Fiberoptic and Waveguide Sensors

Wei-Chih Wang
Department of Mecahnical Engineering
University of Washington

Optical sensors

- Advantages:

  -immune from electromagnetic field interference (EMI)

  - extreme high bandwidth capability

  - high sensitivity and high dynamic range

  - remote sensing

  - ability to be embedded under hostile environments

  - distributed and array sensors covering extensive structures and geographical locations

Fiber Optic Sensor Classification

A. Based on modulation and demodulation process of Sensor
   - intensity, phase, frequency, polarization etc.
B. Based on their applications.
   - physical, chemical, bio-medical, etc.
C. Extrinsic (sensing take place outside of fiber where, fiber only serve as conduit to transmit light to and from the sensing region) or intrinsic sensors (physical properties of the fiber undergo a change as mentioned in A above)

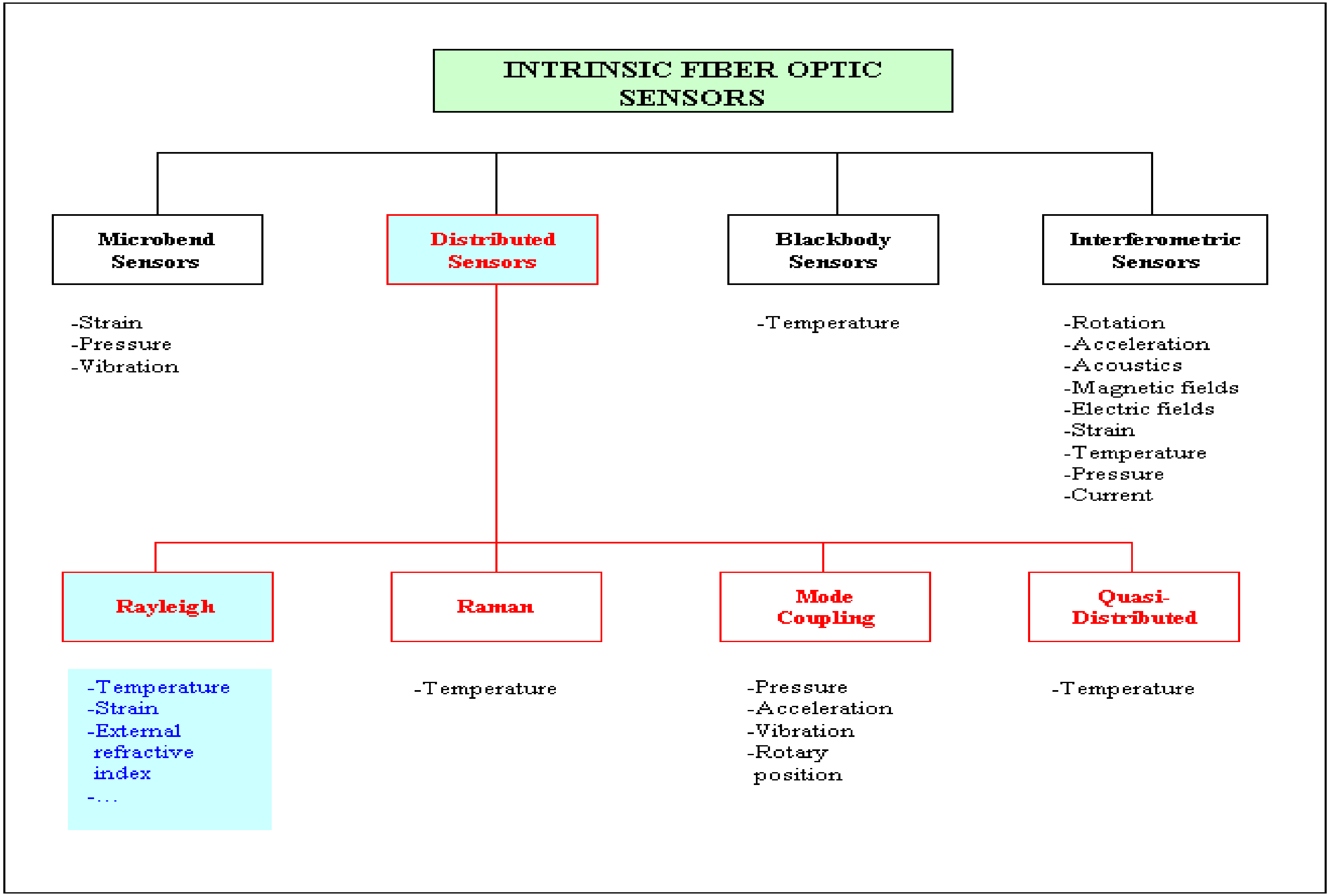
Industrial application

- Pressure
- Flow and viscosity
- Vibration
- Current-voltage
- Chemical
- Smart structure
- Accelerometer, gyroscope
- Acosutic-Microphone hydrophone
- Image acquisition

Other applications

1. Physical sensors for medical applications
    - endoscopes scanner and display
    - pressure sensor (cantilever, diaphragm)
    - blood velocity and flow
    - temperature sensor (non contact)
    - acoustic sensor
    - accelerometer (mechanical inertia, photoelastic, reflection-cantilever)
    - viscosity sensor
    - liquid level sensor
2. Chemical or biochemical sensors
    - glucose detector (viscosity)
    - gas or liquid concentration sensor (mass or viscosity)
    - surface reaction mass loading sensor (mass, viscosity or stiffness change)
    - humidity sensor (detect geometry change due to adsorption)

Intrinsic Fiber Optic Sensors



w.wang

Intrinsic distributed sensors are particularly attractive for use in applications where monitoring of a single measurand is required at a large number of points or continuously over the path of fiber. Examples of application areas include for example

- Stress monitoring of a large structures such as buildings, bridges, storage tanks, and the like, and ships, oil platforms, aircraft spacecraft and so on
- Temperature profiling in electrical power transformers, generators, reactor systems, furnaces, press control systems, and simple fire detection systems
- Leakage detection systems in pipelines, fault diagnostics and detection of magnetic/electrical field anomalies in power distribution systems, and intrusion alarm systems
- Embedded sensors in composite materials for use in the real-time evaluation of stress, vibration, and temperature in structures and shells, especially in aerospace industry

Intrinsic Intensity Modulation Sensors

- Macro Bend
- Micro Bend
- Evanescent
- OTDR (impedance change)

Advantages:
Compact, simple optical setup

Phase modulation

- Mach-Zehnder
- Michelson
- Fabry-Perot
- Sagnac

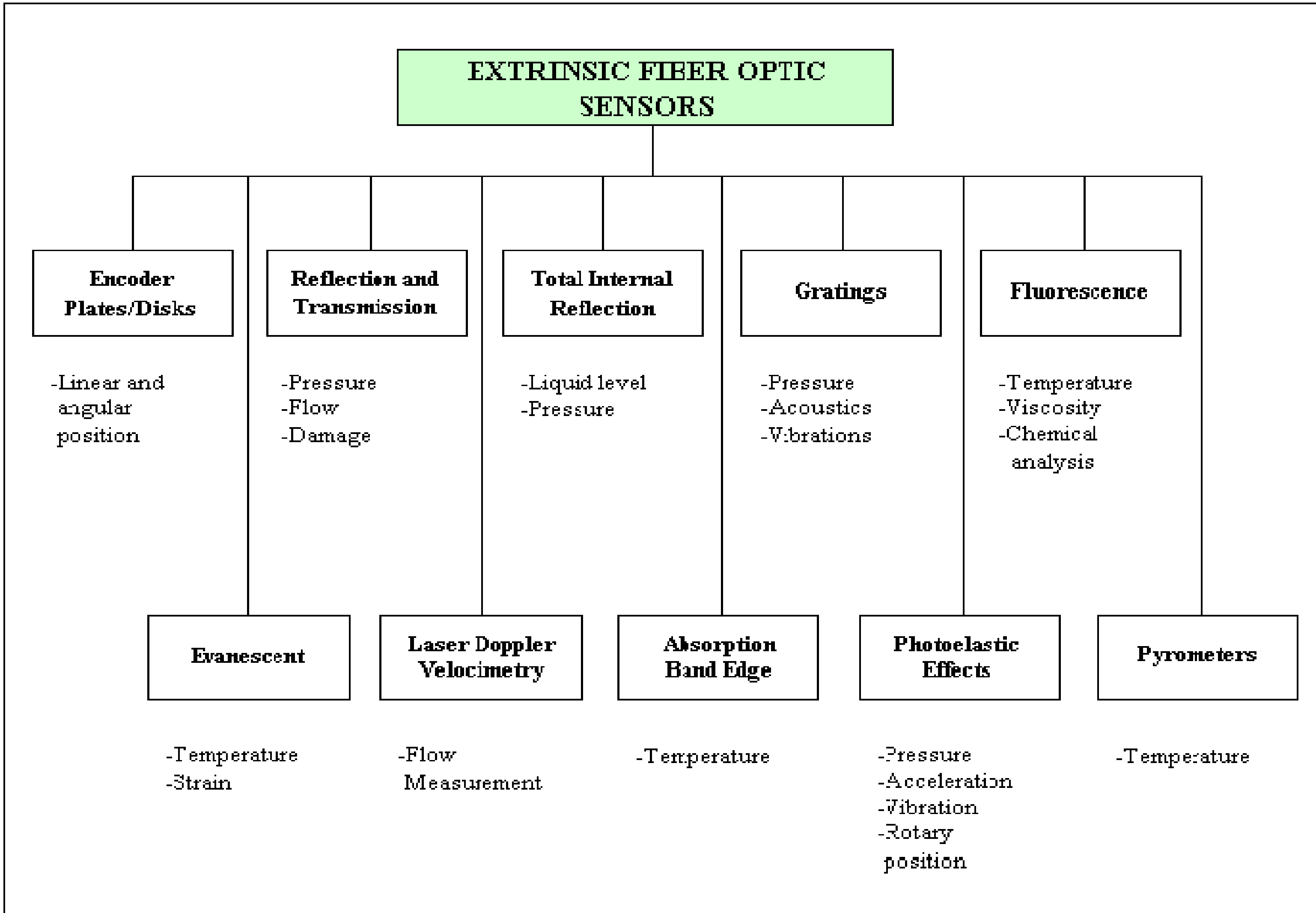
Other phase modulating sensors

- Doppler
- Dual mode fiber sensor
- Polarimetric
- Grating

Wavelength modulation

- Dispersion
- Scattering
- Spectroscopy (Fourier transform, fluroscent, etc)

Extrinsic Optical Sensors



Extrinsic Intensity Modulation Sensors

- Discontinuity
- Transmission and Reflection
- Absorption
- Scattering

Advantages:

Free from dispersion, beam alignment, beam divergence

Phase modulation

- Mach-Zehnder
- Michelson
- Fabry-Perot
- Sagnac

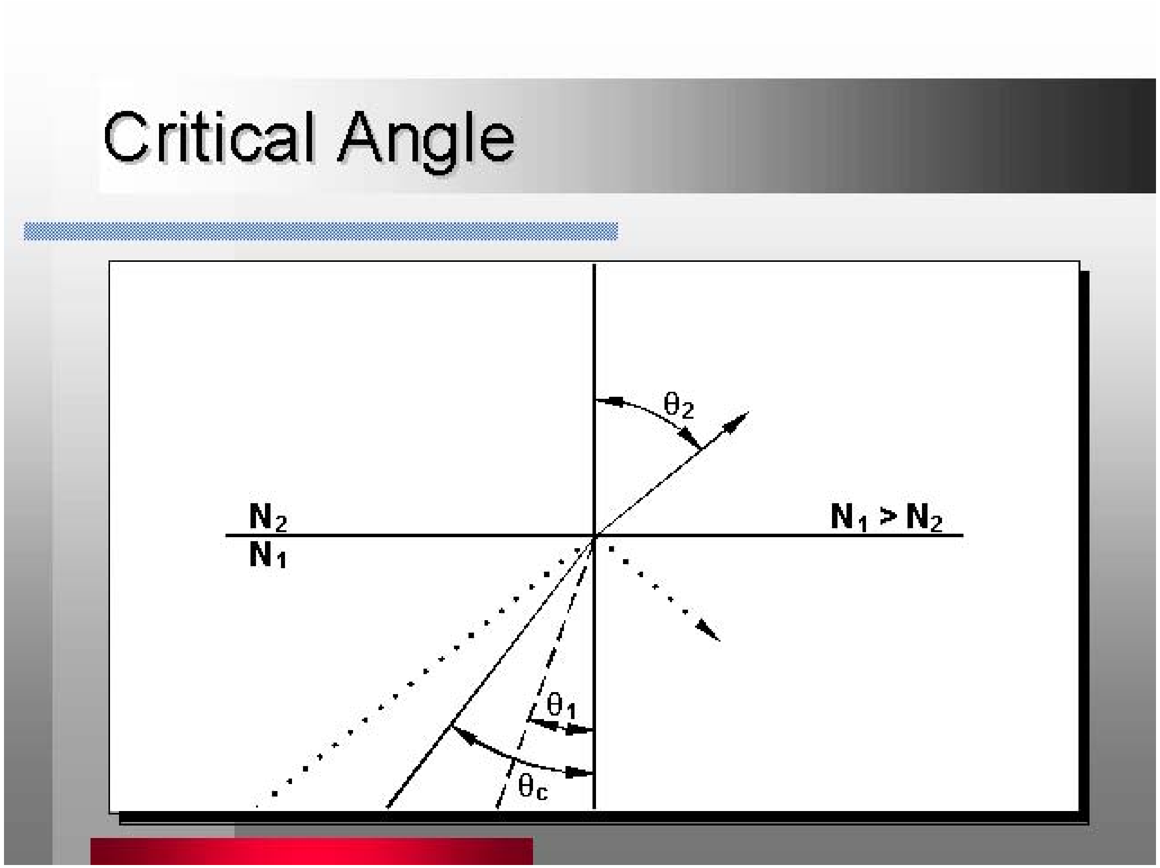
Other phase modulating sensors

- Doppler
- Dual mode fiber sensor
- Polarimetric
- Grating

Wavelength modulation

- Dispersion
- Diffraction
- Interference
- Scattering
- Spectroscopy (Raman, Fourier transform, fluorescent, etc)

Critical angle:



Angles 01 and 02 are related by:

$N_1 \sin\theta_1 = N_2 \sin\theta_2$ (Snell's Law)

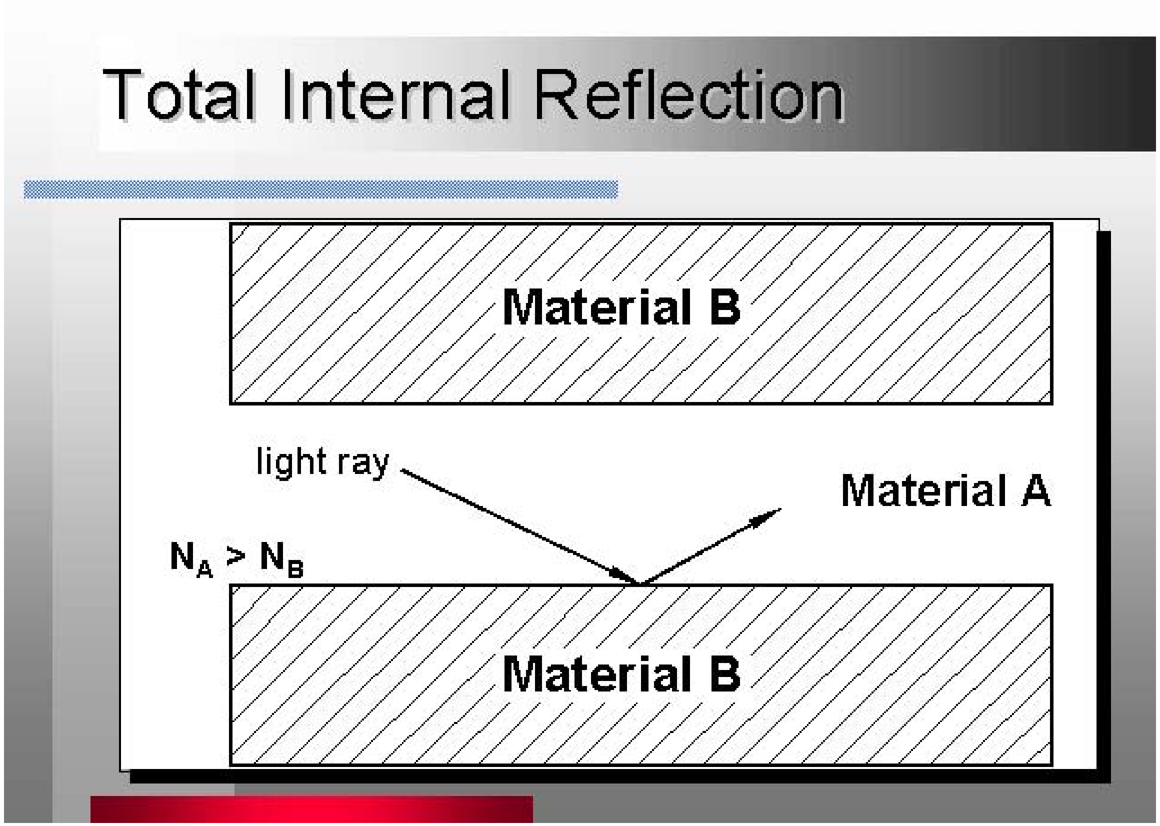
When $\theta_2 = 90$, 01 is called the Critical Angle

$N_1 \sin \theta_1 = N_2 \sin 90$, $\sin 90 = 1$

$\sin \theta c = N_2 / N_1$

For incident angles greater that the critical angle, total internal reflection occurs

Total reflection

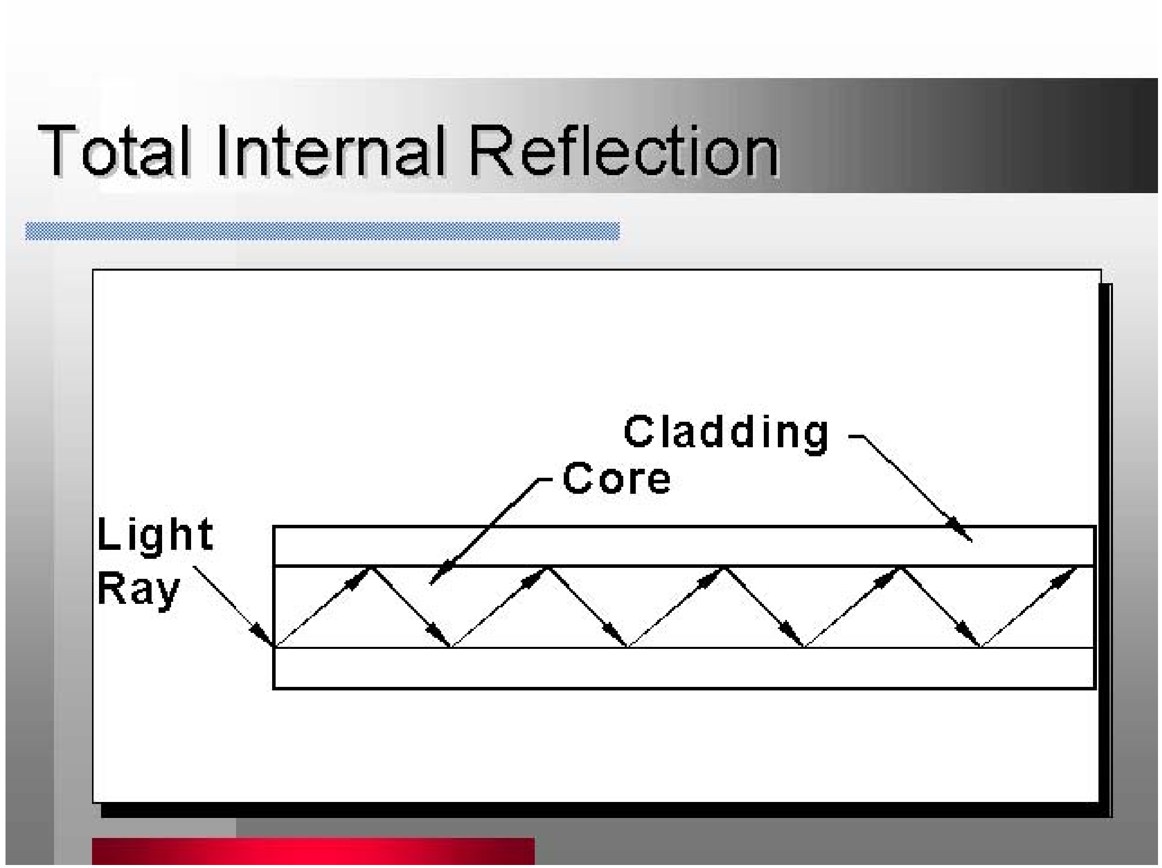


Total Internal Reflection -- The reflection that occurs when a light ray traveling in one material hits a different material and reflects back into the original material without any loss of light

Material A = fiber core

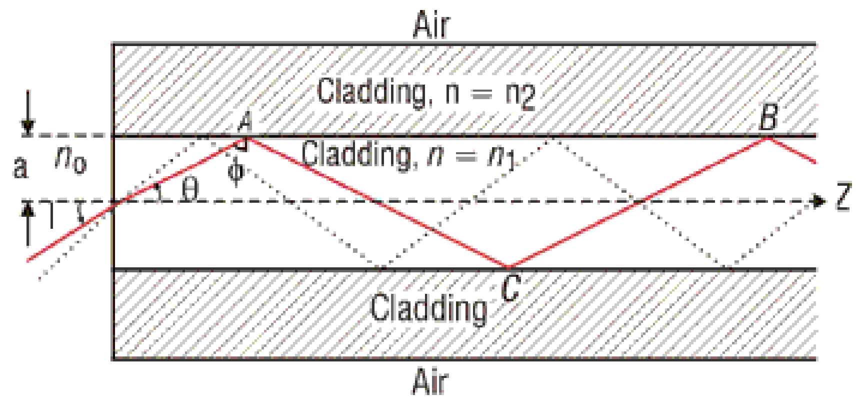
Material B = fiber cladding

w.wang



Light travels down the fiber in a pathway called a light guide

While discussing step-index fibers, we considered light propagation inside the fiber as a set of many rays bouncing back and forth at the core-cladding interface. There the angle θ could take a continuum of values lying between 0 and $\cos^{-1}(n_2/n_1)$, i.e.,



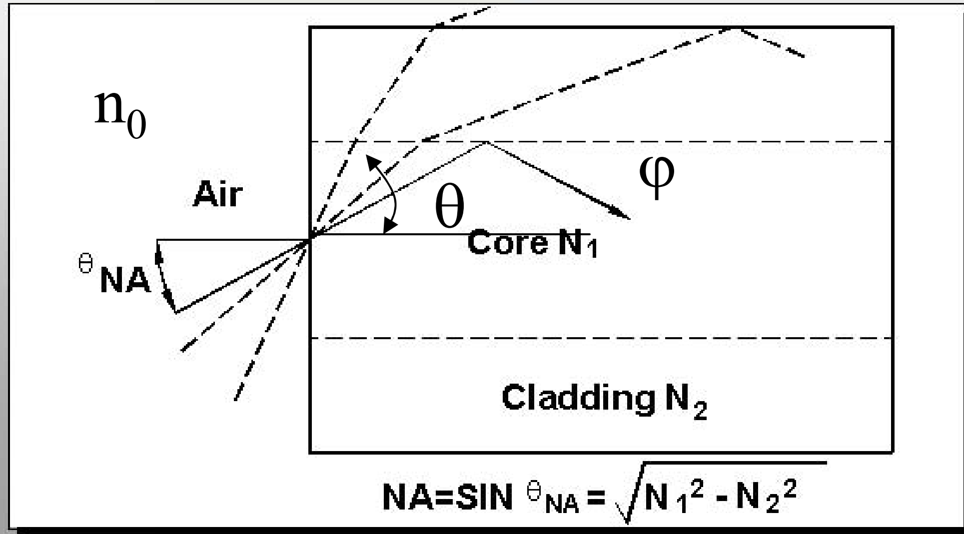
Scientific and Technological Education in Photonics

$$0 < \theta < \cos^{-1}(n_2/n_1)$$

For $n_2 = 1.5$ and $\Delta \approx \frac{n_1 - n_2}{n_1} = 0.01$, we would get $n_2/n_1 \simeq$ and $\cos^{-1}\left(\frac{n_1}{n_2}\right) = 8.1°$, so

$$0 < \theta < 8.1°$$

Numerical Aperture (NA)



- The Numerical Aperture (NA) of a fiber is the measure of the maximum angle (θ_{NA}) of the light entering the end that will propagate within the core of the fiber
- Acceptance Cone = 20NA
- Light rays entering the fiber that exceed the angle θ_{NA} will enter the cladding and be lost
- For the best performance the NA of the transmitter should match the NA of the fiber

NA derivation

We know $\dfrac{\sin i}{\sin \theta} = \dfrac{n_1}{n_0}$ and $\sin \phi (= \cos \theta) > \dfrac{n_2}{n_1}$

Since $\sin \theta = \sqrt{1 - \cos^2 \theta}$ we get $\sin \theta < \left[1 - \left(\dfrac{n_2}{n_1} \right)^2 \right]^{½}$

Assume the θ_{NA} is the half angle of the acceptance cone,

$$\sin\theta_{NA} = (n_1^2 - n_2^2)^{1/2} = n_1 \text{sqrt}(2\Delta)$$

w.wang

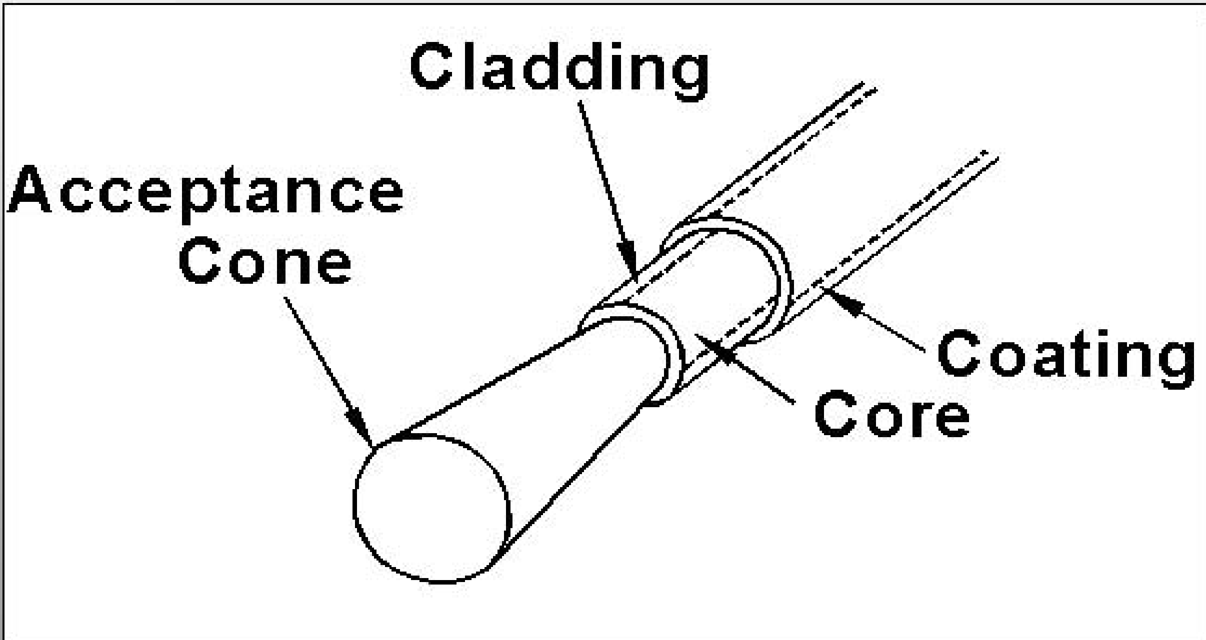
We define a parameter Δ through the following equations.

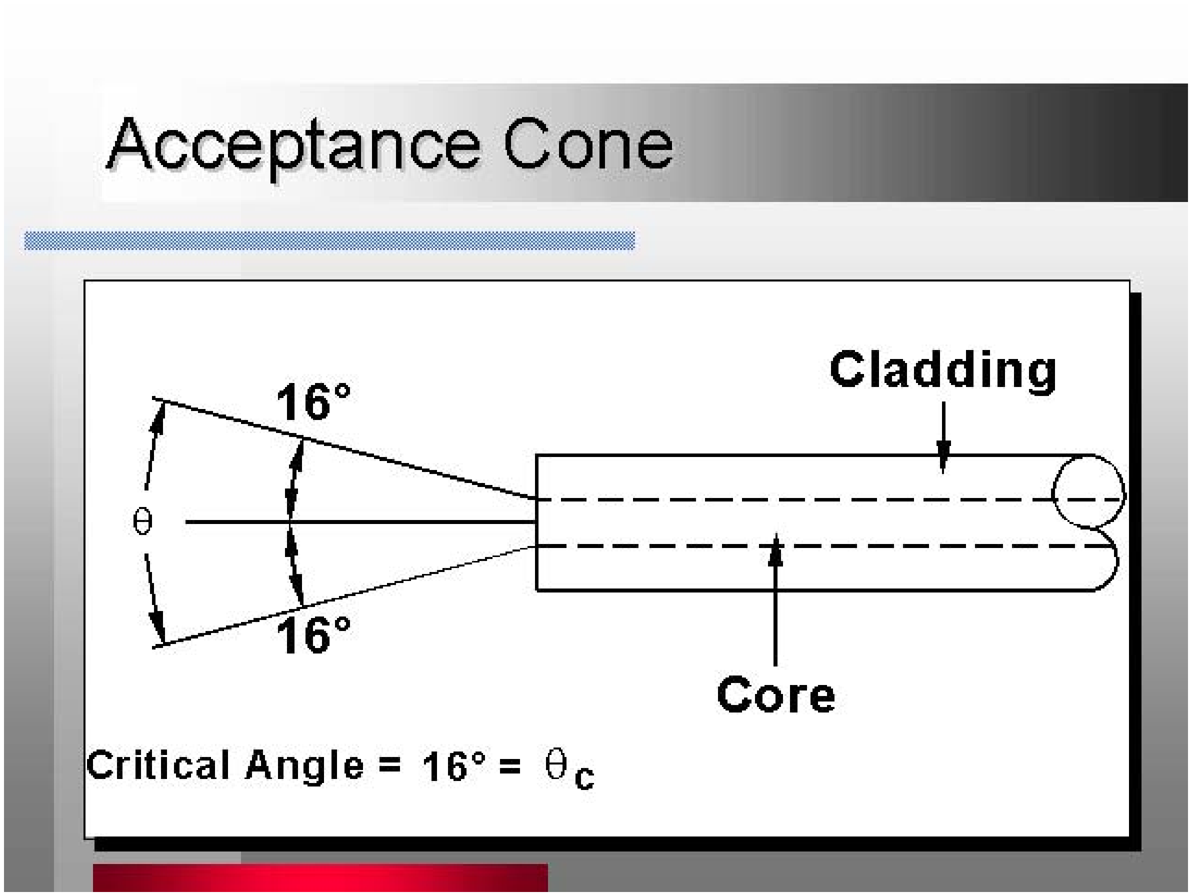
$$\Delta \equiv \frac{n_1^2 - n_2^2}{2n_2^2}$$

When Δ << 1 (as is indeed true for silica fibers where n_1 is very nearly equal to n_2) we may write

$$\Delta = \frac{(n_1 + n_2)(n_1 - n_2)}{2n_1^2} \approx \frac{(n_1 - n_2)}{n_1} \approx \frac{(n_1 - n_2)}{n_2}$$

Acceptance Cone





Single mode fiber critical angle <20^{o}
Multimode fiber critical angle <60 ^{o}

Example

For a typical step-index (multimode) fiber with $n_1 \approx 1.45$ and $\Delta \approx 0.01$, we get

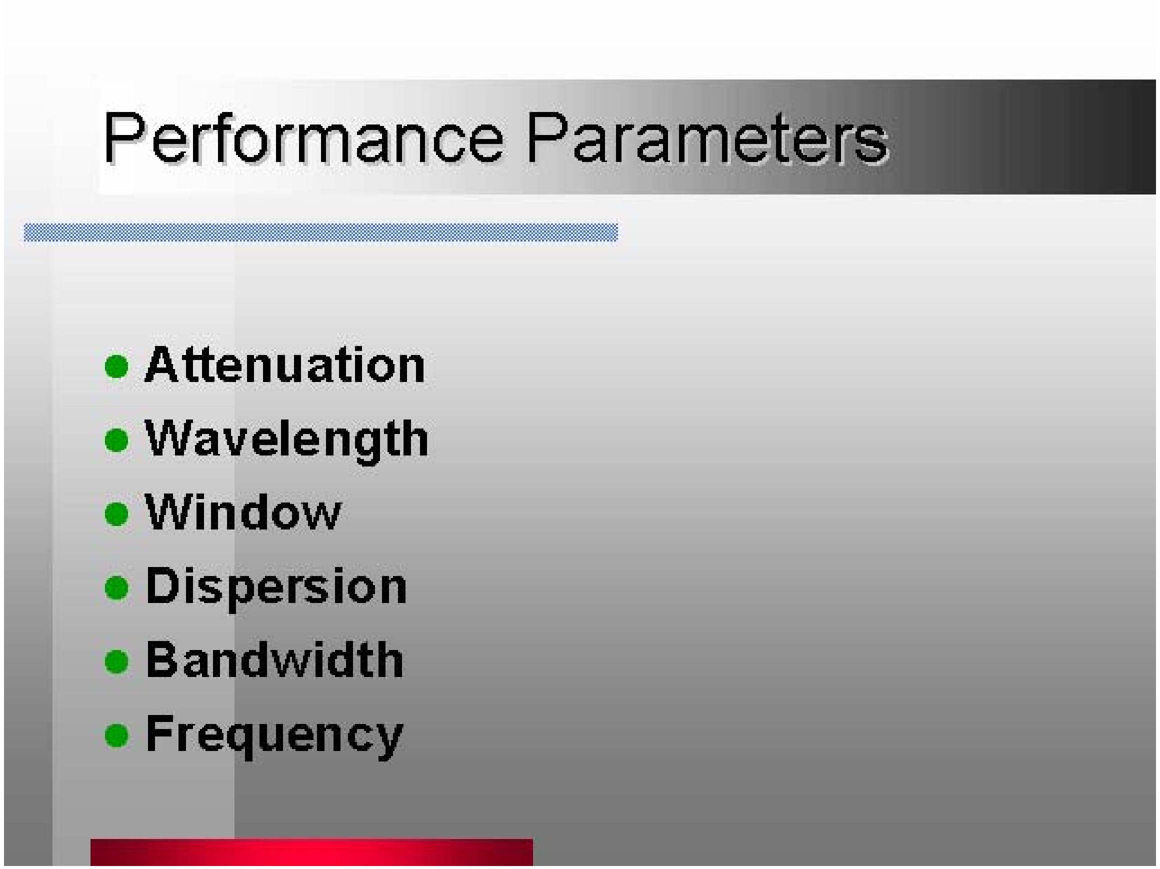
$$\sin i_m = n_1 \sqrt{2\Delta} = 1.45\sqrt{2 \times (0.01)} = 0.205$$

so that $i_m \approx 12°$. Thus, all light entering the fiber must be within a cone of half-angle 12°.

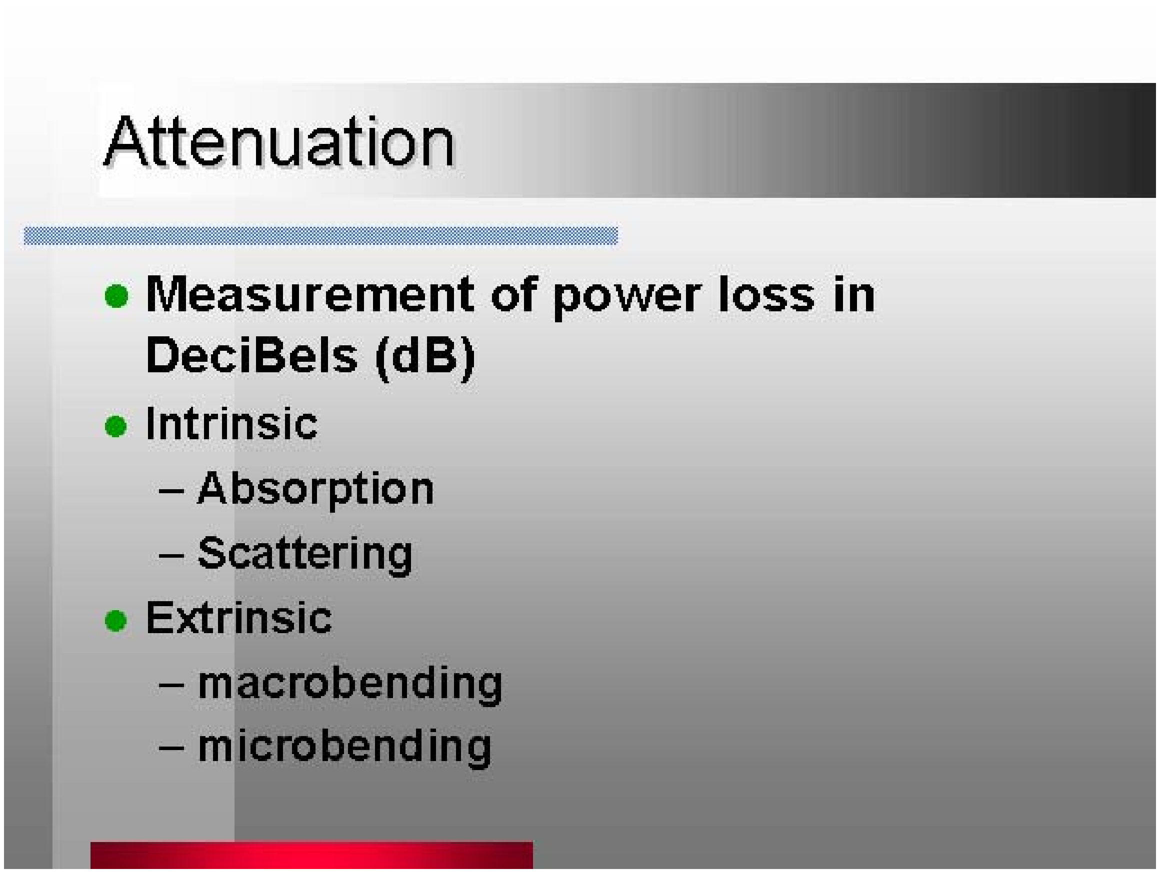
In a short length of an optical fiber, if all rays between $i = 0$ and i_m are launched, the light coming out of the fiber will also appear as a cone of half-angle i_m emanating from the fiber end. If we now allow this beam to fall normally on a white paper and measure its diameter, we can easily calculate the *NA* of the fiber.

w. wang

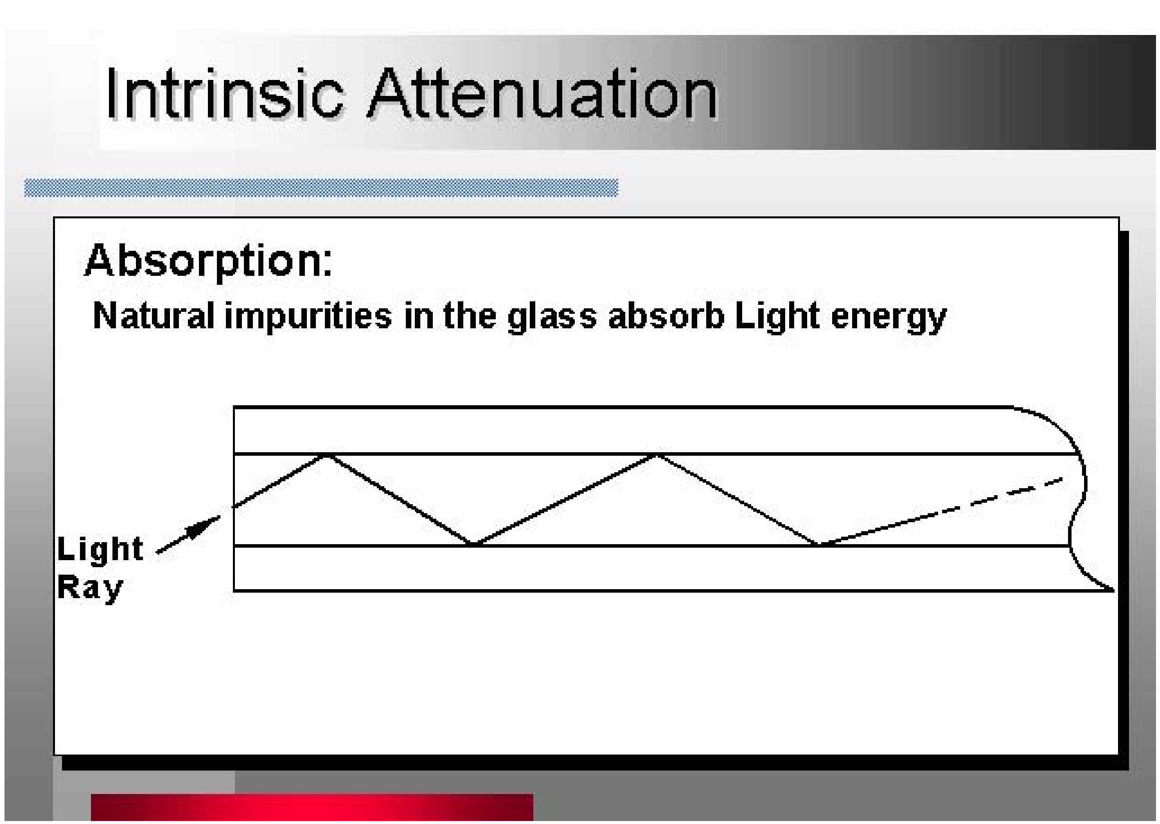
Performance parameters



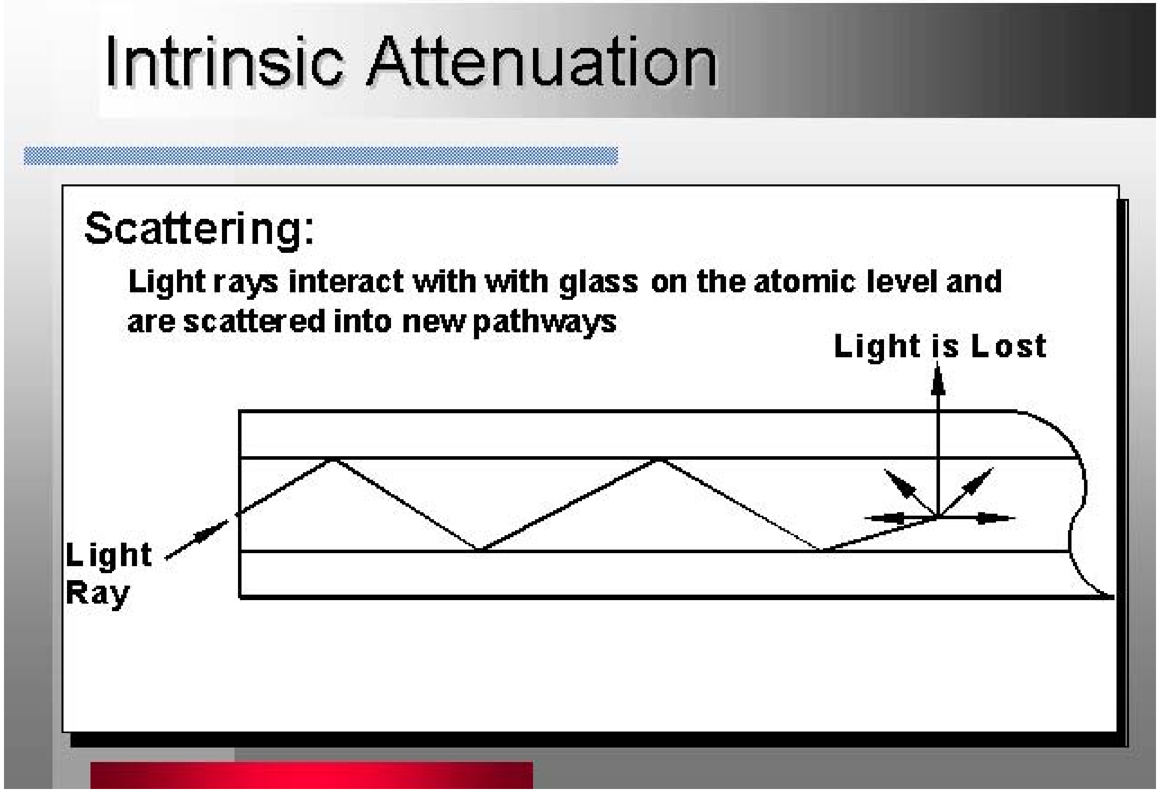
Attenuation



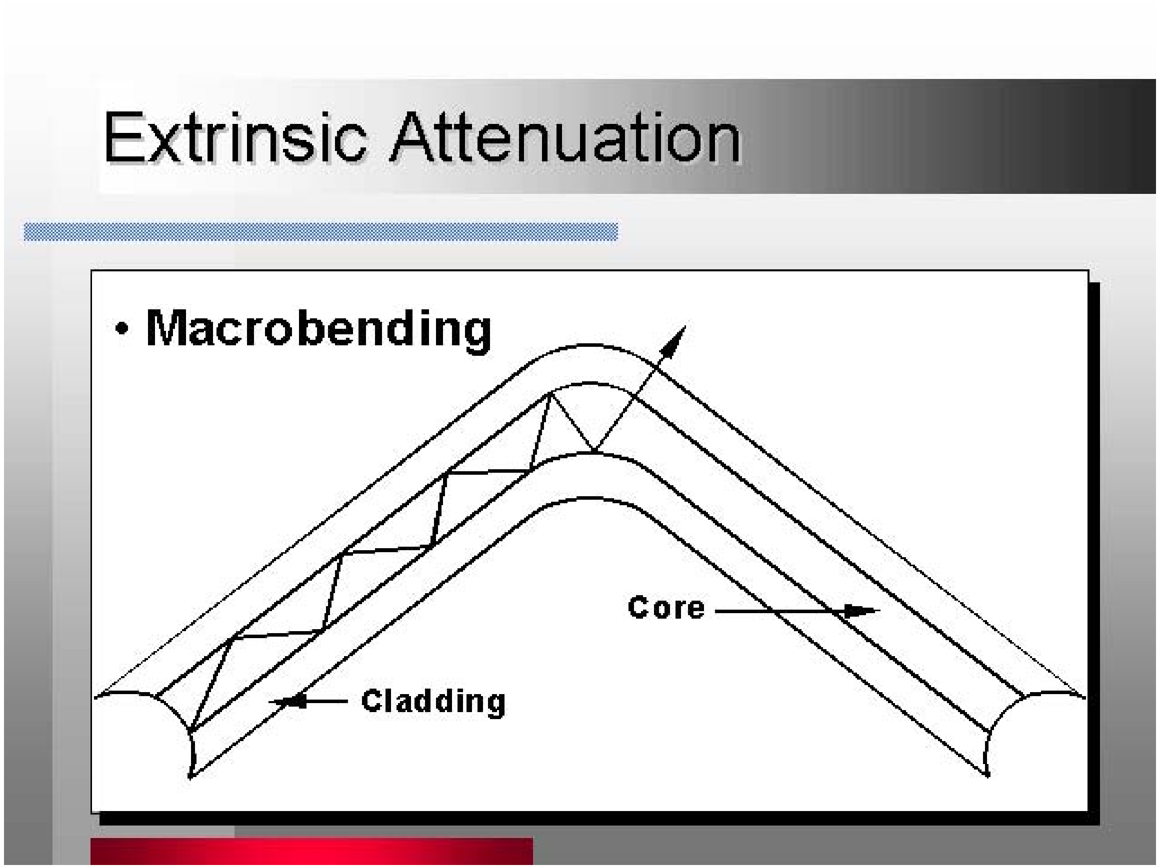
dB is a ratio of the power received verses the power transmitted
Loss (dB) = 10log (power transmitted / power received)



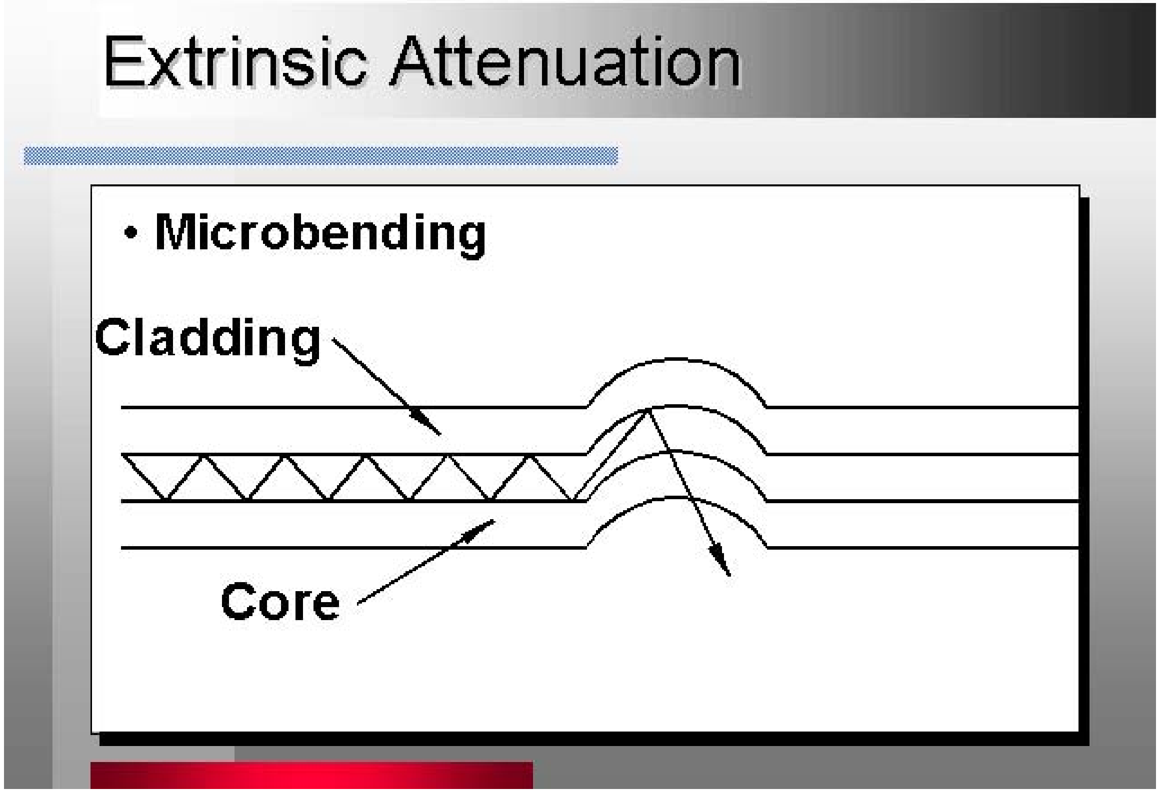
Intrinsic attenuation is controlled by the fiber manufacturer
Absorption caused by water molecules and other impurities
Light strikes a molecule at the right angle and light energy is converted into heat
Absorption accounts for 3-5% of fiber attenuation these is near the theoretical limit



Light striking the Ge molecules in the core can be scattered into new pathways out of the fiber
Rayleigh Scattering accounts for 95% of fiber attenuation
Optical Time Domain Reflectometers (OTDR) use this property to measure loss in a fiber



Extrinsic attenuation can be controlled by the cable installer



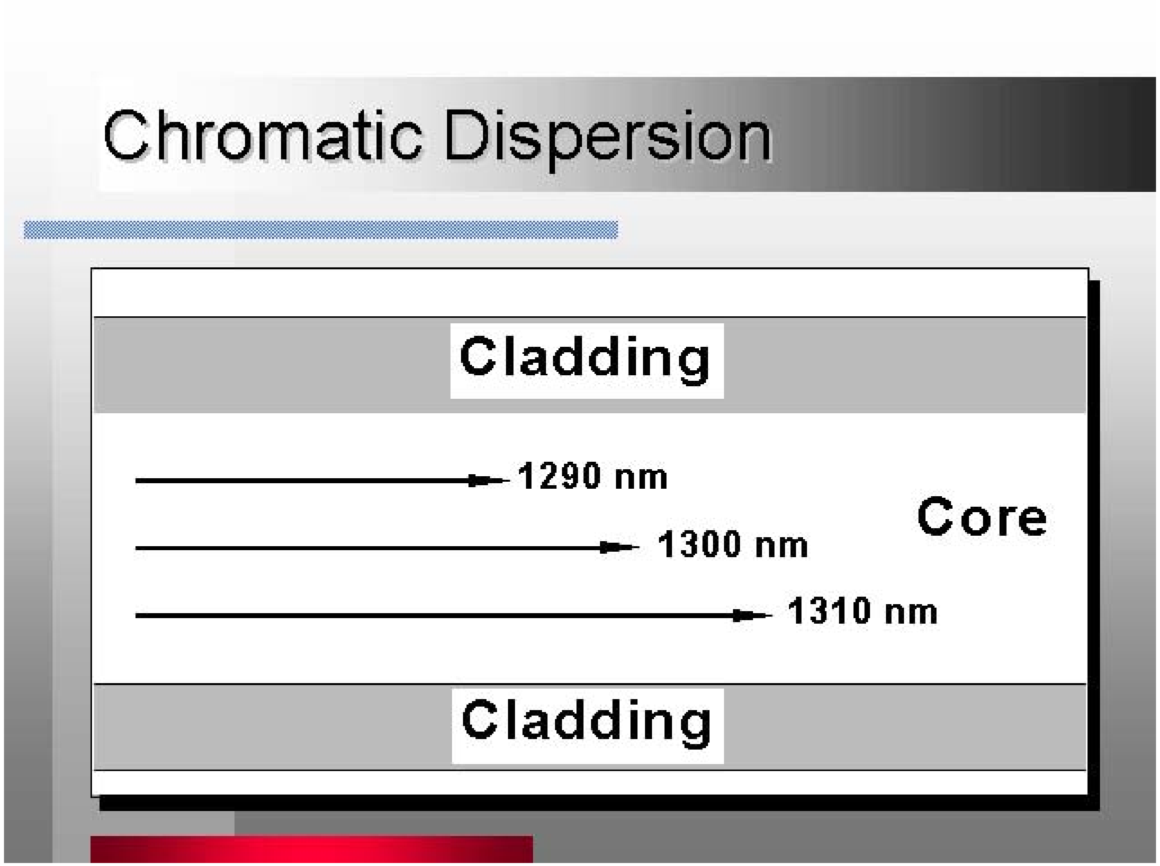
Microbends may not be visible with the naked eye

Microbends may be:

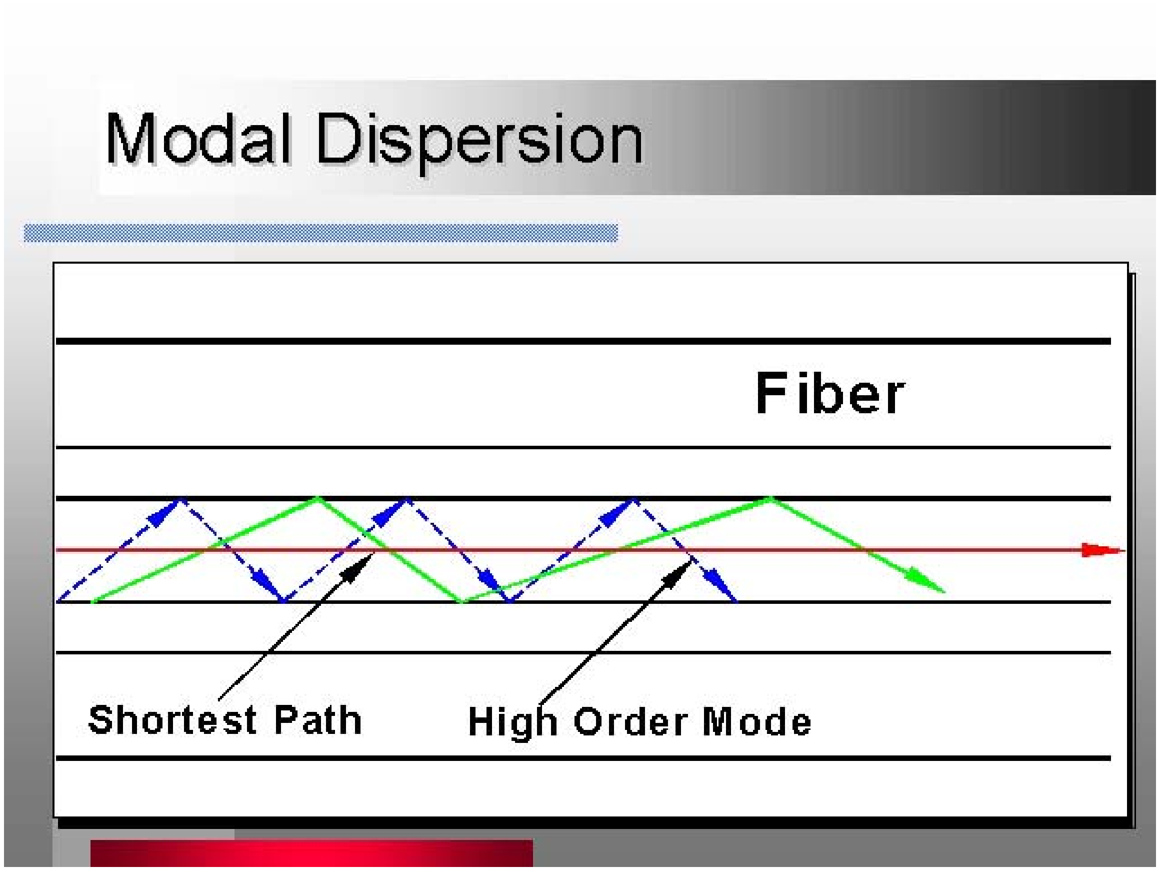
- bend related
- temperature related
- tensile related
- crush related

Dispersion

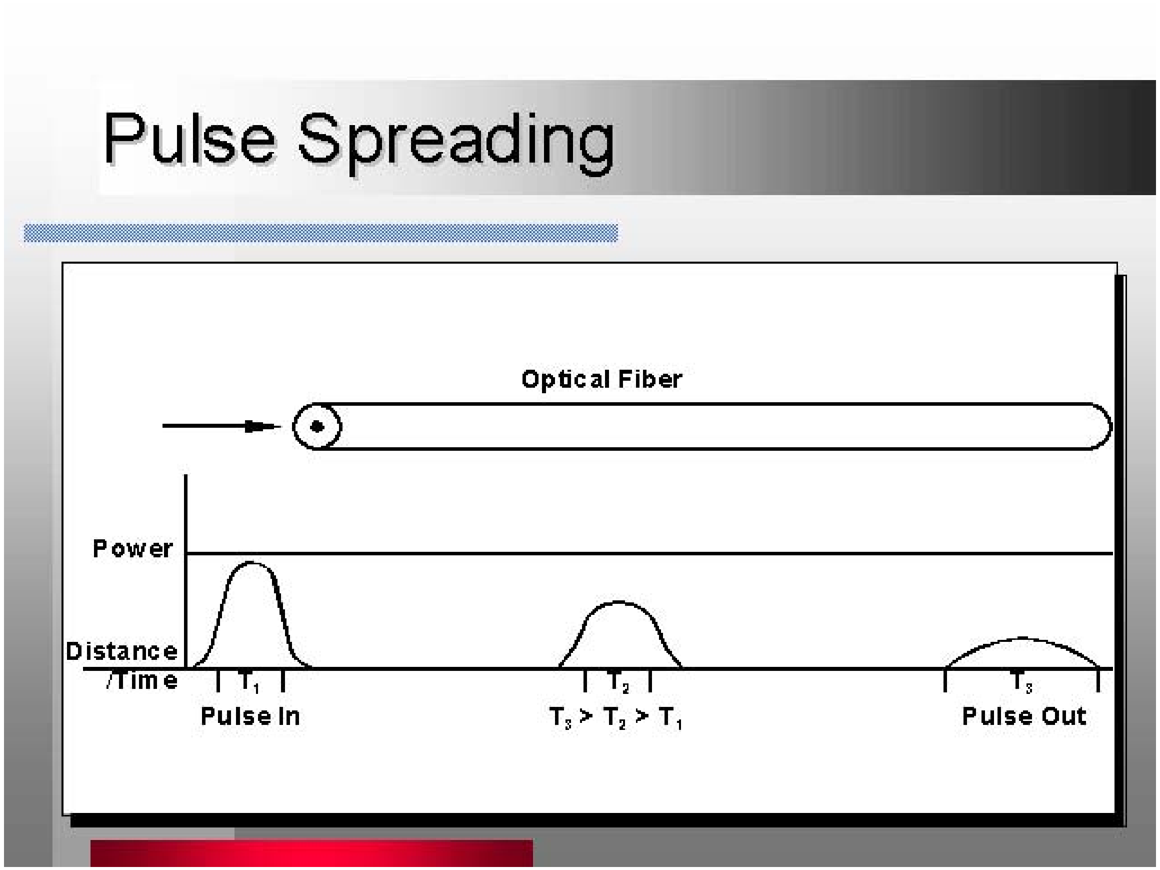
- **Dispersion is the variation of light velocities in a fiber**
  - Modal
  - Chromatic
- **Pulse Spreading**



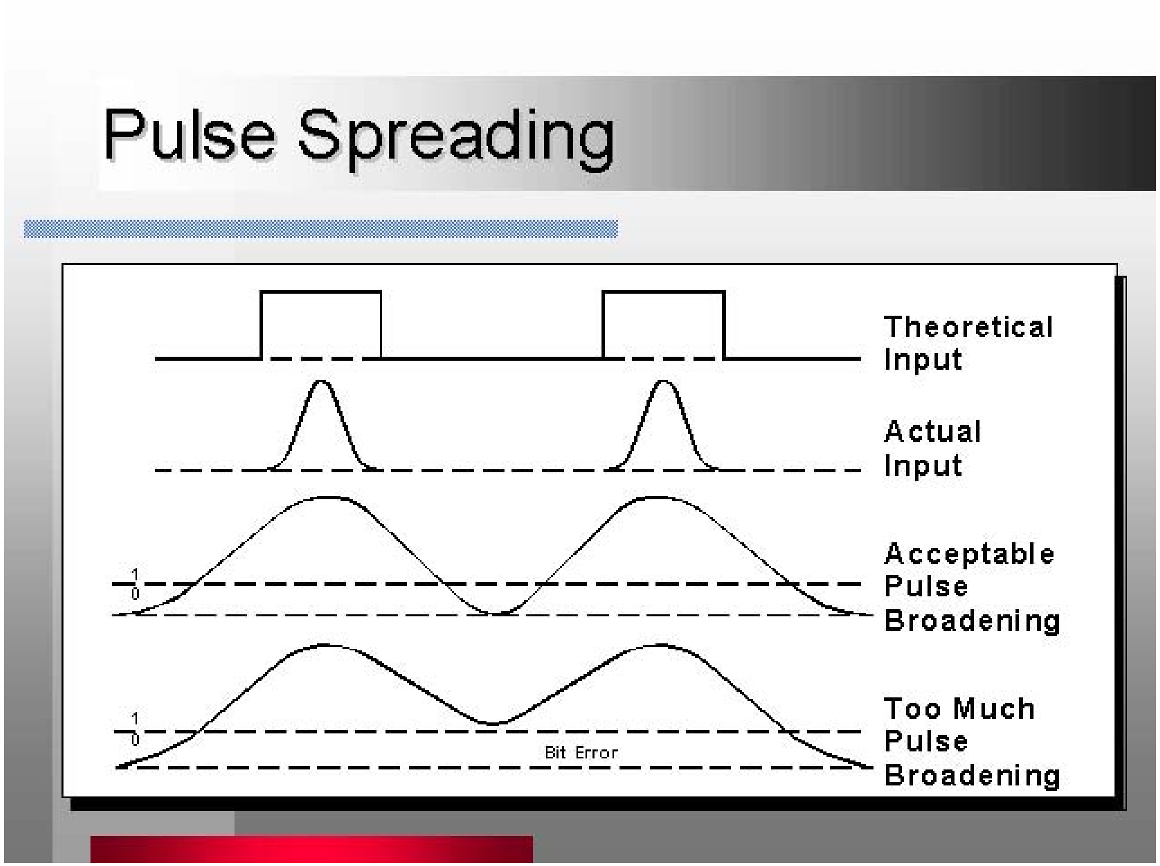
Index of Refraction is a function of wavelength
Since light velocity is a function of index of refraction
light velocity in a given medium is a function of wavelength
Light pulses at different wavelengths will have different propagation times



Various modes follow different paths causing pulse broadening

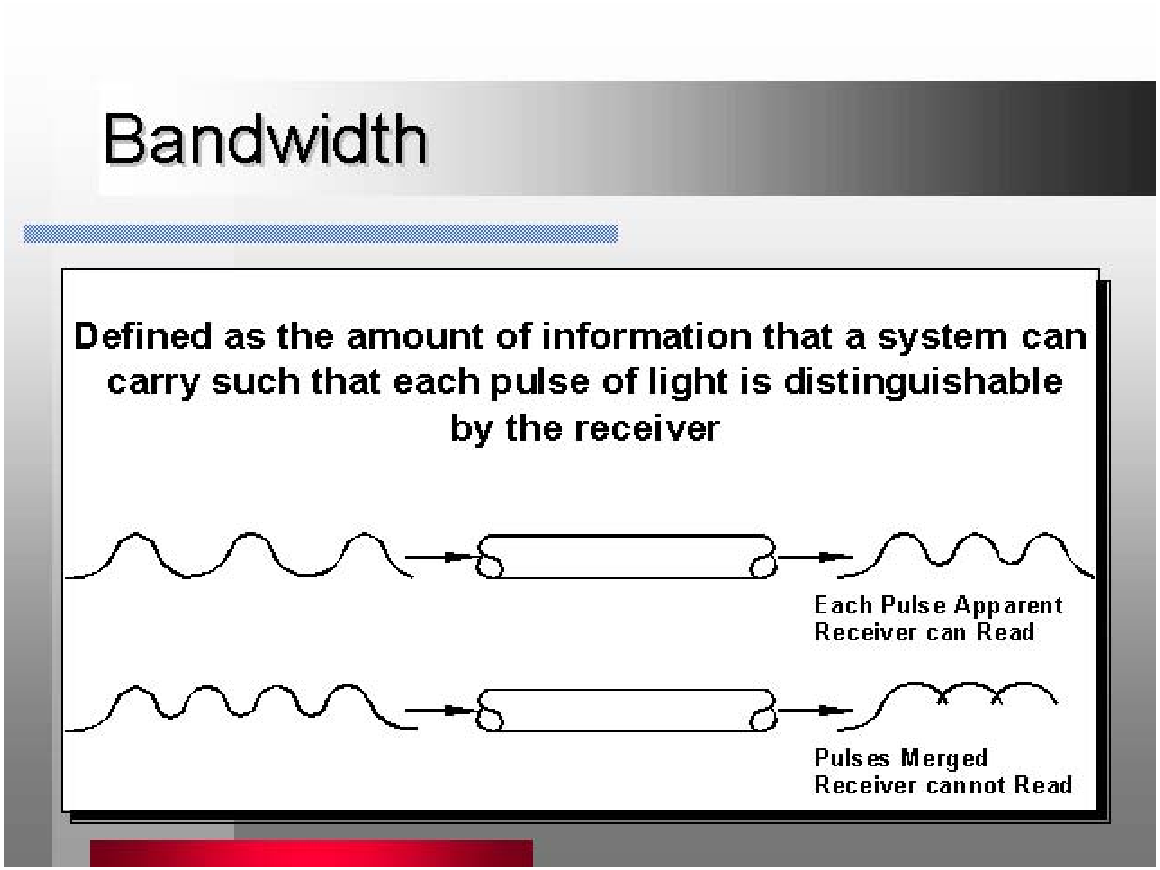


Because a light pulse is made up of different colors and modes of light some portions arrive at the end of the fiber before others causing a spreading effect
This causes pulses to overlap making them unreadable by the receiver

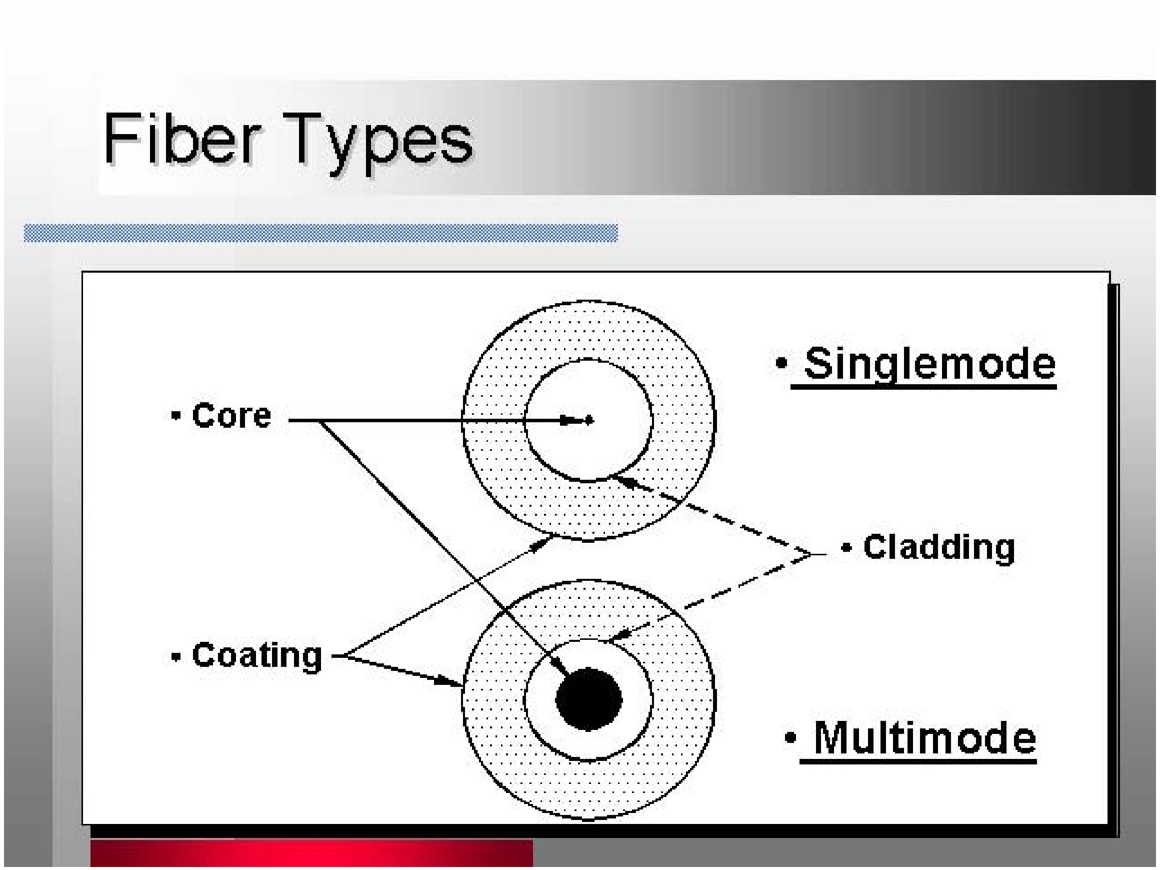


The received pulse must be above the receiver threshold to be detected as an on pulse. Likewise an off pulse must be below the receiver threshold to be detected as an off pulse.

If pulses spread and overlap above the receiver threshold, an off pulse will not be detected and errors in the signal will result

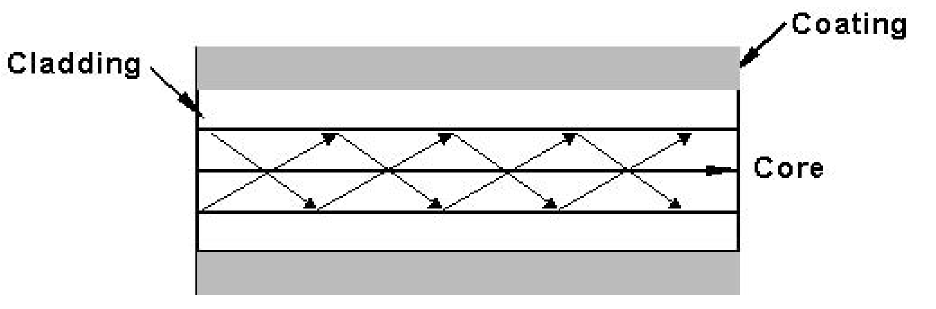


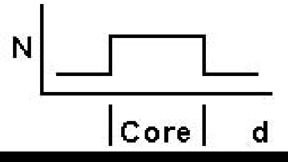
Fiber bandwidth is measured in MHz x Km. A length of glass is measured for bandwidth. By convention the bandwidth specification for that fiber is the length of that fiber times the measured bandwidth for that fiber.



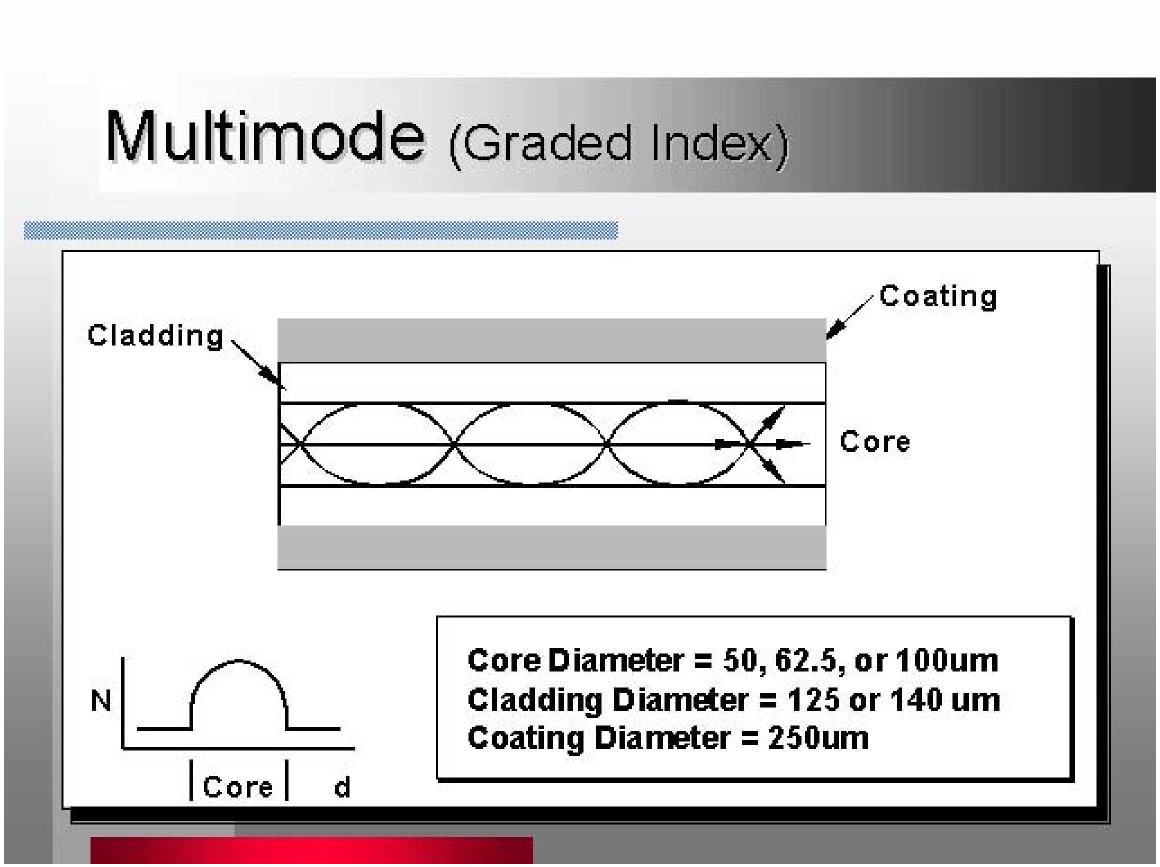
Multimode fiber allows for more than one pathway or mode of light to travel in the fiber
Singlemode fiber allows for only one pathway or mode of light to travel within the fiber at a specific operational wavelength
It is impossible to distinguish between singlemode fiber and multimode with the naked eye

Multimode (Step Index)





Core Diameter = 50, 62.5, or 100um
Cladding Diameter = 125 or 140 um
Coating Diameter = 250um

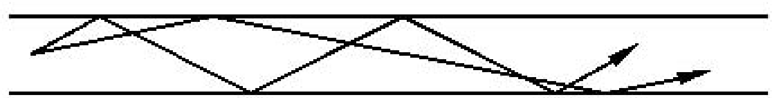


Most commonly used fiber

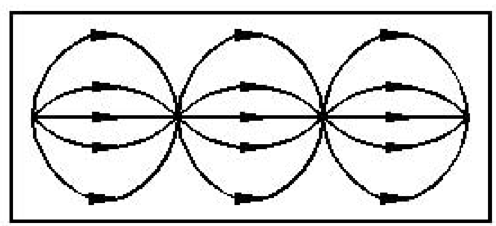
Reduces modal dispersion by equalizing the transit times among the modes

The core is layered with the index of refraction increasing toward the center of the core

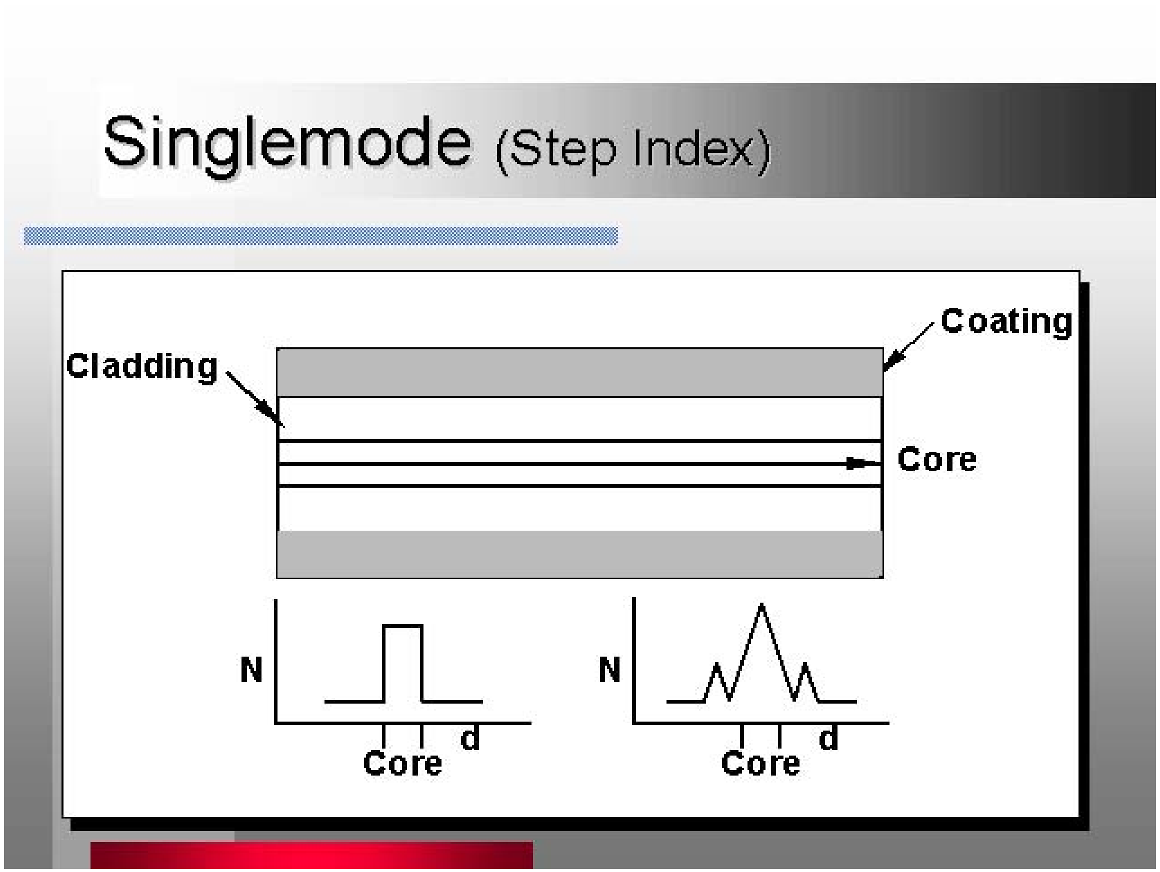
Multimode



Ray Path Step Index Fiber



Ray Path Grin Fiber



In singlemode fiber, there is only one mode at a typical system wavelength; therefore, there is no modal dispersion. This results in much lower dispersion and more information carrying capacity