Optical Fiber Communication Systems

Lecture two

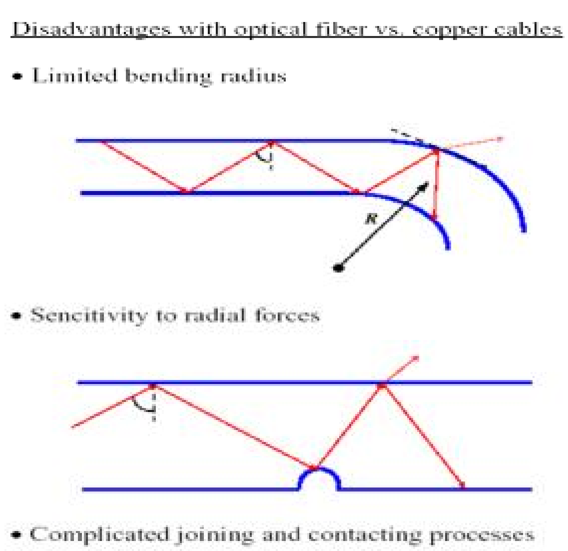
Advantages of Fiber Optics

- Why are fiber-optic systems revolutionizing telecommunications?

  Compared to conventional metal wire (copper wire), optical fibers are:

1. **Less expensive.-**
2. **Thinner**.
3. **Lightweight** Example: 700 km of copper cabling weighs 20 tonnes, while same cable run with fiber weighs 7 kg

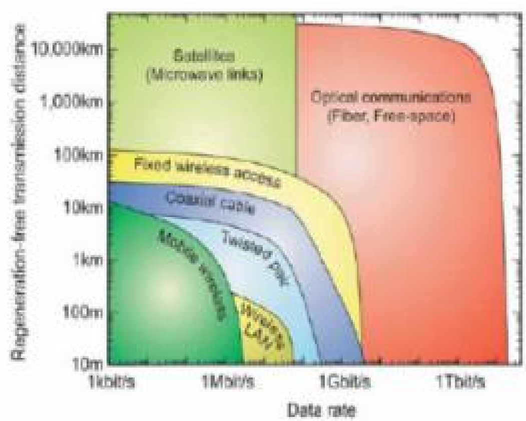
1. **Higher carrying capacity**.
2. **Less signal degradation.**
3. **Flexible.**
4. **Strength**
5. **Immunity to electrical interference**
6. **Longer life expectancy than copper or coaxial cable.**
7. **Immunity to electromagnetic interference (Can be placed alongside powerlines or close to radiative equipment e.g. CAT scanners)**



Cable Size Comparison: Copper vs. Fiber

This is a standard copper cable used for telephone service. This carries about 300 phone calls

One of these fibers can carry up to 10 million telephone Calls.



Transmission distance as a function of the data rate for different transmission technologies. At present the bandwidth-distance product for optical communication is a factor of a billion higher than for DSL!

Fiber Optic Applications

Worldwide communication requirements are growing at an amazing rate. Fiber optics are key to this growth. Fiber Optic Applications provides an overview of voice, video, and data communications. In addition to:

- Voice Networks.
- HDTV, CCTV and CATV Video
- High Speed Data Network
- Next Generation Internet
- All Optical Networks

Table 1.1 *Spectral band designations used in optical fiber communications*

Name	*Designation*	*Spectrum (nm)*	*Origin of Name*
Original band	O-band	1260 to 1360	Original (first) region used for single-mode fiber links
Extended band	E-band	1360 to 1460	Link use can extend into this region for fibers with low water content
Short band	S-band	1460 to 1530	Wavelengths are shorter than the C-band but higher than the E-band
Conventional band	C-band	1530 to 1565	Wavelength region used by a conventional EDFA
Long band	L-band	1565 to 1625	Gain decreases steadily to 1 at 1625 nm in this longer wavelength band
Ultra-long band	U-band	1625 to 1675	Region beyond the response capability of an EDFA

Fig. 1.3 *Designations of spectral bands used for optical fiber communications*

Fig. 1-3: Operating ranges of components

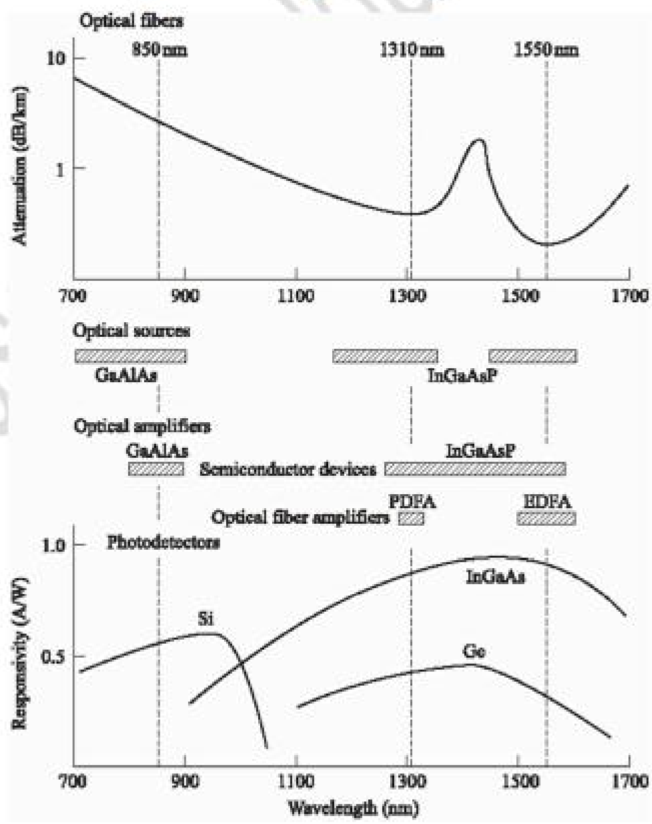
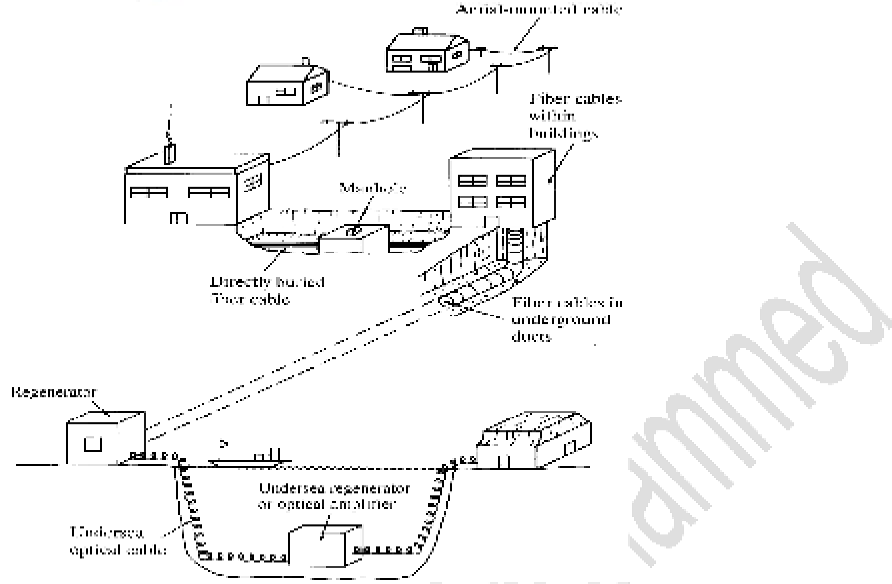
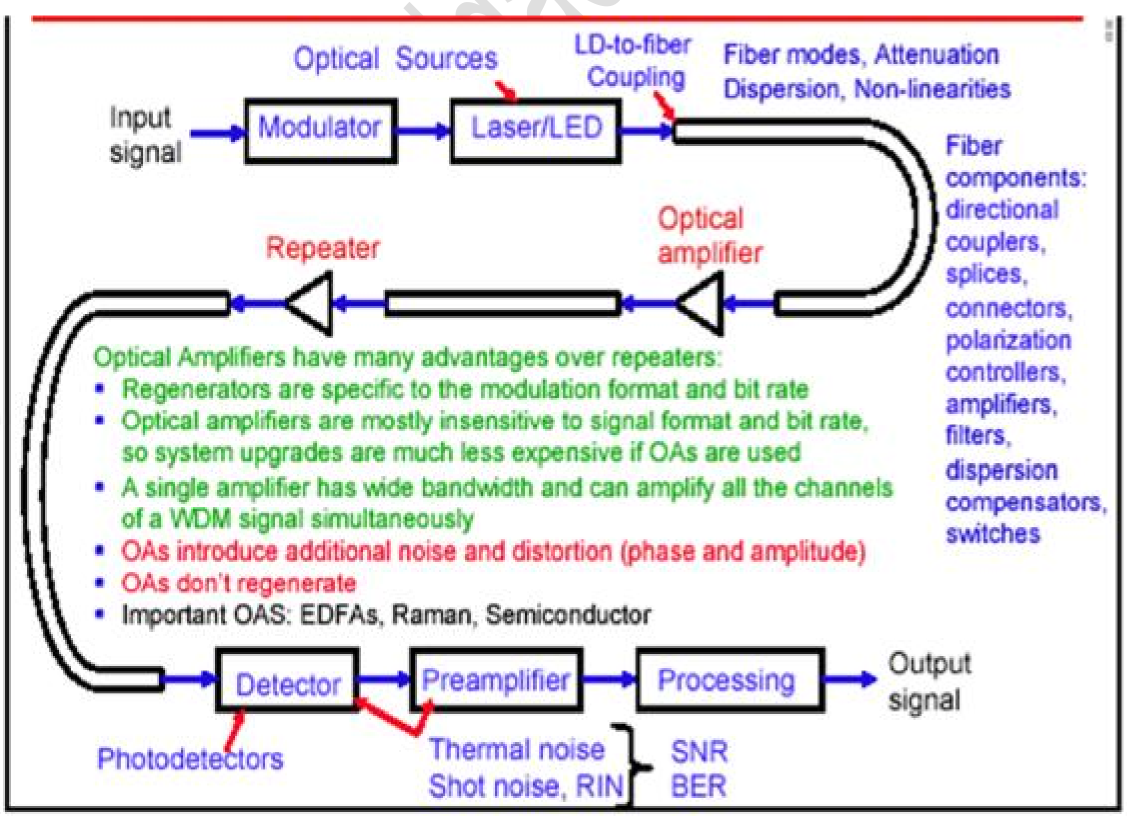


Fig. 1-6: Optical fiber cable installations



Optical Fiber Communication system



- **Transmitter -** Produces and encodes the light signals

1. interface circuit and
2. a source drive circuit
3. optical source (laser diode and light emitting diode LED).

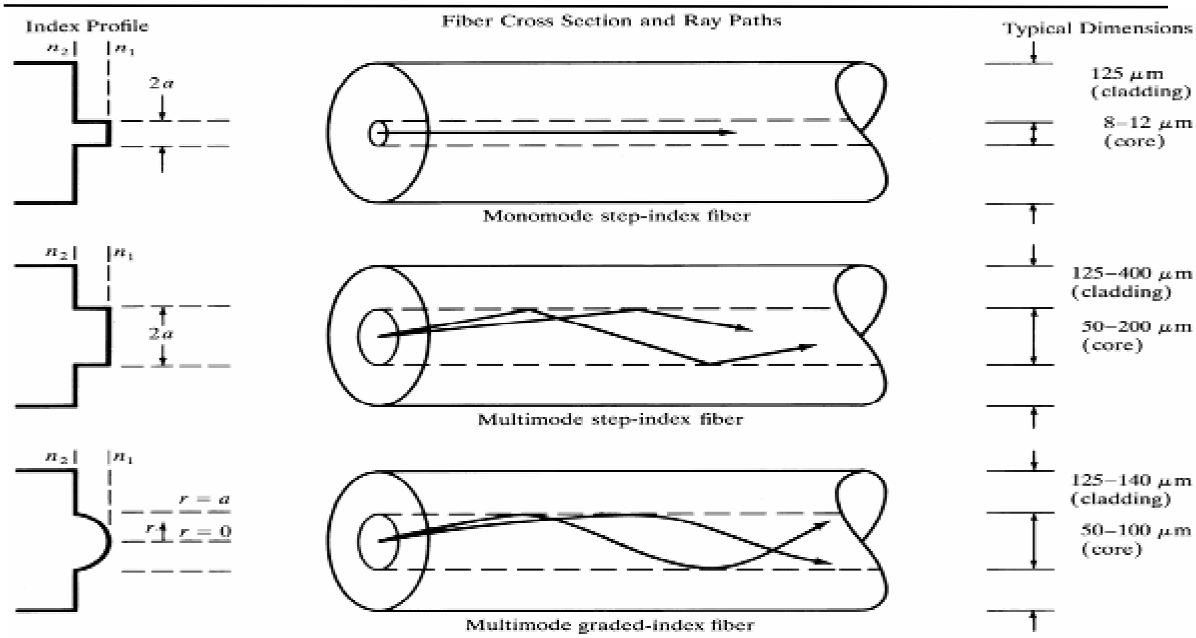
- **Optical fiber -** Conducts the light signals over a distance
- **Optical regenerator -** May be necessary to boost the light signal (for long distances).
- **Optical receiver -** Receives and decodes the light signals

1. the optical detector (semiconductor positive-intrinsic-negative (*PIN*) diode or an avalanche photodiode (APD))
2. the signal-conditioning circuits.

Optical fibers are very thin cylindrical strands of very pure glass about the diameter of a human hair. They are arranged in bundles called **optical cables** and used to transmit light signals over long distances. Some optical fibers can be made from **plastic**. These fibers have a large core (0.04 inches or 1 mm diameter).

- **Parts of a single optical fiber** :
  - **Core -** Thin glass center of the fiber where the light travels with refractive index $\mathbf{n_1}$.
  - **Cladding -** Outer optical material surrounding the core that reflects the light back into the core with refractive index $\mathbf{n_2}$ so that $\mathbf{n_1 > n_2}$.
  - **Buffer coating -** Plastic coating that protects the fiber from damage and moisture.

A set of guided electromagnetic waves is called the **MODES** of an optical fiber



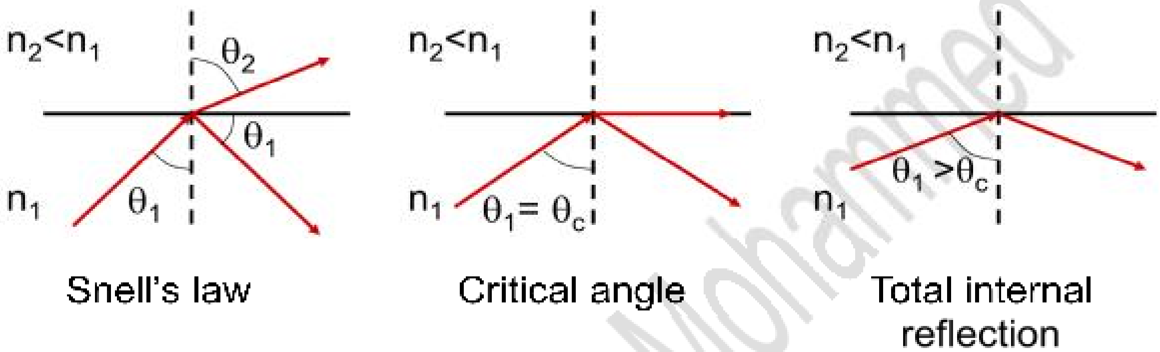
- **Multimode Step Index fiber (MMSI)**: in which the refractive index of the core is uniform throughout and undergoes an abrupt (step) at the core _ cladding boundary. It allows a multiple modes to propagate through this fiber .
- **Multimode Graded Index fiber (MMGI)**: The core refractive index is made to vary as a function of the radial distance from the center of the core of the fiber It allows a multiple modes to propagate along it.

Multimode fibers have larger cores (about 62.5 microns in diameter) and transmit infrared light (wavelength = 850 to 1300 nm). Used to transmit signals (used in computer networks, local area networks).

- **Singlemode Step Index fiber (SMSI):** Only a single path exists througth the cable core through which light can trave. The SMSI fiber has the same refractive index relationship as the MMSI fiber. have small cores (9 µm in diameter) and transmit infrared laser light (wavelength = 1300 to 1550 nm). Used to transmit one signal per fiber (used in telephones and cable TV)

Total internal reflection (TIR)

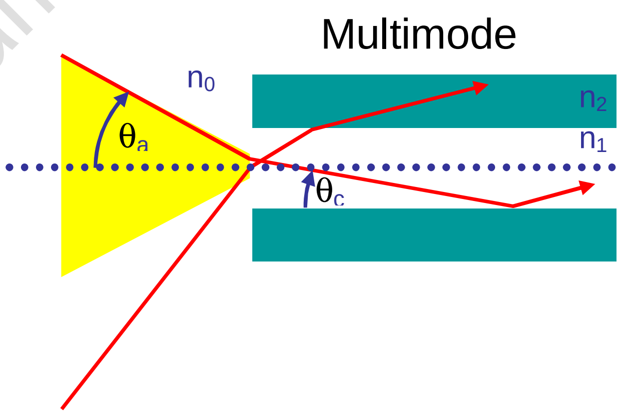
Total internal reflection (TIR) is the most important phenomenon for the guiding of light in optical fibers. Under the condition of total internal reflection, light can be completely reflected at a dielectric interface without any reflective coating. It is required for TIR that the ray of light be incidental on a dielectric interface from the high refractive index to the low refractive side.



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

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

At angle, θ_a a ray will be refracted along the boundary of the core and cladding. The angle θ_a is referred to as the **maximum acceptance angle** and θ_c is the critical angle for internal reflection. The angles θ_a and θ_c are determined by the refractive indices of core and cladding. Therefore,



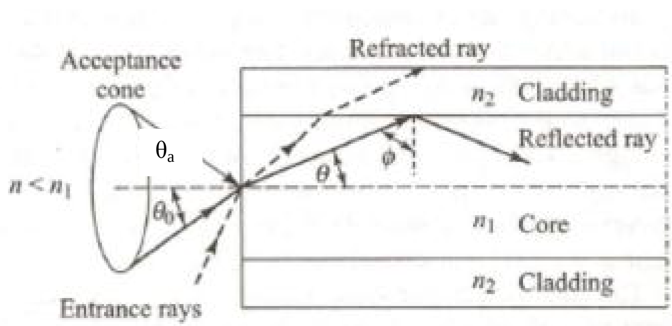


Fig. 2.17 *Meridional ray optics representation of the propagation mechanism in an ideal step-index optical waveguide*

1. a ray incident on the core-cladding boundary at an angle **less** than θ_c will not undergo total internal reflection and finally will be lost.
2. however at an angle **greater** than θ_c, a ray will propagate inside the core by a series of internal reflections.

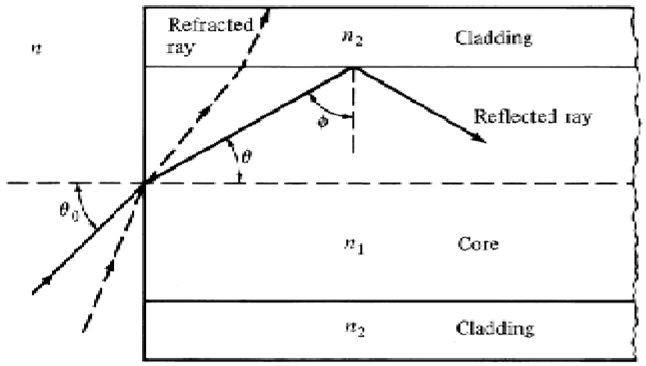
Numerical Aperture NA of an optical fiber and is defined as the light-gathering power of the optical fiber.

Relative refractive Index difference Δ

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

if $n_1 \approx n_2 = n$:

$$\Delta \approx \frac{n_1 - n_2}{n_1} = \frac{\Delta n}{n}$$



Numerical aperture:

$$NA \equiv n_0 \sin \theta_a = \sqrt{n_1^2 - n_2^2}$$

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

$$NA = 0.1 \Rightarrow \theta_a \approx 6^\circ$$

NA lies between 0 and 1.when:

- NA = 0 that means the fiber gathers no light (corresponding to $\phi_a = 0^o$)..
- NA = 1 means the fiber gathers all light falls on it (corresponding to $\phi_a = 90^o$).

Homework derive the equation $NA = \sin^{-1}(\theta_a) = (n_1^2 - n_2^2)^{1/2}$ stating from Snell's law.

The refractive index profile, n(r), in GRIN fiber can be expressed as,

$n(r) = n_1 (1 - 2\Delta(r/a)^g$ for r < a [core]

$n(r) = n_2$ for $r \geq a$ [cladding]

Where r is the distance from the fiber axis, a is the radius of the core and g is the profile of refractive index.

g = 1 ⟶ refractive index falls linearly.

g = 2 → refractive index falls parabola.

if g is infinity → light rays would be the same as that of **SI** fiber.

- When the profile of refractive index in a GRIN fiber is parabolic (g = 2), the bandwidth is maximized.

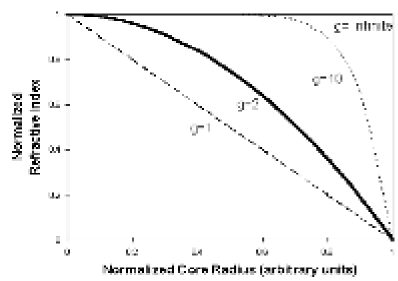


Figure shows the profile of refractive index from core center to the outside edge of GRIN fiber with different g-values.

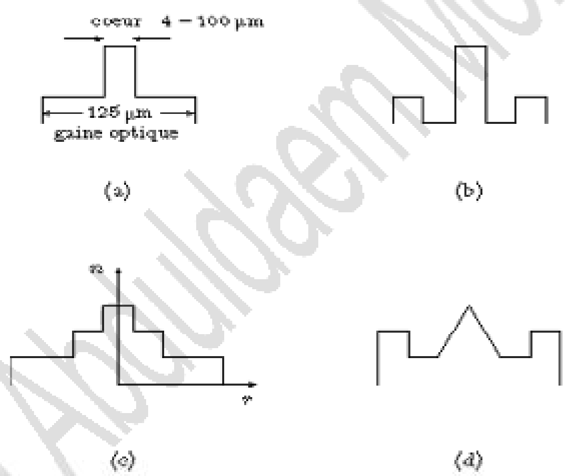


Figure: Index profiles: (a) Matched Cladding Step Index Profile; (b) W- profile or Depressed Cladding Profile; (c) Raise Cladding Profile; (d) Depressed Cladding

Example1: A typical relative refractive index difference for an optical fiber designed for long distance transmission is 1%. Estimate the **NA** and the solid angle acceptance angle in air for the fiber when the core index is 1.46. Further, calculate the **critical angle at the core-cladding interface** within the fiber. It may be assumed that the concepts of geometric optics hold for the fiber.

Sol.

$NA = n_1(2\Delta)^{1/2} = 1.46\,(0.02)^{1/2}$
$= 0.21$

For small angles the solid acceptance angle in air ξ is given by:

$\xi = \pi\theta_a^2 = \pi\sin^2\theta_a$

But $\xi = \pi(NA)^2 = \pi\, 0.04$
$= 0.13$ rad

Using

$\Delta = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$

$\therefore\ n_2/n_1 = 1 - \Delta$
$= 0.99$

The critical angle at the core-cladding interface is

$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1} 0.99$
$= 81.9^\circ$

q Normalized Frequency(V).

$$V = \frac{2p}{l} a\, NA = \frac{2p}{l} a n_1 (2\Delta)^{1/2} \qquad 1$$

where *a* is the core radius, and λ; is the operating wavelength of light in air.

Ø V determines how many modes a fiber can support.

$$N = \frac{V^2}{2}\frac{g}{g+2}$$

Ø V is a dimensionless quantity.

Ø is also related to the fiber's cutoff wavelength. The **cutoff wavelength** of a single mode fiber is the wavelength above which the fiber propagates only the fundamental mode. A single mode operation only occurs above a theoretical cutoff wavelength lc is given by

$$l_c = \frac{2p a n_1}{V_c}(2\Delta)^{1/2} \qquad 2$$

Where V_c is the cutoff normalized frequency. Hence λ_c is the cutoff wavelength above which a particular fiber becomes single moded. By dividing eq. 2 by eq.1 for the same fiber one can obtain the inverse relationship:

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c} \qquad 3$$

- Thus for step index fiber where $V_c = 2.405$, the cutoff wavelength is given by:

$$\lambda_c = \frac{V\lambda}{2.405} \qquad 4$$

Senior 95

Ex. A graded index fiber has a core with a parabolic refractive index 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 1μ.

Sol. The normalized frequency for the fiber is:

$$V = \frac{2\pi}{\lambda} a (NA) = \frac{2\pi \times 25\times10^{-6} \times 0.2}{1\times10^{-6}} = 31.4$$

The mode volum number may be obtained for a parabolic profile

$$N \simeq \frac{V^2}{2} \cdot \frac{\alpha}{\alpha+2} \simeq \frac{V^2}{4} \simeq \frac{986}{4} = 247$$

Hence the fiber supports approximately 247 guided modes.

Types of Fibers

Type	Diameter Core/ Cladding (Micrometers)	NA	Attenuation (dB/km)	Distance -Bandwidth Product (MHz-km)
Short distance multimode)	100/200	0.3	5 - 10	20 - 200
Single mode	6/125	0.03	□ 1	□ 1000
Long distance graded index	50/125	0.2	1 - 5	500 - 1500

Characteristics of Cables Based on Copper Wire and on Optical Fibers

	Copper	Fiber
Diameter (inches)	2.8	0.5
Weight (lb/1000-ft length)	4800	80
Data capacity (megabits/sec)	3.15	417

Consideration of **performance** comes to answering three questions:

1) How much light can be **coupled** into the core through the external acceptance angle?

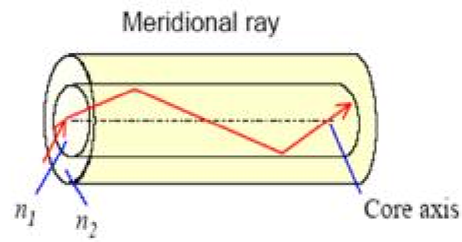
2) How much **attenuation** will a light ray experience in propagating down the core?

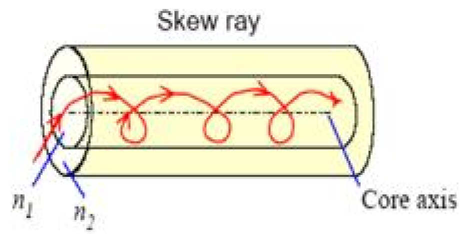
3) How much time **dispersion** will light rays representing the same input pulse experience in propagating down the core?

Ray Transmission in Fibers

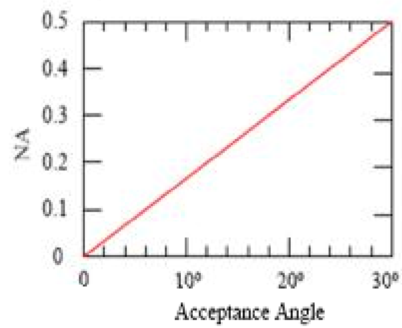
- Meridional rays: pass through the core axis ⇒ TE and TM modes
- Skew rays: follow a helical path through the fiber ⇒ hybrid modes (EH and HE)
- Acceptance angle:

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



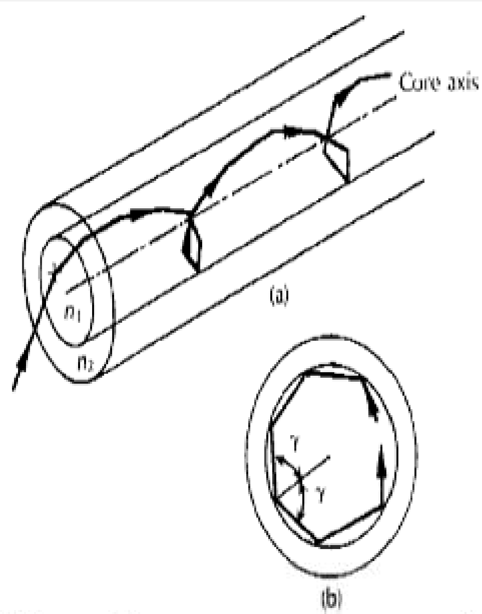


Fiber	Δ	NA	θ_a
All-glass	0.0135	0.24	13.9°
PCS	0.041	0.41	24.2°
All-plastic	0.054	0.48	29°



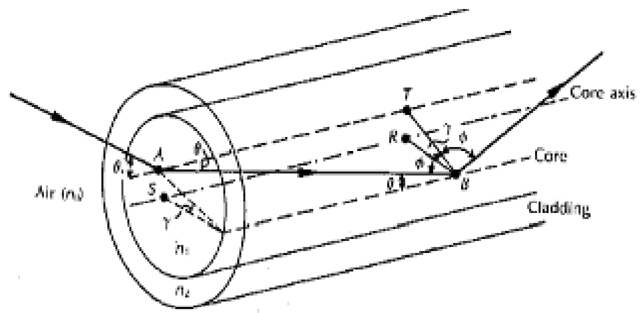
- Meridional rays are not the only type of ray which propagate in a fibre.
- Skew rays do not pass through the fibre centre axis.
- Skew rays greatly outnumber meridional rays.
- Skew rays follow a helical path within the fibre.

- Skew ray propagation is difficult to visualise, but looking at the fibre end on we see a 2d projection of the rays. Seen in this way reflection takes place with an angle γ to the radius
- With meridional rays at the fibre output the angle depends on the input angle. For skew rays this is not so, instead the output angle depends on the number of reflections undergone. Thus skew rays tend to make the light output from a fibre more uniform.



Acceptance angle for Skew Rays

A further possible advantage of the transmission of skew rays becomes apparent when their acceptance conditions are considered.



- Analysis for skew rays is much more involved.
- Ray direction defined in two planes as shown.

$$\text{Acceptance angle for skew rays} = \sin^{-1}\left[\frac{\sqrt{(n_1^2 - n_2^2)}}{\cos\gamma}\right]$$

- γ is the angle of reflection for skew rays within the fibre, defined previously
- Since $\cos\gamma$ is < 1, acceptance angle is higher for skew rays.

Example:\

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

Solution

Acceptance angle for meridional rays = 23.6 degrees

Skew rays change direction by 100 degrees so γ is 50 degrees

Using the formula for the acceptance angle for skew rays gives:

Skew ray acceptance angle = 38.5 degrees

Notice that the acceptance angle for skew rays is higher than that for meridional rays