Lecture 02

ECE 423

Optical Communications

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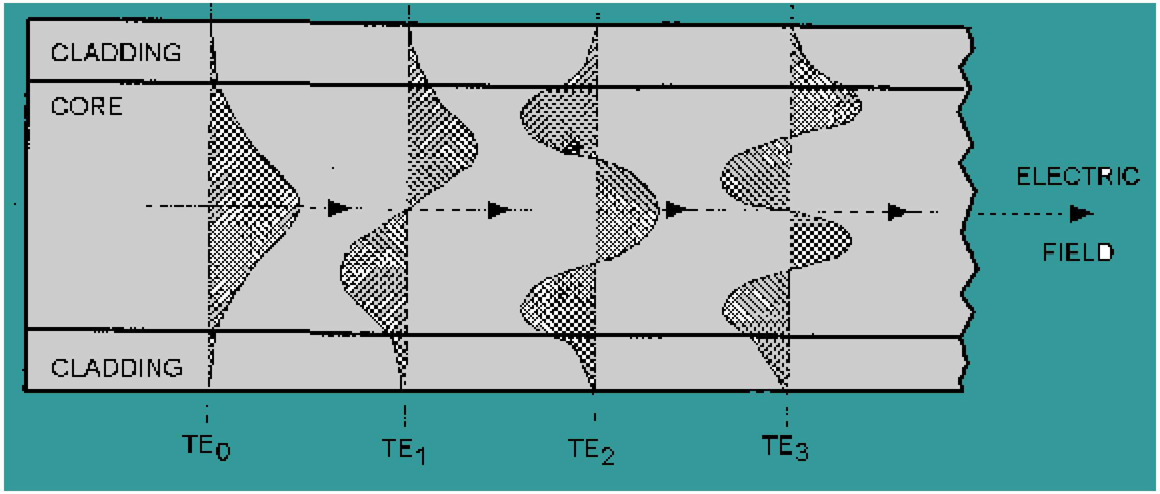
The modes



- A fiber mode refers to a specific solution of this wave equation that satisfies the fiber boundary conditions while maintaining a constant spatial distribution during propagation.
- Different electromagnetic wave patterns can propagate in a fiber optic. These patterns are called **modes**.
- The number of maxima of each pattern is the **order of the mode** (e.g. TE_0 has one maximum, TE_2 has 3, etc.).
- Each mode can be realized with different wavelength.

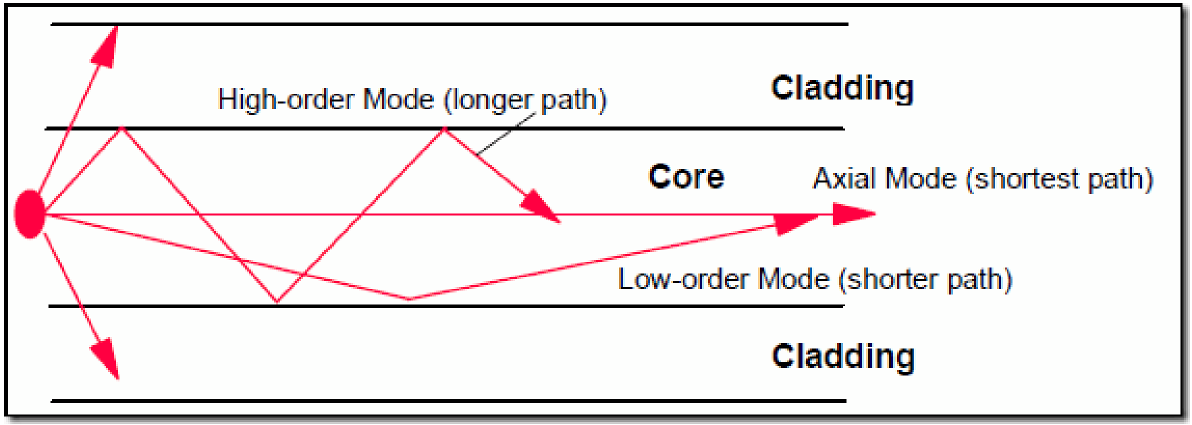
The modes

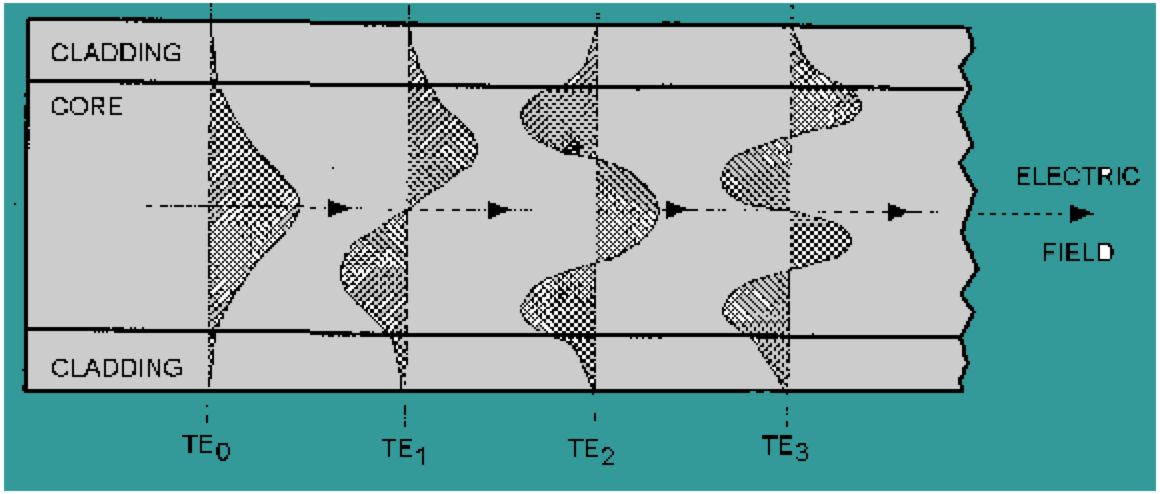
- Modes: the allowed rays that can be incident on the core-cladding interface and can propagate constructively.
- There are discrete incident angles on that interface which satisfy these conditions (these modes are derived using Maxwell' equations like any waveguide)
- In a step-index fiber, the corresponding (discrete) value of θ is approximately given by the following empirical formula.

$$\cos\theta \approx 1 - \Delta\left[1 - \left(1.1428 - \frac{0.996}{V}\right)^2\right]$$

Low order and High order modes

- **Low order** modes have **high incident angle**, while **high order modes** have **low incident angle**.





The modes

Propagation Mode

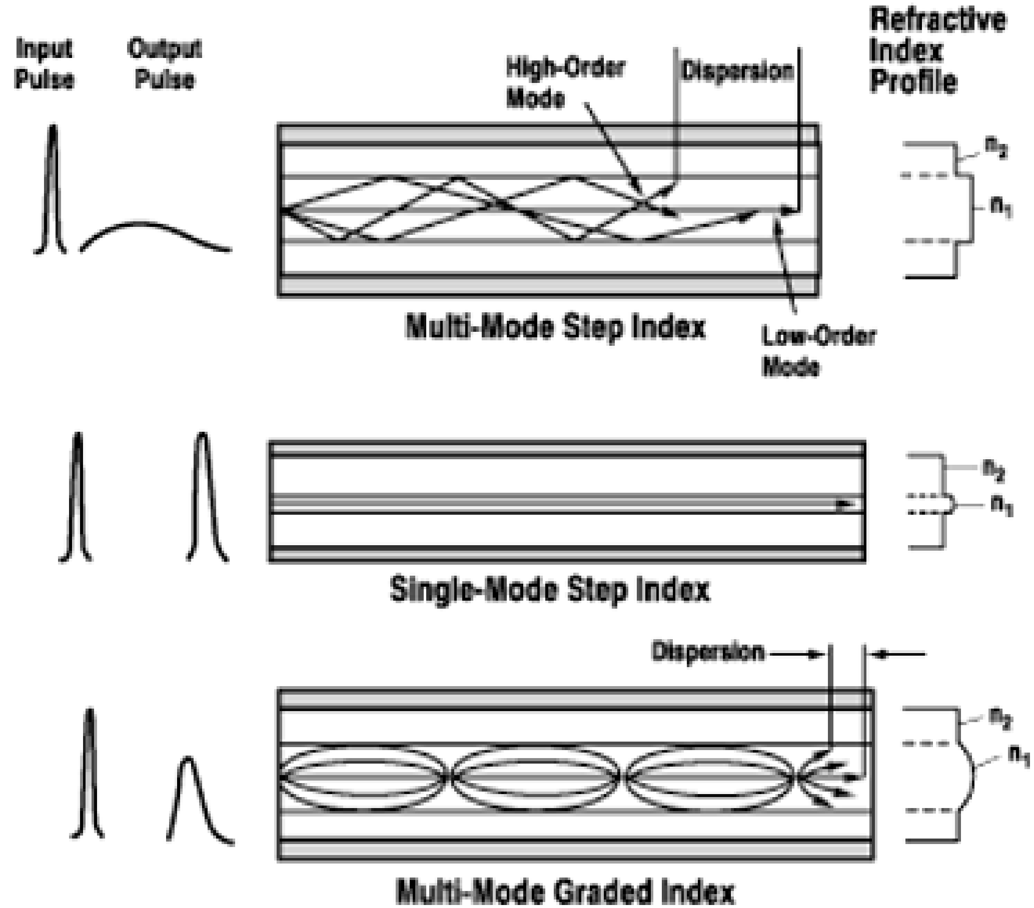
- There are 2 types of propagation modes in fiber optics cable which are multi-mode and single-mode.
- These provide different performance with respect to both attenuation and time dispersion.
- The single-mode fiber optic cable provides the better performance at a higher cost.

The modes

$$n(r) = \begin{cases} n_1, & r \le a \\ n_2, & r > a \end{cases}$$

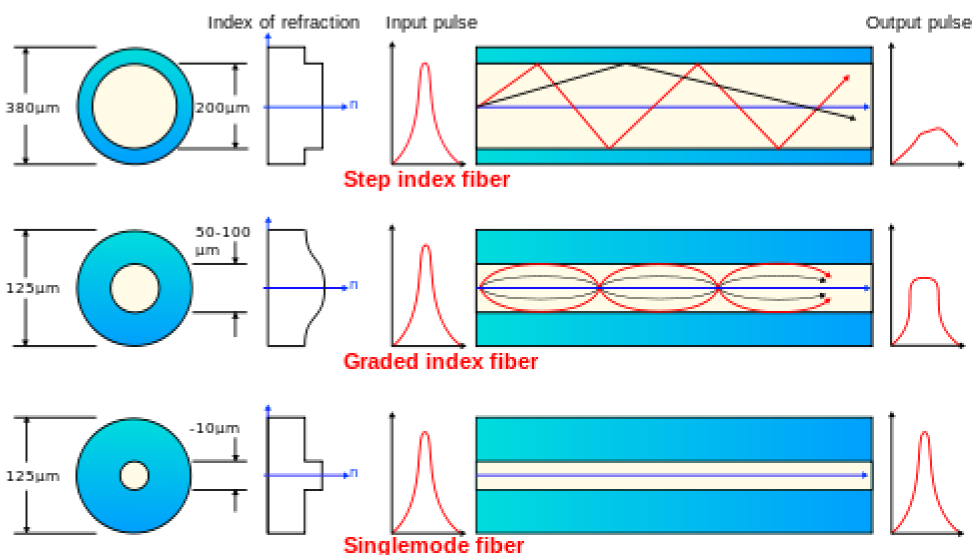
$$n(r) = \begin{cases} n_1, & r \le a \\ n_2, & r > a \end{cases}$$

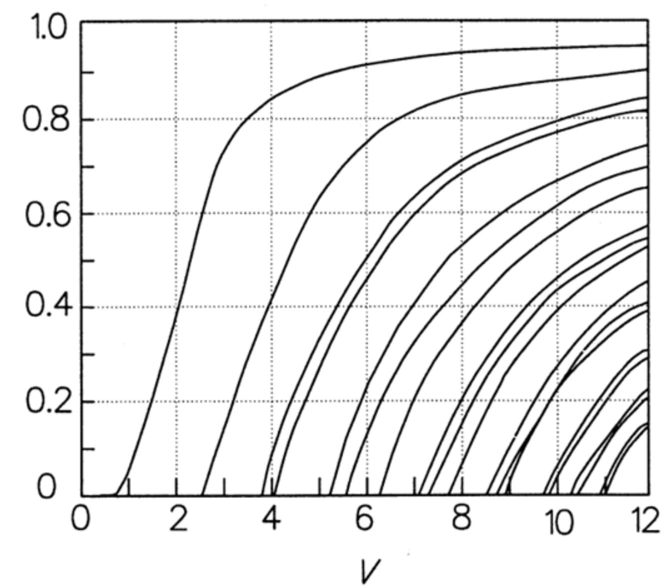
$$n(r) = \begin{cases} n_1\sqrt{1 - 2\Delta(r/a)^{\alpha}}, & r \le a \\ n_2, & r > a \end{cases}$$



α is the profile parameter which gives the characteristic refractive index profile of the core.

Single vs. Multi-mode Optical Fibers





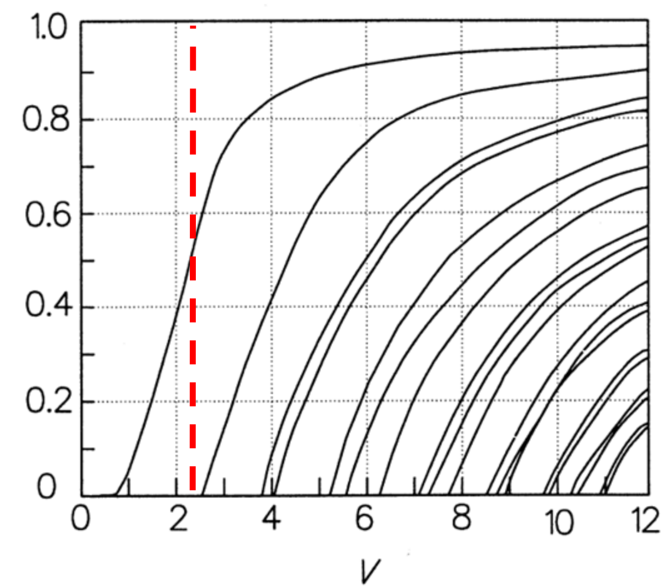
- The number of modes that can propagate depend on:
  - n_{core}, $n_{cladding}$, wavelength (λ) of the fiber optic and core diameter (α).

$$V = \frac{2\pi \cdot a}{\lambda}\sqrt{\left(n_{core}^2 - n_{cladding}^2\right)}$$

- **Normalized frequency** (V) show the number of modes that a fiber optic can support.
- The larger the V, the more modes can be supported.

Single vs. Multi-mode Optical Fibers

- Each fiber optic has a specific normalized frequency.
- Fiber optics with V < 2.405 can support only one mode. They are called **single mode fibers**.
- Fiber optics with V > 2.405 can support more modes. They are called **multi-mode fibers**.

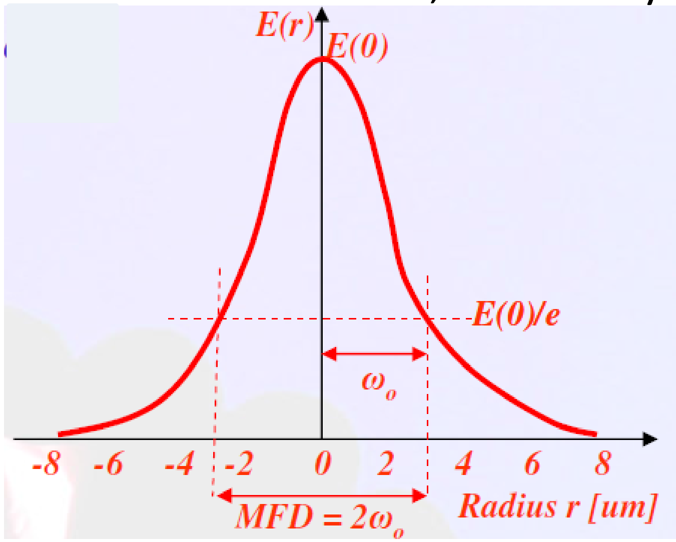


- Y axis shows the **propagation constant**.
- The higher the propagation constant, the less the **dispersion** of the wave during the propagation.
- The higher the mode order, the higher the dispersion.

Modal field diameter (MFD) and spot size

- A single mode fiber supports only one mode that propagates through the fiber. This mode is also referred as the fundamental mode.
- The transverse field distribution associated with the fundamental mode determines various important parameters like splice loss at joints, launching efficiencies, and bending loss.
- The fundamental mode field is well approximated by Gaussian distribution, which may be written in the form.

$$\psi(r) = Ae^{-r^2/w^2}$$



MFD :

is the distance between 1/e field amplitude points of the corresponding values at the fiber axis

Spot size w_o:

is the mode field radius, the nominal half width of the input excitation field i.e., MFD =2 w_o

The optimum values of the spot size related to the core radius *a* and the normalized frequency V as:

$$\frac{w}{a} = \left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}\right)$$

Number of modes propagation in optical fiber

- ***Condition of single mode***

SI fiber: $0 \le V < 2.405$, $V = \frac{2\pi a}{\lambda} NA$ *is the normalized frequency*

GI fiber: $0 \le V < 2.405\sqrt{1 + \frac{2}{\alpha}}$

- ***Number of modes :***

The number of modes that can be propagated in

SI fiber

$$M_{SI} = \frac{V^2}{2}$$

GI fiber

$$M_{GI} = M_{SI}\left(\frac{\alpha}{\alpha+2}\right)$$

α is the profile parameter

- ***Cut off wavelength***

Is the wavelength above which the fiber becomes single moded

$$\lambda_c = \frac{2\pi a}{V_c} NA$$

Example on the cutoff wavelength

- Consider a step-index fiber (operating at 1300 nm) with n_1 = 1.447, Δ = 0.003, and a = 4.2 μm.

$$V = \frac{2\pi a}{\lambda_o} NA$$

$$V = \frac{2\pi(4.2 \times 10^{-6})}{1.3 \times 10^{-6}} 1.447\sqrt{2 \times 0.003} = 2.275$$

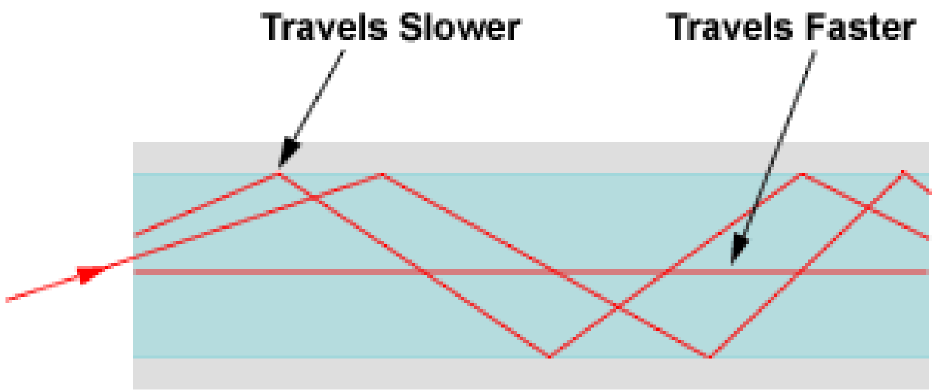
$$\therefore V \leq 2.405$$

$$\frac{2\pi a}{V_c} NA \leq \lambda_o$$

$$\lambda_o \geq \frac{2.958}{2.405} = 1.23\ \mu\text{m}$$

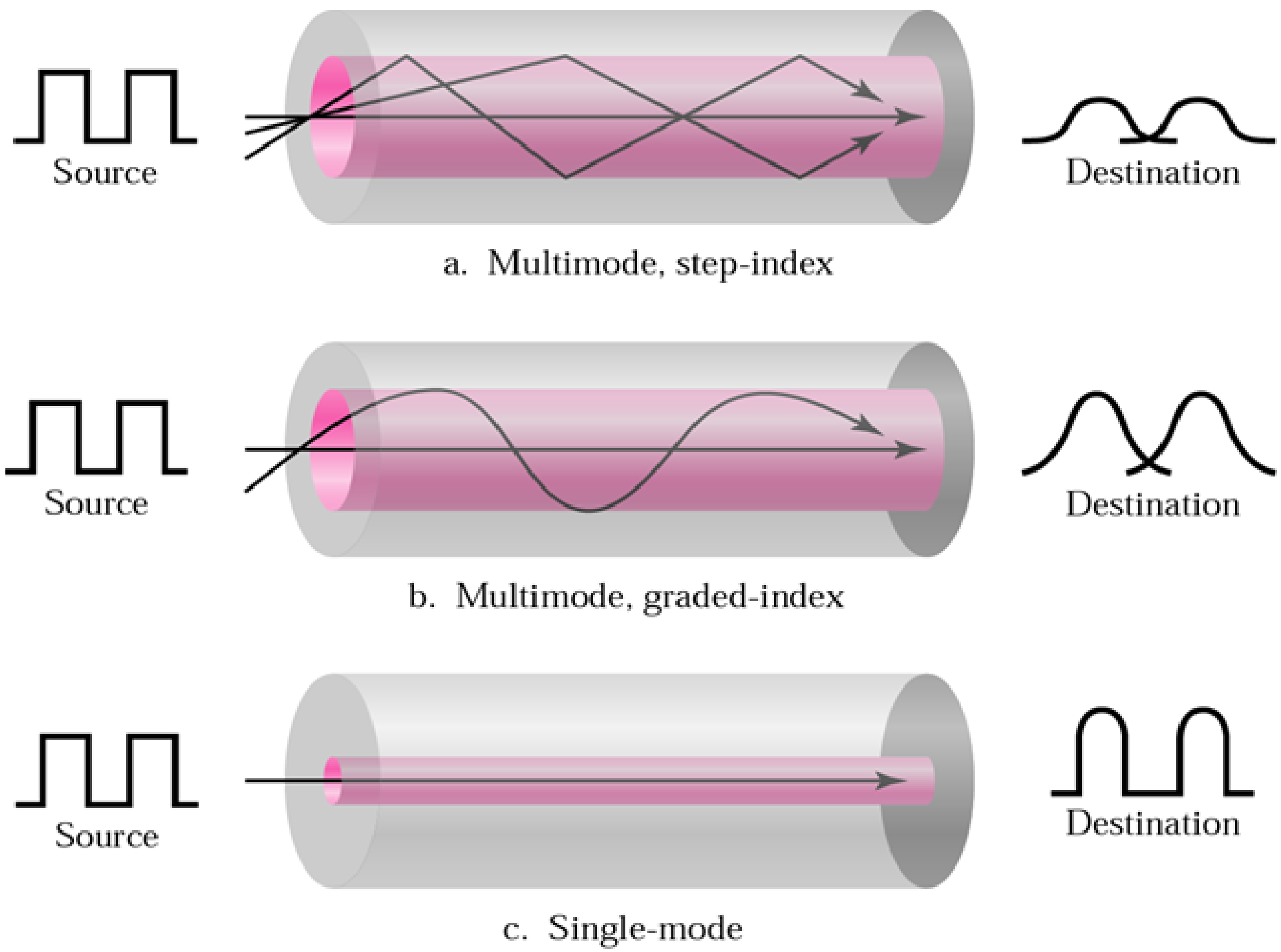
Modal Dispersion

- The arrival of different modes of the light at different times is called **Modal Dispersion**.
- Modal dispersion causes pulses to spread out as they travel along the fiber, the more modes the fiber transmits, the more pulses spread out.
- This significantly limits the bandwidth of step-index multimode fibers.
- For example, a typical step-index multimode fiber with a 50 µm core would be limited to approximately 20 MHz for a one kilometer length, in other words, a bandwidth of 20 MHz·km.



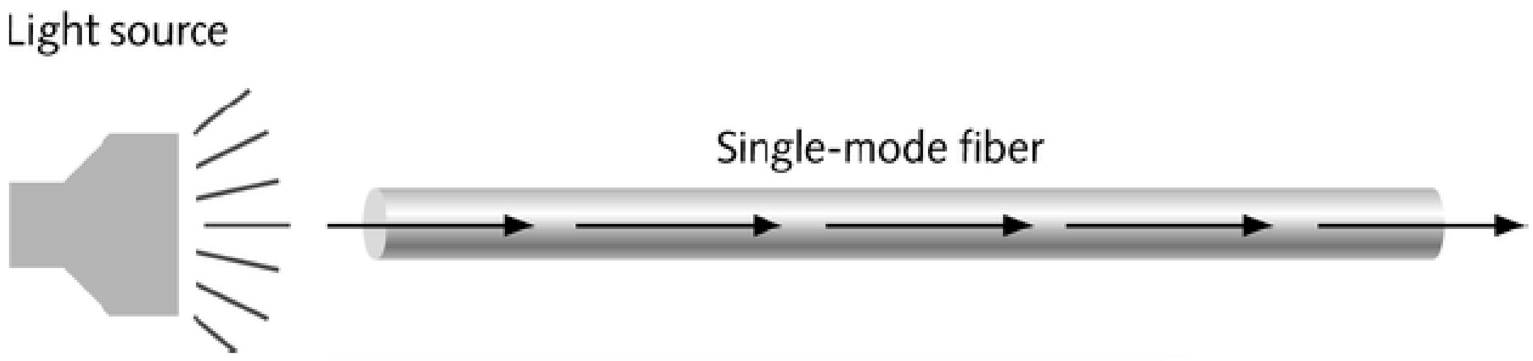
Step-Index Multimode Fiber

Fiber Types


Source
Destination
a. Multimode, step-index
Source
Destination
b. Multimode, graded-index
Source
Destination
c. Single-mode

Single Mode Fibers

- Carries light pulses along **single path.** Only the lowest order mode (**fundamental mode**) can propagate in the fiber and all higher order modes are under cut-off condition (**non-propagating**)
- Uses Laser Light source



Single Mode Fibers

Advantages

- Less dispersion
- Less degradation
- Large information capacity
- Core diameter is about 10 μm
- Difference between the RI of core and cladding is small

Drawbacks

- Expensive to produce
- Joining two fibers is difficult
- Launching of light into single mode is difficult

Optical Specifications

SINGLE MODE FIBER

ATTENUATION

Parameters		
Attenuation (dB/km)	@ 1310 nm	≤ 0.34
	@ 1550 nm	≤ 0.21
	@ 1625 nm	≤ 0.24

DISPERSION

Dispersion	@ 1285 ~ 1330 nm	≤ 3.0 ps/nm·km
	@ 1550 nm	≤ 17.5 ps/nm·km
	@ 1625 nm	≤ 22.0 ps/nm·km
Zero Dispersion Wavelength		1302 ~ 1322 nm

Fiber Length

- Standard: 25.2 km, 50.4 km per spool
- Other fiber lengths up to 50.4 km are available upon request

Dimensional Specifications

Parameters		Unit	Specification
Glass	Clad Diameter	µm	125.0 ± 0.7
	Clad Non-Circularity	%	≤ 0.8
	Core-Clad Concentricity Error	µm	≤ 0.5
	Fiber Curl	m	≥ 4.0
Coating	Coating Diameter	µm	245 ± 3
	Coating Outer Non-Circularity	%	≤ 5.0
	Coating Concentricity Error	µm	≤ 10.0

Environmental Specifications

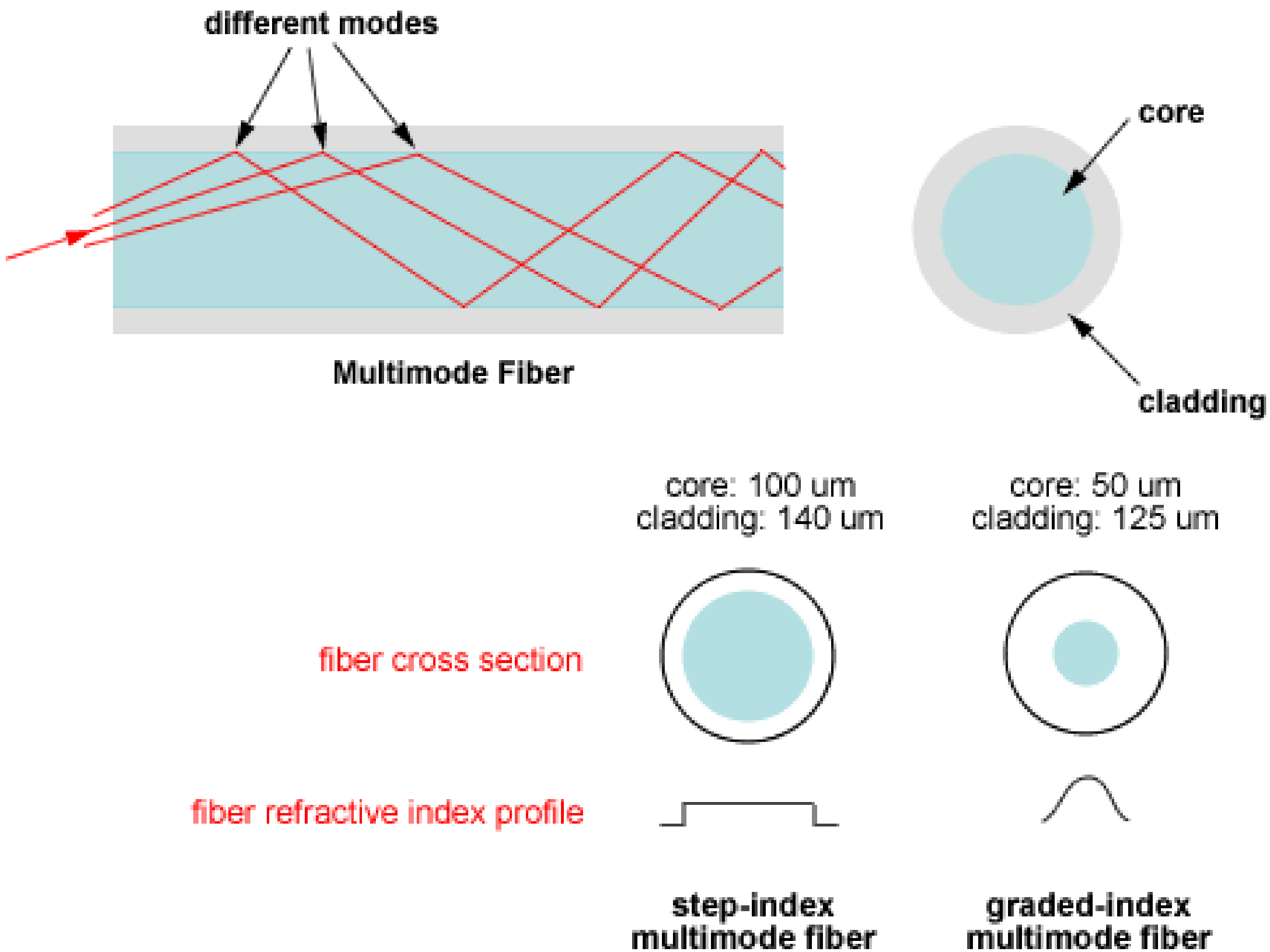
Parameters	Specifications
Temperature Dependence (-60 °C ~ +85 °C)	≤ 0.05 dB/km @ 1310 nm & 1550 nm
Temp.-Humidity Cycling (-10 °C ~ +85 °C, 98% RH)	≤ 0.05 dB/km @ 1310 nm & 1550 nm
Water Immersion, 23 ± 2 °C	≤ 0.05 dB/km @ 1310 nm & 1550 nm
Heat Aging, 85 ± 2 °C	≤ 0.05 dB/km @ 1310 nm & 1550 nm

Multi-mode Optical Fiber

- **Multi-mode optical fiber** is a type of optical fiber mostly used for communication over short distances, such as within a building or on a campus.
- Typical multimode links have data rates of 10 Mbit/s to 10 Gbit/s over link lengths of up to 600 meters.
- Multi-mode fibers are described by their core and cladding diameters. example: 62.5/125 µm multi-mode fiber.
- The two types of multi-mode optical fibers are:
  - ✓ Step index multi-mode optical fibers
  - ✓ Graded index multi-mode optical fibers

The transition between the core and cladding can be sharp, which is called a step-index profile, or a gradual transition, which is called a graded-index profile.

Multi-mode Optical Fiber



Step Index Multimode Fiber

- **Step-index multimode fiber** has a large core, up to 100 microns in diameter.
- As a result, some of the light rays that make up the digital pulse may travel a direct route, whereas others zigzag as they bounce off the cladding.
- These alternative pathways cause the different groupings of light rays, referred to as **modes**, to arrive separately at the receiver.

Step Index Multimode Fiber

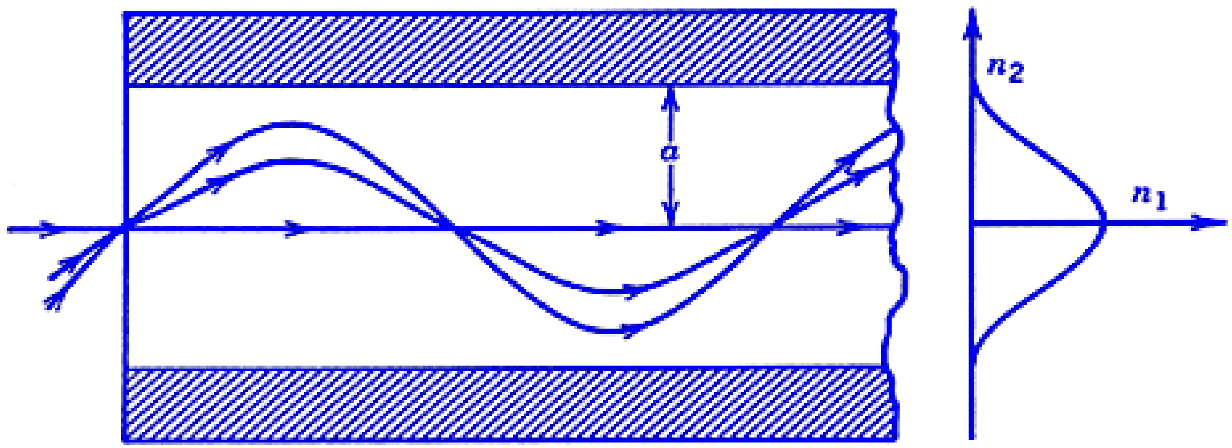
- The pulse begins to spread out, thus losing its well-defined shape.
- The need to leave spacing between pulses to prevent overlapping limits bandwidth that is, the amount of information that can be sent.
- Consequently, this type of fiber is best suited for transmission over short distances, in an endoscope, for instance.

Graded-Index Multimode Fibers

- **Graded-index** multimode fibers solves the problem of modal dispersion to a considerable extent.
- Graded-index multimode fiber contains a core in which the refractive index decreases gradually from the center axis out toward the cladding.
- The higher refractive index at the center makes the light rays moving down the axis advance more slowly than those near the cladding.

Graded-Index Multimode Fibers

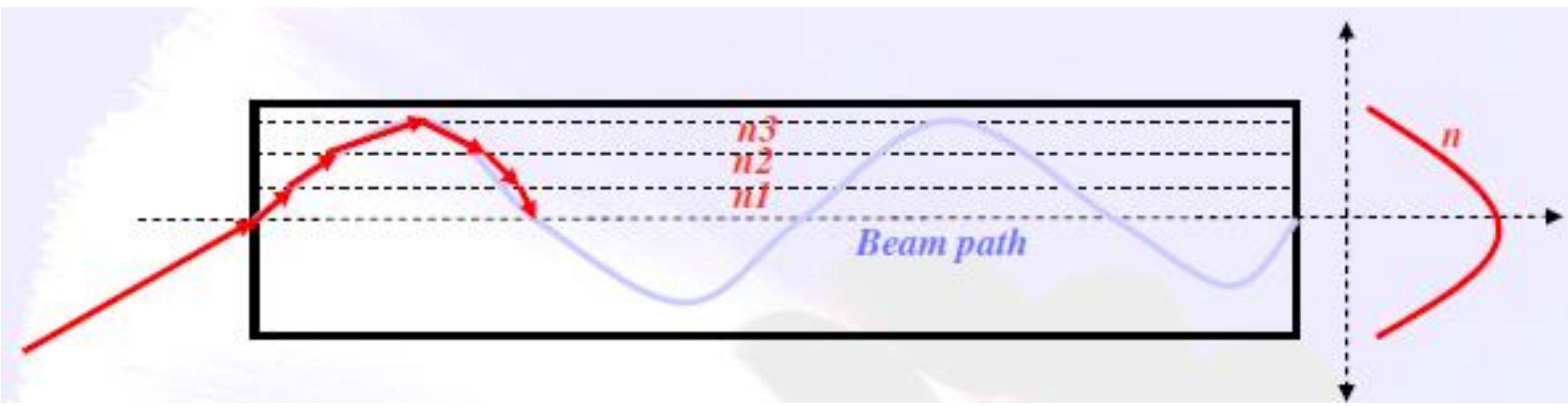
- Instead of zigzag fashion, light in the core curves helically because of the graded index, reducing its travel distance.
- The shortened path and the higher speed allow light at the periphery to arrive at a receiver at about the same time as the slow but straight rays in the core axis.
- The result: a digital pulse suffers less modal dispersion.



Graded-Index Multimode Fibers

Rays travelling near the axis have a shorter path than rays travelling into the outer region of the core. However, near axial rays are transmitted through a region with higher refractive index and so travel with a slower speed than the outer rays.

This compensate for the path difference and reduces dispersion in the fibre.



Advantages of Multi-mode Fiber

- easily supports most distances required for premises and enterprise networks can support 10 Gb/s transmission up to 550 meters
- easier to install and terminate in the field
- connections can be easily performed in the field, offering installation flexibility and cost savings
- have larger cores that guide many modes simultaneously.

OPTICAL SPECIFICATIONS

Multi Mode Fiber

ATTENUATION AND BANDWIDTH

Parameters		Premium	Standard
Attenuation (dB/km)	@ 850 nm	≤ 2.4	≤ 2.5
	@ 1300 nm	≤ 0.6	≤ 0.7
Point Discontinuity (@ 850 nm & 1300 nm)		≤ 0.10 dB	
Bandwidth (MHz-km)	@ 850 nm	≥ 600	≥ 400
	@ 1300 nm	≥ 1000	≥ 600

DIMENSIONAL SPECIFICATIONS

Parameters		Unit	Specification
Glass	Core Diameter	μm	50.0 ± 3.0
	Clad Diameter	μm	125.0 ± 1.0
	Clad Non-Circularity	%	≤ 2.0
	Core-Clad Concentricity Error	μm	≤ 3.0
Coating	Coating Diameter	μm	245 ± 10
	Coating Concentricity Error	μm	≤ 10.0

MECHANICAL & ENVIRONMENTAL SPECIFICATIONS

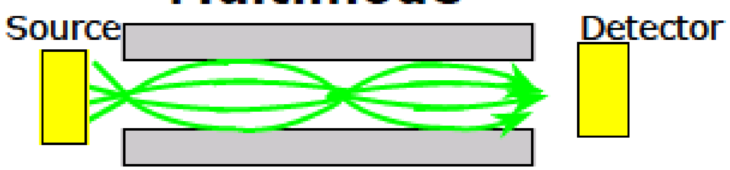
Parameters	Specifications
Proof Test Level	≥ 100 kpsi
Temperature Dependence (-60°C ~ +85°C)	≤ 0.2 dB/km @ 850 nm & 1300 nm
Temp.-Humidity Cycling (-10°C ~ +85°C, 98% RH)	≤ 0.2 dB/km @ 850 nm & 1300 nm
Coating Strip Force	1.3 ~ 5.5 N

Single vs. Multi-mode Optical Fibers

- Single mode fibers:
  - The core diameter is small: 8 – 10 µm.
  - Only the lowest mode can be propagated (around 1300nm wavelength).
  - Normalized frequency less or equal to 2.405.
  - Lower signal loss in comparison with multi-mode and higher bandwidth. Low fiber dispersion.
  - They use laser diodes to generate light.
- Multi-mode fibers:
  - Typical core sizes: 50 – 100 µm.
  - The light enters easily the fiber and the connections are easier.
  - They use LED to generate light (cheaper, less complex and last longer).
  - However, they have higher dispersion than the single mode.

Multi-mode v/s Single mode

Multimode

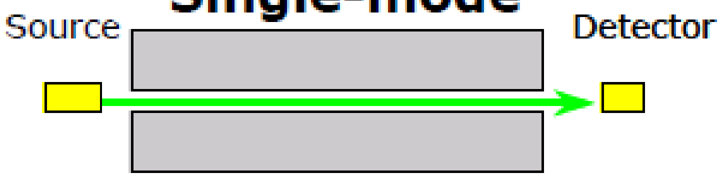


+ Low cost sources
    + 850 nm and 1310 nm LEDs
    + 850 nm lasers at 1 & 10 Gb/s
    + Low precision packaging
+ Low cost connectors
+ Lower installation cost
- Higher fiber cost
+ **Lower system cost**
- Higher loss, lower bandwidth
- Distance up to 2 km

Best for:

• ***LAN, SAN, Data Center, CO***

Single-mode



- High cost sources
    - 1310+ nm lasers 1 and 10 Gb/s
    - 1 Gb/s + w/ DWDM
    - High precision packaging
- Higher cost connectors
- Higher installation cost
+ Lower fiber cost
- **Higher system cost**
+ Lower loss, higher bandwidth
+ Distance to 60 km+

Best for:

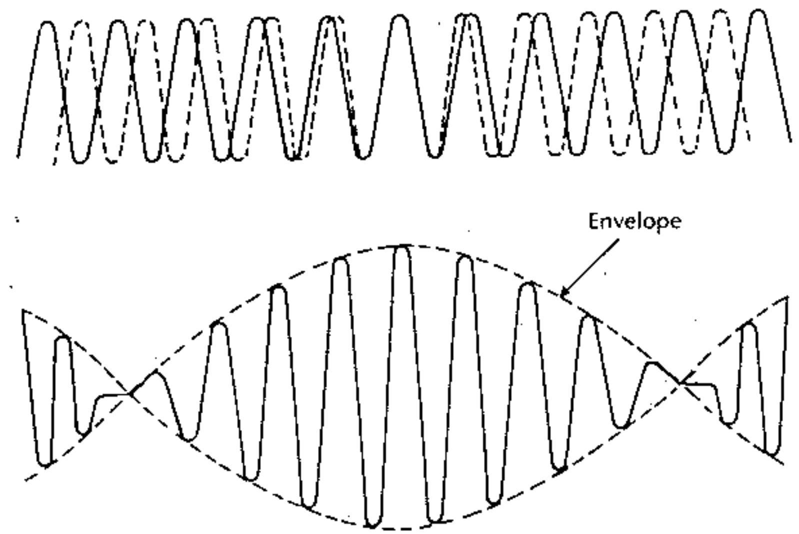
• ***WAN, MAN, Access, Campus***

Phase and Group Velocity

Phase Velocity: For plane wave, there are points of constant phase, these constant phase points forms a surface, referred to as a **wavefront**.

- As light (plane wave $e^{(j\omega t - j\beta_1 z)}$) propagates along a waveguide in the z-direction, wavefront travel at a phase velocity ; $v_p = {}^{\omega}/_{\beta_1} = {}^{c}/_{n_1}$

- ❑ Non-monochromaticity leads to group of waves with closely similar frequencies ⇒ **Wave Packet**
- ❑ **Wave packet** observed to move at a group velocity, $\mathrm{V_g} = d\omega/d\beta$ ⇒ **Group Velocity**
- ❑ $\mathrm{V_g}$ is of great importance in study of TCs of optical fibers:-relates to the propagation characteristics of observable wave groups



Formation of wave packet from combination of two waves of nearly equal frequencies

Phase and Group Velocity

The Group Velocity:

It is the speed at which the energy in a particular mode travels along the fiber

$$\mathrm{V_g} = d\omega / d\beta$$

The Group Delay:

The time needed for an optical mode to travel a distance $\boldsymbol{l}$ with a velocity $\mathbf{V_g}$ is referred to as "group delay" $\boldsymbol{\tau}_{\mathbf{g}}$

$$\tau_{\mathrm{g}} = \frac{l}{\mathrm{V_g}} = l \frac{d\beta}{d\omega}$$

- ❑ Note that all above quantities depend both on the frequency & the propagation mode. Light sources (LED & Laser diodes) have a finite spectral width $\Delta\boldsymbol{\lambda}$

Phase and Group Velocity

- Hence within that range $\Delta\lambda$, each mode travels with its own group velocity V_g and takes its own time τ_g to travel a certain distance in the fiber.
- There is a "spread" $\Delta\tau_g$ in the times of arrivals ($\tau_{g1}, \tau_{g2}, \ldots$etc) of the modes in the fiber.

$$\Delta\tau_g = \frac{d\tau_g}{d\lambda}\Delta\lambda$$

- **Dispersion:** $D = \frac{d\tau_g}{d\lambda}$
- **Phase Velocity:** $V_p = \frac{c}{n_1}$
- **Group Velocity:** $V_g = \frac{c}{N_g} = \frac{c}{(n_1 - \lambda\frac{dn_1}{d\lambda})}$

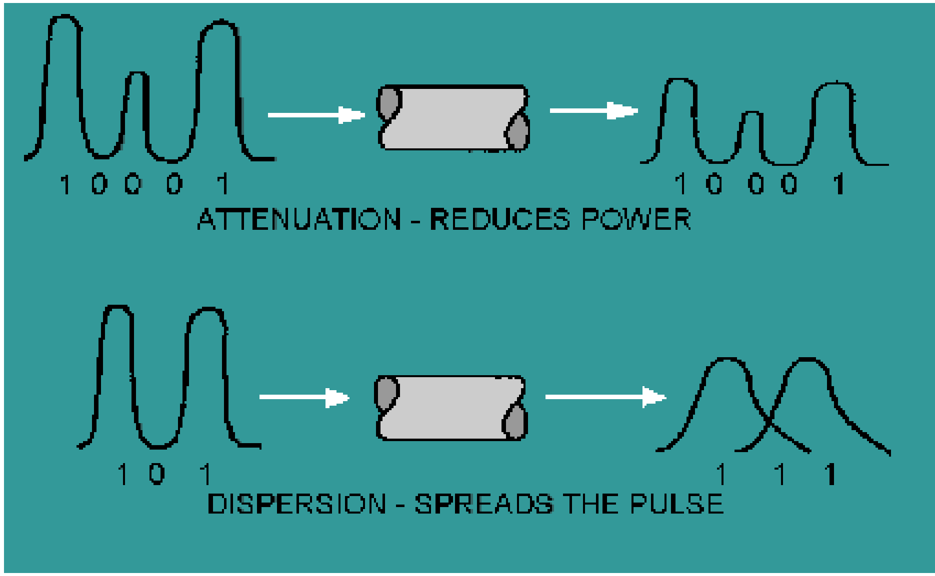
Parameter N_g is known as the ***group index*** of the guide

Performance of Fiber Optics

- Performance is affected by:
  - Signal loss (attenuation)
  - Bandwidth (due to dispersion)
    - Bandwidth in telecommunications is defined as the difference between the highest and the lowest frequency of the signal.
    - Bandwidth in data transmission is defined as bits transmitted per second.

Performance of Fiber Optics

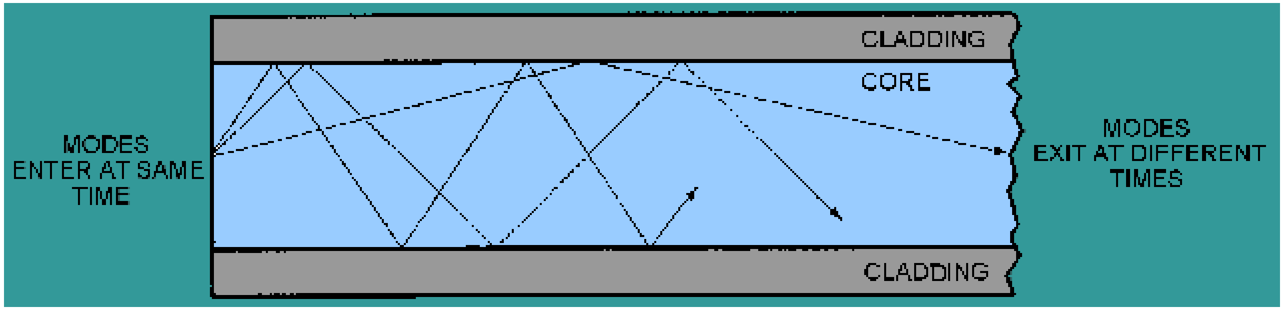
- Fiber optics properties that affect performance are:
  - Attenuation
  - Dispersion
- **Attenuation** is a result of:
  - Light absorption
  - Light scattering
  - Bending losses
- If the signal **strength** is reduced below a specific point, the receiver is unable to detect it.



- **Dispersion** is the spreading of the signal. The **spreading** limits how fast data can be transmitted along the fiber.
- The receiver is unable to distinguish between input pulses caused by the spreading of each pulse.

Dispersion

- 2 types of dispersion:
  - **Intramodal dispersion**: Occurs in all kinds of optical fibers, where more than one wavelengths are used (e.g in WDM).
    - Different wavelengths of signals of the same mode travel at different speeds inside the fiber, so exit the fiber at different times. n is function of wavelength.
  - **Intermodal dispersion**: Occurs only in multi-mode fibers.
    - Each mode travels at different speed inside the fiber, so, they do not exit from the fiber at the same time.



- Single mode fibers exhibit less dispersion than multi-mode.

Dispersion in Optical Fibers

- **Dispersion**: Any phenomenon in which the velocity of propagation of any electromagnetic wave is wavelength dependent.
- In communication, dispersion is used to describe any process by which any electromagnetic signal propagating in a physical medium is degraded because the various wave characteristics (i.e., frequencies) of the signal have different propagation velocities within the physical medium.
- There are two "crucial" dispersion types in a single mode optical fiber:

  1- Material Dispersion

  2- Waveguide Dispersion

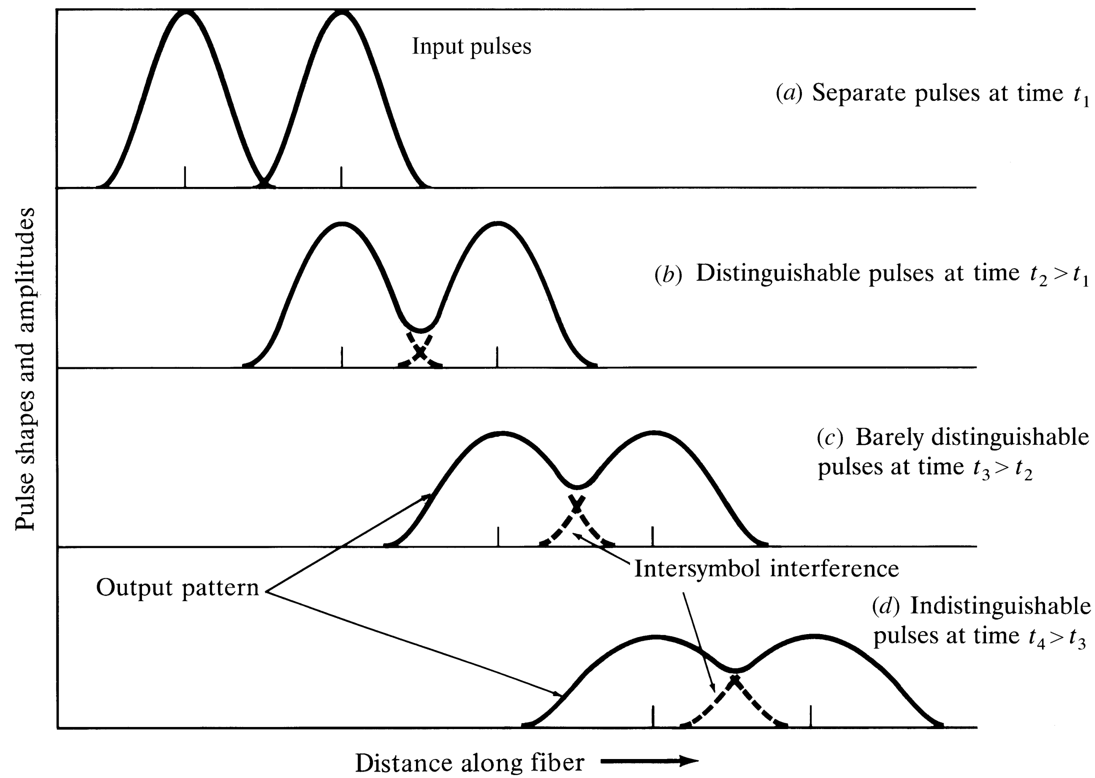
- Material & Waveguide dispersions are grouped as CHROMATIC dispersion, and sometimes are called Intramodal Dispersion.

Intramodal Dispersion

- As the output signal is collectively represented by group velocity & group delay this phenomenon is called **intramodal dispersion or Group Velocity Dispersion (GVD)**. **This phenomenon arises due to a finite bandwidth of the optical source, dependency of refractive index on the wavelength and the modal dependency of the group velocity**.
- In the case of optical pulse propagation down the fiber, GVD causes pulse broadening, leading to Inter Symbol Interference (ISI).

Dispersion & ISI

A measure of information capacity of an optical fiber for digital transmission is usually specified by the **bandwidth distance product** $BW \times L$ **in GHz.km.**
For multi-mode step index fiber this quantity is about 20 MHz.km, for graded index fiber is about 2.5 GHz.km & for single mode fibers are higher than 10 GHz.km.



Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000