COURSE: *OPTICAL COMMUNICATION* (EC317)

UNIT-II

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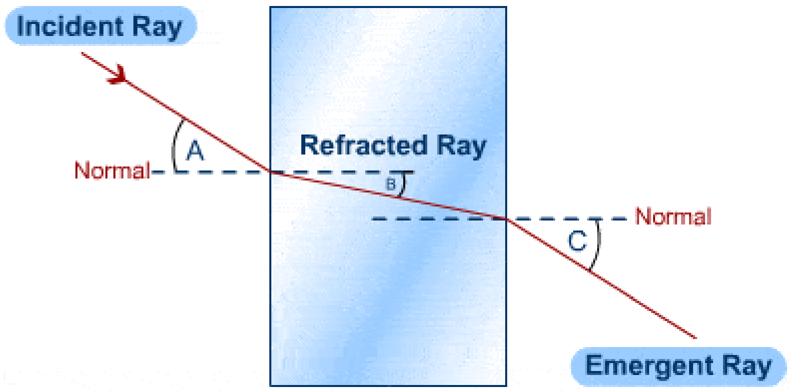
REFRACTIVE INDEX

- The most important optical parameter of any medium is its refractive index n.
- The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum (c) to the velocity of light in the medium (*v*).

$$n = \frac{c}{v}$$

- As *v* is always less than c, n is always greater than 1. For air, $n_a = 1$.

Material	*Refractive index*
Acetone	1.356
Air	1.000
Diamond	2.419
Ethyl alcohol	1.361
Fused quartz (SiO_2): varies with wavelength	1.453 @ 850 nm
Gallium arsenide (GaAs)	3.299 (infrared region)
Glass, crown	1.52–1.62
Glycerin	1.473
Polymethylmethacrylate (PMMA)	1.489
Silicon (varies with wavelength)	3.650 @ 850 nm
Water	1.333

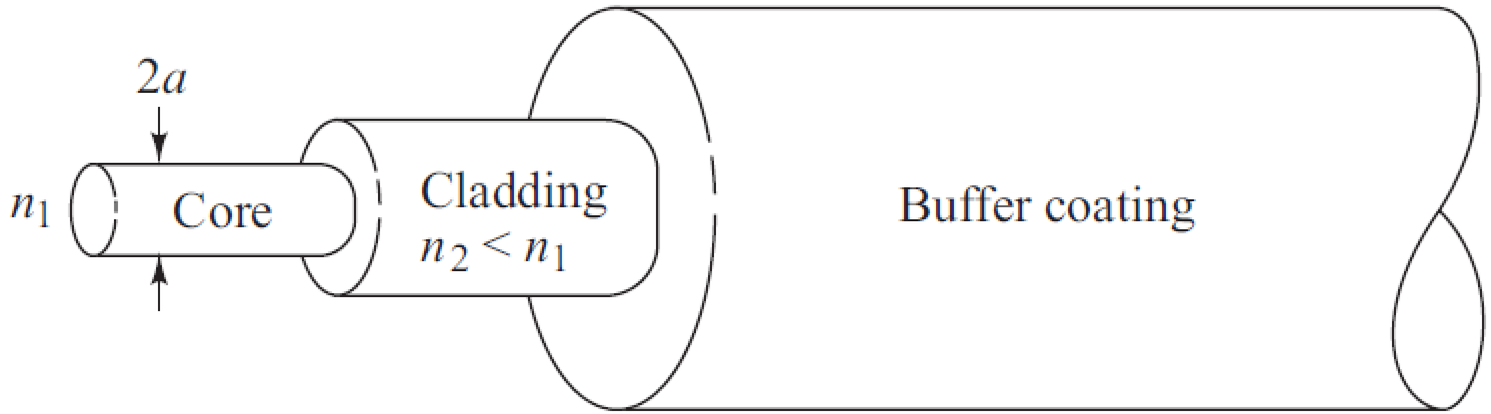


As the light wave goes into the block of higher refractive index it **slows down** and **bends towards the normal line,** so angle A is always bigger than angle B.

As the ray comes out of the block the light wave **speeds up** again and **bends away from the normal line**, so angle B is always smaller than angle C.

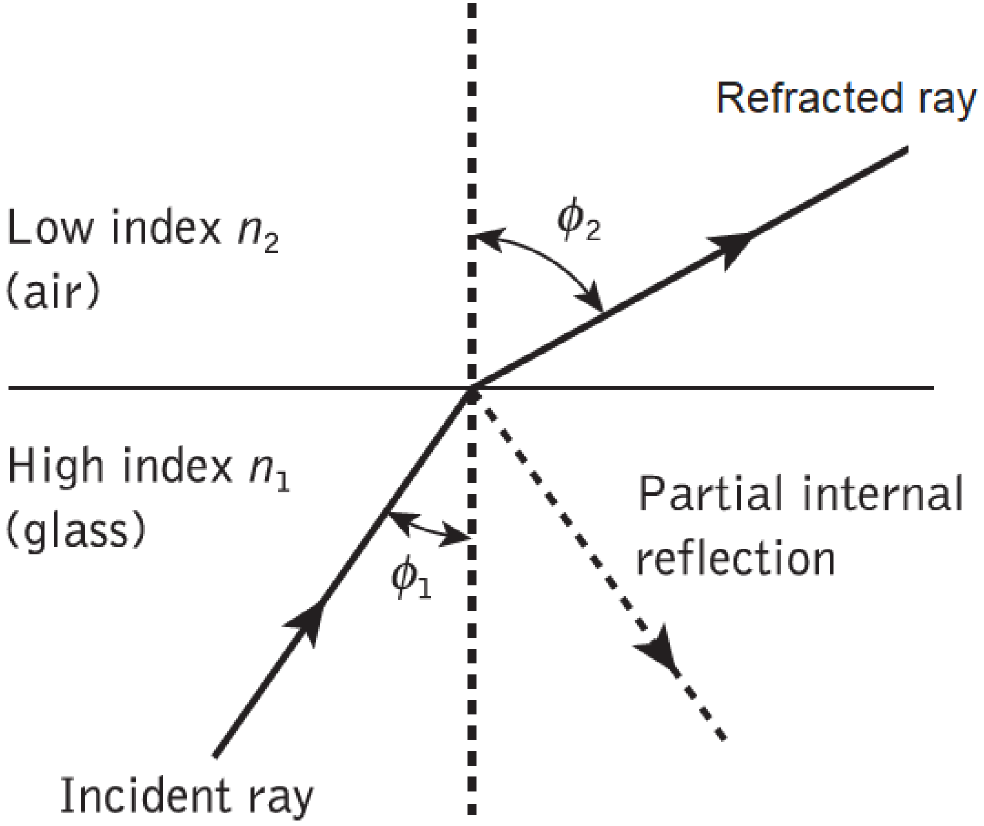
Optical fiber

- Optical fiber is backbone of the optical network and is a dielectric waveguide that operates at optical frequencies
- It consists of a cylindrical dielectric core surrounded by dielectric cladding.
- A polymer buffer coating is commonly used to enhance its mechanical strength and protect it from environmental effects.
- Both the core and the cladding are made of silica (SiO_2) or plastics
- It carrying information in the form of light



Basic optical laws

- When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs
- As n_1 is greater than n_2, the angle of refraction is always greater than the angle of incidence.



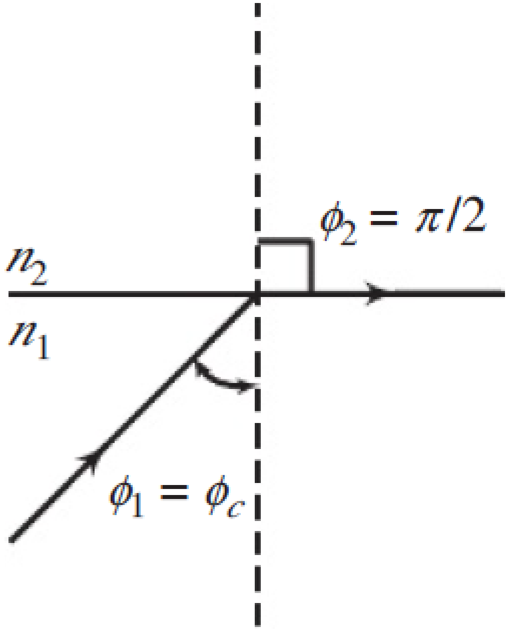
By Snell's law

$$n_1 \sin \emptyset_1 = n_2 \sin \emptyset_2$$

BASIC OPTICAL LAWS

Critical angle :

- As $n_1 > n_2$, if the angle of incidence $\emptyset_1$ increases , the angle of refraction $\emptyset_2$ will go on increasing until a critical situation is reached, when for a certain value of $\emptyset_1 = \emptyset_c$, $\emptyset_2$ becomes 90^0, and the refracted ray passes along the interface. This angle $\emptyset_1 = \emptyset_c$ is called the **critical angle**.

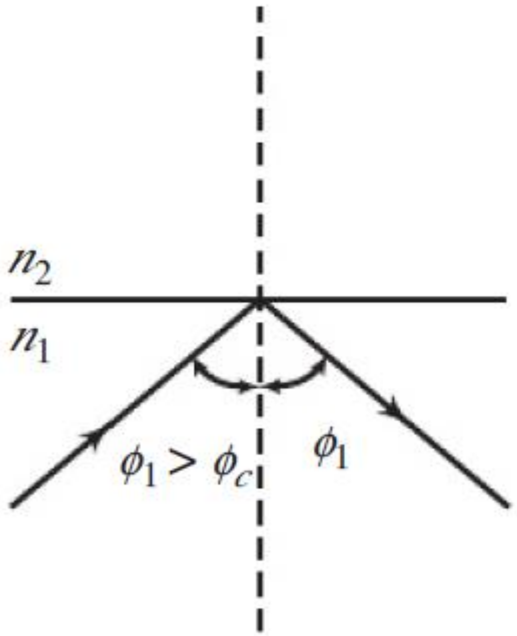


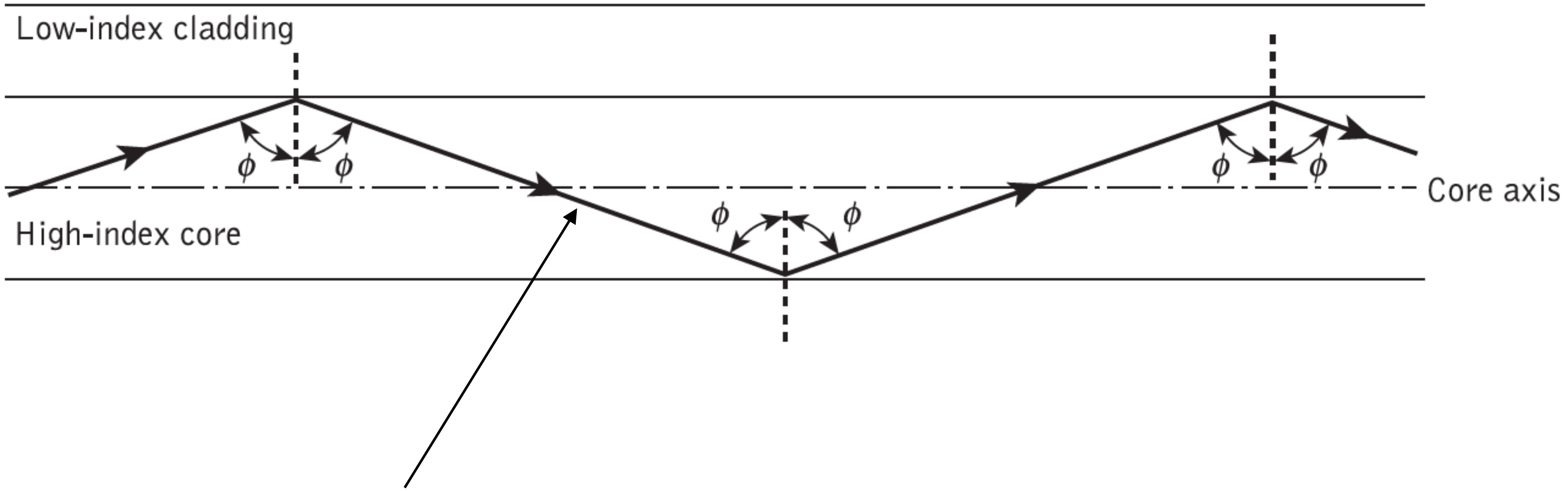
$$\sin \emptyset_c = \frac{n_2}{n_1}$$

BASIC OPTICAL LAWS

Total internal reflection:

- If the angle of incidence $\emptyset_1$ is further increased beyond $\emptyset_c$, the ray is no longer refracted but is reflected back into the same medium. This is called total internal reflection. This phenomenon is responsible for the propagation of light through optical fibers.





meridional ray

Ray Optics Representation

- The two types of rays that can propagate in a fiber: **meridional rays** and **skew rays**.

Meridional rays:

- confined to the meridian planes of the fiber, which are the planes that contain the axis of symmetry of the fiber (the core axis).
- these rays lies in a single plane, so its path is easy to track as it travels along the fiber.
- Meridional rays can be divided into two general classes: **bound rays** that are trapped in the core and propagate along the fiber axis according to the laws of geometrical optics, and **unbound rays** that are refracted out of the fiber core.

Skew rays:

- not confined to a single plane, but instead tend to follow a helical-type path along the fiber.
- more difficult to track as they travel along the fiber because they do not lie in a single plane.

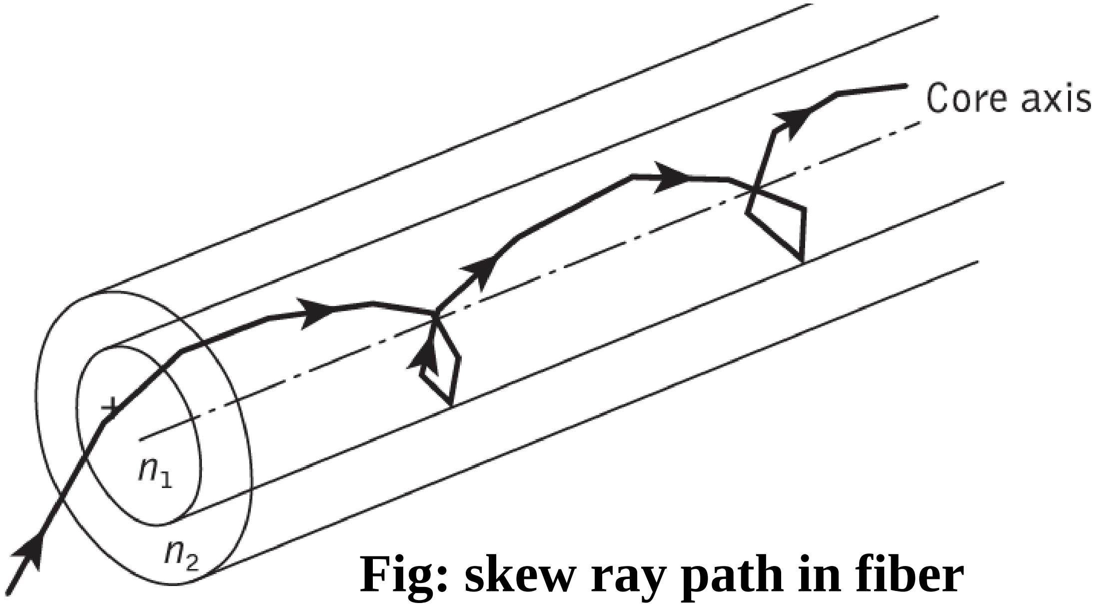
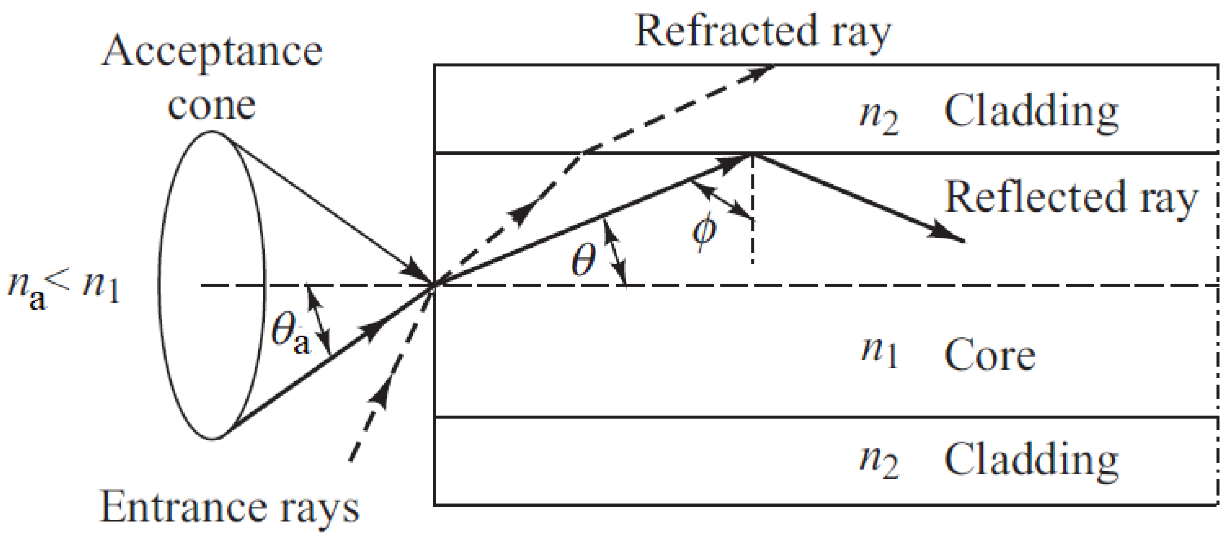


Fig: skew ray path in fiber

ACCEPTANCE ANGLE

- It may be observed that the ray enters the fiber core at an angle θ_a to the fiber axis and is refracted at the air–core interface before transmission to the core–cladding interface at the critical angle.
- Any rays which are incident into the fiber core at an angle greater than θ_a will be transmitted to the core–cladding interface at an angle less than ϕ_c, and will not be totally internally reflected (refract out of the core and be lost in the cladding, as the dashed line shows).
- The rays to be transmitted by total internal reflection within the fiber core, they must be incident on the fiber core within an acceptance cone defined by the conical half angle θ_a.



- The maximum angle (θ_a) to the axis at which light may enter the fiber in order to be propagated is referred to as the **acceptance angle** for the fiber.

NUMERICAL APERTURE

At the air–core interface, by Snell's law: $n_a \sin\theta_a = n_1 \sin\theta$

Where $\theta = \frac{\pi}{2} - \emptyset$

$$n_a \sin\theta_a = n_1 \cos\emptyset = n_1\sqrt{1 - sin^2\emptyset}$$

for total internal reflection is considered, $\emptyset$ becomes equal to the critical angle for the core–cladding interface

$$\sin\emptyset = \frac{n_2}{n_1}$$

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

- The term $n_a \sin\theta_a$ is called the numerical aperture (NA) of the fiber; it determines the light-gathering capacity of the fiber.

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

- The *NA* may also be defined in terms of the relative refractive index difference Δ between the core and the cladding which is defined as

$$NA = n_1\sqrt{2\Delta}$$

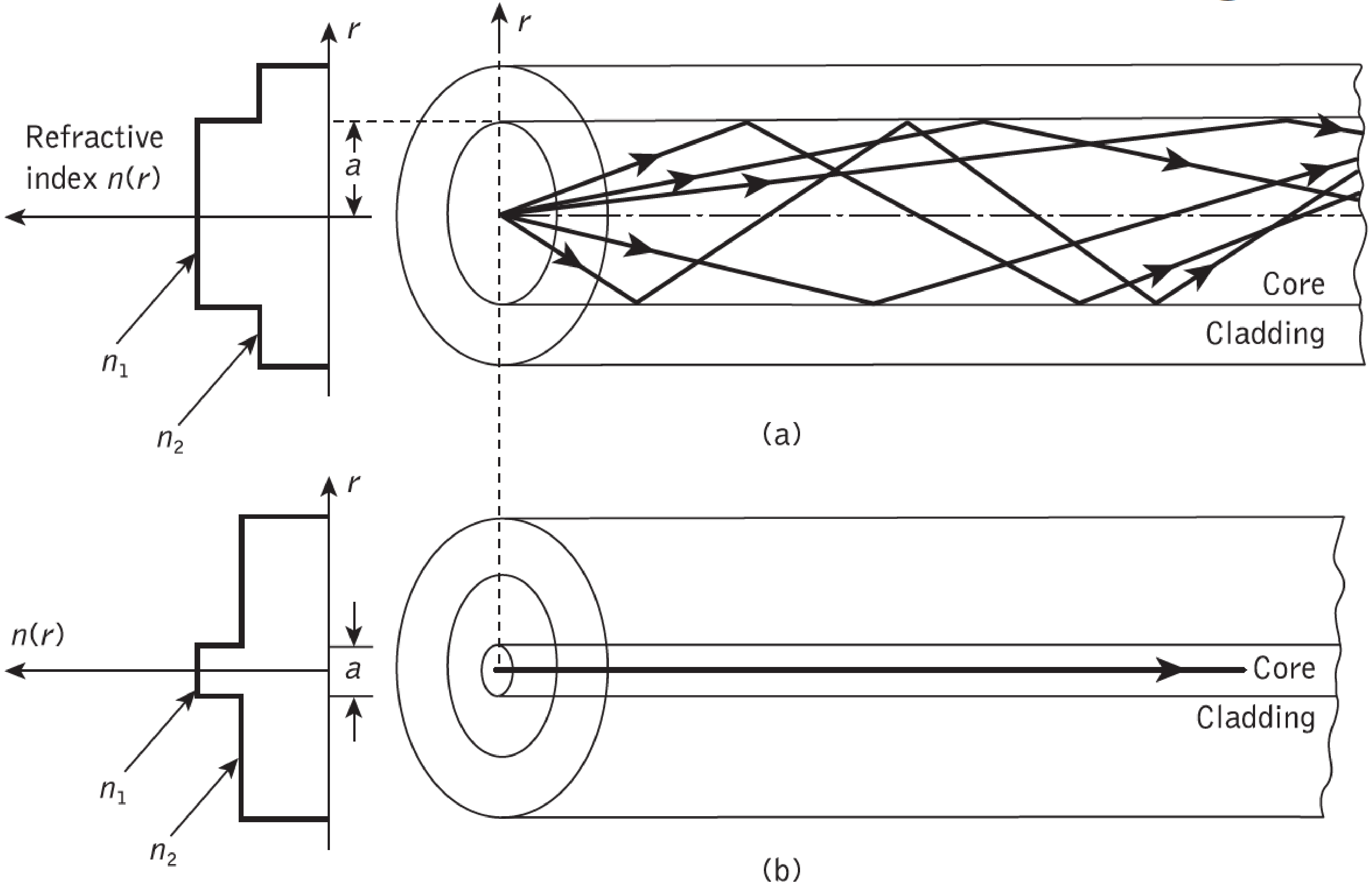
Where $\Delta = \frac{{n_1}^2 - {n_2}^2}{2{n_1}^2}$

OPTICAL FIBER TYPES

- Variations in the material composition of the core give rise to the two commonly used fiber types
- **Step index fiber**: the refractive index of the core is uniform throughout and undergoes an abrupt change (or step) at the cladding boundary
- **Graded index fiber**: the core refractive index is made to vary as a function of the radial distance from the center of the fiber

Step index fiber

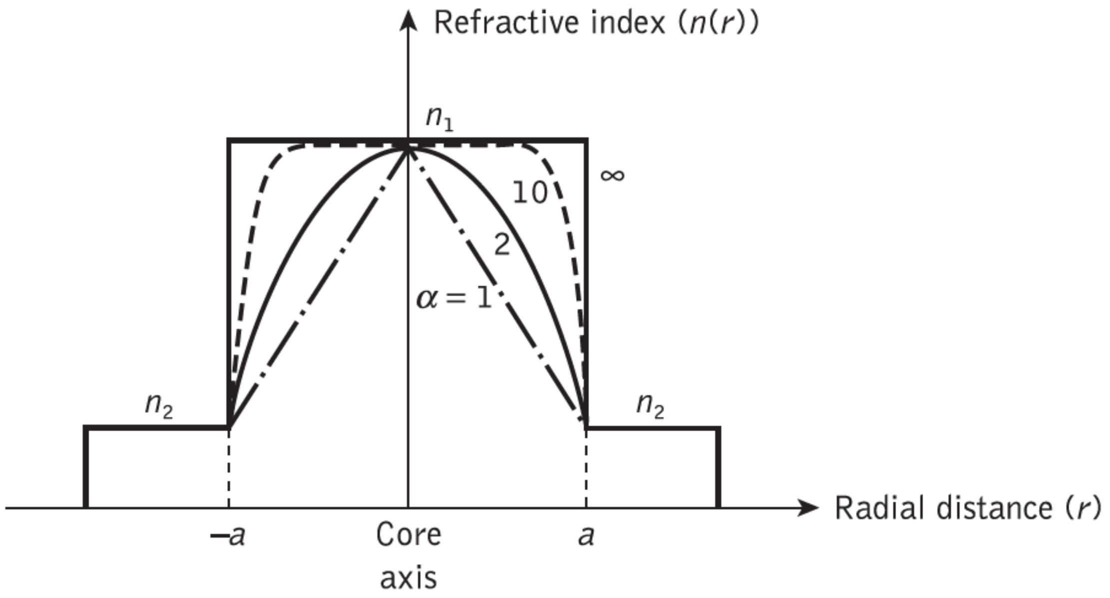
$$n(r) = \begin{cases} n_1 & r < a \quad \text{(core)} \\ n_2 & r \geq a \quad \text{(cladding)} \end{cases}$$



Graded index fiber

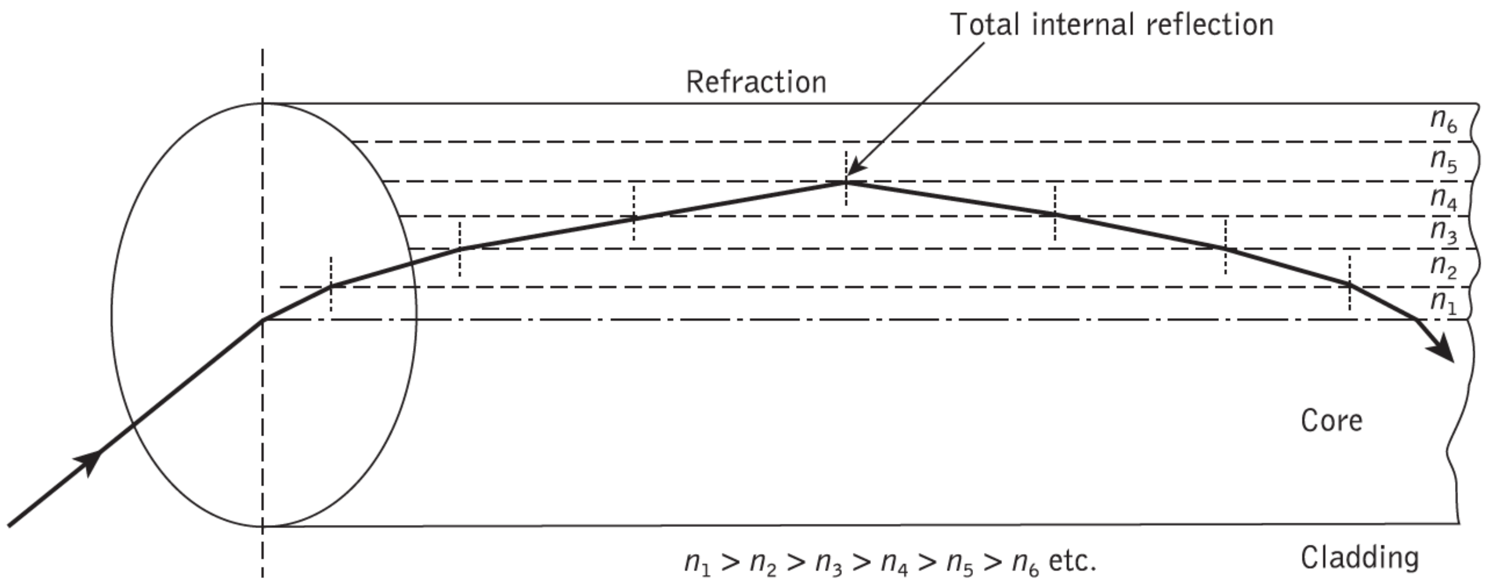
$$n(r) = \begin{cases} n_1(1 - 2\Delta(r/a)^{\alpha})^{\frac{1}{2}} & r < a \quad \text{(core)} \\ n_1(1 - 2\Delta)^{\frac{1}{2}} = n_2 & r \geq a \quad \text{(cladding)} \end{cases}$$

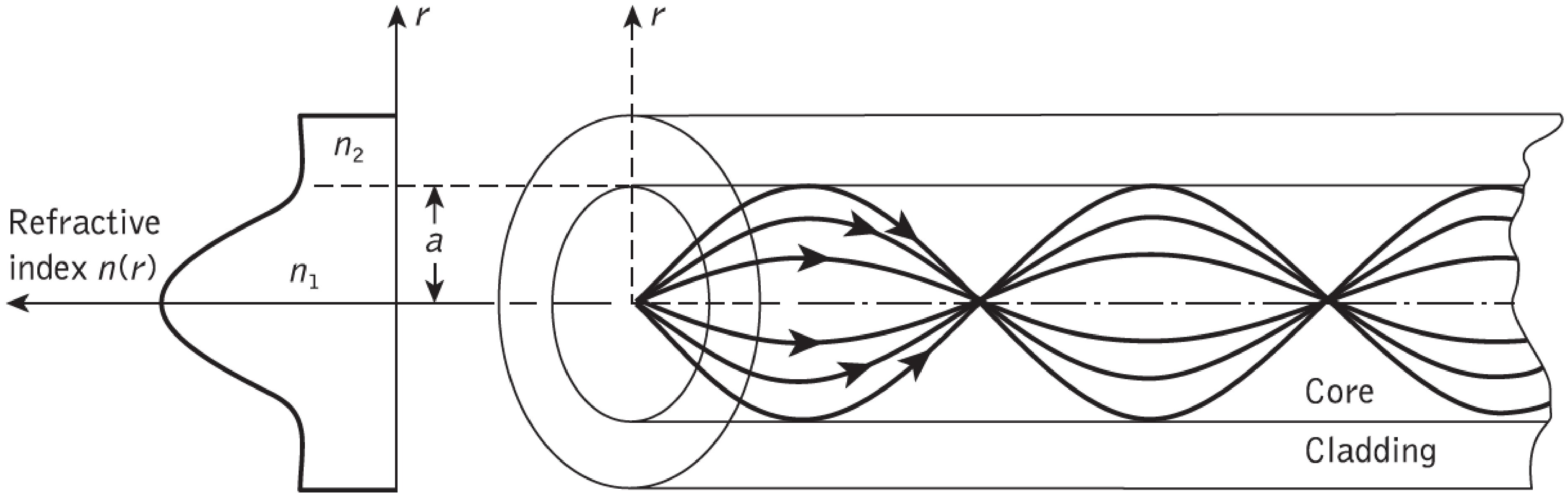
where Δ is the relative refractive index difference and α is the profile parameter which gives the characteristic refractive index profile of the fiber core.



- It may be observed that the meridional rays shown appear to follow curved paths through the fiber core.
- Using the concepts of geometric optics, the gradual decrease in refractive index from the center of the core creates many refractions of the rays as they are effectively incident on a large number or high to low index interfaces where a ray is shown to be gradually curved, with an ever-increasing angle of incidence, until the conditions for total internal reflection are met, and the ray travels back towards the core axis, again being continuously refracted

Ray propagation in Graded index fiber





PROBLEMS

1. A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47. *Determine:* (a) the critical angle at the core–cladding interface; (b) the *NA* for the fiber; (c) the acceptance angle in air for the fiber. (**Ans: (a) 78.5°; (b) 0.3; (c) 17.4°)**
2. The velocity of light in the core of a step index fiber is 2.01×10^8 m/s, and the critical angle at the core–cladding interface is 80°. Determine the numerical aperture and the acceptance angle for the fiber in air, assuming it has a core diameter suitable for consideration by ray analysis. The velocity of light in a vacuum is 2.998×10^8 m/s.
3. A step index fiber with a large core diameter compared with the wavelength of the transmitted light has an acceptance angle in air of 22° and a relative refractive index difference of 3%. Estimate the numerical aperture and the critical angle at the core–cladding interface for the fiber.
4. A step index fiber has a solid acceptance angle in air of 0.115 radians and a relative refractive index difference of 0.9%. Estimate the speed of light in the fiber core.

TEXT BOOKS

- Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
- Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.
- R.P. Khare, *Fiber optics and optoelectronics, Oxford University Press 2004*