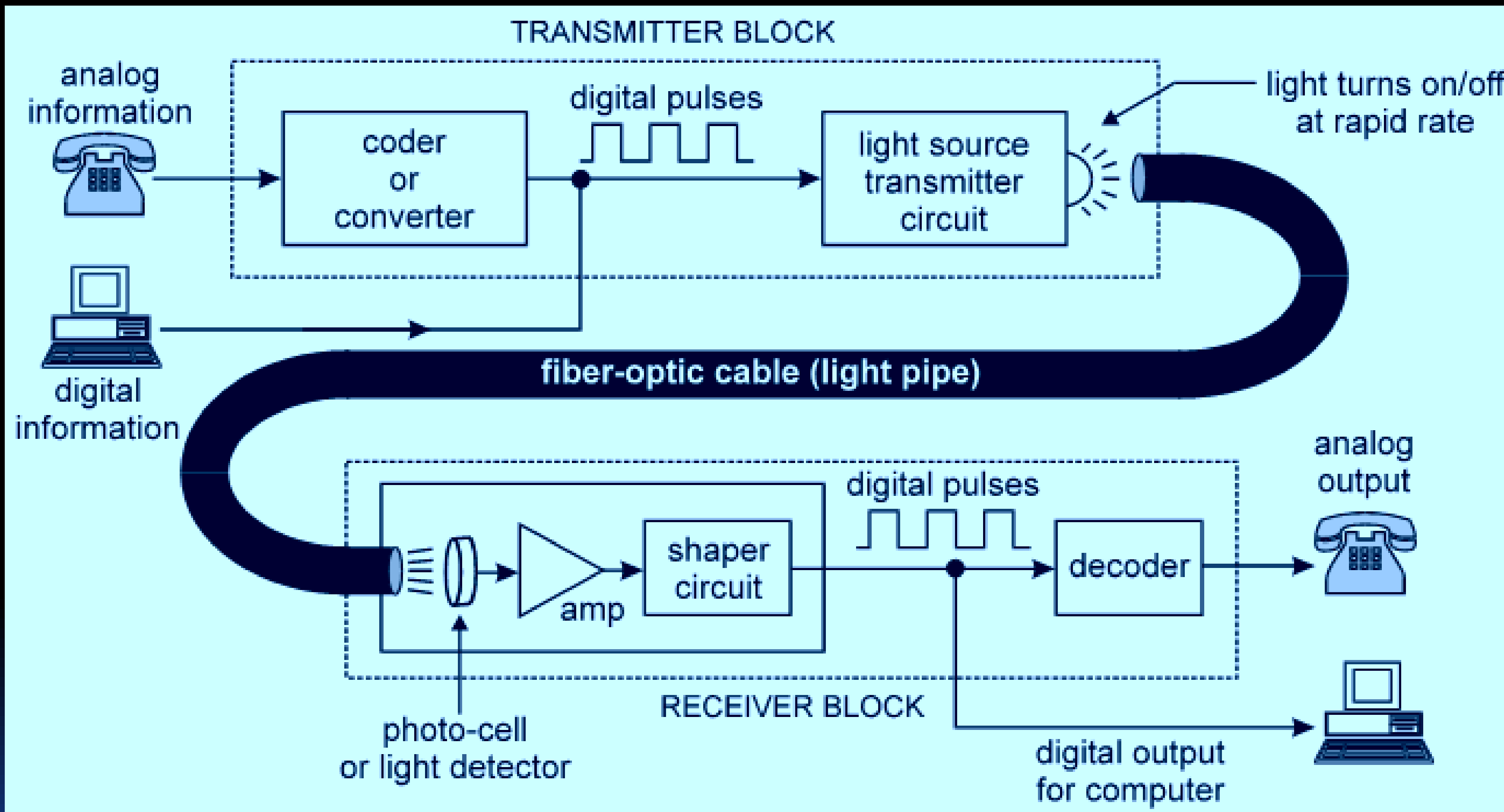


Dispersion Vs Attenuation

Optical fibre communication system



Optical fibre communication system



An optical fibre communication system consists of transmitter unit, optical fibre and receiver unit as shown in figure (3.14). In transmitter unit, the information that is to be transmitted is first converted into an optical signal from an electric signal. Transmitter unit consists of modulator and optical source, which may be either light emitting diode (LED) or laser diode (LD). The optical fibre essentially serves the purpose of transmitting the light signal by multiple total internal reflections. The receiver unit consists of optical detector and demodulator. The optical detector may be a semiconductor device or most commonly a PIN diode, which convert the optical signal back into an electric signal. The response of a detector should be well matched with the optical frequency of signal received. The signal output is finally communicated by load speaker (if it is audio signal) or by CRO (if it is video signal).

Assignment:

1. What are Optical Fibres? Summarize the principle behind the transmission of light signal through an optical Fibre.
2. Write the advantages of using optical fibre communication system.
3. Explain the structure/construction of an optical fibre with the help of an appropriate diagram.
4. The refractive index of core should be slightly greater than that of cladding. Justify the statement by citing appropriate reasons.
5. Compare single mode and multimode optical fibres.
6. Justify the name “step index optical fibre” .
7. Difference between step index and graded index multimode OF
8. Derive the expression for (i) Critical Angle (ii) Acceptance Angle (iii)Numerical Aperture.
9. Define and/or write expressions for : (i) Critical Angle (ii) Acceptance Angle (iii)Numerical Aperture (iv) Fractional Refractive Index Difference (v) V-number (vi) Number of Modes
10. Express acceptance angle and numerical aperture in terms of fractional refractive index difference.

Scalar and Vector Field

A field is defined as the region in which at every point some physical quantity (temperature, electric field etc.) has a defined value.

Afield may also be defined as a quantity which can be specified everywherein space as a function of position.

Henceforth, field implies both the regionand function defined in that region.

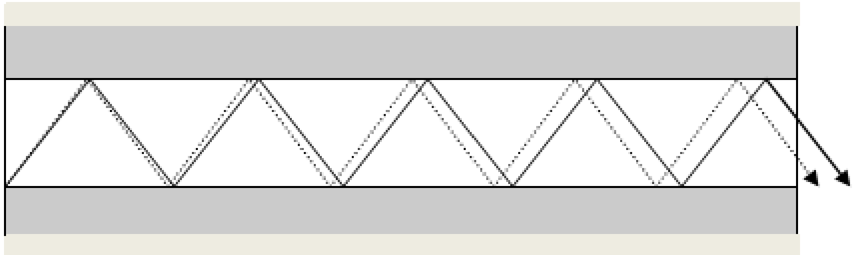
The quantity that is specified may be a scalar or a vector.

Region in space, every point of which is characterized by a scalar quantity is known as scalar field.

- An example of a scalar field in electromagnetism is the electric potential. Other examples include temperature field, pressure field , gravitational potential etc.

Region in space, each point of which is characterized by a vector quantity is known as vector field.

- Examples of vector field are electric field, gravitation field, magnetic field etc.



Dispersion occurs when photons from the same light pulse take slight different paths along the optical fiber. Because some paths will be longer or shorter than other paths the photons will arrive at different times thus smearing the shape of the pulse.

Over long distances, one pulse may merge with another pulse. When this happens, the receiving device will not be able to distinguish between pulses.

Refractive indices of core and cladding of an optical fibre are 1.42 and 1.40, respectively. Calculate the critical angle, acceptance angle and numerical aperture of the fibre.

The value of numerical aperture and fractional refractive index difference of an optical fibre are 0.22 and 0.012 respectively. Calculate the refractive indices of core and cladding of the material used in the fabrication of fibre.

A multimode step index fibre with a core diameter of 80 μm and relative index difference of 1.5% is operating at an wavelength of 0.85 μm. If the core refractive index is 1.48, estimate (a) the normalized frequency for the fibre (b) the number of guided modes.

When the mean optical power launched into an 8 km length of fibre is 120 μW, the optical power at the fibre output is 3 μW. Determine

(a) the overall signal attenuation or loss in decibels through the fibre assuming there are no connectors or splicers,

(b) the signal attenuation per km of the fibre,

(c) the overall signal attenuation for a 10 km optical link using the same fibre with splices at 1 km interval each giving attenuation of 1 dB and

(d) numerical input/output ratio in (c).