# Dispersion in Optical Fiber Communcation systems II

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## Dispersion Management: Limitation Chromatic Dispersion

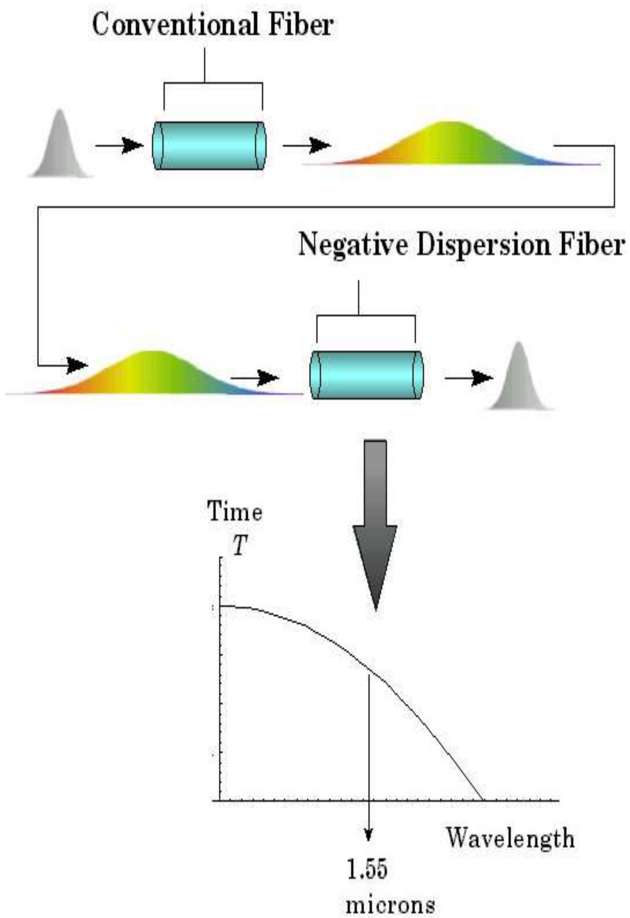
•CD places a limit on the maximum distance a signal can be transmitted without electrical regeneration:

•For directly modulated (high chirp laser)

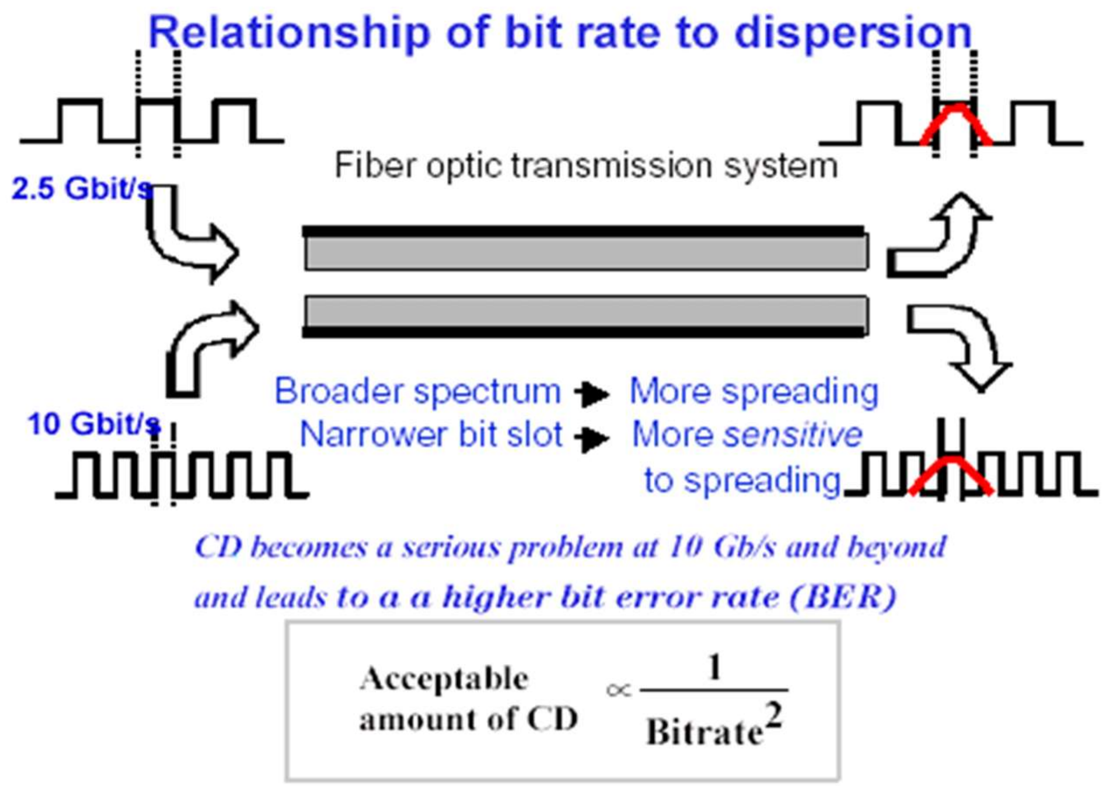
$$L_D = 1/ B \, |M_\lambda| \sigma \quad (1)$$

# Dispersion Compensating Fiber:

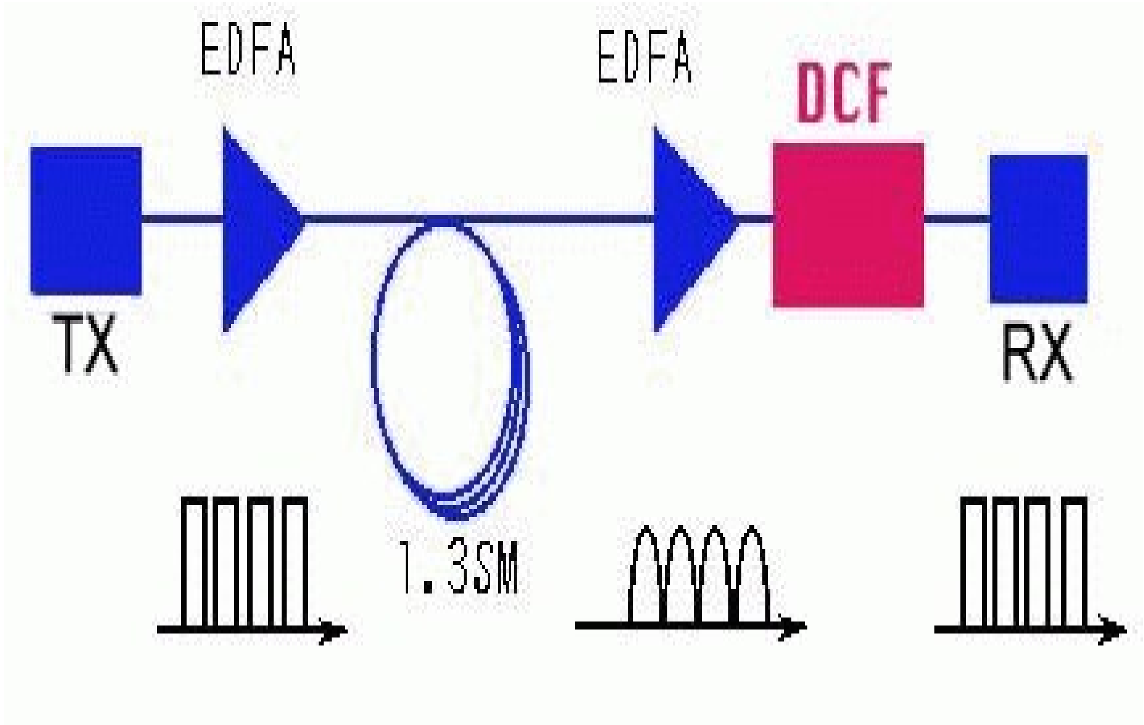
By joining fibers with CD of opposite signs and suitable lengths an average dispersion close to zero can be obtained; the compensating fiber can be several kilometers and the reel can be inserted at any point in the link, at the receiver or at the transmitter



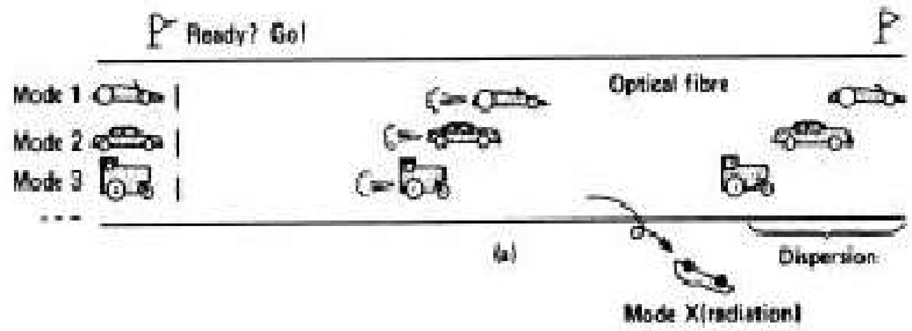
# Why Require Dispersion Compensation ?

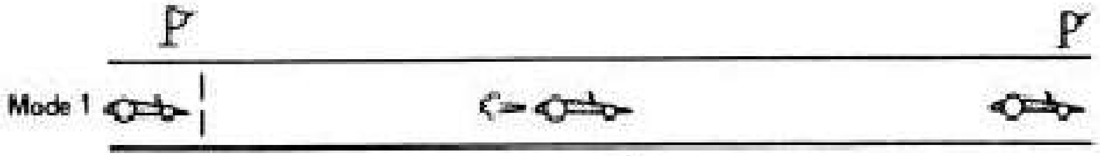


# Dispersion Compensating Fiber (DCF) Application

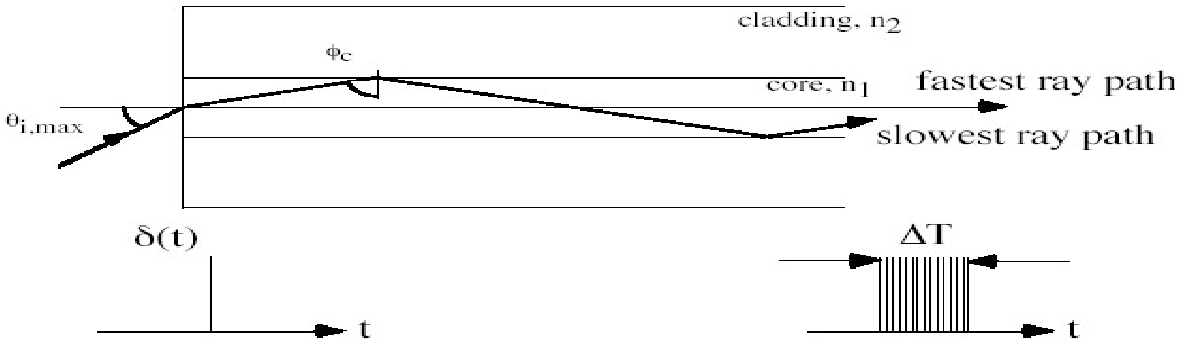


# Modal Dispersion



# Multimode step index fiber




- The time taken for the axial ray to travel along a fiber of length L gives the minimum delay time $T_{min}$ and

$$T_{min} = \frac{dis\tan ce}{velocity} = \frac{L}{C/n_1} = \frac{Ln_1}{C} \qquad 1$$

- The extreme material ray exhibits the maximum delay time $T_{max}$ where:

$$T_{max} = \frac{L/\cos\theta}{C/n_1} = \frac{Ln_1}{C\cos\theta} \qquad 2$$

- Using Snell's law of refraction at the core-cladding interface

$$\sin \phi_c = \frac{n_2}{n_1} = \cos \theta$$

This yields to

$$T_{max} = \frac{Ln_1^2}{cn_2} \qquad 3$$

The delay difference $\delta T_s$ between the meridional ray and the axial ray is

$$\delta T_s = T_{max} - T_{min} \cong \frac{Ln_1^2}{cn_2}\left(\frac{n_2 - n_2}{n_1}\right) \cong \frac{Ln_1^2}{cn_2}\Delta \quad when \Delta << 1 \qquad 4$$

When

$$\Delta << 1 \Rightarrow \Delta \approx \frac{n_1 - n_2}{n_2}$$

By rearranging eq. 4

$$\delta T_s = \frac{Ln_1}{c}\left(\frac{n_2 - n_2}{n_2}\right) \cong \frac{Ln_1\Delta}{c} \qquad 5$$

$$\delta T_s \approx \frac{L(NA)^2}{2n_1 c}$$

- It must be noted that this simple analysis only considers pulse broadening due to meridional rays and totally ignores skew rays with acceptance angle $\theta_{as} > \theta_{a.}$

- The rms pulse broadening $\sigma_s$ resulting from intermodal dispersion mechanism along the multimode step index fiber is

$$\sigma_s \approx \frac{Ln_1\Delta}{2\sqrt{3}c} \approx \frac{L(NA)^2}{4\sqrt{3}cn_1} \qquad 6$$

If we assume that the maximum bit-rate (B) is limited by a maximum allowed pulse broadening equal to the bit-period : $T_B = 1/B > \delta T$
we find: $B\ L < (n_2 c)/(n_1^2 \Delta)$

Example: Silica core without cladding (air): $n_1 = 1.5$, $n_2 = 1 \rightarrow BL <$ $4 \cdot 108$ [bits/(s m)] = 0.4 Mbit/(s km)
A large index-step gives small bandwidth !!!
Typical communication fiber: $\Delta \approx 0.5\% \rightarrow BL <$ 40 Mbit/s.km

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Ex. (K)

A 6 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate:

a The delay difference between the slowest and fastest modes at the fiber output;

b The rms pulse broadening due to intermodal dispersion on the link;

c the maximum bit rate that may be obtained without substantial errors on the link assuming only intermodal dispersion;

d the bandwidth-length product corresponding to (c).

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a. The delay difference between the slowest and fastest modes at the fiber output;

b. The rms pulse broadening due to intermodal dispersion on the link;

Sol:

a. The dalay difference is:

$$\delta T_s \simeq \frac{L n_1 \Delta}{c} = \frac{6\times10^3 \times 1.5 \times 0.01}{2.998\times10^8}$$

$$= 300\text{ns}.$$

b. The rms pulse broadening due to intermodal dispersion:

$$\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}\,c} = \frac{1}{2\sqrt{3}} \cdot \frac{6\times10^3 \times 1.5 \times 0.01}{2.998\times10^8}$$

$$= 86.7\text{ns}.$$

c the maximum bit rate that may be obtained without substantial errors on the link assuming only intermodal dispersion;

c The maximum bit rate may be estimated in two ways:

1 to get an idea of the maximum bit rate when assuming no pulse overlap.

$$B_T(max) = \frac{1}{2\tau} = \frac{1}{2\delta T_s} = \frac{1}{600 \times 10^{-9}}$$

$$= 1.7 \text{ Mbit } s^{-1}$$

2 Alternatively an improved estimate may be obtained using the calculated rms pulse broadening.

$$B_T(max) = \frac{0.2}{\sigma_s} = \frac{0.2}{86.7 \times 10^{-9}}$$

$$= 2.3 \text{ Mbit } s^{-1}$$

d the bandwidth-length product corresponding to (c).

d Using the most accurate estimate of the maximum bit rate from (c), and assuming return to zero pulses, the bandwidth-length product is

$$B_{opt} \times L = 2.3 \text{ MHz} \times 6 \text{ km} = 13.8 \text{ MHz.km}.$$

# Multimode graded index fiber

- Intermodal dispersion in multimode fibers is minimized with the use of graded index fiber. This is due to varying (reducing) the refractive index of the core region with distance from the axis of the core.

- The delay difference $\delta T_g$ is

$$\delta T_g \cong \frac{L n_1 \Delta^2}{2c} \approx \frac{L(NA)^4}{8 n^3 c} \qquad 1$$

- The rms pulse broadening of a near parabolic index profile graded index $\sigma_g$ is reduced compared to the similar broadening for corresponding step index fiber $\sigma_s$ ( i.e. the same relative refractive index difference ) following

$$\sigma_g = \frac{\Delta}{D} \sigma_s \qquad 2$$

Where D is a constant between 4 & 10 depending on the precise evaluation and exact optimum profile chosen.

- The best minimum theoretical rms pulse broadening for GRI fiber with an optimum characteristics refractive index profile for the core $\alpha_{op}$ of

$$\alpha_{op} = 2 - \frac{12\Delta}{5}$$

- Is given by combining

$$\sigma_s \approx \frac{Ln_1\Delta}{2\sqrt{3}c}$$

and eq. 3 as

$$\sigma_g \approx \frac{Ln_1\Delta^2}{20\sqrt{3}c}$$

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EX

A multimode graded index fiber exhibits total pulse broadening of 1.0 μs over a distance of 15 km. Estimate:

0.1

a the maximum possible bandwidth on the link assuming no intersymbol interference.

b the pulse dispersion per unit length.

c the bandwidth-length product for the fiber.

Sol:

a The maximum possible optical bandwidth which is equivalent to the maximum possible bit rate (for return to zero pulses) assuming no ISI may be written as:

$$B_{opt} = B_T = \frac{1}{2\tau} = \frac{1}{0.2 \times 10^{-6}} = 5 MHz$$

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EX

A multimode graded index fiber exhibits total pulse broadening of 1.0 μs (0.1) over a distance of 15 km. Estimate:

a the maximum possible bandwidth on the link assuming no intersymbol interference.

b the pulse dispersion per unit length

c the bandwidth-length product for the fiber

b The dispersion per unit length may be acquired simply by dividing the total dispersion by the total length of the fiber:

$$\text{dispersion} = \frac{0.1 \times 10^{-6}}{15} = 6.67 \text{ ns km}^{-1}$$

c The bandwidth-length product may be obtain in two ways:

1 $B_{opt} L = 5 \text{ MHZ} \times 15 \text{ km} = 75 \text{ MHZ.km}.$

2 $B_{opt} L = \frac{1}{2 \times 6.67 \times 10^{-9}} = 75 \text{ MHZ.km}$ [ from dispersion per unit length.

## *Toatal fiber dispersion*

- The total dispersion is given by the following square sum expression:

$$\sigma^2_{total} = \sigma^2_M = \sigma^2_{inter}$$

where $\sigma_{inter}$ is the intermodal dispersion of the fiber.

The total propagation delay difference is proportional to ($\sigma_{total}$. L), the fiber bandwidth B is defined as:

$$B = \frac{1}{\sigma_{total} . L}$$

- This means that the larger the total dispersion and the longer the distance, the lower the transmitted bit rate.

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Ex

Compare the rms pulse broadening per kilometere due to intermodal dispersion for the multimode step index fiber of example (K) with the corresponding rms pulse broadening for an optimum near parabolic profile graded index fiber with the same core axis refractive index and relative refractive index difference ($n_1$ 1.5, $\Delta$ 0.01).

Sol.)

In example k, $\sigma_s$ over 6 km of fiber is 86.7 ns.

Hence the rms pulse broadening per kilometere for the multimode step index fiber is:

$$\frac{\sigma_s(1km)}{L} = \frac{86.7}{6} = 14.4 \; ns.km^{-1}.$$

P118
Ex

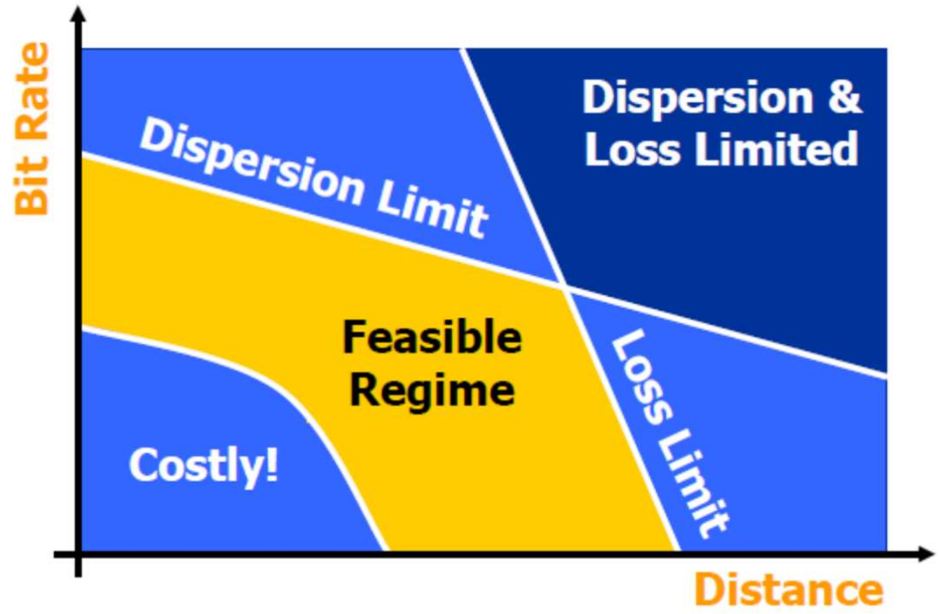
Compare the rms pulse broadening per kilometere due to intermodal dispersion for the multimode step index fiber of example (K) with the corresponding rms pulse broadening for an optimum near parabolic profile graded index fiber with the same core axis refractive index and relative refractive index difference ($n_1$ 1.5, $\Delta$ 0.01).

The rms pulse broadening per kilometere for the corresponding graded index fiber is:

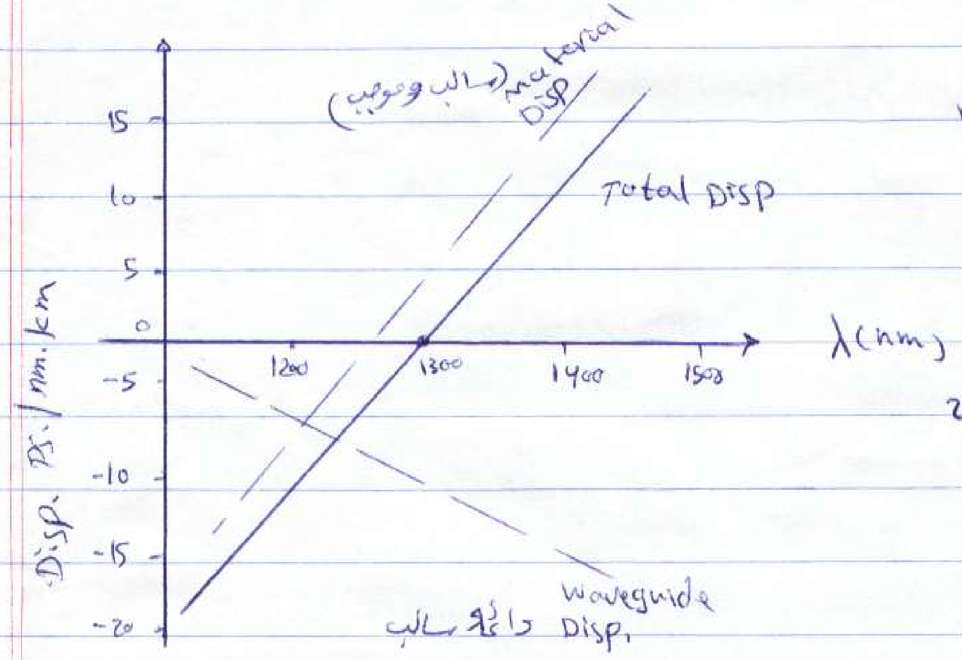
$$\sigma_g(1km) = \frac{L n_1 \Delta^2}{20\sqrt{3}\,c} = \frac{10^3 \times 1.5 \times (0.01)^2}{20\sqrt{3} \times 2.998 \times 10^8}$$

$$= 14.4 \ ps\,km^{-1}$$

# Fiber limitations



| Type | units | effect in | typical value | mechanism |
|---|---|---|---|---|
| material | ps/nm.km | step index + GRI + mono-mode | -20 ps/nm.km To -5 ps/nm.km | Index of refraction of material is a function of wavelength. |
| waveguide | ps/nm.km | monomode | -5 ps/nm.km | Waveguide propagation constant is a function of wavelength. |
| multimode | ps/km | step index GRI | 20 ps/km To 50 ps/km | delta path difference for each mode is translated to delta velocity for each path. |




1- at 1.3μm intramodal Disp is zero nothing happens to signal passing through fiber

2- multimode disp. is alway positive because smallest an is the straight path and the others are greater positively

Total = material + waveguide.

Dispersion - single mode fiber

# Dispersion: some numbers

**Intermodal**

| Fiber type | Δt/L (ns/km) |
|---|---|
| Step-index | 50 |
| Graded-index | 0.5-0.05 |
| Single-mode | 0 |

**Intramodal / Chromatic**

waveguide + material dispersion

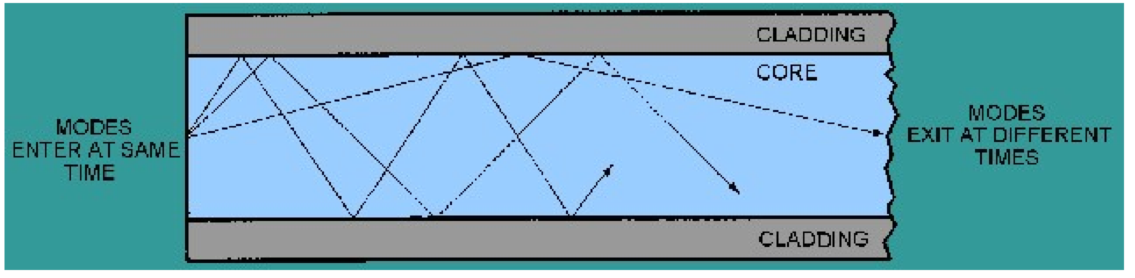
| λ (μm) | Source | Δt/L (ns/km) |
|---|---|---|
| 900 | LED | 2 |
| | FP-LD | 0.2 |
| 1300 | LED | 0.1 |
| | FP-LD | 0.01-0.001 |
| 1550 | LED | 1 |
| | FP-LD | 0.1 |
| | DFB-LD | <0.01 |

LED: $\Delta\lambda/\lambda \approx 0.04$ (Light-Emitting Diode)
FP-LD: $\Delta\lambda/\lambda \approx 0.004$ (Fabry-Perot Laser Diode)
DFB-LD: $\Delta\lambda/\lambda \approx 0.0004$ (Distributed FeedBack Laser Diode)

## ❑ Intermodal (Mode or Modal) Dispersion

➢Intermodal or modal dispersion results from the propagation delay difference between modes within a multimode fiber.

➢As the length of the fiber increases, modal dispersion increases.




**Distance traveled by each mode over the same time span**.