Module:6 Propagation of EM waves in Optical fibers

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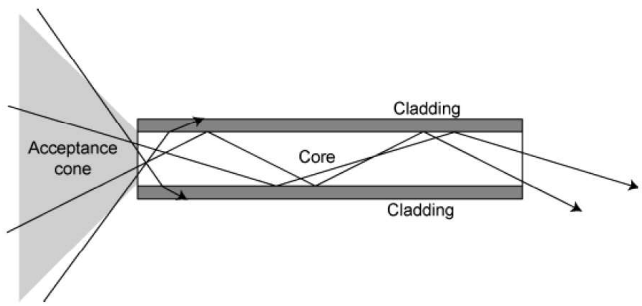
Acceptance cone



- The maximum angle, represented in three-dimensional view as a cone, at which an optical fiber will accept incident light. Within that cone, as defined by those angles, a light source can inject an optical signal into the fiber core and the signal will remain in the core, reflecting off of the interface between the core and cladding.

- Incident rays which fall within the acceptance cone of the fiber are transmitted, whereas those which fall outside of the acceptance cone are lost in the cladding.

Acceptance cone

- The imaginary light cone with twice the acceptance angle as the vertex angle, is known as the acceptance cone.

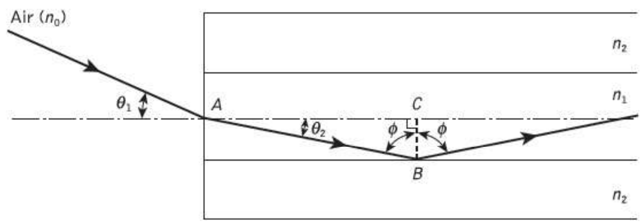
- The maximum angle, represented in three-dimensional view as a **cone**, at which an **optical fiber** will accept incident light. ... At a more severe angle, i.e., outside the **cone**, the signal will penetrate the interface and enter, and perhaps be lost in, the cladding.

- a light **ray** must **enter** the core with an **angle less than** a particular **angle** called the **acceptance angle of** the **fibre**. **A ray which enters the fiber with an angle** greater **than the acceptance angle** will be lost in the cladding.

Numerical Aperture (NA) :

Numerical aperture (NA) of the fiber is the light collecting efficiency of the fiber and is a measure of the amount of light rays can be accepted by the fiber.

Relation between acceptance angle and refractive index is achieved through **Numerical Aperture**



Derivation for Numerical aperture:

Apply Snell's law at point A

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0} \text{ ----------------------------> } \textbf{(1)}$$

Apply Snell's law at point B

$$\frac{\sin\theta_c}{\sin 90} = \frac{n_2}{n_1}$$

$$\sin\theta_c = \frac{n_2}{n_1} \text{ ----------------------------> } \textbf{(2)}$$

From equation 1

In the triangle ABC, $\theta_r = \frac{\pi}{2} - \phi$

$$\sin\theta_1 = n_1 \sin\left(\frac{\pi}{2} - \theta\right) = n_1 \cos\theta$$

$$\sin\theta_i = \frac{n_1}{n_0}\cos\theta_c$$

$$\sin\theta_i = \frac{n_1}{n_0}\sqrt{1 - \sin^2\theta_c}$$

From equation 2

$$\sin\theta_i = \frac{1}{n_0}\sqrt{n_1^2 - n_2^2}$$

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

Since the refractive index of air is 1, then $n_o = 1$

Where $\sqrt{n_1^2 - n_2^2}$ is called numerical aperture (N.A) of the fiber

$$\boxed{N.A = \sin\theta_i = \sqrt{n_1^2 - n_2^2}}$$

Fractional refractive index or relative refractive index

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

$$\boxed{N.A = n_1\sqrt{2\Delta}}$$

Acceptance angle

$$\theta_i = \sin^{-1}(N.A)$$

$$\boxed{\theta_i = \sin^{-1}\sqrt{n_1^2 - n_2^2}}$$

Numerical Problems

Activity 1: The refractive indices for core and cladding for a step index fibre are 1.52 and 1.41 respectively. Calculate (1) Critical angle (2) Numerical Aperture (3) The maximum incidence angle

Hints: Given Here $= \mu_1 = \mu_{core} = 1.52$, and $\mu_2 = \mu_{clad} = 1.41$

Critical angle $\theta_c = \sin^{-1}(\mu_2 / \mu_1)$ **Ans = 68.06⁰**

Numerical Aperture $\sqrt{\mu_1^2 - \mu_2^2}$ **Ans = 0.568**

Maximum incidence angle $(\theta_0) = \sin^{-1}\left(\sqrt{\mu_1^2 - \mu_2^2}\right)$

Ans $\theta_0 = 34.6^0$

Solved Problem (1) : A fiber has the following characteristics: $n_1 = 1.35$ (core index) and $\Delta = 2\%$. Find the N.A and the acceptance angle.

n1 = 1.35 ; $\Delta = 2\% = 0.02$

W.K.T

$= 1.35 \times (2 \times 0.02)^{1/2} = 0.27$

$\theta_a = \sin^{-1}(N.A) = \sin^{-1}(0.27) = 15.66^\circ$

Solved Problem (2): A silica optical fiber has a core refractive index of 1.50 and a cladding refractive index of 1.47. Determine (i) the critical angle at the core – cladding interface, (ii) the N.A for the fiber and (iii) the acceptance angle for the fiber.

The critical angle $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.47}{1.5}\right) = 78.5^\circ$

The numerical aperture $NA = (n_1^2 - n_2^2)^{\frac{1}{2}}$

$(1.50^2 - 1.47^2)^{1/2} = 0.30$

The acceptance angle $= 2\theta_a = 2\sin^{-1}(N.A) = 2\sin^{-1}(0.30) = 34.9^\circ$

Critical angle = 78.5º ; N.A = 0.30 ; Acceptance angle = 34.9º

Activity 1: Calculate the numerical aperture for the optical fiber whose core refractive index is 1.52 and cladding has 1.43;

Activity 2: Calculate the acceptance angle for the fiber of NA = 0.39

Types of Optical fiber

Dependents of the refractive index, the optical fiber classified as two types

- **Step index fiber**
- **Graded index fiber**

Step index fiber

A step-index **fiber has a central core with a *uniform* refractive index. The core is surrounded by an outside cladding with a uniform refractive index less than that of the central core.**

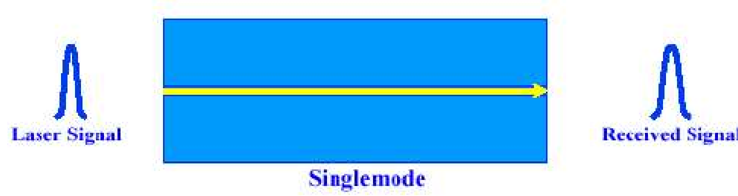
Single-Mode Step-Index Fiber

It has a central core that is sufficiently small so that there is essentially only one path that light may take as it propagates down the cable.

The refractive index of the cladding is slightly less than that of the central core and is uniform throughout the cladding.

Consequently, all light rays follow approximately the same path down the cable and take approximately the same amount of time to travel the length of the cable.

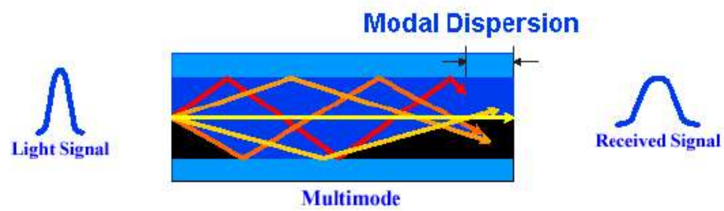
Used for very high speed, large bandwidth and long-distance transmission.



Multi-mode Step-Index Fiber

- The light rays that strike the core/cladding interface at an angle greater than the critical angle are propagated down the core in a zigzag fashion, continuously reflecting off the interface boundary.
- There are many paths that a light ray may follow as it propagates down the fiber. As a result, all light rays do not follow the same path and hence do not take the same amount of time to travel the length of the fiber.

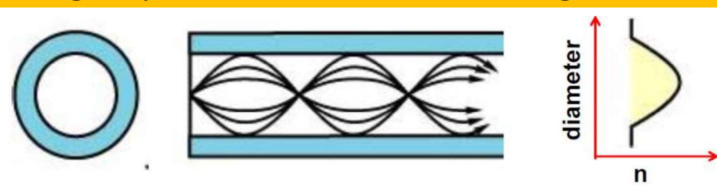
Best designed for short transmission distances and is suited for use in LAN systems and video surveillance



Graded-Index Fibers

The refractive index of core gradually changes, while the refractive index of cladding remains constant

In graded index fibers, the core center has high refractive index and it is radially decreases on moving away from the center to core-cladding interface



Graded-index fibers are in general multimode fibers

Large core diameter (> 50 µm) Example: 62.5/125

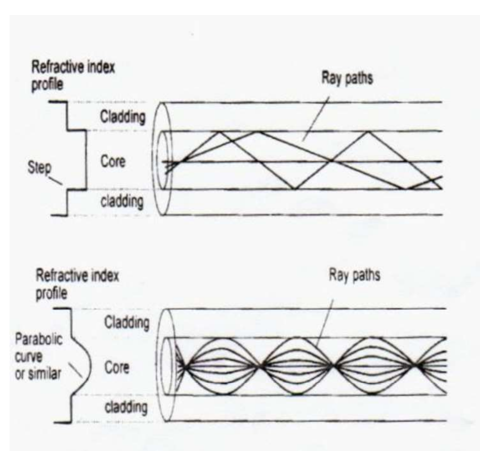
Two main types of cables

Step Index Fibre

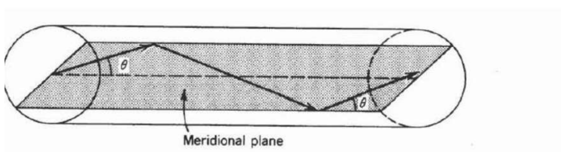
This cable has a specific index of refraction for the core and the cladding. It causes deformations due to the various paths lengths of the light ray. This is called modal distortion. It is the cheapest type of cabling. Within the cladding and the core, the refractive index is constant.

Graded Index Fibre

In graded index fibre, rays of light follow sinusoidal paths. Although the paths are different lengths, they all reach the end of the fibre at the same time. Multimode dispersion is eliminated and pulse spreading is reduced. Graded Index fibre can hold the same amount of energy as multimode fibre. The disadvantage is that this takes place at only one wavelength.

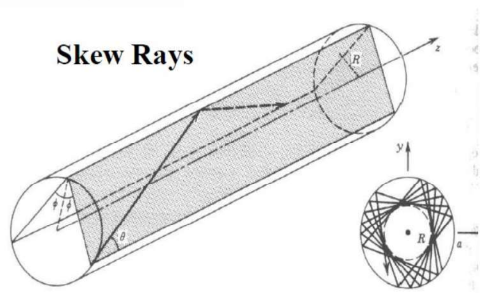


Step Index	Graded Index
Refractive index is single step	Refractive index is gradually decreasing from center to wards interface of core and cladding
Propagation is in the form of meridional rays and it passes through the fiber axis	Propagation is in the form of Skew rays and it will not cross the fiber axis
Path of propagation is in zig-zag	Path of propagation is in Helical
Lower bandwidth	Higher bandwidth
Distortion is more (high angle ray arrive later than low angle ray, hence signal pulse is broadened)	Distortion is less due to self focusing effect (different paths in different speeds, at outer it has faster than inner, hence reach at same time)
No. of modes propagation $N_{step} = 4.9(d*NA/\lambda)^2$	No. of modes propagation $N_{graded} = N_{step}/2$



Meridional Rays

Skew Rays



A **meridional ray** is a **ray** that passes through the axis of an optical fiber. A skew **ray** is a **ray** that travels in a non-planar zig-zag path and never crosses the axis of an optical fiber.

V-number (fiber parameter)

The number of propagation modes in step-index optical fiber can be determined from v-number or a normalized frequency (horizontal wave number)

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

Where a is core radius and n_1 is core refractive index

If V <2.405, single mode optical fiber only one mode can propagates through the fiber

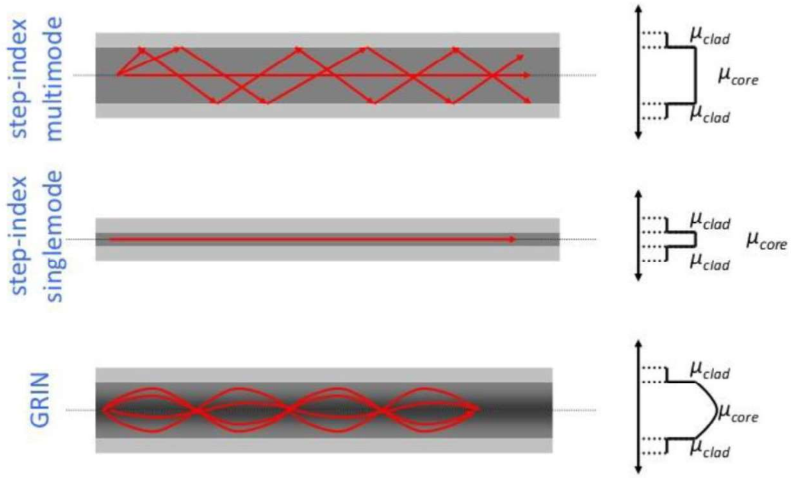
If V >> 2.405, it is multimode optical fiber

Number of modes can be

$M = V^2/2$ (Step index fiber)

$M = V^2/4$ (Graded index fiber)

Types of Fibers



Parameters of Optical fibres

Acceptance angle =

$$\sin\theta_0 = \sqrt{\mu_1^2 - \mu_2^2}$$

$$\theta_0 = \sin^{-1}\left(\sqrt{\mu_1^2 - \mu_2^2}\right)$$

Acceptance Cone = $2\theta_0$

Numerical Aperture (NA) = $\sin\theta_0$ = $\sqrt{\mu_1^2 - \mu_2^2}$