2.2.4 Optical Rays Types

We have seen that rays approaching from within the cone of acceptance are successfully propagated along the fiber. The position and the angle at which the ray strikes the core will determine the exact path taken by the ray. There are three possibilities, called the **meridional**, the **axial** and the **skew** ray as shown in **Figure 2.5**.

- The **meridional** ray **enters the core and passes through its center**.
- The **axial** ray is a particular ray that just happens to travel straight through the center of the core.
- The **skew ray never passes through the center of the core.** Instead, it reflects off the core/cladding interface and bounces around the outside of the core. It moves forward in a shape reminiscent of a spiral staircase built from straight sections.

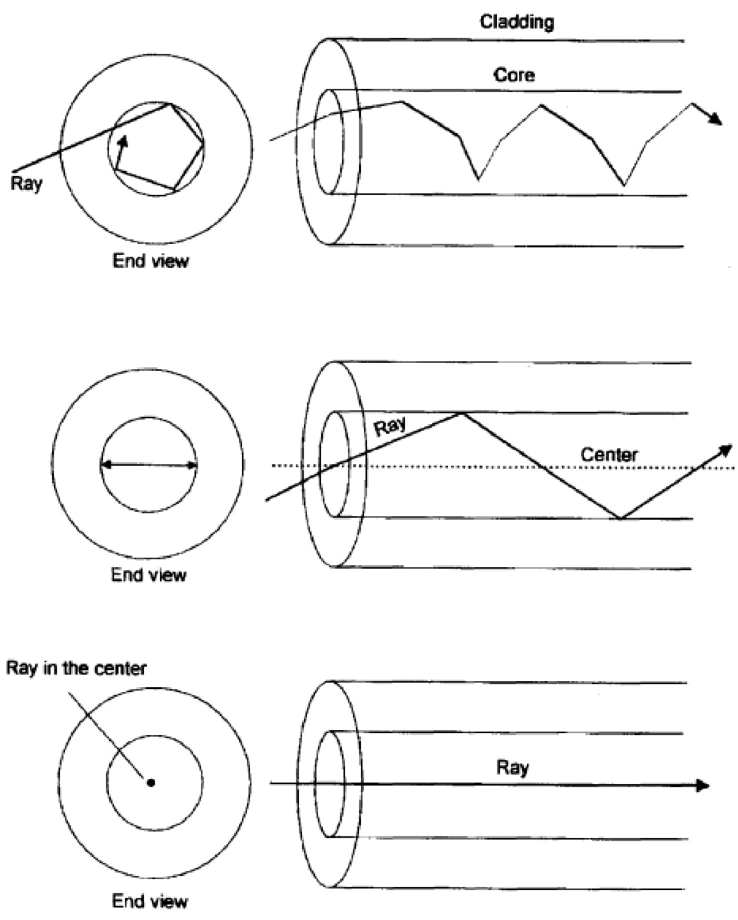


Figure 2.5: The skew ray does not pass through the center (top); the meridional ray passes through the center (middle); the axial ray stays in the center all the time (bottom).

Assistant Prof.
Dr. Abdulla K. Abass

Note: The ***NA*** for the skew rays is given by the equation below:

$$NA = \sin\theta_{as}\cos\gamma \qquad \text{(Equation 2.11)}$$

Where:

$\sin\theta_{as}$ Is the acceptance angle of the skew rays.

$\cos\gamma$ is the angle between the projection of the ray in two dimensions and the radius of the fiber core at the point of reflection. The helical path traced through the fiber gives a change in direction of 2γ at each reflection as shown as in **Figure 2.6**.

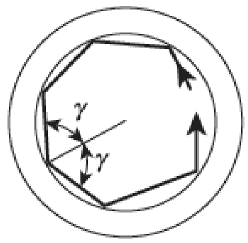


Figure 2.6: Cross-sectional view of the fiber with skew rays.

Example 2.2

An optical fiber in the air has an NA of 0.4. Compare the acceptance angle for meridional rays with that for skew rays which change direction by 100° at each reflection.

Solution:

The acceptance angle of meridional rays is given by (Equation 2.9) with n_o = 1as:

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.4 = 23.6^0$$

The skew rays change direction by 100° at each reflection, therefore $\gamma = 50^0$. Hence, using (Equation 2.11) the acceptance angle of skew rays is:

$$\theta_{as} = \sin^{-1}\left(\frac{NA}{\cos\gamma}\right) = \sin^{-1}\left(\frac{0.4}{\cos 50^0}\right) = 38.5^0$$

In this example, the acceptance angle of the skew rays is about 15° greater than the corresponding angle for meridional rays. However, it must be noted that we have only compared the acceptance angle of one particular skew ray path. When the light input to the fiber is at an angle to the fiber axis, it is possible that γ will vary from zero for meridional rays to 90° for rays which enter the fiber at the core–cladding interface giving acceptance of skew rays over a conical half angle of π/2 radians.

2.3 Modes Theory for Optical Fiber

The electromagnetic theory shows that the waveguide light propagation is not that simple, as multiple reflections in the core-cladding interfaces will induce constructive interference in the form of transverse standing waves only for a discrete number of incident angles below the maximum acceptance angle given by *NA*. Each of them is called a **propagation mode**, and both the light density transverse distribution and the polarization of each of them remain stable throughout the waveguide.

A mode, in this sense, **is a spatial distribution of optical energy in one or more dimensions that remains constant in time.** For a given mode, a change in wavelength can prevent the mode from propagating along the fiber.

- Maxwell's equations describe electromagnetic waves or modes as having two .components
- .The two components are the electric field, E(x, y, z), and the magnetic field, H(x, y, z) .The electric field, E, and the magnetic field, H, are at right angles to each other
- Modes traveling in an optical fiber are said to be transverse. The transverse modes propagate along the axis of the fiber. In **TE** modes, **the electric field is perpendicular .to the direction of propagation**
- .In **TM** modes, **the magnetic field is perpendicular to the direction of propagation** .The electric field is in the direction of propagation

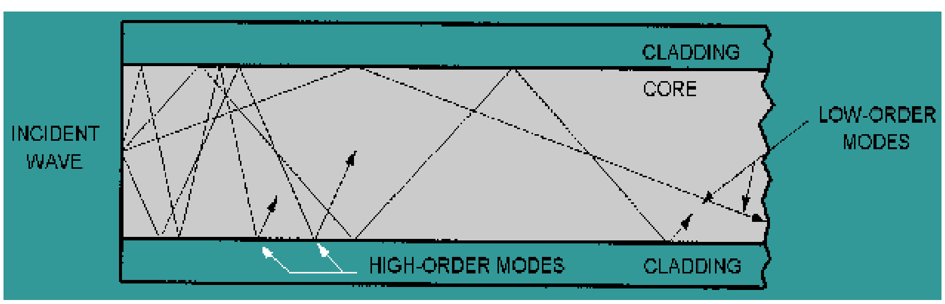


Figure 2.7: Modes in optical fiber.

Assistant Prof.
Dr. Abdulla K. Abass

2.3.1 Normalized Frequency (V number)

The **normalized frequency** is a dimensionless parameter and hence is also sometimes simply called the ***V* number** or value of the fiber. It combines in a very useful manner, the information about three important design variables for the fiber: namely, the **core radius *a***, the **relative refractive index difference *Δ*** and the **operating wavelength *λ*.**

$$V = \frac{2\pi}{\lambda} a (NA) \quad \text{(Equation 2.12)}$$

$$V = \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}} \quad \text{(Equation 2.13)}$$

The analysis of how the V-number is derived is beyond the scope of undergraduate, but it can be shown that by reducing the diameter of the fiber to a point at which the V-number is less than **2.405**, higher-order modes are effectively extinguished and single-mode operation is possible.

2.3.2 Number of Modes (M)

The number of modes can decrease with increasing the wavelength of the light. However, this alone cannot result in reducing the number of **modes to 1**. Changing from the **850** nm window to the **1550** nm window will only reduce the number of modes by a factor of **3 or 4** which is not enough on its own.

Similarly, a change in the numerical aperture can help but it only makes a **marginal improvement**. We are left with the core diameter. **The smaller the core, the less the modes.** When the **core is reduced sufficiently** the **number of modes can be reduced to just one**.

$$M = \frac{V^2}{2} \quad \text{(Equation 2.14)}$$

2.3.3 Cutoff Wavelength λ_c

The cutoff wavelength for any mode is defined as **the maximum wavelength at which that mode propagates.**

$$\lambda_c = \frac{2\pi}{V_c} a (NA) \quad \text{(Equation 2.15)}$$

$$\lambda_c = \frac{2\pi}{V_c} a n_1 (2\Delta)^{\frac{1}{2}} \quad \text{(Equation 2.16)}$$

For a fiber to operate single mode, the operating wavelength must be longer than the cutoff wavelength.

Assistant Prof.
Dr. Abdulla K. Abass

Example 2.3

What is the maximum core diameter of a fiber if it is to operate in single mode at a wavelength of 1550 nm if the NA is 0.12.

:Solution

From (Equation 2.12)

$$V = \frac{2\pi}{\lambda} a (NA)$$

Solving for a yield $a = V\lambda / (2\pi)(NA)$

For single-mode operation, V must be 2.405 or less. The maximum core diameter occurs when $V = 2.405$. So, plugging into the equation, we get

$$a_{max} = \frac{(2.405)(1550 \times 10^{-9})}{(2\pi)(0.12)} = 9.9 \mu m$$

$$d_{max} = 2 \times a = 19.7 \mu m$$

Example 2.4

Determine the cutoff wavelength for a step-index fiber to exhibit single-mode operation when the core refractive index is 1.46 and the core radius is 4.5 μm, with the relative index difference of 0.25 %.

Solution:

From (Equation 2.16)

$$\lambda_c = \frac{2\pi}{V_c} a n_1 (2\Delta)^{\frac{1}{2}} = 1214\ nm$$

Hence, the fiber is single-mode for λ> 1214 nm.

Example 2.5

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

Solution:

(a) $V = \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}} = 75.8$

(b) $M \approx V^2 / 2 = 2873$ (i.e. nearly 3000 guided modes!)

Assistant Prof.
Dr. Abdulla K. Abass

2.4 Optical Fiber Types

.Optical fibers are the actual media that guide the light. They can be made of glass or plastic The plastic fibers exhibit **much losses and tend to have low bandwidths so glass fibers are** eht si eroc ehT .tekcaj a dna gniddalc ،eroc a fo pu edam si rebif lacipyt A **.usually preferred** to5 center or the actual fiber where the light propagates. It has dimensions on the order of eht fo taht naht rewol noitcarfer fo xedni na sah dna eroc eht sdnuorrus gniddalc ehT .mµ 600 .core, in this way the light will propagate through the core by means of internal reflection Surrounding the cladding is the jacket, the outer part of the fiber. The jacket serves to protect .the entire optical fiber

When it comes to the **refractive index profiles**, optical fibers classify in ***step index*** (one homogeneous index in the core and cladding) and ***graded index*** (where the core index value decreases gradually from the fiber axis to the cladding). When it comes to the supported ***propagation modes*** they can be ***single mode*** or ***multimode***.

2.4.1 Step Index Fibers

The optical fiber with a core of constant refractive index n_1 and a cladding of a slightly lower refractive index n_2 is known as **step index fiber**. This is because the refractive index profile for this type of fiber makes a step change at the core–cladding interface, as indicated in **Figure 2.8**, which illustrates the two major types of step index fiber. The refractive index profile may be defined as:

$$n(r) = \begin{cases} n_1, & r < a \ (\text{core}) \\ n_2, & r \geq a \ (\text{cladding}) \end{cases} \qquad \text{(Equation 2.17)}$$

Figure 2.8 (a) shows a multimode step index fiber (**MMF-step index**) with a core diameter of around **50 µm** or greater, which is large enough to allow the propagation of many modes within the fiber core. This is illustrated in **Figure 2.8** (a) by the many different possible ray paths through the fiber. **Figure 2.8** (b) shows a single-mode or monomode step index fiber (**SMF**) which allows the propagation of only one transverse electromagnetic mode, and hence the core diameter must be of the order of **2 to 10 µm**. The propagation of a SMF is illustrated in **Figure 2.8** (b) as corresponding to a single ray path only (usually shown as the axial ray) through the fiber.

The SMF has the distinct advantage of low **intermodal dispersion (broadening of transmitted light pulses)**, as only one mode is transmitted, whereas with multimode step index fiber considerable dispersion may occur due to the differing group velocities of the propagating modes. This in turn restricts the maximum bandwidth attainable with MMF-step index, especially when compared with SMF. However, for lower bandwidth applications MMF have several advantages over single-mode fibers. These are:

(a) The use of spatially incoherent optical sources (e.g. most light-emitting diodes) which cannot be efficiently coupled to SMF;

(b) Larger numerical apertures, as well as core diameters, facilitating easier coupling to optical sources;

(c) Lower tolerance requirements on fiber connectors.

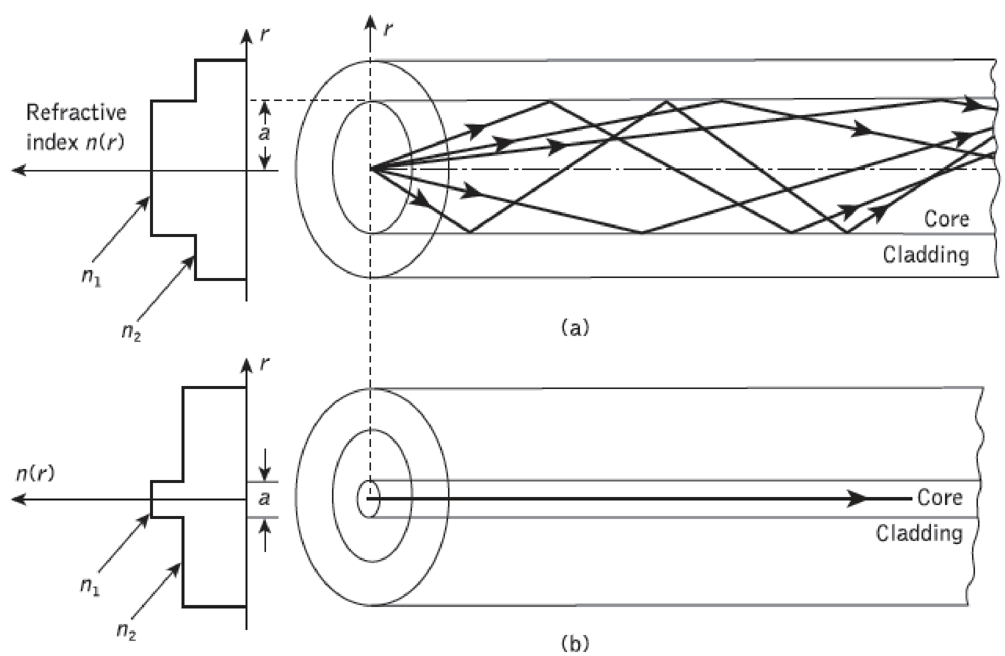


Figure 2.8: The refractive index profile and ray transmission in step index fibers:
(a) Multimode step index fiber; (b) single-mode step index fiber

Assistant Prof.
Dr. Abdulla K. Abass

2.4.2 Graded Index Fibers

Graded index fibers do not have a constant refractive index in the core but a decreasing core index *n(r)* with radial distance from a maximum value of n_1 at the axis to a constant value n_2 beyond the core radius a in the cladding.

$$n(r) = \begin{cases} n_1\left(1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right)^{\frac{1}{2}} & r < a \quad (\text{core}) \\ n_1(1-2\Delta)^{\frac{1}{2}} = n_2 & r \geq a \quad (\text{cladding}) \end{cases} \qquad \text{(Equation 2.18)}$$

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. Equation (2.75) which is a convenient method of expressing the refractive index profile of the fiber core as a variation of α, allows representation of the step index profile when α = ∞, a parabolic profile when α = 2 and a triangular profile when α = 1.

This range of refractive index profiles is illustrated in **Figure 2.9**. The graded index profiles, which at present produce the best results for multimode optical propagation have a near parabolic refractive index profile core with α ≈2.

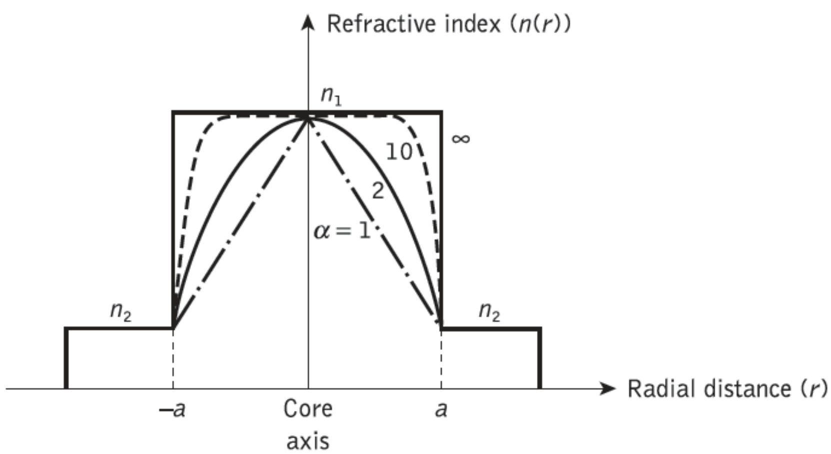


Figure 2.9: Possible fiber refractive index profiles for different values of α (given in (Equation 2.18)).

Assistant Prof.
Dr. Abdulla K. Abass

A multimode graded index fiber with a parabolic index profile core is illustrated in **Figure 2.10**. 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. This mechanism is illustrated in **Figure 2.11** 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.

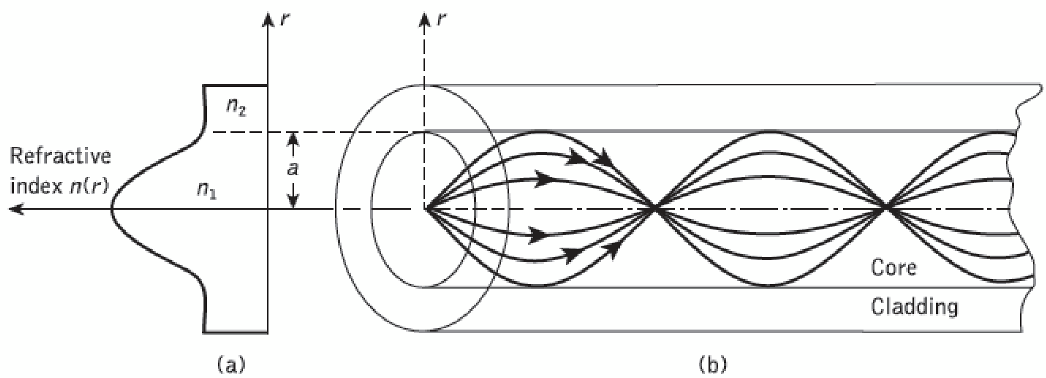


Figure 2.10: The refractive index profile and ray transmission in a multimode graded.

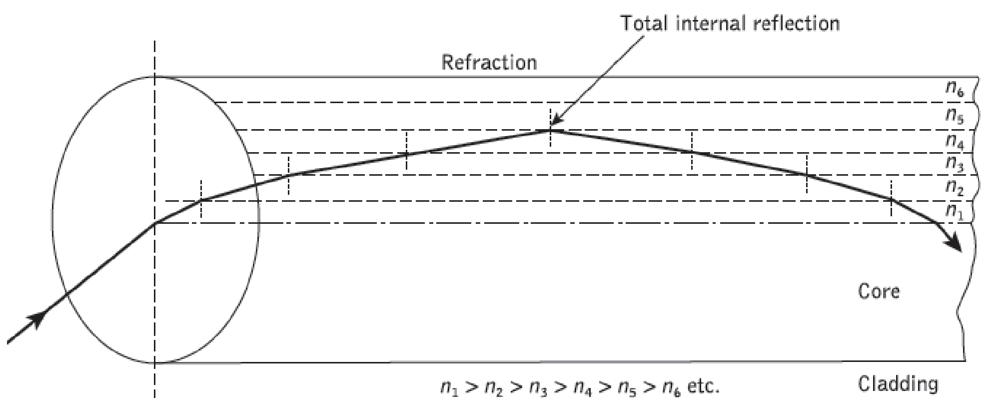


Figure 2.11: An expanded ray diagram showing refraction at the various high to low index interfaces within a graded index fiber, giving an overall curved ray path.

Assistant Prof.
Dr. Abdulla K. Abass

Example 2.6

A graded index fiber has a core with a parabolic refractive index profile which has a diameter of 50 μm. The fiber has a numerical aperture of 0.2. Estimate the total number of guided modes propagating in the fiber when it is operating at a wavelength of 1 μm.

Solution: Using (Equation 2.12), the normalized frequency for the fiber is:

$$V = \frac{2\pi}{\lambda} a (NA) = \frac{2\pi \times 25 \times 10^{-6} \times 0.2}{1 \times 10^{-6}} = 31.4$$

$$M_g = \frac{V^2}{4} = \frac{986}{4} = 247$$

Hence the fiber supports approximately 247 guided modes.

2.4.3 Single Mode Fibers

The advantage of the propagation of a single mode within an optical fiber is that the signal dispersion caused by the delay differences between different modes in a multimode fiber may be avoided. Multimode step index fibers do not lend themselves to the propagation of a single mode due to the difficulties of maintaining single-mode operation within the fiber when mode conversion (i.e. coupling) to other guided modes takes place at both input mismatches and fiber imperfections. Hence, for the transmission of a single mode the fiber must be designed to allow propagation of only one mode, while all other modes are attenuated by leakage or absorption. Following the emergence of SMF as a viable communication medium in 1983, they quickly became the dominant and the most widely used fiber types within telecommunications. Major reasons for this situation are as follows:

1. They exhibit the greatest transmission bandwidths and the lowest losses of the fiber transmission media.
2. They offer a substantial upgrade capability (i.e. future proofing) for future wide-bandwidth services using either faster optical transmitters and receivers or advanced transmission techniques (e.g. coherent technology).
3. They are compatible with the developing integrated optics technology.
4. The above reasons 1 to 3 provide confidence that the installation of single-mode fiber will provide a transmission medium which will have adequate performance, such that it will not require replacement over its anticipated lifetime of more than 20 years.

2.5 Problems

1. In each case, choose the best option.

1.1 The speed of light in a transparent material:

(a) is always the same regardless of the material chosen.
(b) is never greater than the speed of light in free space.
(c) increases if the light enters a material with a higher refractive index.
(d) is slowed down by a factor of a million within the first 60 meters.

1.2 A ray of light in a transparent material of refractive index 1.5 is approaching a material with a refractive index of 1.48. At the boundary, the critical angle is:

(a) 90°.
(b) 9.4°.
(c) 75.2°.
(d) 80.6°.

1.3 If a ray of light approaches a material with a greater refractive index:

(a) The angle of incidence will be greater than the angle of refraction.
(b) TIR will always occur.
(c) The speed of the light will increase immediately as it crosses the boundary.
(d) The angle of refraction will be greater than the angle of incidence.

If a light ray crosses the boundary between two materials with different refractive 1.4 :indices

.0° saw ecnedicni fo elgna eht fi ecalp ekat dluow noitcarfer on (a)
.rucco syawla lliw noitcarfer (b)
.lamron eht gnola gnilevart si yar tnedicni eht fi egnahc ton lliw thgil eht fo deeps eht (c)
.segnahc reven thgil fo deeps eht (d)

1.5 As the meridional ray is propagated along the optical fiber it:

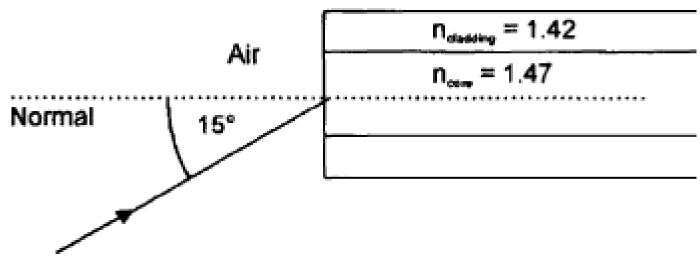
(a) Travels in a sort of spiral shape.
(b) Stays in the center of the fiber.
(c) Passes repeatedly through the center of the core.
(d) Is reflected off the inside surface of the primary buffer. This is called TIR.

1.6 No material could have a refractive index of:

(a) 1.5
(b) 1.3
(c) 1.1
(d) 0.9

1.7 The ray enters the optic fiber at an angle of incidence of 15° as shown in the figure below. The angle of refraction in the core would be:

(a) 8.3°
(b) 14.71°
(c) 75°
(d) 15.54°



1.8 If the refractive index of the core of an optical fiber was 1.47 and that of the cladding was 1.44, the cone of acceptance would have an angle of approximately:

(a) 17.19°
(b) 72.82°
(c) 78.4°
(d) 34.36°

2. Using simple ray theory, describe the mechanism for the transmission of light within an optical fiber.

3. Briefly discuss with the aid of a suitable diagram what is meant by the acceptance angle for an optical fiber.

4. Derive an expression for the numerical aperture NA.

5. An optical fiber has a numerical aperture of 0.2 and a cladding refractive index of 1.59. Determine:

(a) The acceptance angle of the fiber in **water** which has a refractive index of 1.33.

(b) The critical angle at the core–cladding interface.

Ans. (a) 8.6^0, (b) 83.6^0

Assistant Prof.
Dr. Abdulla K. Abass