Optical Communication
ECL 402
4 Credit Course

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Course Coordinator: Ms.Amanpreet Kaur , Asstt.Prof. (Senior) EECE Department
Available @ Room No.206 ,Second Floor Email:amanpreet@ncuindia.edu

Books

Text Books	**1. John M.Senior , Optical Fiber Communication Principles & Practice,PHI Publication: (3rd Edition),2008.** **2. Gerd Keiser, Optical Fiber Communication, Mc Graw Hill International Publications: (4th Edition)2010.**
Reference Books	**1 John Gowar, Optical Communication Systems, PHI Publications (2nd Edition)2001.** **2. R. Ramaswami, Kumar N. Sivarajan , Optical Networks, A practical prespective ,(2nd Edition)2002.**

Optical Communication?
Advantages?
Disadvantages?
Applications ?
Future Aspects ?

Contents of Lecture 1 @ 2:30 pm -3:20 pm in Seminar Hall

Ray theory transmission in optical fibers

- Nature of light
- Ray optics
- Refractive indices
- Snell’s Law
- Total internal reflection
- Acceptance angle
- Numerical Aperture
- V Number (Normalized Frequency)
- Modes and Cut off Wavelength

Suggested Reading: John M. Senior and Gerd Keiser

A Brief Historical Note

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- **Beyond the middle ages**:
  –Newton (1642-1726) and Huygens (1629-1695) fight over nature of light
- **18th–19th centuries**
  –Fresnel, Young experimentally observe diffraction, defeat Newton's particle theory
  –Maxwell formulates electro-magnetic equations, Hertz verifies antenna emission principle (1899)
- **20th century**
  –Quantum theory explains wave-particle duality
  –Invention of holography (1948)
  –Invention of laser principle (1954)
  –1st demonstration of laser (1960)
  –Proposal of fiber optic communications (1966)
  –1st demonstration of low-loss optical fibers (1970)
  –Optical applications proliferate **into the 21st century**:
  nonlinear optics, fiber optics, laser-based spectroscopy, computing, communications, fundamental science, medicine, biology, manufacturing, entertainment, … (Let all flowers blossom!)

The nature of light

– Modeling light:
  - ***Ray optics:*** propagation of **light rays** through simple optical components and systems.
  - ***Wave optics:*** propagations of **light waves** through optical components and systems.
  - ***Electromagnetic optics***: description of light waves in terms of **electric and magnetic fields**.
  - ***Quantum optics***: emission/absorption of **photons**, which are characteristically quantum mechanical in nature and cannot be explained by classical optics (e.g. lasers, light-emitting diodes, photodiode detectors, solar cells)

Light as waves, rays and photons

- Light is an ***electromagnetic wave***.

- While light is a wave, it nevertheless travels along straight lines or ***rays***, enabling us to analyze simple optical components (e.g. *lenses* and *mirrors*) and instruments in terms of <u>geometrical optics</u>.

- Light is also a stream of ***photons***, discrete particles carrying packets of *energy* and *momentum*. (We will cover this after mid-term.)

Ray Optics: basic laws

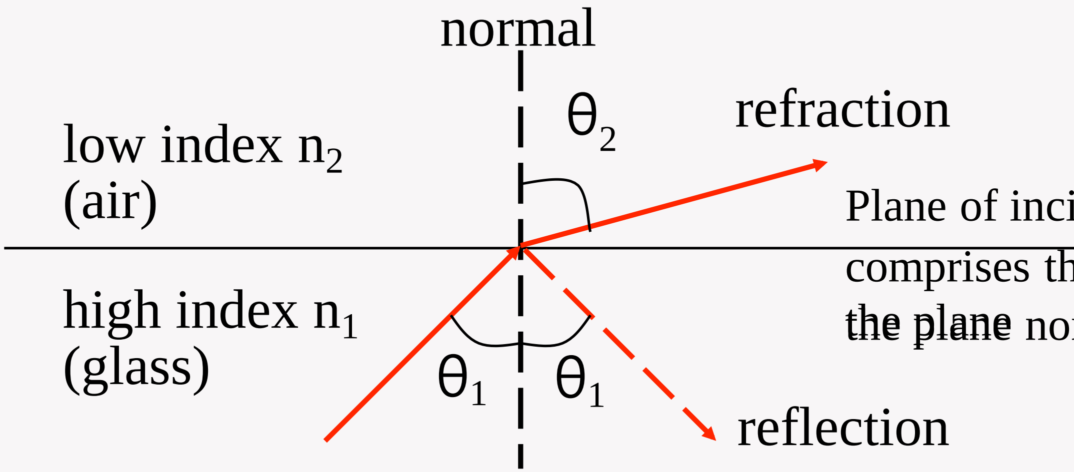
- Ray optics is based on three laws which describe the propagation of rays:

1. Light rays in homogeneous media are straight lines.
2. **Law of reflection**: Reflection from a mirror or at the boundary between two media of different *refractive indices*: the reflected ray lies in the plane of incidence, the angle of reflection equals the angle of incidence (i.e. $\theta_r = \theta_i$)
5. **Snell's law of refraction:** At the boundary between two media of different refractive index n, the refracted ray lies in the plane of incidence; the angle of refraction θ_t is related to the angle of incidence θ_i by

$$n_i \sin \theta_i = n_t \sin \theta_t$$

Snell's Law

When a ray is incident on the interface between two dielectrics of different refractive indices (e.g. glass-air), reflection and refraction occur.



Plane of incidence ≡ plane that comprises the incident ray and the plane normal

The *angle of incidence* θ_1 and the *angle of refraction* θ_2 are related to each other, and to the refractive indices of the dielectrics by Snell's law of refraction:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Refractive index

- In any dielectric medium, the speed of light becomes

$$v = c/n$$

The factor n is the *index of refraction* (or *refractive index*) of the medium.

e.g. For air and gases, v ~ c, so that n ~ 1. At optic frequencies, the refractive index of water is 1.33.

e.g. Glass has many compositions, each with a slightly different n. An approximate refractive index of 1.5 is representative for the silica glasses used in fibers; more precise values for these glasses lie between ~1.45 and ~1.48.

Index of refraction for some materials

Air	1.0
Water	1.33
Magnesium fluoride	1.38
Fused silica (SiO_2)	1.46
Sapphire (Al_2O_3)	1.8
Lithium niobate ($LiNbO_3$)	2.25
Indium phosphide (InP)	3.21
Gallium arsenide (GaAs)	3.35
Silicon (Si) 3.48	
Indium gallium arsenide phosphide (InGaAsP)	3.51
Aluminum gallium arsenide (AlGaAs)	3.6
Germanium (Ge)	4.0

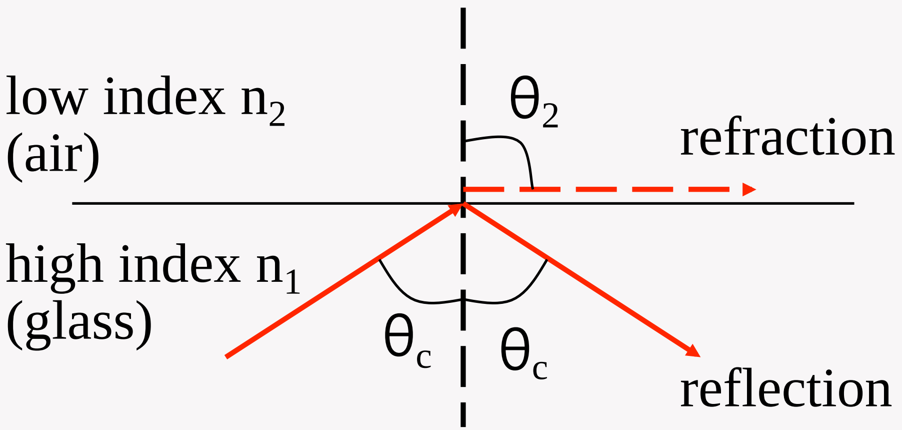
*The index varies with a number of parameters, such as wavelength and temperature.

Critical angle

For $n_1 > n_2$, the angle of refraction θ_2 is always *greater* than the angle of incidence θ_1.

- When the angle of refraction θ_2 is 90^o, the refracted ray emerges *parallel* to the interface between the media.

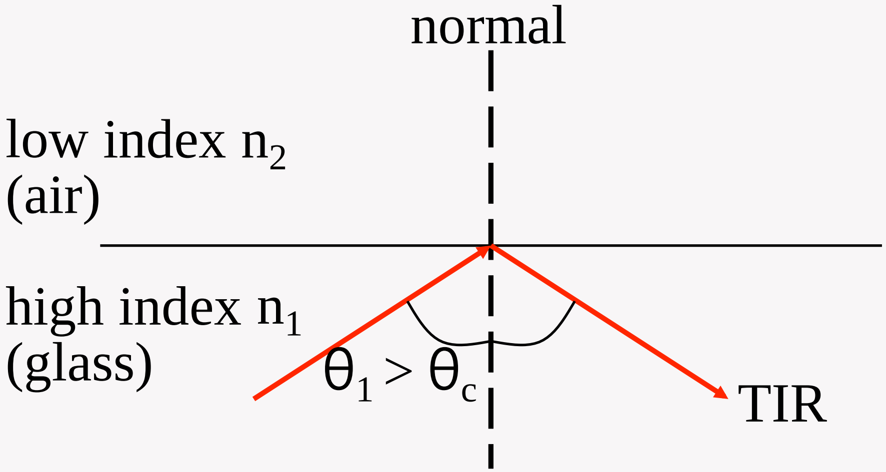
This is the *limiting* case of refraction and the angle of incidence is known as the <u>critical angle</u> θ_c.



$$\sin \theta_c = n_2 / n_1$$

Total internal reflection

- At angles of incidence $\theta > \theta_c$, the light is totally reflected back into the incidence higher refractive index medium. This is known as <u>total internal reflection</u>.

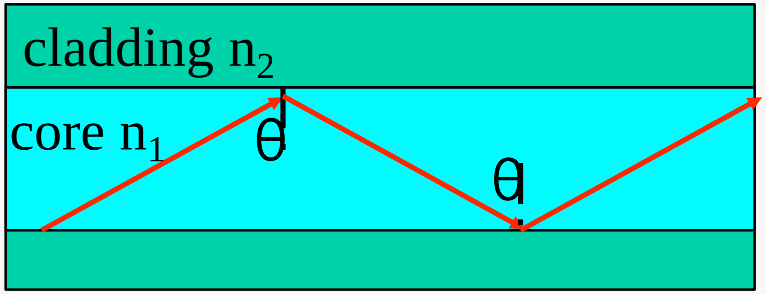


e.g. $n_1 = 1.44$, $n_2 = 1$, then $\theta_c = \sin^{-1}(1/1.44) = 44^o$

Total internal reflection: $\theta_1 > \theta_c$

Light ray guiding condition

- Light ray that satisfies *total internal reflection* at the interface of the higher refractive index core and the lower refractive index cladding can be guided along an optical fiber.



e.g. Under what condition will light be trapped inside the fiber core?
$n_1 = 1.46$; $n_2 = 1.44$

$$\theta > \theta_c$$

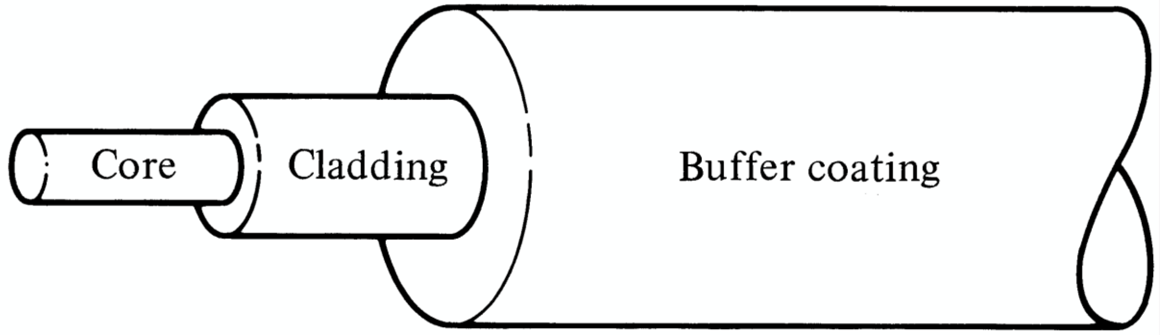
$$\theta_c = \sin^{-1}(n_2/n_1) = \sin^{-1}(1.44/1.46) = 80.5^o$$

Evanescent wave

- In spite of the fact that the incident energy is totally reflected when the angle of incidence exceeds the critical angle, there is still an electromagnetic wave field in the region beyond the boundary. This field is known as the *evanescent wave*.

Optical fiber structures

- A typical bare fiber consists of a core, a cladding and a polymer jacket (buffer coating).



- The polymer coating is the first line of mechanical protection.

- The coating also reduces the internal reflection at the cladding, so light is only guided by the core.

Silica optical fibers

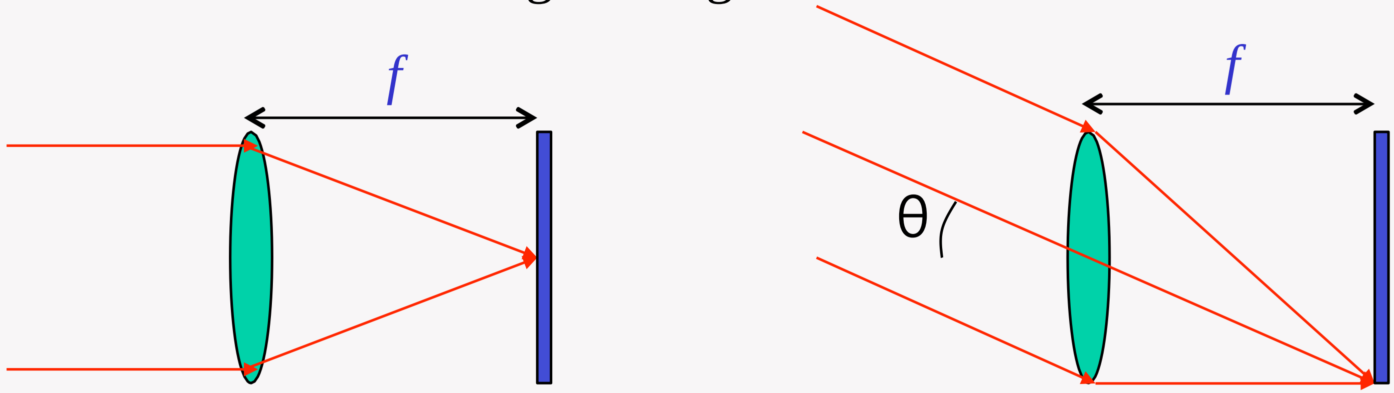
- Both the core and the cladding are made from a type of glass known as silica (SiO_2) which is *almost transparent in the visible and near-IR*.

- In the case that the refractive index changes in a "step" between the core and the cladding. This fiber structure is known as step-index fiber.

- The higher core refractive index (~ 0.3% higher) is typically obtained by doping the silica core with germanium dioxide (GeO_2).

Numerical aperture

- An important characteristic of an optic system is its ability to collect light incident over a wide range of angles.



The numerical aperture (NA) is defined as:

$$NA = n_o \sin \theta$$

where n_o is the refractive index of the medium between the lens and the image plane (e.g. a photodetector) and θ is the maximum acceptance angle.

- The definition of numerical aperture applies to *all light-collecting systems*, including optical fibers.

e.g. Light rays incident at angles *outside* the collection cone for a fiber will *not* propagate along the fiber (*instead will attenuate rapidly*).

- The numerical aperture is often measured in air, $n_o = 1$

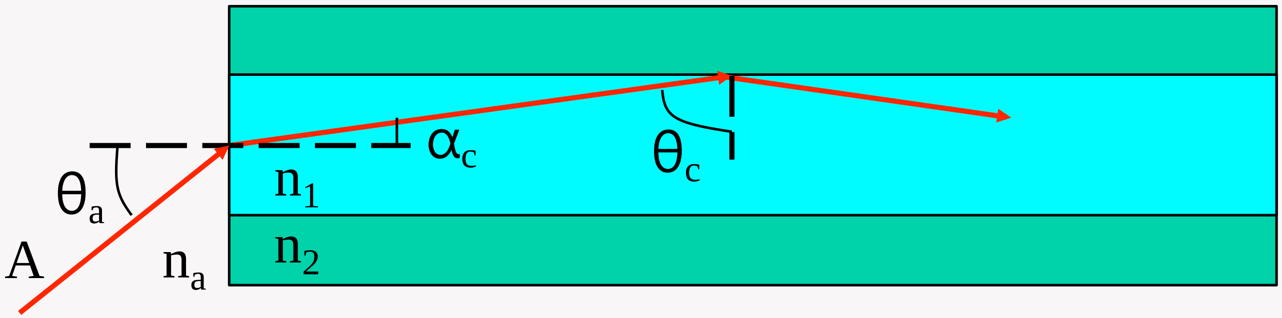
$$NA = \sin \theta$$

- A *low* NA indicates a *small* acceptance angle.

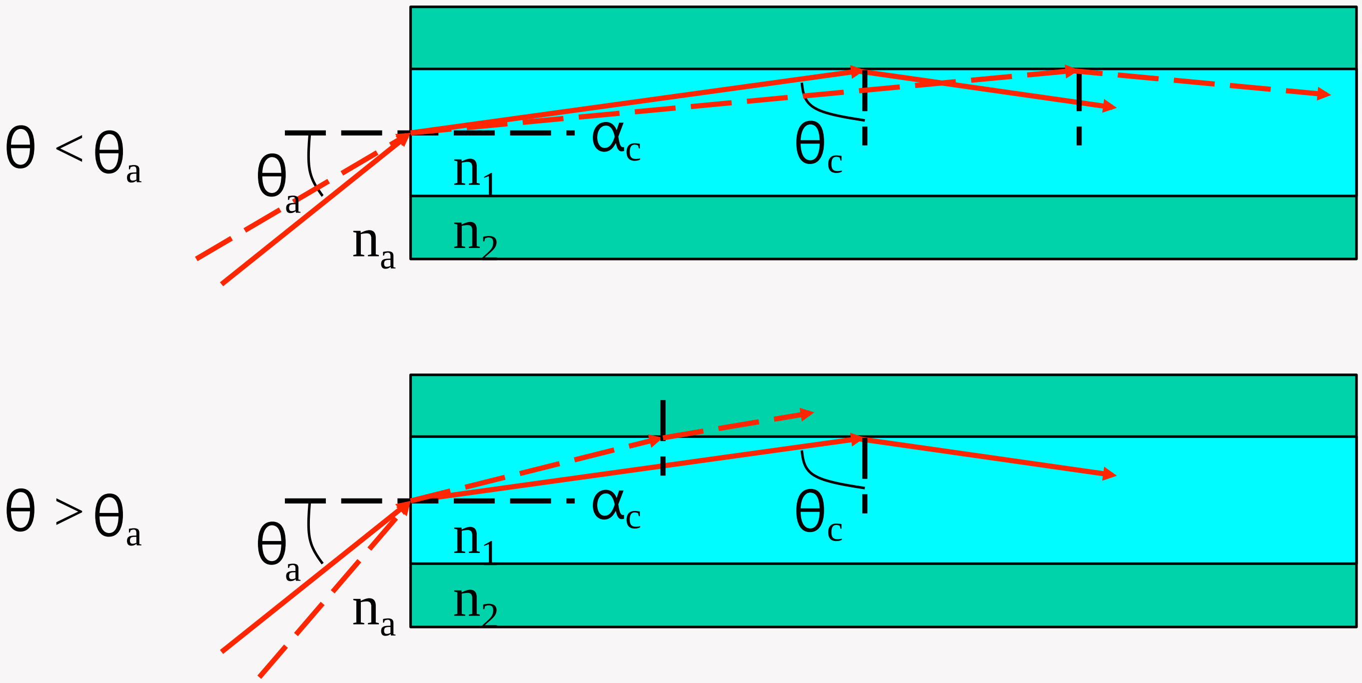
$\Rightarrow$ Light coupling to a low-NA optical system (e.g. fiber) is more difficult (*alignment is more sensitive*) and less efficient (*some of the rays are outside the acceptance angle*) than is coupling to a high-NA optical system.

Acceptance angle

- Only rays with a sufficiently shallow grazing angle (i.e. with an angle to the normal greater than θ_c) at the core-cladding interface are transmitted by total internal reflection.



- Ray A incident at the critical angle θ_c at the core-cladding interface <u>enters the fiber core at an angle θ_a to the fiber axis</u>, and is refracted at the <u>air-core</u> interface.



- Any rays which are incident into the fiber core at an angle > θ_a have an incident angle less than θ_c at the core-cladding interface.

These rays will NOT be totally internal reflected, thus eventually loss to radiation (at the cladding-jacket interface).

- Light rays will be confined inside the fiber core if it is input-coupled at the fiber core end-face within the acceptance angle θ_a.

e.g. What is the fiber acceptance angle when $n_1 = 1.46$ and $n_2 = 1.44$?

$\theta_c = \sin^{-1}(n_2/n_1) = 80.5^o \Rightarrow \alpha_c = 90^o - \theta_c = 9.5^o$

using $\sin\theta_a = n_1 \sin\alpha_c$ (taking $n_a = 1$)

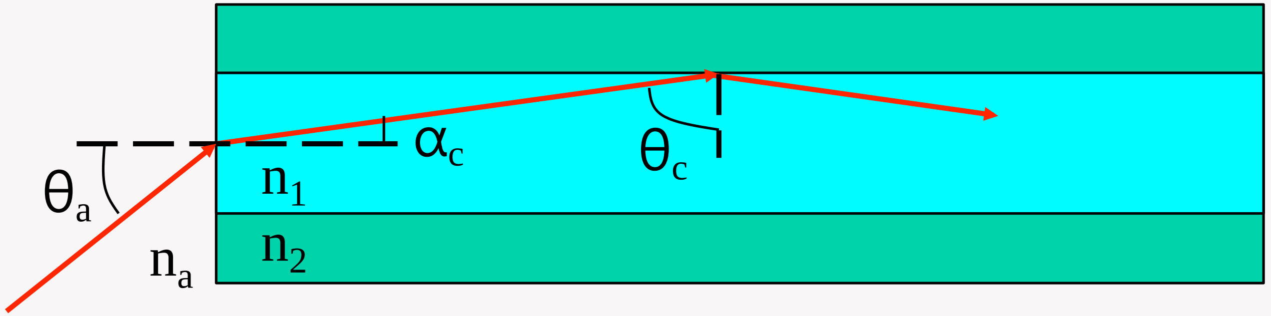
$\theta_a = \sin^{-1}(n_1 \sin\alpha_c) = \sin^{-1}(1.46 \sin 9.5^o) \sim 14^o$

=> the acceptance angle $\theta_a \sim 14^o$

Fiber numerical aperture

In fiber optics, we describe the fiber acceptance angle using **Numerical Aperture (NA):**

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



- We can relate the acceptance angle θ_a and the refractive indices of the core n_1, cladding n_2 and air n_a.

- Assuming the end face at the fiber core is *flat* and *normal* to the fiber axis (when the fiber has a “nice” cleave), we consider the refraction at the air-core interface using Snell’s law:

$$\text{At } \theta_a\text{:} \quad n_a \sin\theta_a = n_1 \sin\alpha_c$$

launching the light from air: $\quad \sin\theta_a = n_1 \sin\alpha_c$

$(n_a \sim 1)$ $\quad = n_1 \cos\theta_c$

$$= n_1 (1 - \sin^2\theta_c)^{1/2}$$

$$= n_1 (1 - n_{2_2}/n_{1_2})_{1/2}$$

$$= (n_1^2 - n_2^2)^{1/2}$$

- Fiber NA therefore characterizes the fiber's ability to gather light from a source and guide the light.

> **e.g.** What is the fiber numerical aperture when $n_1 = 1.46$ and $n_2 = 1.44$?
>
> $$NA = \sin \theta_a = (1.46^2 - 1.44^2)^{1/2} = 0.24$$

- It is a common practice to define a relative refractive index Δ as:

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

$$(n_1 \sim n_2) \quad \Rightarrow \quad NA = n_1 (2\Delta)^{1/2}$$

i.e. Fiber NA only depends on n_1 and Δ.

Large-NA fibers?

- Developing ways for fiber to collect light efficiently was an important early step in developing practical fiber optic communications (particularly in the 1970s)

- It seems logical to have optical fibers with NA as large as possible … with as large Δ as possible … in order to couple maximum amount of light into the fiber.

- Soon, we will find out that such large-NA fibers tend to be "multimode" and are *unsuitable* for high-speed communications because of a limitation known as modal dispersion.

- Relatively small-NA fibers are therefore used for high-speed optical communication systems.

Typical fiber NA

- Silica fibers for long-haul transmission are designed to have numerical apertures from about 0.1 to 0.3.

- Plastic, rather than glass, fibers are available for short-haul communications (e.g. within an automobile). These fibers are restricted to short lengths because of the relatively high attenuation in plastic materials.

Plastic optical fibers (POFs) are designed to have high numerical apertures (typically, 0.4 – 0.5) to improve coupling efficiency, and so partially offset the high propagation losses and also enable alignment tolerance.

Optical Fiber Type Comparisons

- The indices are uniform in a step-index fiber
- The index varies with the core radius in a graded-index fiber

Typical diameters

SM core: 8-10 μm

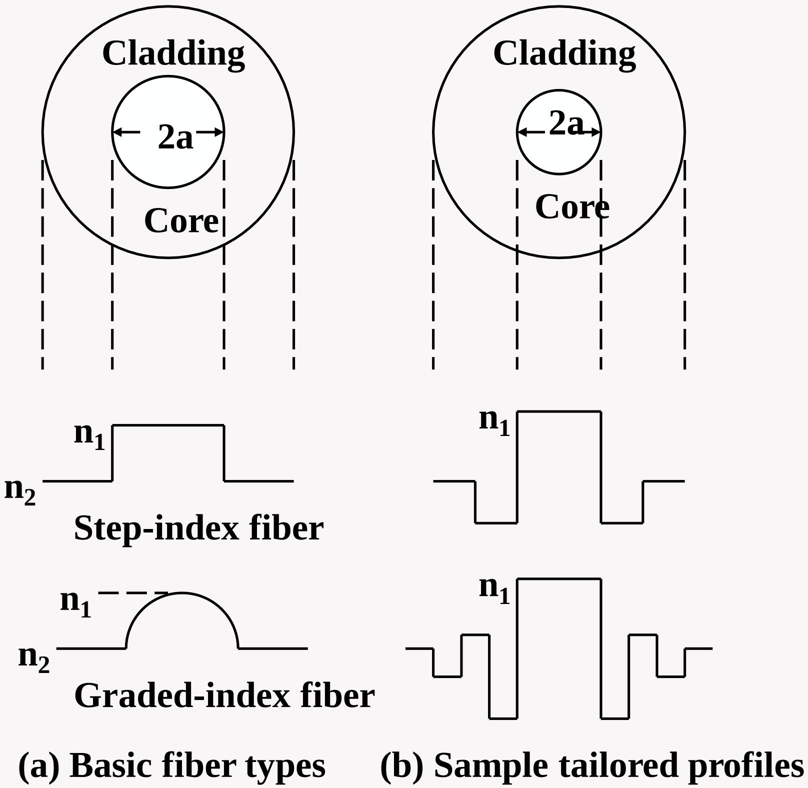
SM cladding: 125 μm

MM core: 50 or 62.5 μm

MM cladding: 125 μm

(SM = single mode)

(MM = multimode)



Numerical Aperture Example

Example 2.4 Consider a multimode silica fiber that has a core refractive index $n_1 = 1.480$ and a cladding index $n_2 = 1.460$. Find (a) the critical angle, (b) the numerical aperture, and (c) the acceptance angle.

Solution: (a) From Eq. (2.21), the critical angle is given by

$$\varphi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.460}{1.480} = 80.5^\circ$$

(b) From Eq. (2.23) the numerical aperture is

$$\mathrm{NA} = \left(n_1^2 - n_2^2\right)^{1/2} = 0.242$$

(c) From Eq. (2.22) the acceptance angle in air ($n = 1.00$) is

$$\theta_A = \sin^{-1}\mathrm{NA} = \sin^{-1}0.242 = 14^\circ$$

Example 2.5 Consider a multimode fiber that has a core refractive index of 1.480 and a core-cladding index difference 2.0 percent ($\Delta = 0.020$). Find the (a) numerical aperture, (b) the acceptance angle, and (c) the critical angle.

Solution: From Eq. (2.20), the cladding index is $n_2 = n_1(1 - \Delta) = 1.480(0.980) = 1.450$.

(a) From Eq. (2.23) we find that the numerical aperture is

$$\mathrm{NA} = n_1\sqrt{2\Delta} = 1.480(0.04)^{1/2} = 0.296$$

(b) Using Eq. (2.22) the acceptance angle in air ($n = 1.00$) is

$$\theta_A = \sin^{-1}\mathrm{NA} = \sin^{-1}0.296 = 17.2^\circ$$

(c) From Eq. (2.21) the critical angle at the core–cladding interface is

$$\varphi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}0.980 = 78.5^\circ$$

V Number Definition

- An important parameter connected with the cutoff condition is the ***V number*** defined by

$$V = \frac{2\pi a}{\lambda}\left(n_1^2 - n_2^2\right)^{1/2} = \frac{2\pi a}{\lambda}\mathrm{NA}$$

Example 2.6 A step-index fiber has a normalized frequency $V = 26.6$ at a 1300-nm wavelength. If the core radius is 25 μm, what is the numerical aperture?

Solution: From Eq. (2.27) the NA is

$$NA = V\frac{\lambda}{2\pi a} = 26.6\frac{1.30\,\mu\text{m}}{2\pi \times 25\,\mu\text{m}} = 0.22$$

The total number of guided modes M for a *step-index* fiber is *approximately* related to the V number (for $V > 20$) as follows,

$$M \approx V^2 / 2$$

e.g. 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.

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

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

Cutoff wavelength

- The cutoff wavelength for any mode is defined as the maximum wavelength at which that mode propagates. It is the value of λ that corresponds to V_c for the mode concerns.

$$\lambda_c = (2\pi a/(V_c)\,(n_1^2 - n_2^2)^{1/2}$$

The range of wavelengths over which mode will propagate is thus $0 < \lambda < \lambda_c$.

- *For a fiber to operate single mode*, the operating wavelength must be *longer* than the cutoff wavelength for the mode. *This is an important specification* for a single-mode fiber, and is usually given the designation λ_c. We find λ_c by setting $V_c = 2.405$. The range of wavelengths for singlemode operation is $\lambda > \lambda_c$.

Singlemode condition

For single-mode operation, *only the fundamental mode exists*.

The ***cutoff normalized frequency*** (V_c) for the next higher order mode in step-index fibers occurs at $\mathbf{V_c = 2.405}$.

=> single-mode propagation of the mode in step-index fibers:

$$V < 2.405$$

e.g. 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 %.

$$\lambda_c = (2\pi a n_1/2.405)\,(2\Delta)^{1/2} = 1214 \text{ nm.}$$

Hence, the fiber is single-mode for $\lambda > 1214$ nm.

Any Questions ???

Thank You !!