Optical Fiber Communication Systems

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Lecture One

Advantages of Fiber Optics

- Why are fiber-optic systems revolutionizing telecommunications? Compared to conventional metal wire (copper wire), optical fibers are:

1. **Less expensive** - Several miles of optical cable can be made cheaper than equivalent lengths of copper wire. This saves your provider (cable TV, Internet) and you money.

2. **Thinner** - Optical fibers can be drawn to smaller diameters than copper wire.

3. **Higher carrying capacity** .

4. **Less signal degradation** - The loss of signal in optical fiber is less than in copper wire.

5. **Light signals** - Unlike electrical signals in copper wires, light signals from one fiber do not interfere with those of other fibers in the same cable. This means clearer phone conversations or TV reception.

6. **Low power** - Because signals in optical fibers degrade less, lower-power transmitters can be used instead of the high-voltage electrical transmitters needed for copper wires. Again, this saves your provider and you money.

7. **Lightweight** - An optical cable weighs less than a comparable copper wire cable.

8. **Flexible** - Because fiber optics are so flexible and can transmit and receive light, they especially useful in computer networks.

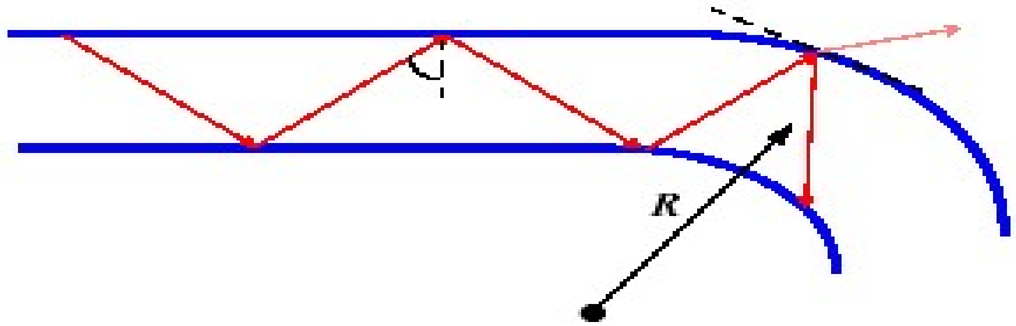
9. **Strength:** perception: Fiber is fragile. Fact: Fiber is 4+ times stronger than copper

10. optic cables take up less space in the ground. So they are used in many flexible digital cameras for the following purposes:

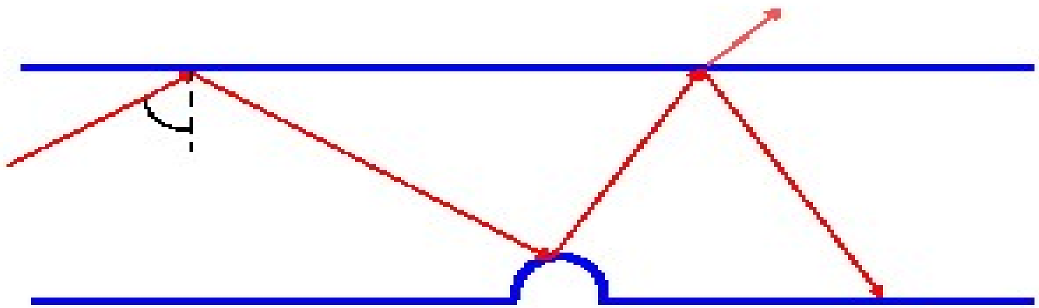
- ✓ Medical imaging.
- ✓ Mechanical imaging.

Disadvantages with optical fiber vs. copper cables

- Limited bending radius



- Sencitivity to radial forces



- Complicated joining and contacting processes

Fiber's New Characteristics

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❑ Optical Fiber Communication System

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

1. interface circuit and
2. a source drive circuit
3. optical source

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

4. **Optical receiver** - Receives and decodes the light signals

- the optical detector (semiconductor positive-intrinsic-negative (*PIN*) diode or an avalanche photodiode (APD))

and,

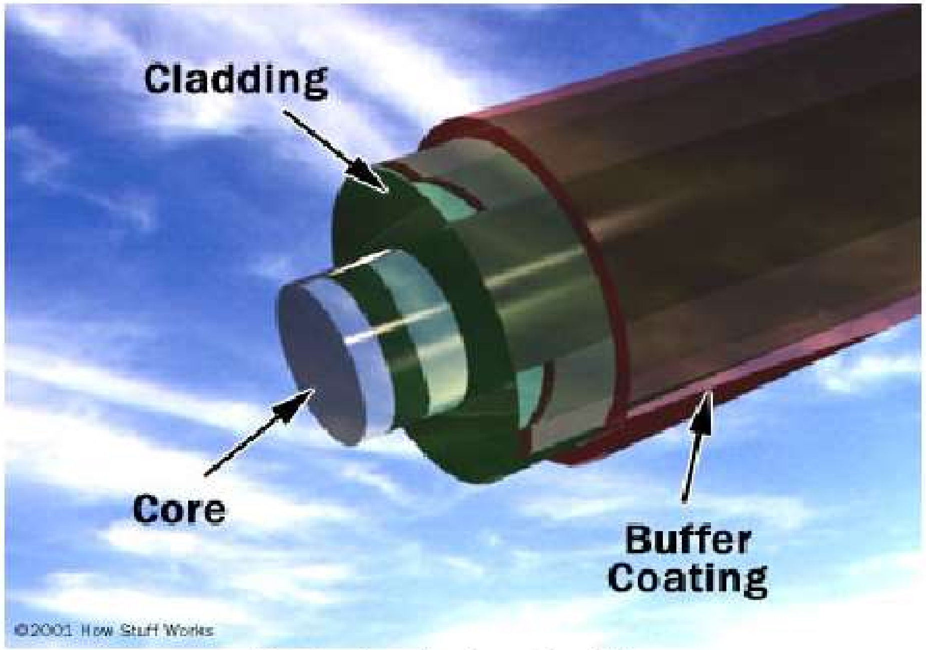
- the signal-conditioning circuits.

❑ **Fiber optics** (optical fibers) are long, thin 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) and transmit visible red light (wavelength = 650 nm) from LEDs.

- **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



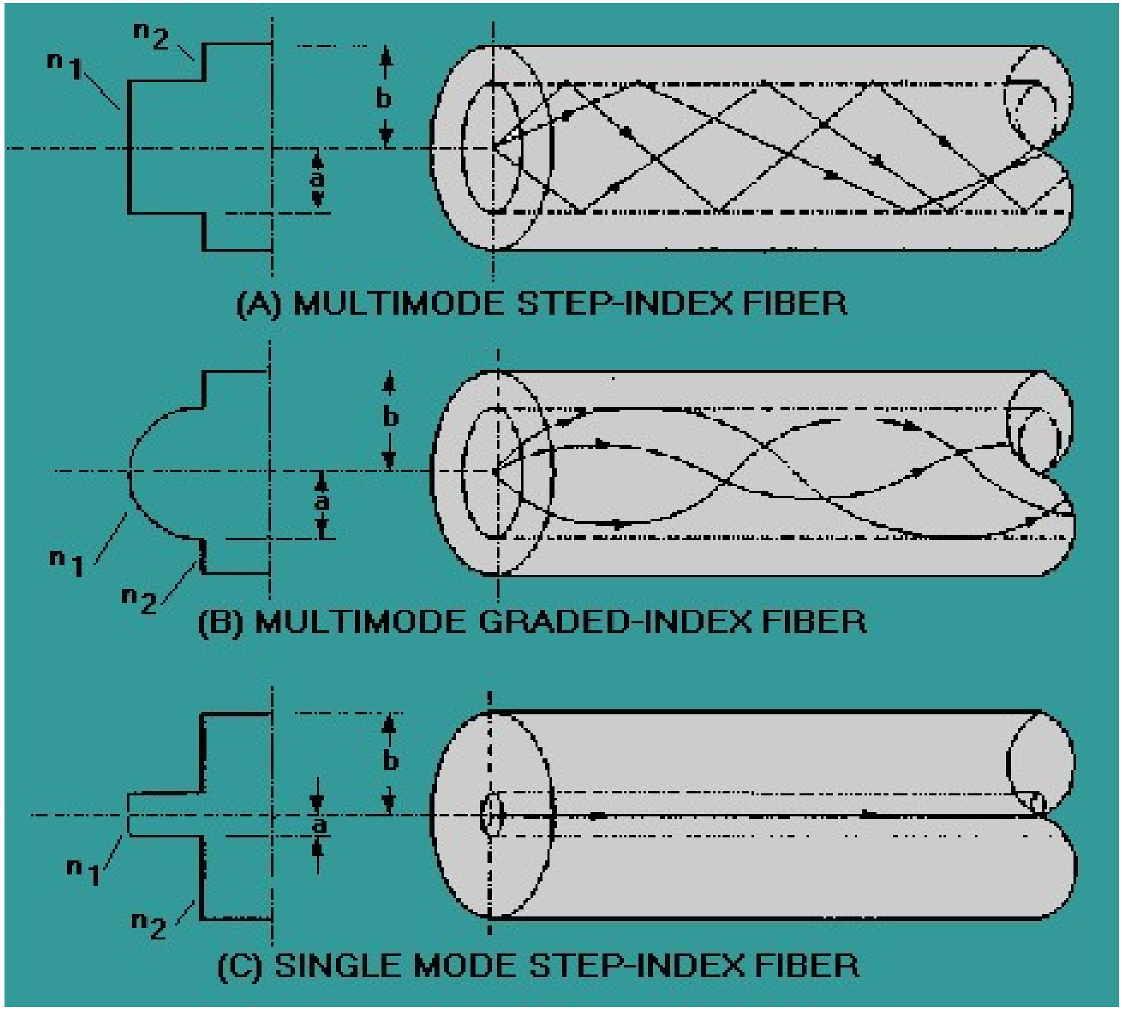
Parts of a single optical fiber

❑ Optical fibers come in two types:

➢ **Single-mode fibers**

➢ **Multi-mode fibers**

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



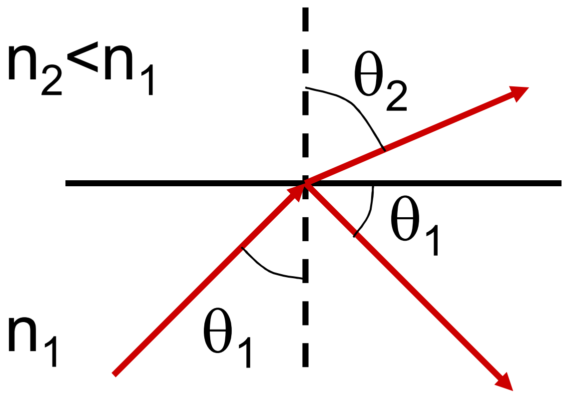
- **Multimode Step Index fiber (MMSI)**: in which the refractive index of the core is uniform throughout and undergoes an abropt (step) at the core _ cladding boundary. Only one mode is allowed to propagate through this fiber .

- **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 2.5 x 10^{-3} inches or 62.5 microns in diameter) and transmit infrared light (wavelength = 850 to 1,300 nm) from light-emitting diodes (LEDs). Used to transmit signals (used in computer networks, local area networks).

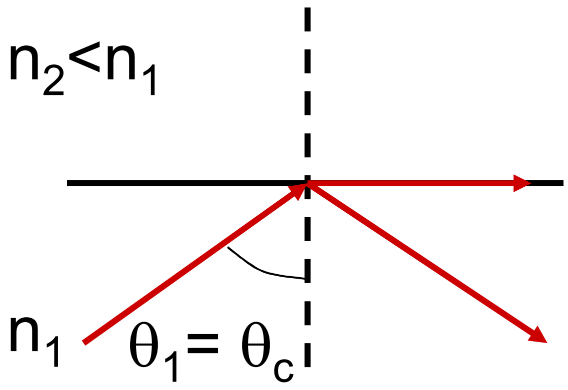
- **Singlemode Step Index fiber (SMSI):** Only a single path exists throught the cable core through which light can trave. The SMSI fiber has the same refractive index relationship as the MMSI fiber. have small cores (about 3.5 x 10^{-4} inches or 9 microns in diameter) and transmit infrared laser light (wavelength = 1,300 to 1,550 nanometers). Used to transmit one signal per fiber (used in telephones and cable TV)

- **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 index side**.



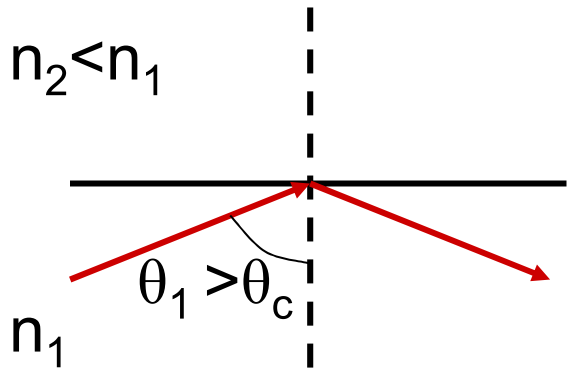
Snell's law

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



Critical angle

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



Total internal reflection

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.

At an angle **greater** than θ_c, a ray will propagate inside the core by a series of internal reflections. And

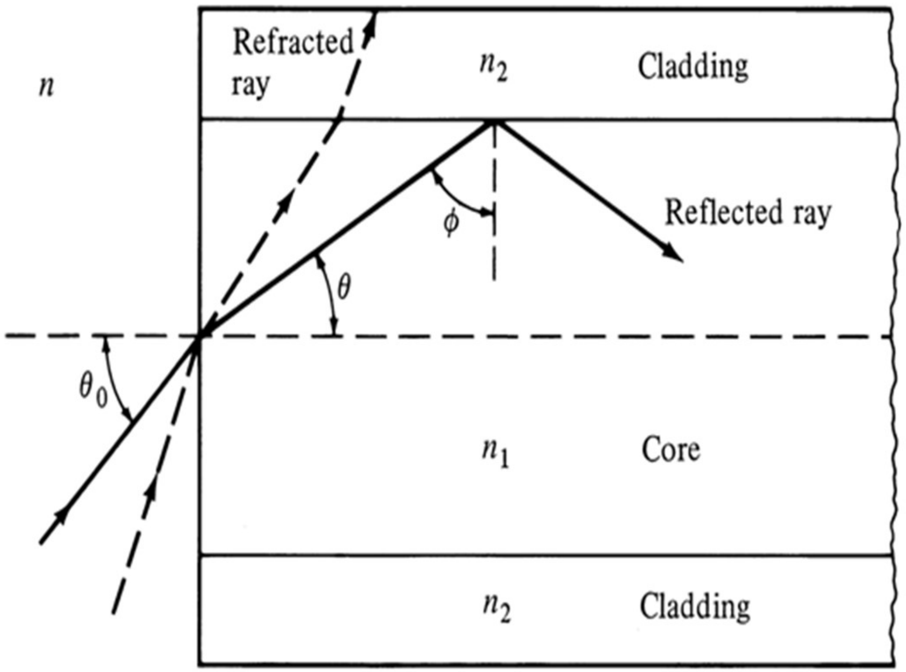
NA is the numerical aperture of the fiber and is defined as the light-gathering power of an optical fiber. When the face of the fiber is in contact with air (${n_o} = 1$ for air),

Relative refractive Index difference Δ

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

$$\text{if} \quad n_1 \approx n_2 = n :$$

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



Critical angle: $\sin\theta_c = \dfrac{n_2}{n_1}$

Maximum entrance angle:

$$\sin \theta_a = \frac{n_1}{n_o} \sin \theta_c$$

Numerical aperture:

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

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

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

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 $\phi_a = 90^o$).

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

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

$$n(r) = n_2 \qquad \text{for } r \geq a \quad [\text{ cladding }]$$

where C is a constant of proportionality and r is the distance from the fiber axis. **The key parameter of g** controls the shape of the propagating light rays.

In communication fibers, the **g** -value determines he btandwidth of the optical fiber.
In a GRIN fiber is parabolic (g = 2), the bandwidth is maximized.

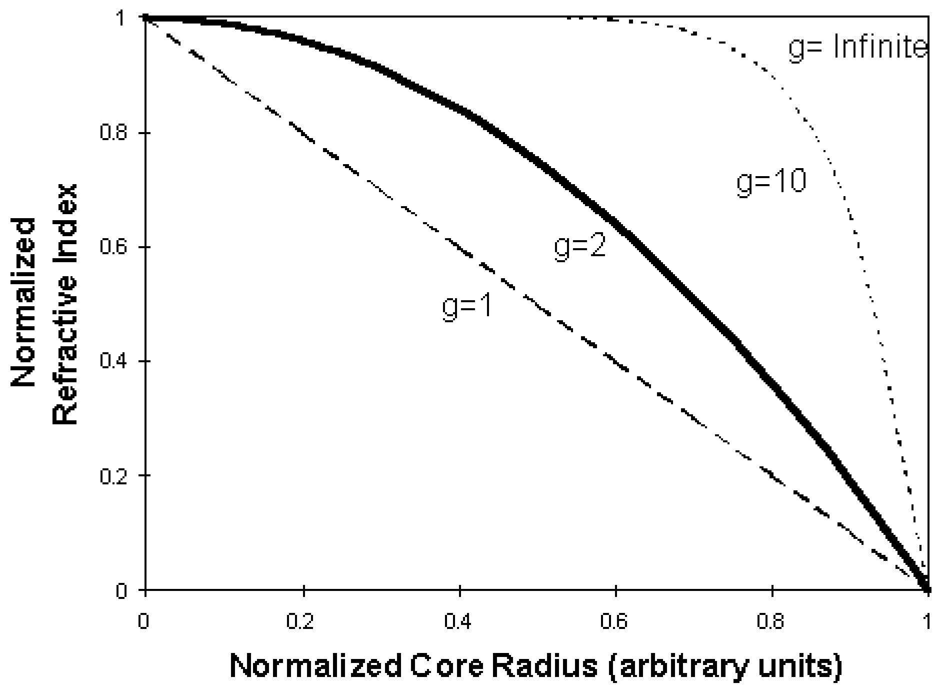


Figure shows the profile of refractive index from core center to the outside edge of GRIN fiber with different g-values.

Example1: A typical refractive index differencefor 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 ζ is given by:

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

But
$$\zeta = \pi (NA)^2 = \pi\, 0.04$$
$$= 0.13 \text{ rad}$$

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

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

- **NORMALIZED FREQUENCY. V -** Electromagnetic waves bound to an optical fiber are described by the fiber's normalized frequency.

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

The number of modes that can exist in a fiber (core) is a function of V and can be calculated as

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

As the value of V increases, the number of modes supported by the fiber increases.

For α=2 for parabolic profile fiber.

$$N = \frac{V^2}{4}$$

- The wavelength at which a mode ceases to propagate is called the **cutoff wavelength for that mode**. However, an optical fiber is always able to propagate at least one mode, the fundamental mode.

- The fundamental mode can never be cut off.

- 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 λ_c is given by

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

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:

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

Example:

Serior 55
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 1 µ.

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 for a parabolic profile may be obtained

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

$$\simeq \frac{986}{4} = 247$$

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

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

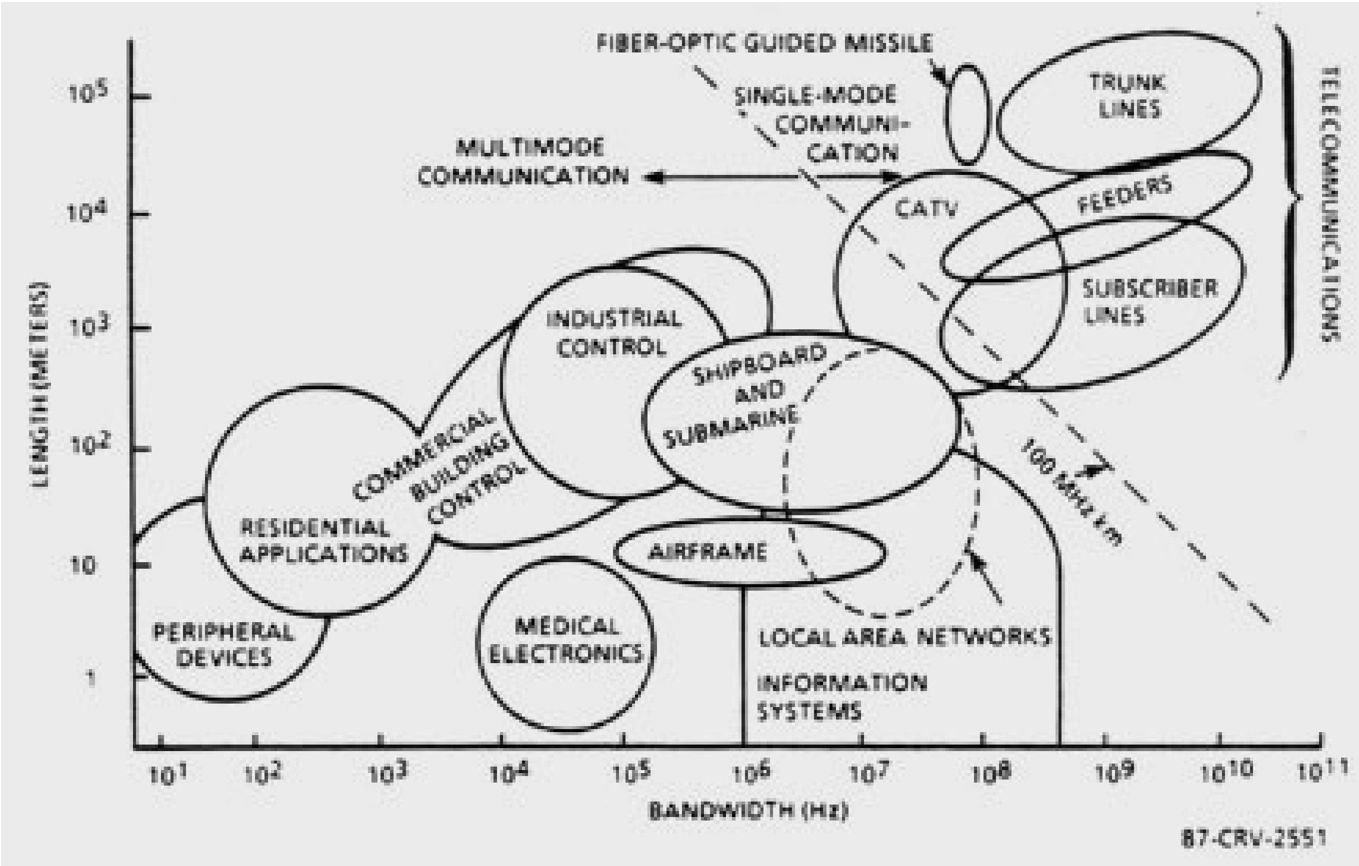
1) How much light can be **coupled** into the core through the external acceptance angle?

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?

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


FIBER-OPTIC GUIDED MISSILE
SINGLE-MODE COMMUNI-CATION
MULTIMODE COMMUNICATION
TRUNK LINES
FEEDERS
CATV
SUBSCRIBER LINES
TELECOMMUNICATIONS
INDUSTRIAL CONTROL
SHIPBOARD AND SUBMARINE
COMMERCIAL BUILDING CONTROL
RESIDENTIAL APPLICATIONS
PERIPHERAL DEVICES
MEDICAL ELECTRONICS
AIRFRAME
LOCAL AREA NETWORKS
INFORMATION SYSTEMS
100 MHz km
LENGTH (METERS)
BANDWIDTH (Hz)
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