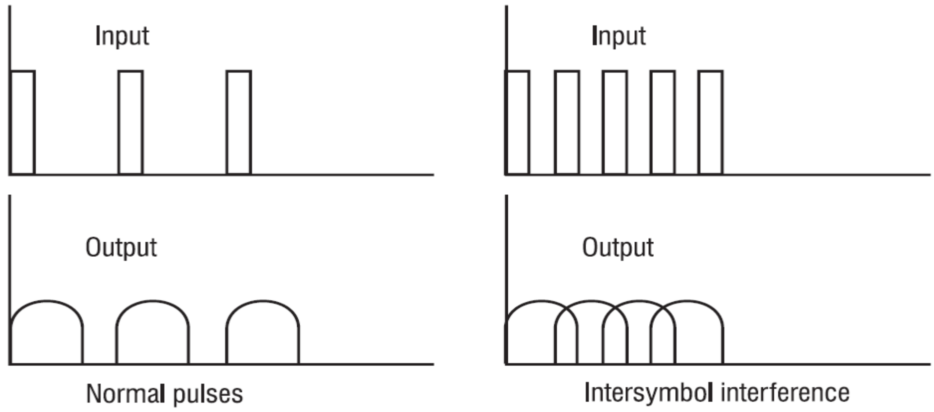
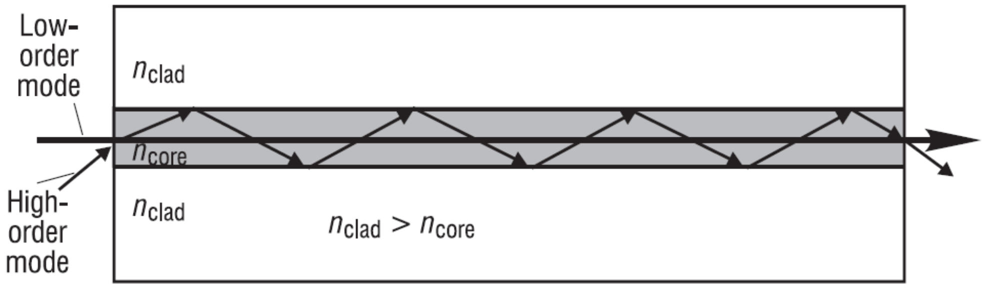
The overall effect of dispersion on the performance of a fiber optic system is known as *intersymbol interference* (Figure below). Intersymbol interference occurs when the pulse spreading caused by dispersion causes the output pulses of a system to overlap, rendering them undetectable. If an input pulse is caused to spread such that the rate of change of the input exceeds the dispersion limit of the fiber, the output data will become indiscernible.



Dispersion is generally divided into two categories: *Modal dispersion and Chromatic dispersion*.

Modal dispersion: is defined as pulse spreading caused by the time delay between lower-order modes (modes or rays propagating straight through the fiber close to the optical axis) and higher-order modes (modes propagating at steeper angles). This is shown in Figure below. Modal dispersion is problematic in multimode fiber, causing bandwidth limitation, but it is not a problem in single-mode fiber where only one mode is allowed to propagate.



Chromatic dispersion: is pulse spreading due to the fact that different wavelengths of light propagate at slightly different velocities through the fiber. All light sources, whether laser or LED, have finite linewidths, which means they emit more than one wavelength. Because the index of refraction of glass fiber is a wavelength-dependent quantity, different wavelengths propagate at different velocities. Chromatic dispersion is typically expressed in units of nanoseconds or picoseconds per (km-nm).

Chromatic dispersion consists of two parts: material dispersion and waveguide dispersion.

$$\Delta t_{chromatic} = \Delta t_{material} + \Delta t_{waveguide}$$

Material dispersion is due to the wavelength dependency on the index of refraction of glass. Waveguide dispersion is due to the physical structure of the waveguide.

When considering the total dispersion from different causes, we can approximate the total dispersion by Δt_{tot}.

$$\Delta t_{tot} = [(\Delta t_1)^2 + (\Delta t_2)^2 + \ldots + (\Delta t_n)^2]^{1/2}$$

where Δt_n represents the dispersion due to the various components that make up the system. The transmission capacity of fiber is typically expressed in terms of *bandwidth* × *distance*.

For example, the *bandwidth* × *distance* product for a typical 62.5/125 μm (core/cladding diameter) multimode fiber operating at 1310 nm might be expressed as 600 MHz • km.

The approximate bandwidth (BW) of a fiber can be related to the total dispersion by the following relationship:

$$BW = 0.35/\Delta t_{total}$$

Example: A 2-km-length multimode fiber has a modal dispersion of 1 ns/km and a chromatic dispersion of 100 ps/km • nm. If it is used with an LED of linewidth 40 nm, (a) what is the total dispersion? (b) Calculate the bandwidth (BW) of the fiber.

a) Δt_{modal} = 2 km × 1 ns/km = 2 ns

$\Delta t_{chromatic}$ = (2 km) × (100 ps/km • nm) × (40 nm) = 8000 ps = 8 ns

$\Delta t_{total} = [(\Delta t_1)^2 + (\Delta t_2)^2 + \ldots + (\Delta t_n)^2]^{1/2}$

$[(2\text{ ns})^2 + (8\text{ ns})^2]^{1/2} = 8.24\text{ ns}$

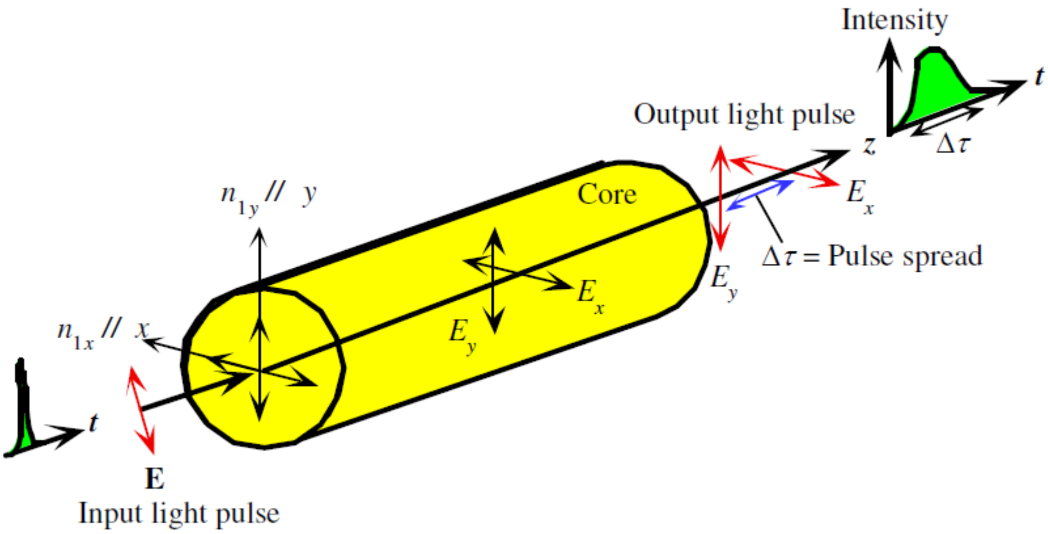
b) $BW = 0.35/\Delta t_{total}$

$= 0.35/8.24\text{ ns} = 42.48\text{ MHz}$

Expressed in terms of the product (BW • km), we get (BW • km) = (42.5 MHz)(2 km) ~ 85 MHz • km.

❖ Polarization mode dispersion (PMD)

Suppose that the core refractive index has different values along two orthogonal directions corresponding to electric field oscillation direction (polarizations). We can take *x* and *y* axes along these directions. An input light will travel along the fiber with E_x and E_y polarizations having different group velocities and hence arrive at the output at different times:



In optical fibers a phenomenon of birefringence can occur. The birefringence in fibers is described by a parameter called the mode birefringence B_m :

$$B_m = \frac{|\beta_y - \beta_x|}{k_0} = n_{ef}^x - n_{ef}^y,$$

where β_x and β_y are the propagation constants of the orthogonal modes, and n_{ef}^x and n_{ef}^y are the effective refraction index in *x* and *y* direction, k_0 is the wave vector.

Another parameter which defines a fiber birefringence is a **beat length**:

$$L_B = \frac{2\pi}{|\beta_y - \beta_x|} = \frac{\lambda}{B_m},$$

where L_B is optical the path, on which the phase difference of the orthogonal modes increases by π/2. The phase difference π/2 means that the power between the orthogonal modes is exchanged. This phenomenon repeats periodically.

The birefringence results in the mode dispersion related to polarization. The parameter characterizing the polarization-mode dispersion (PMD) is the time delay ΔT between the two orthogonal components. This parameter is a measure of the pulse deformation (the temporal pulse broadening) on the path L for the optical fiber characterized by the mode birefrigence B_m and it is expressed by the formula:

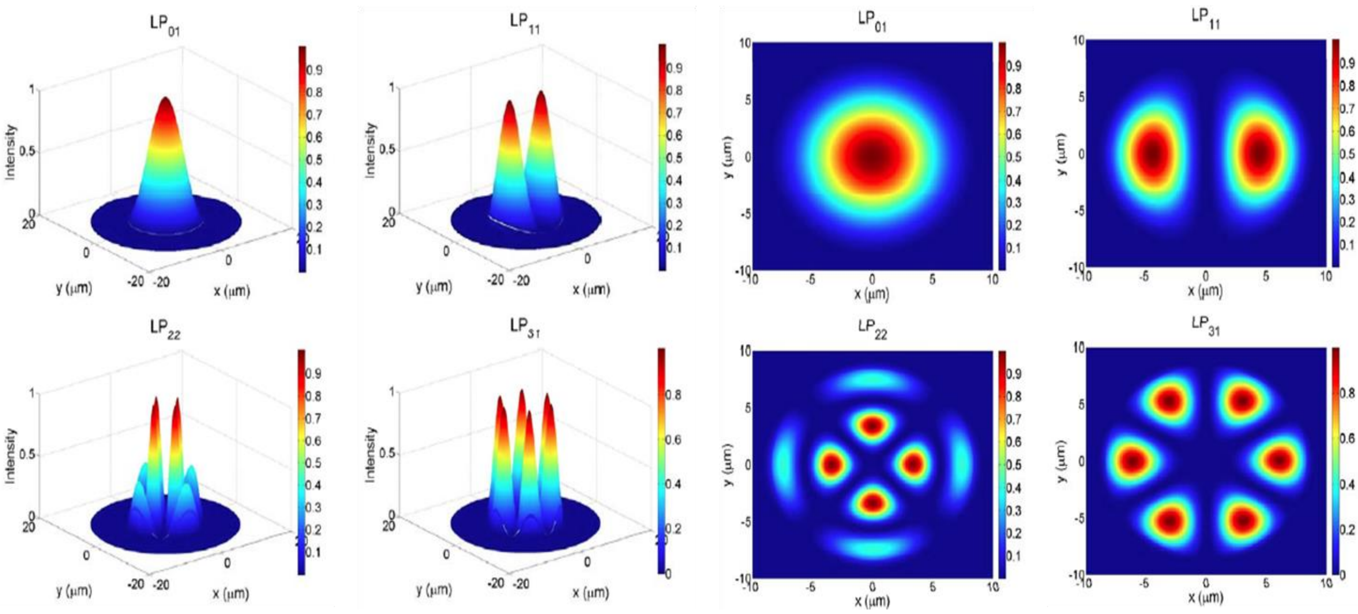
$$\Delta T = \left| \frac{L}{\upsilon_{gx}} - \frac{L}{\upsilon_{gy}} \right| = L|\beta_{1x} - \beta_{1y}| = L\delta\beta_1$$

Where:

$$\delta\beta_1 = k_0(dB_m / d\omega)$$

Examples of Modes in an Optical Fiber

λ =0.6328 μm, a =8.335 μm, n1 =1.462420, δ =0.034



❖Group Velocity & Group Delay

Wave Velocities:

1- ***Plane wave velocity:*** For a plane wave propagating along *z*-axis in an unbounded homogeneous region of refractive index n_1, which is represented by $exp(j\omega t - jkz)$, the velocity of constant phase plane is:

$$v = \frac{\omega}{k_1} = \frac{c}{n_1}$$

2- ***Modal wave phase velocity:*** For a modal wave propagating along *z*-axis represented by $exp(j\omega t - j\beta z)$, the velocity of constant phase plane is:

$$v = \frac{\omega}{\beta}$$

3- For transmission system operation the most important & useful type of velocity is the ***group velocity***, V_g. This is the actual velocity which the signal information & energy is traveling down the fiber. It is always less than the speed of light in the medium. The observable delay experiences by the optical signal waveform & energy, when traveling a length of *l* along the fiber is commonly referred to as **group delay**.

- The group velocity V_g is given by:

$$V_g = \frac{d\omega}{d\beta}$$

- The group delay τ_g is given by:

$$\tau_g = \frac{1}{V_g} = l\,\frac{d\beta}{d\omega}$$

It is important to note that all above quantities depend both on **frequency** & the **propagation mode**. In order to see the effect of these parameters on group velocity and delay, the following analysis would be helpful.