Basics of optics

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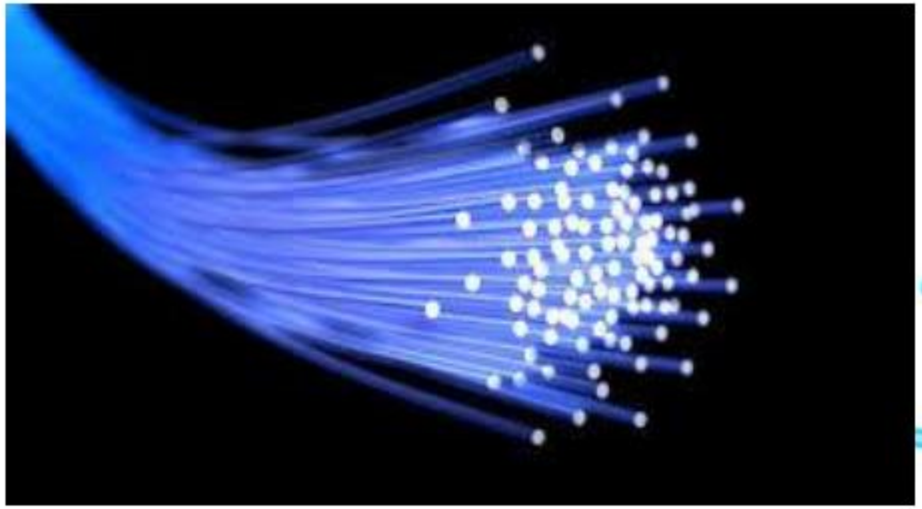
About fiber optics

- An optical fiber is a flexible, transparent fiber made by drawing glass (silica) or plastic to a diameter slightly thicker than that of a human hair.
- Optical fibers are used most often as a means to transmit light between the two ends of the fiber and find wide usage in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidths (data transfer rates) than electrical cables.
- Fibers are used instead of metal wires because signals travel along them with less loss; in addition, fibers are immune to electromagnetic interference, a problem from which metal wires suffer



Advantages

- **Increased bandwidth**: The high signal bandwidth of optical fibers provides significantly greater information carrying capacity. Typical bandwidths for multimode (MM) fibers are between 200 and 600MHz-km and >10GHz-km for single mode (SM) fibers. Typical values for electrical conductors are 10 to 25MHz-km.
- **Electromagnetic/Radio Frequency Interference Immunity**: Optical fibers are immune to electromagnetic interference and emit no radiation. ▫
- **Decreased cost, size and weight**: Compared to copper conductors of equivalent signal carrying capacity, fiber optic cables are easier to install, require less duct space, weigh 10 to 15 times less and cost less than copper. ▫
- **Lower loss:** Optical fiber has lower attenuation (loss of signal intensity) than copper conductors, allowing longer cable runs and fewer repeaters. ▫
- **No sparks or shorts:** Fiber optics do not emit sparks or cause short circuits, which is important in explosive gas or flammable environments. ▫
- **Security:** Since fiber optic systems do not emit RF signals, they are difficult to tap into without being detected. ▫
- **Grounding:** Fiber optic cables do not have any metal conductors; consequently, they do not pose the shock hazards inherent in copper cables. ▫
- **Electrical Isolation:** Fiber optics allow transmission between two points without regard to the electrical potential between them.

Fiber Optic Link Components

- In order to comprehend how fiber optic applications work, it is important to understand the components of a fiber optic link. Simplistically, there are four main components in a fiber optic link.
- Optical Transmitter
- Optical Fiber/Cable
- Connectors
- Optical Receiver

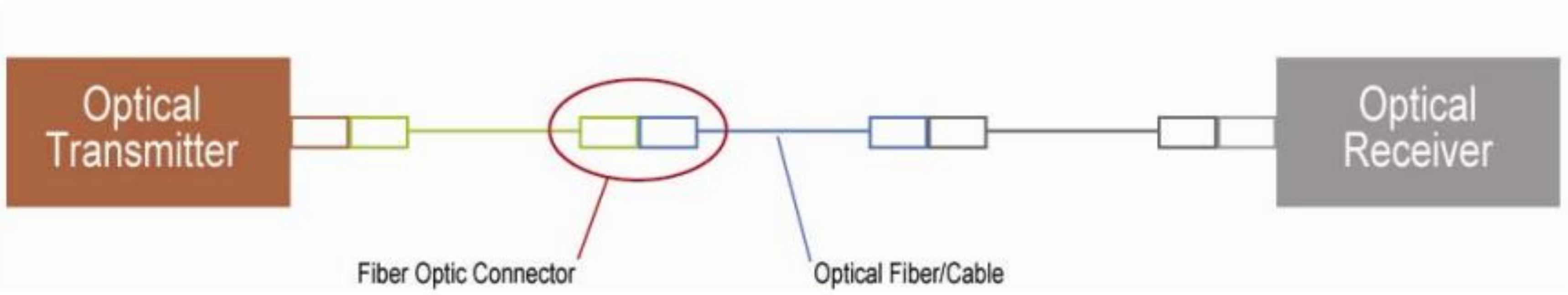


Figure 1: Simple Fiber Optic Link

Transmitter

- The transmitter converts the electrical signals to optical. A transmitter contains a light source such as a Light Emitting Diode (LED) or a Laser (Light Amplification by Stimulated Emission of Radiation) diode, or a Vertical Cavity Surface Emitting Laser (VCSEL).
- LED: Is used in multimode applications and has the largest spectral width that carries the
- least amount of bandwidth.
- VCSEL: Is also used in multimode applications with a narrower spectral width that can carry
- more bandwidth than the LED.
- LASER: Has the smallest spectral width, carries the most bandwidth, and is used in
- Single mode applications.
- These sources produce light at certain wavelengths depending upon the materials from which they are made. Most fiber optic sources use wavelengths in the infrared band, specifically 850nm (1nm=10-9m), 1300nm and 1550nm. For reference, visible light operates in the 400-700nm range

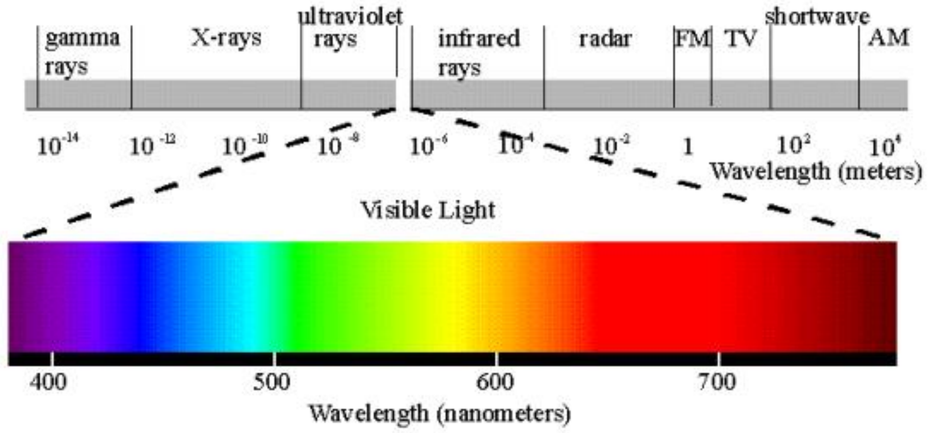


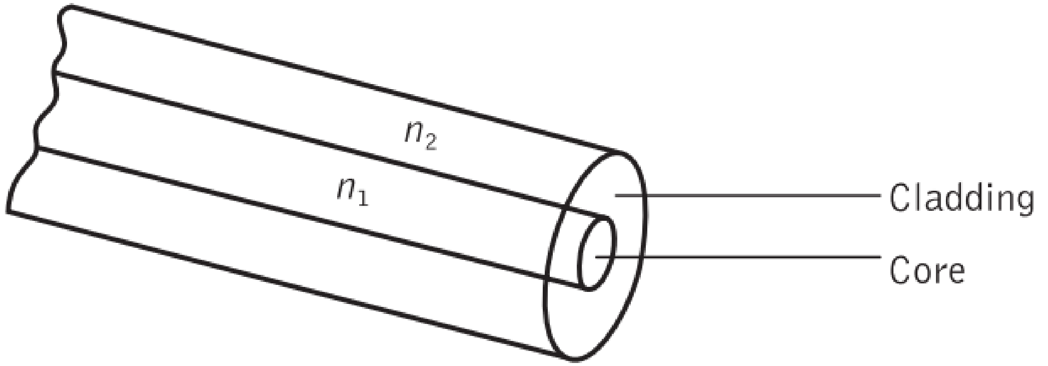
Figure 2: Electromagnetic Spectrum

History of optical fiber

- The transmission of light via a dielectric waveguide structure was first proposed and investigated at the beginning of the twentieth century.
- In 1910 Hondros and Debye conducted a theoretical study, and experimental work was reported by Schriever in 1920.
- However, a transparent dielectric rod, typically of silica glass with a refractive index of around 1.5, surrounded by air, proved to be an impractical waveguide due to its unsupported structure (especially when very thin waveguides were considered in order to limit the number of optical modes propagated) and the excessive losses at any discontinuities of the glass-air interface.
- Interest in the application of dielectric optical waveguides in such areas as optical imaging and medical diagnosis (e.g. endoscopes) led to proposals for a clad dielectric rod in the mid-1950s in order to overcome these problems.

Optical Fiber/Cable

- An optical fiber is made of 3 concentric layers (see Figure 3):
- Core: This central section, made of silica or doped silica, is the light transmitting region of the fiber. ▫
- Cladding: This is the first layer around the core. It is also made of silica, but not the same composition as the core. This creates an optical waveguide which confines the light in the core by total internal reflection at the core-cladding interface.
- Coating: The coating is the first non-optical layer around the cladding. The coating typically consists of one or more layers of polymer that protect the silica structure against physical or environmental damage. The coating is stripped off when the fiber is connectorized or fusion spliced.
- Buffer: The buffer is an important feature of the fiber. It is 900 microns and helps protect the fiber from breaking during installation and termination and is located outside of the coating.



Optical fiber waveguide showing the core of refractive index n1, surrounded by the cladding of slightly lower refractive index n2

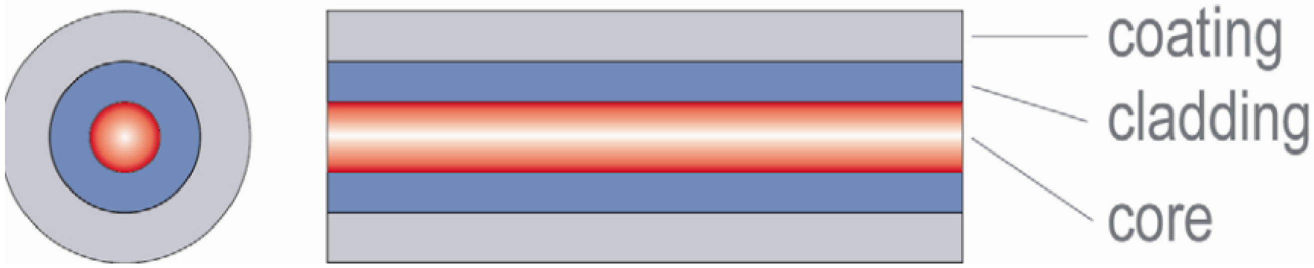
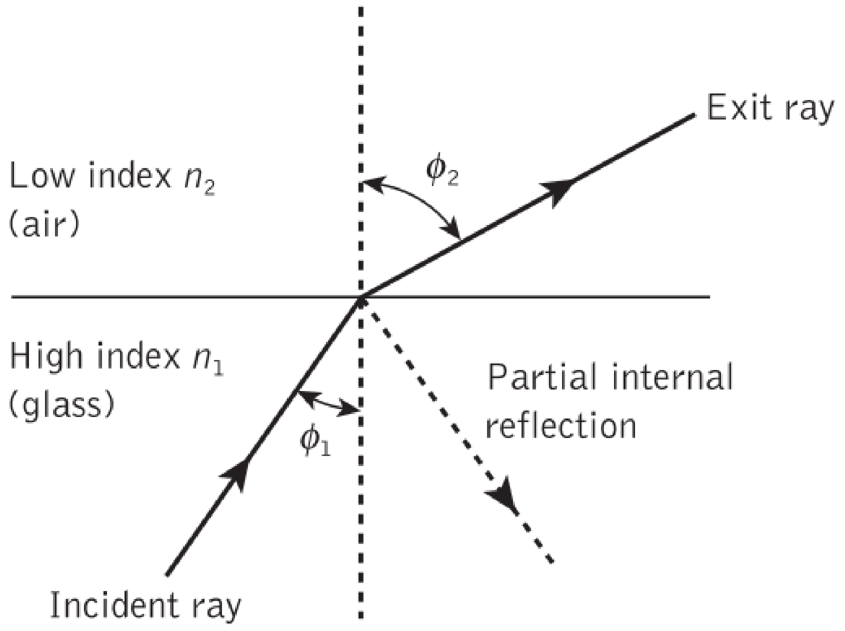


Figure 3: Optical Fiber Construction

Ray theory transmission

- **Total internal reflection**
- To consider the propagation of light within an optical fiber utilizing the ray theory model it is necessary to take account of the refractive index of the dielectric medium.
- The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium.
- A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect.
- When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs, as illustrated in Figure.
- It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index n1 and is at an angle φ1 to the normal at the surface of the interface.



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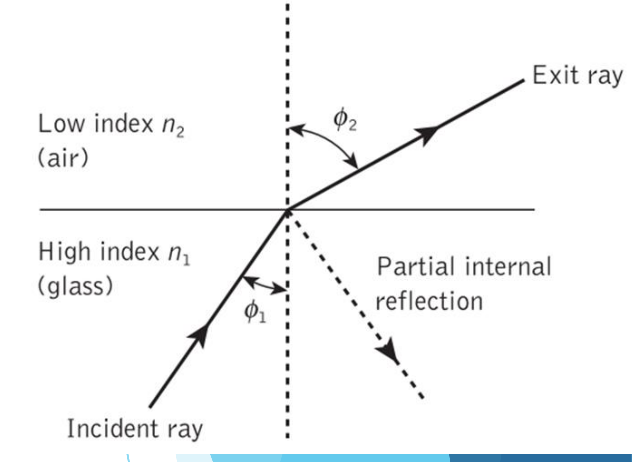
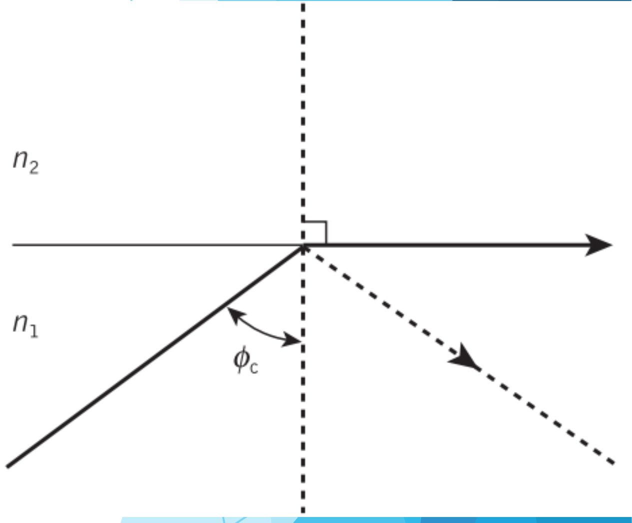
- The angles of incidence φ1 and refraction φ2 are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction, which states that

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1} \qquad \boxed{n = \frac{c}{v}}$$

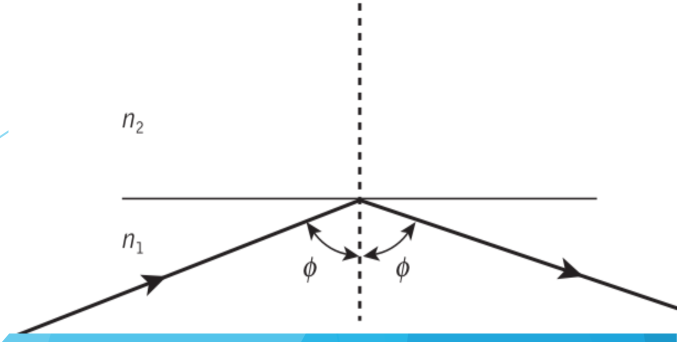


- It may also be observed in Figure that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection).
- As n1 is greater than n2, the angle of refraction is always greater than the angle of incidence.
- Thus when the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90°.



- This is the limiting case of refraction and the angle of incidence is now known as the critical angle φc, as shown in Figure. From Eq. the value of the critical angle is given by:

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



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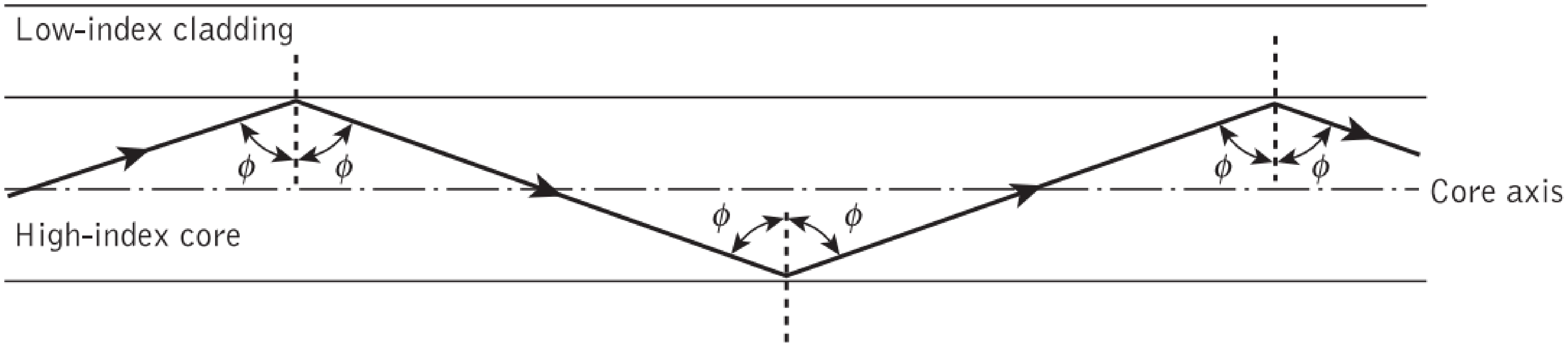
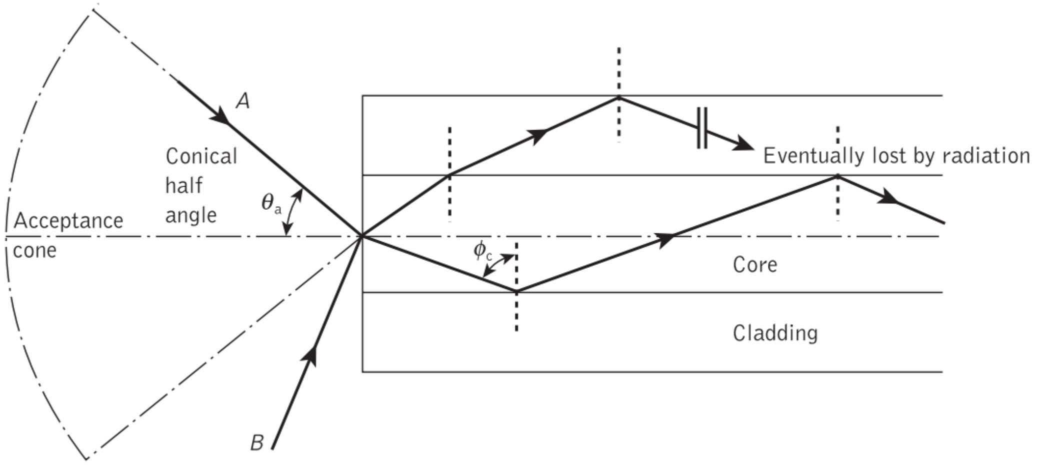
- At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency (around 99.9%).
- Hence, it may be observed in Figure that total internal reflection occurs at the interface between two dielectrics of differing refractive indices when light is incident on the dielectric of lower index from the dielectric of higher index, and the angle of incidence of the ray exceeds the critical value
- This is the mechanism by which light at a sufficiently shallow angle (less than 90° − φc) may be considered to propagate down an optical fiber with low loss.



meridional ray

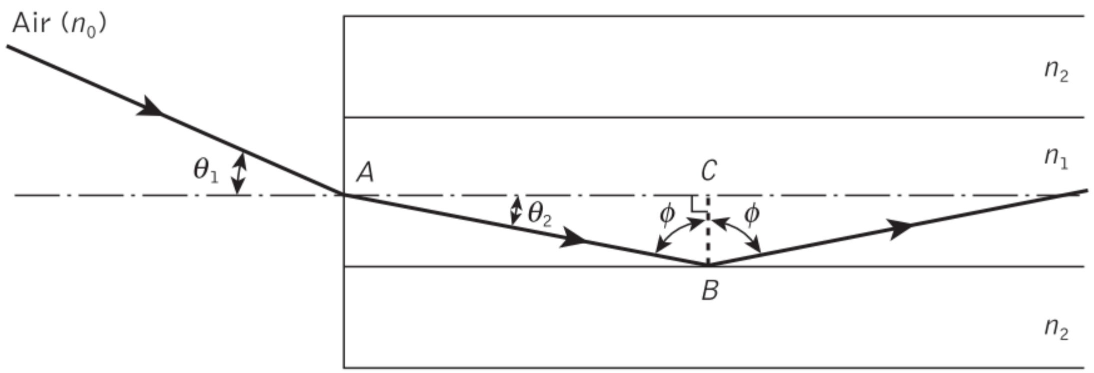
Acceptance angle

- Since only rays with a sufficiently shallow grazing angle (i.e. with an angle to the normal greater than φc) at the core–cladding interface are transmitted by total internal reflection, it is clear that not all rays entering the fiber core will continue to be propagated down its length.
- The geometry concerned with launching a light ray into an optical fiber is shown in Figure, which illustrates a meridional ray A at the critical angle φc within the fiber at the core–cladding interface.
- This ray enters the fiber core at an angle θa to the fiber axis and is refracted at the air–core interface before transmission to the core–cladding interface at the critical angle.
- Hence, any rays which are incident into the fiber core at an angle greater than θa will be transmitted to the core–cladding interface at an angle less than φc, and will not be totally internally reflected.
- In Figure, where the incident ray B at an angle greater than θa is refracted into the cladding and lost by radiation.
- Thus for rays to be transmitted by TIR within the fiber core they must be incident on the fiber core within an acceptance cone defined by the conical half angle θa.
- Hence θa is the maximum angle to the axis at which light may enter the fiber in order to be propagated, and is often referred to as the acceptance angle* for the fiber.



Numerical aperture

- Figure shows a light ray incident on the fiber core at an angle θ1 to the fiber axis which is less than the acceptance angle for the fiber θa. The ray enters the fiber from a medium (air) of refractive index n0, and the fiber core has a refractive index n1, which is slightly greater than the cladding refractive index n2.



- Assuming the entrance face at the fiber core to be normal to the axis, then considering the refraction at the air-core interface and using Snell's law given by Eq.

$$n_0 \sin \theta_1 = n_1 \sin \theta_2$$

- Considering the right-angled triangle ABC indicated in Figure, then:

$$\phi = \frac{\pi}{2} - \theta_2$$

- where φ is greater than the critical angle at the core-cladding interface. Hence Eq. Becomes

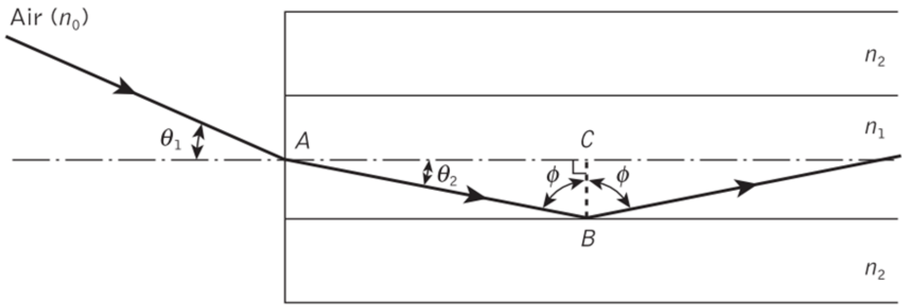
$$n_0 \sin \theta_1 = n_1 \cos \phi$$

- Using the trigonometrical relationship $\sin^2 \varphi + \cos^2 \varphi = 1$, Eq. may be written in the form

$$n_0 \sin \theta_1 = n_1(1 - \sin^2 \phi)^{\frac{1}{2}}$$

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

- When the limiting case for total internal reflection is considered, $\varphi = \varphi_c$ critical angle for the core-cladding interface and is given by Eq. Here θ1 becomes the acceptance angle for the fiber θa. Combining these limiting cases into Eq. gives



$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}}$$

- Above equation, relate the acceptance angle to the refractive indices, also define important optical fiber parameter, the numerical aperture (NA). Hence the NA is defined as:

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \qquad \text{(a)}$$

- Since the NA is used with the fiber in air where n0 is unity, it is simply equal to sin θa. The incident meridional rays over the range 0 ≤ θ1 ≤ θa will be propagated within the fiber.

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

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

$$\simeq \frac{n_1 - n_2}{n_1} \qquad \text{for } \Delta \ll 1 \qquad \text{(b)}$$

Hence combining Eq. (2.8) with Eq. (2.9) we can write:

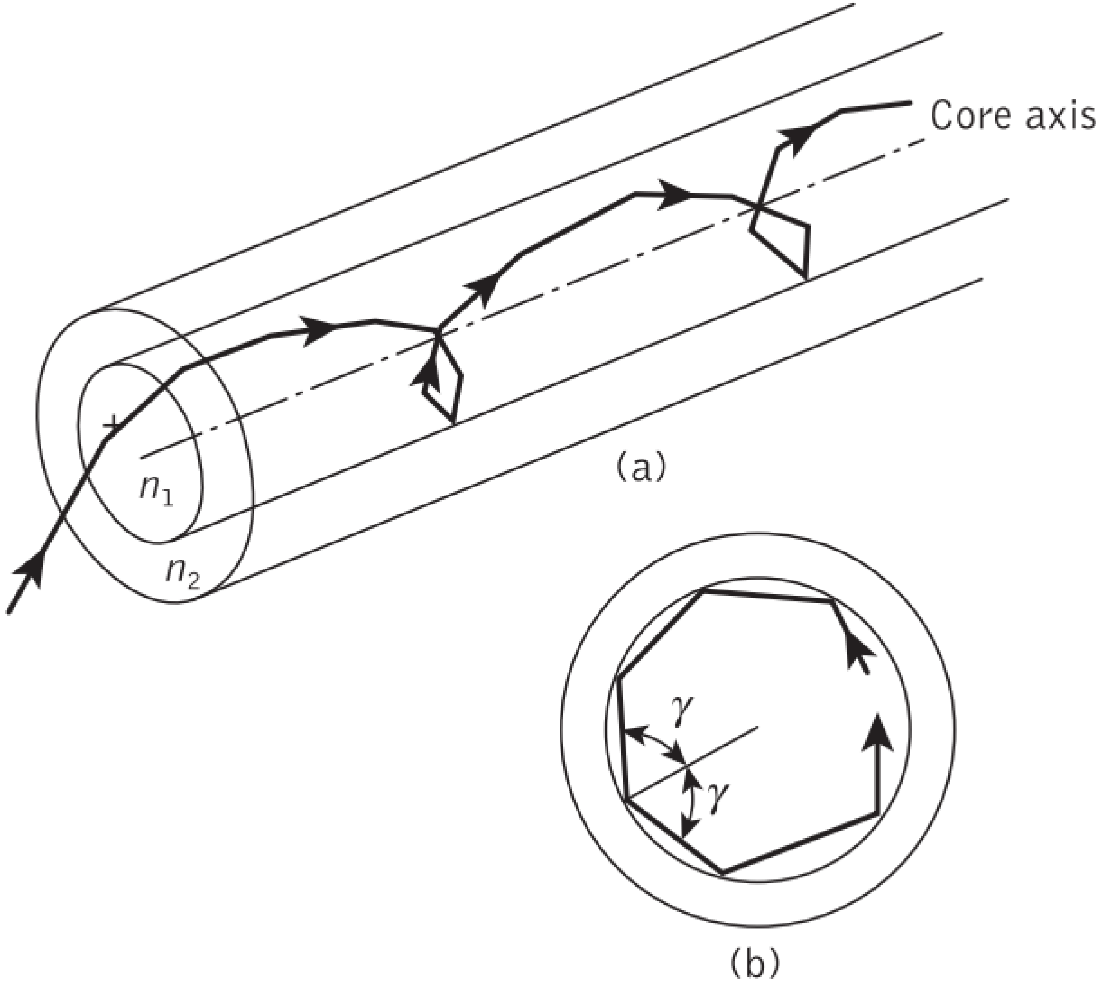
$$\boxed{NA = n_1(2\Delta)^{\frac{1}{2}}}$$

Problem

- 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

Skew rays

- These rays follow a helical path through the fiber, as illustrated in Figure, and are called skew rays.
- It is not easy to visualize the skew ray paths in two dimensions, but it may be observed from Figure that the helical path traced through the fiber gives a change in direction of 2γ at each reflection, where γ is the angle between the projection of the ray in two dimensions and the radius of the fiber core at the point of reflection.
- Hence, unlike meridional rays, the point of emergence of skew rays from the fiber in air will depend upon the number of reflections they undergo rather than the input conditions to the fiber.
- When the light input to the fiber is nonuniform, skew rays will therefore tend to have a smoothing effect on the distribution of the light as it is transmitted, giving a more uniform output.
- The amount of smoothing is dependent on the number of reflections encountered by the skew rays.



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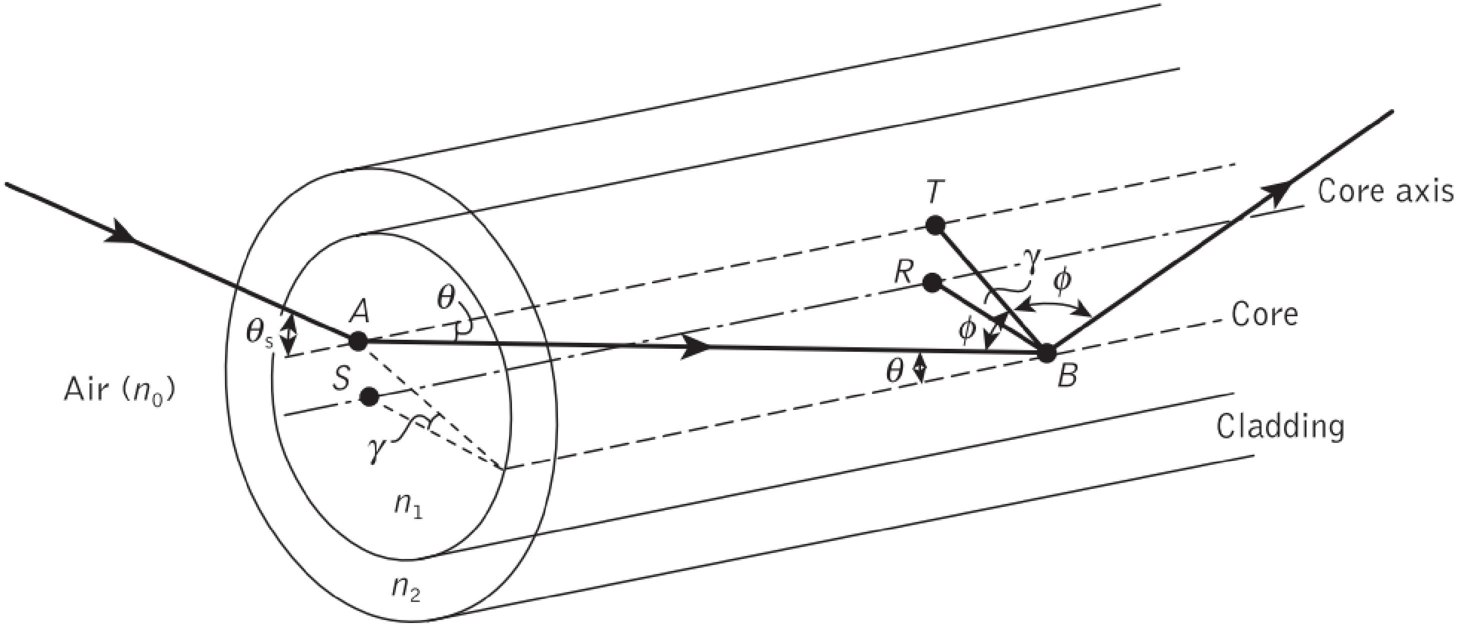
- A further possible advantage of the transmission of skew rays becomes apparent when their acceptance conditions are considered.
- In order to calculate the acceptance angle for a skew ray it is necessary to define the direction of the ray in two perpendicular planes.
- The ray is refracted at the air-core interface before traveling to the point B in the same plane. The angles of incidence and reflection at the point B are φ, which is greater than the critical angle for the core-cladding interface.

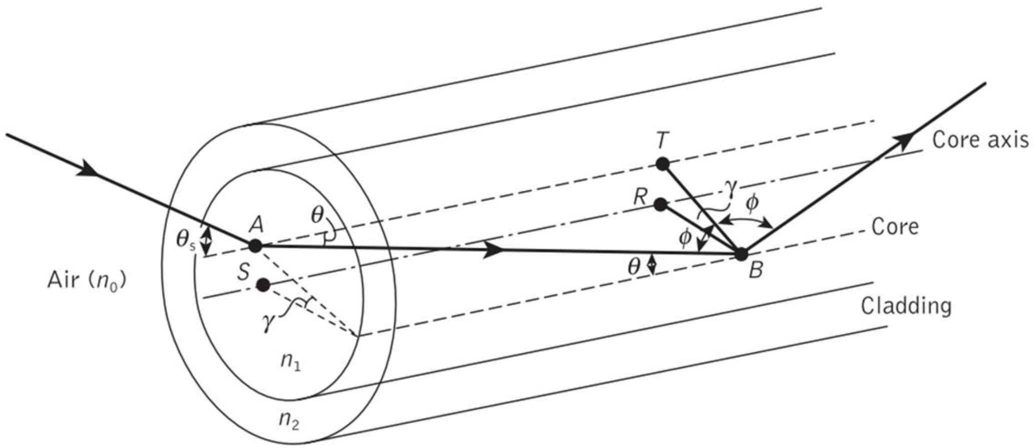


- the reflection at point B at an angle φ may be given by:

$$\cos \gamma \sin \theta = \cos \phi$$

- Using the trigonometrical relationship $\sin^2 \varphi + \cos^2 \varphi = 1$, Eq. becomes:

$$\cos \gamma \sin \theta = \cos \phi = (1 - \sin^2 \phi)^{\frac{1}{2}}$$



- If the limiting case for total internal reflection is now considered, then φ becomes equal to the critical angle φc for the core–cladding interface and, following Eq., is given by sin φc = n2/n1. Hence, Eq. may be written as:

$$\cos \gamma \sin \theta \leq \cos \phi_c = \left(1 - \frac{n_2^2}{n_1^2}\right)^{\frac{1}{2}} \qquad \text{(a)}$$

- Furthermore, using Snell's law at the point A, following Eq. we can write:

$$n_0 \sin \theta_a = n_1 \sin \theta \qquad \text{(b)}$$

- where θa represents the maximum input axial angle for meridional rays, and θ is the internal axial angle. Hence substituting for sin θ from Eq. a into Eq. (b) gives:

$$\sin \theta_{as} = \frac{n_1}{n_0} \frac{\cos \phi_c}{\cos \gamma} = \frac{n_1}{n_0 \cos \gamma} \left(1 - \frac{n_2^2}{n_1^2}\right)^{\frac{1}{2}}$$

- where θas now represents the maximum input angle or acceptance angle for skew rays. It may be noted that the inequality shown in Eq. a is no longer necessary as all the terms in Eq. are specified for the limiting case. Thus the acceptance conditions for skew rays are:

$$n_0 \sin \theta_{as} \cos \gamma = (n_1^2 - n_2^2)^{\frac{1}{2}} = NA$$

- and in the case of the fiber in air (n0 = 1):

$$\sin \theta_{as} \cos \gamma = NA$$

- Therefore by comparison with meridional rays, it may be noted that skew rays are accepted at larger axial angles in a given fiber than meridional rays, depending upon the value of cos γ.
- Hence, as may be observed from Figure, skew rays tend to propagate only in the annular region near the outer surface of the core, and do not fully utilize the core as a transmission medium.
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