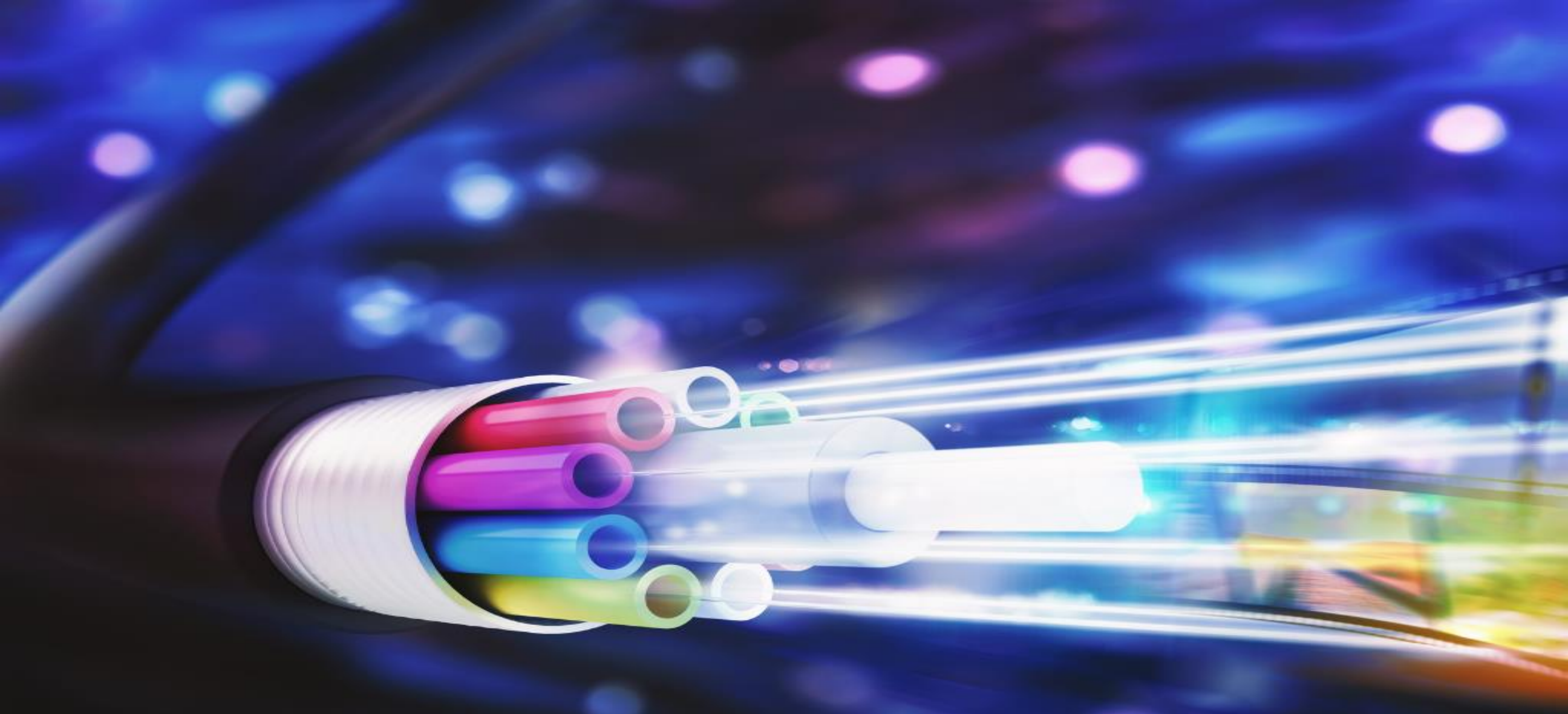


Module – 1
Optical Fiber: Structures, Waveguides

Light propagation in fiber

- Ray model
- Wave model
- Quantum model

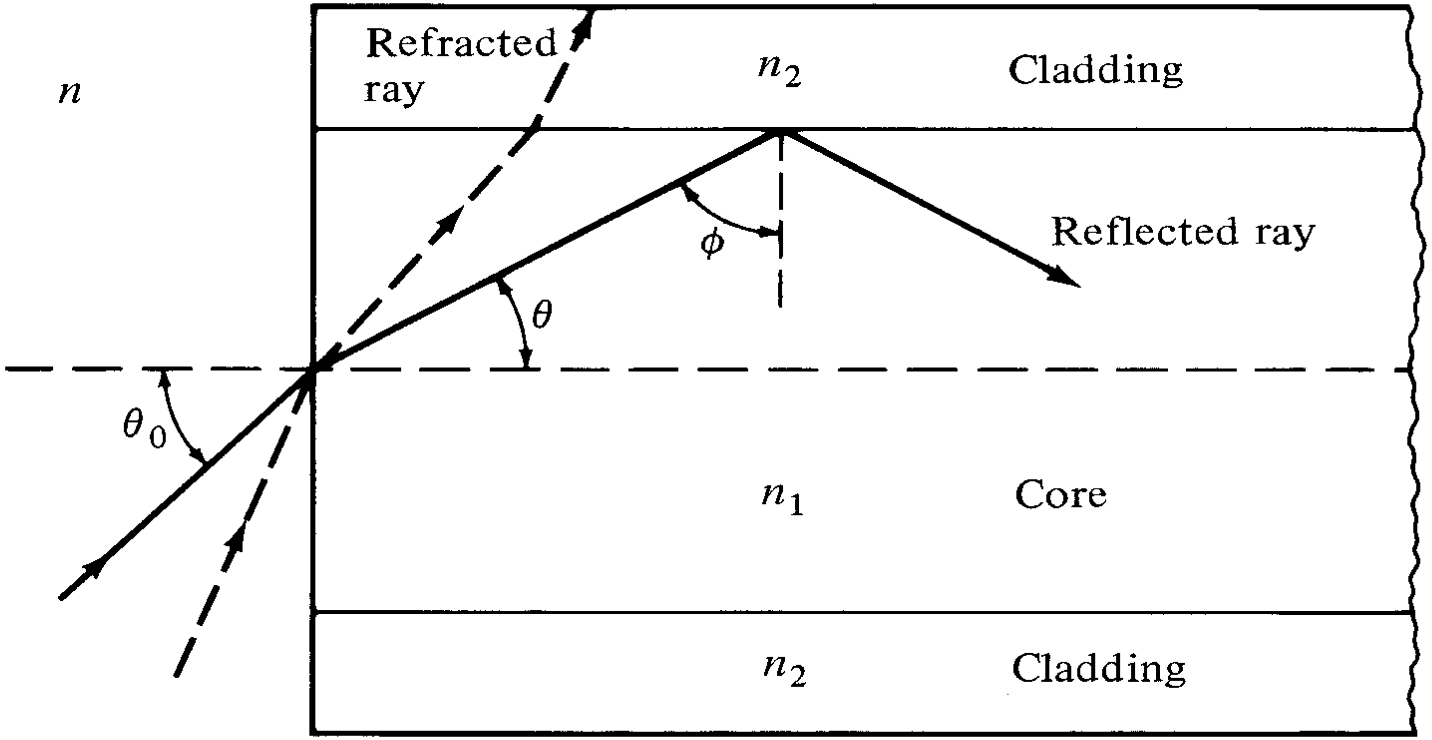
Ray Theory approach

- A light ray is a line or curve that is perpendicular to the light's wavefronts
- Study of propagation characteristics of light in optical fiber can be made based on geometrical optics or ray theory
- Ray theory is valid when **$a / \lambda >> 1$**
- Wavelength of light λ $<<$ a dimension of fiber

$0.7\ \mu m < \lambda < 1.55\ \mu m$ **$6\ \mu m < a < 100\ \mu m$**

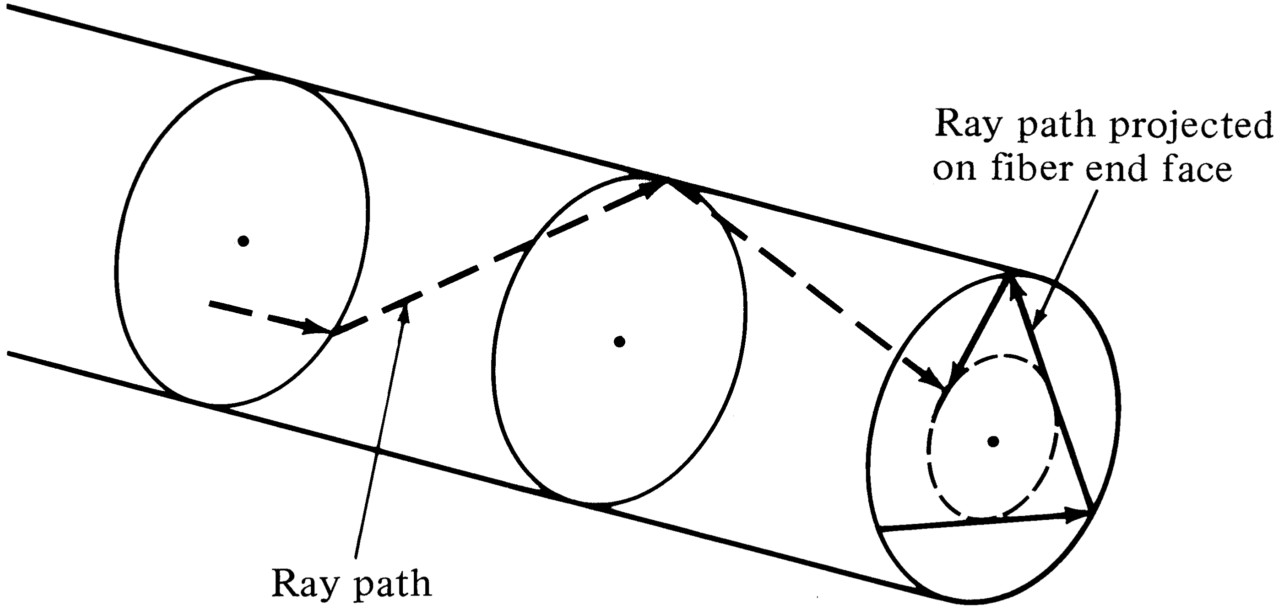
Meridional rays

- A meridional ray is a ray that passes through the axis of an optical fiber



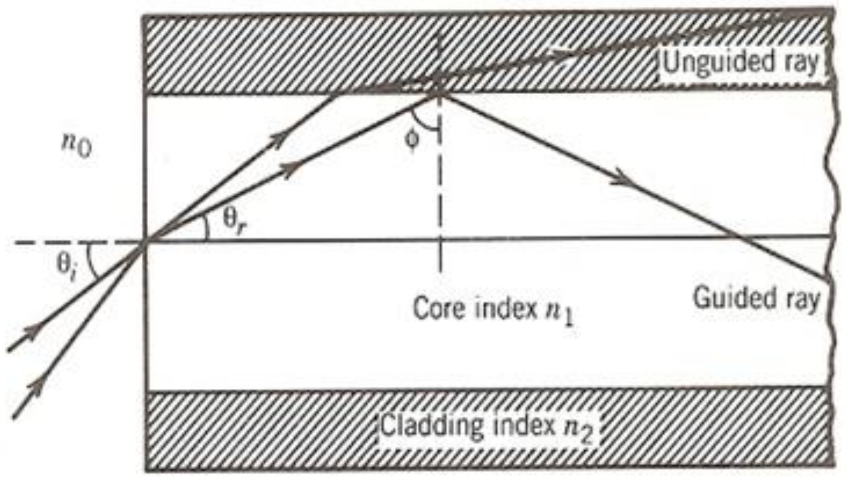
Skew rays

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



Numerical Aperture – Light gathering capacity (Meridional Rays)

- NA is a measure of the light gathering ability of a fiber and it also indicates how easy it is to couple light into a fiber



$n_0 \text{ Sin } \theta_i = n_1 \text{ Sin } \theta_r$; n_0 = refractive index of air

n_1 = refractive index of fiber core

$n_1 \text{ Sin } \phi = n_2 \text{ Sin } \phi_2$

As $\phi \rightarrow \phi_c$, $\phi_2 \rightarrow 90$

$n_1 \text{ Sin } \phi_c = n_2 \text{ Sin } 90°$

So, $\text{Sin } \phi_c = n_2 / n_1$

$\theta_r = \pi / 2 - \phi_c$

NA = Numerical Aperture

= Light gathering capacity

$= n_0 \text{ Sin } \theta_{o\,max} = n_1 \text{ Sin } (\pi / 2 - \phi_c)$

$= n_1 \text{ Cos } \phi_c$

$= n_1 (1 – \text{Sin}^2 \phi_c)^{1/2} = n_1 [1 – (n_2 / n_1)^2]^{1/2} = \text{NA}$

Fractional Refractive Index Δ

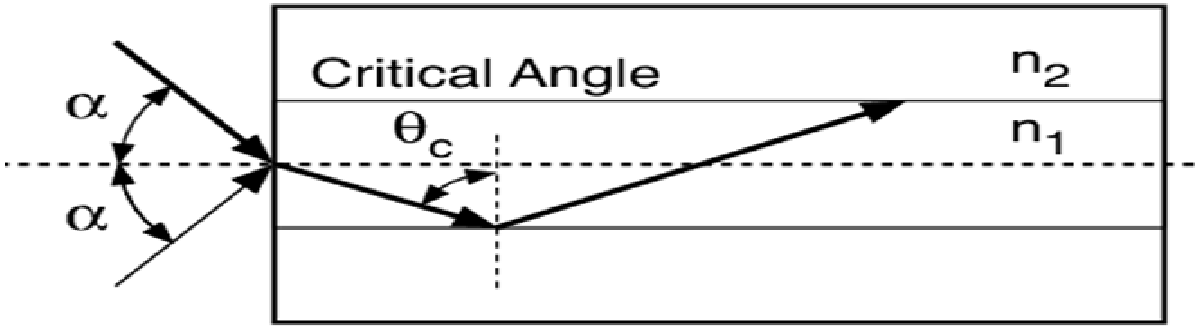
Numerical Aperture = NA $= n_1 [1 - (n_2 / n_1)^2]^{1/2}$

$= [n_1^2 - n_2^2]^{1/2}$

When $n_1 \approx n_2$, then NA $= n_1 \sqrt{(2\Delta)}$

where, $\Delta = (n_1 - n_2) / n_1$

- The light collecting capability of the fiber is directly proportional to the choice of n_1 and n_2

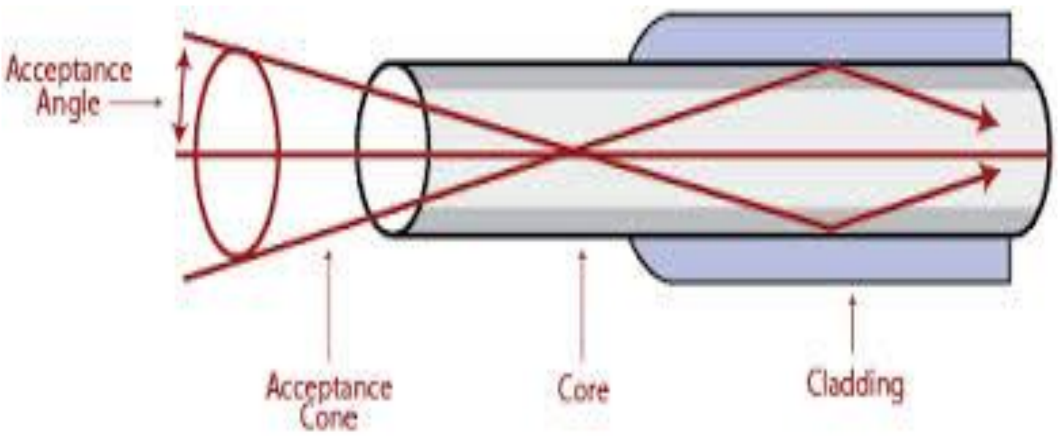


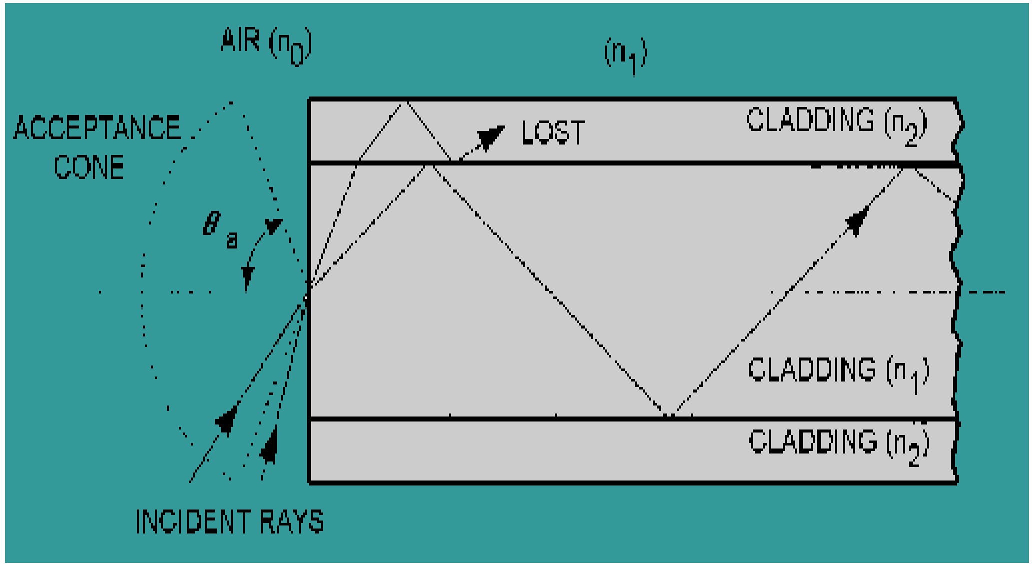
$$NA = \sin\alpha = \sqrt{n_1^2 - n_2^2}$$

Full Acceptance Angle $= 2\alpha$

Acceptance Angle

- 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.



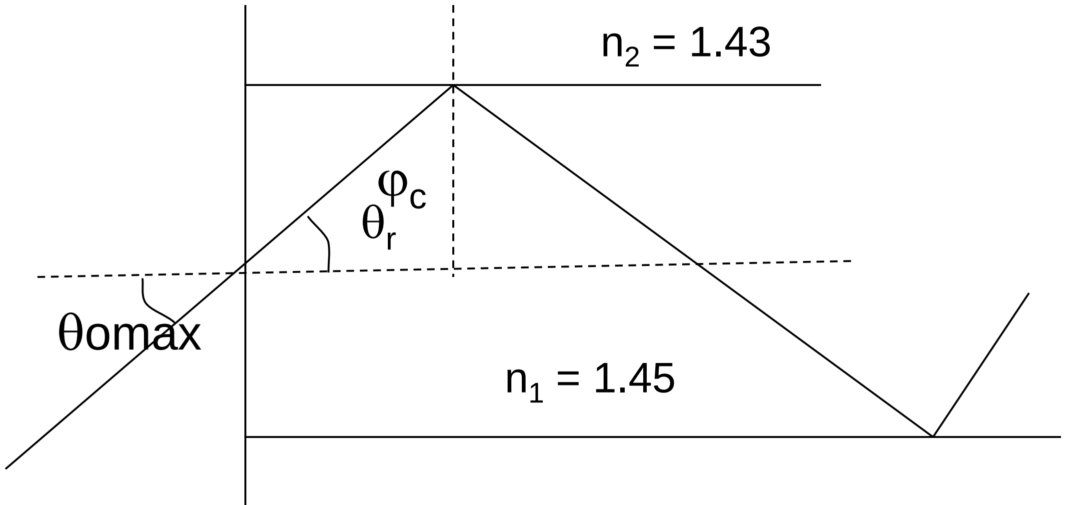


Light Guidance $\theta < \theta_{o\,max}$, $\varphi > \varphi_c$

$\sin \varphi_c = n_2 / n_1$

$\theta_1 = 90^0 - \varphi_c$

$n_0 \sin \theta_{omax} = n_1 \sin \theta_1$



$n_1 = 1.45$

n_2 =	1.44	1.43	1.42	1.41	1.40	1.33	1.05
ϕ_C =	83.26^0	80.47^0	78.32^0	76.5^0	74.90^0	66.5^0	46.4^0
θ_a =	9.8^0	13.89^0	17.07^0	19.78^0	22.19^0	35.3^0	89.2^0

Lesser the value of n_2 from n_1 , More the acceptance angle

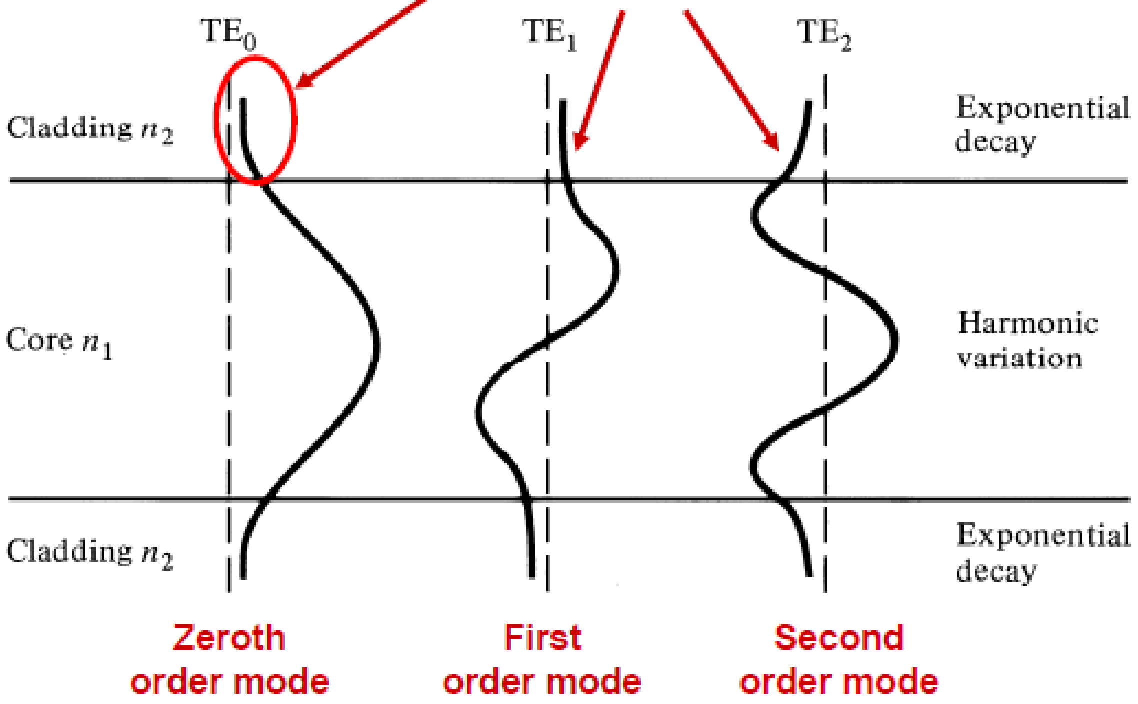
Larger the light accepted and guided by the fiber

Mode Theory

- Modes are electromagnetic field distributions that satisfy Maxwell's equations within a given geometry (e.g. rectangular/circular waveguide)
- Mode theory is required to explain the following:
  - Coherence phenomena
  - Interference phenomena
  - Field distribution of individual mode
    1. To excite an individual mode
    2. To analyse coupling of power between modes at the wave guide imperfections
  - Power distribution among the modes.
  - Study of core cladding modes
  - Study of radiation modes
  - Accounting for power losses due to bending

Mode field patterns

Evanescent tails extend into the cladding



Zeroth-order mode = Fundamental mode
A single-mode fiber carries only the fundamental mode

Optical Modes

- An optical mode --->
  - a specific solution to the wave equation subject to the boundary conditions
  - describes the spatial distribution of the field , which does not change with propagation
  - fiber modes can be classified as

    Guided modes

    Leaky modes

    Radiation modes
- A mode remains guided as long as the β satisfies the given condition

$$n_2 k < \beta < n_1 k$$

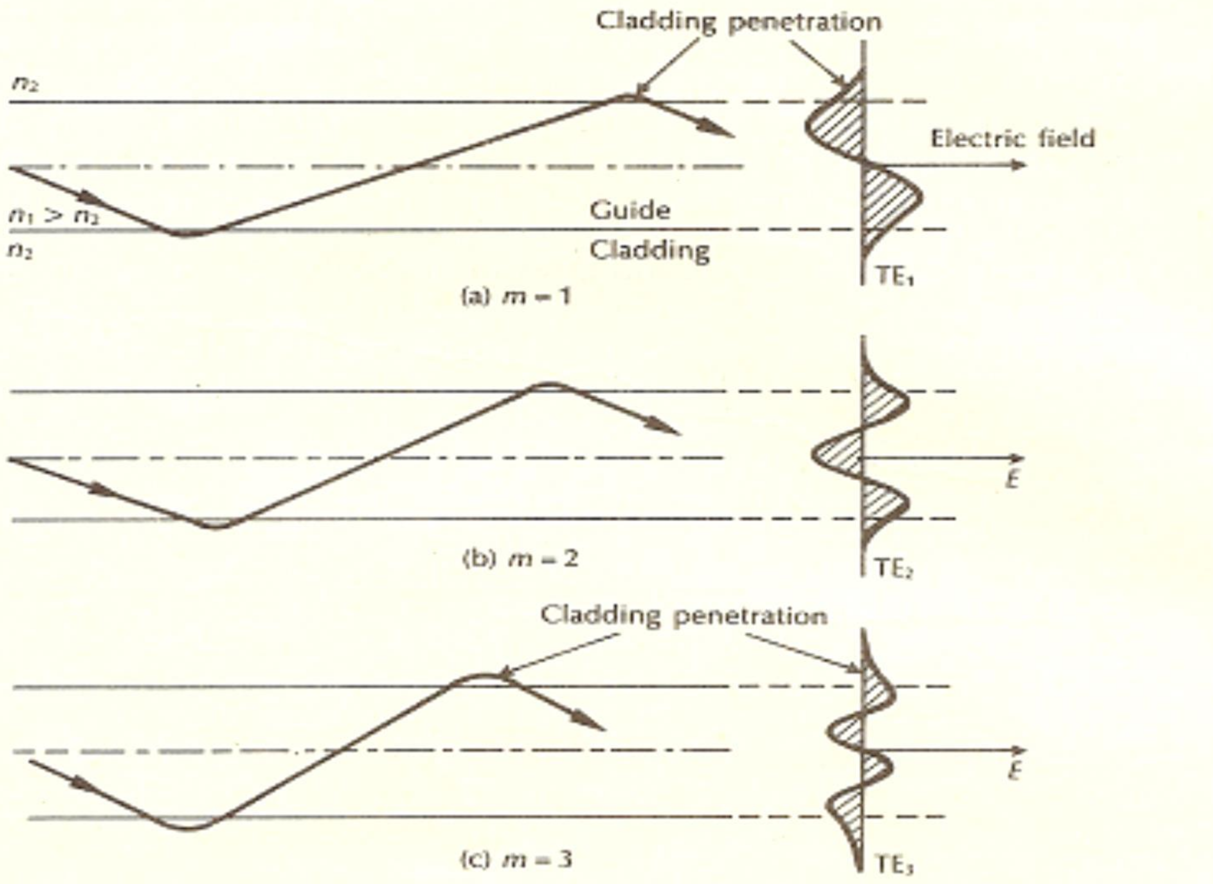
Optical Modes

<u>Dominant Modes</u>: Plane waves corresponding to rays at specific angle in a planar guide, giving rise to constructive interference to form standing wave patterns <u>sine and cosine variations</u> across the guide.

Rays for m = 1,2,3 , with electric field distribution in x direction.

<u>m</u> denotes no. of zeros in the transverse field pattern, is known as **<u>mode number</u>**

<u>TE, TM, HE, EH</u>



Physical model showing the ray propagation and the corresponding transverse electric (TE) field patterns of three lower order models ($m = 1, 2, 3$) in the planar dielectric guide.

Mode types

- TE_m – Electric field is perpendicular to direction of propagation (E_z=0) and magnetic field is in the direction of propagation
- TM_m – Magentic field is perpendicular to direction of propagation (H_z=0) and electric field is in the direction of propagation
- TEM – Total field lies in the tranverse plane (both E_z and H_z are zero)

Hybrid Modes – Both E_z and H_z are non zero

- HE
- EH

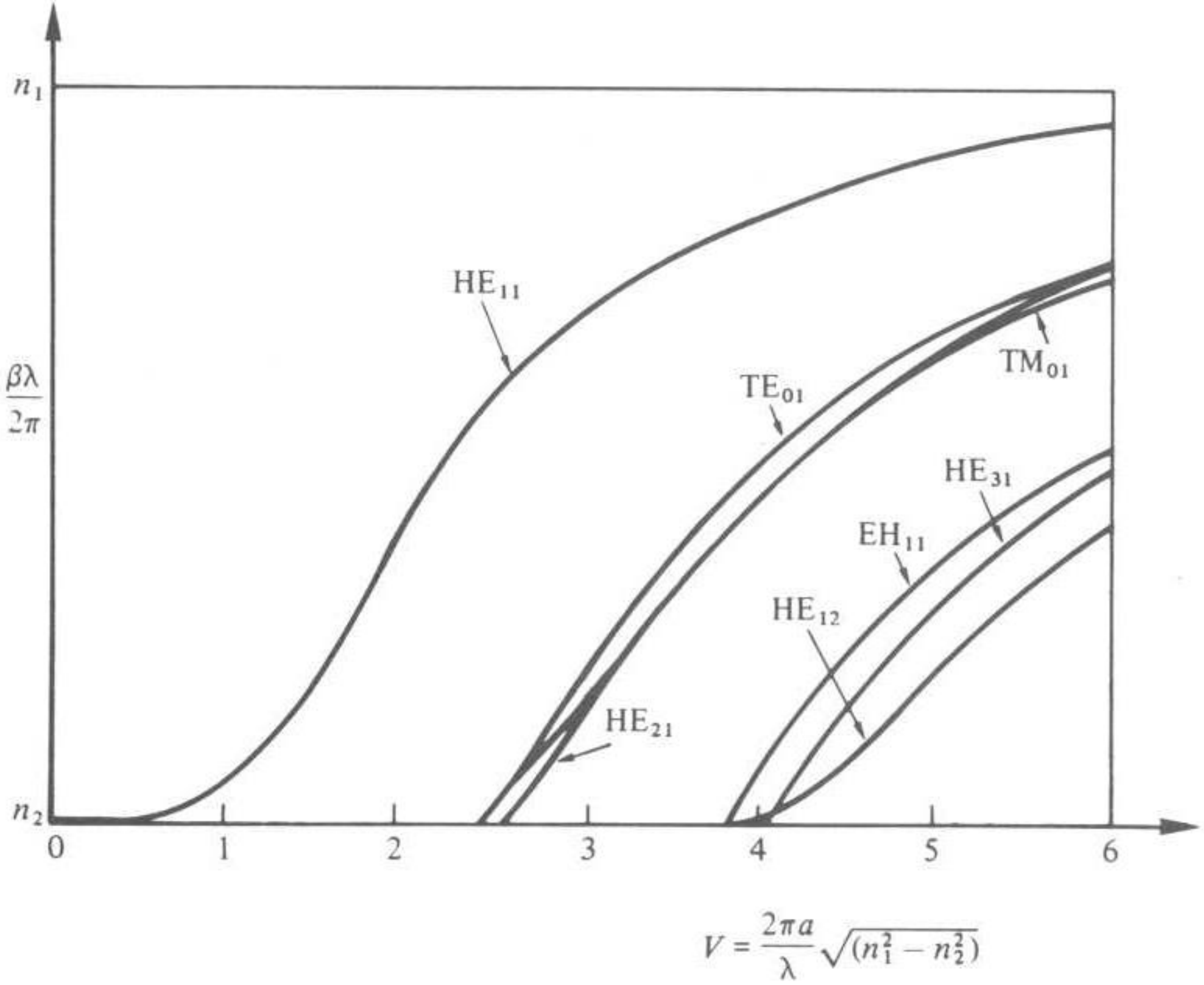
V number or Normalized frequency

- V number decides the number of modes in an optical fiber cable
- It is an important parameter connected with the cut off condition
- Mathematically, V number is defined as

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

- Modes will cutoff when $\beta = n_2 k$ and this occurs when $V \leq 2.405$

Optical Fibers: Guided Modes



Relationship between number of modes and V number

- The total number of guided modes M for a step index fiber is approximately related to the V number

$$M \approx \frac{V^2}{2}$$

- For graded index fiber,

$$M \approx \left(\frac{\alpha}{\alpha + 2}\right)\frac{V^2}{2}$$

- α=infinity for step index, 1 for triangular index, 2 for parabolic index