Signal Distortion

By

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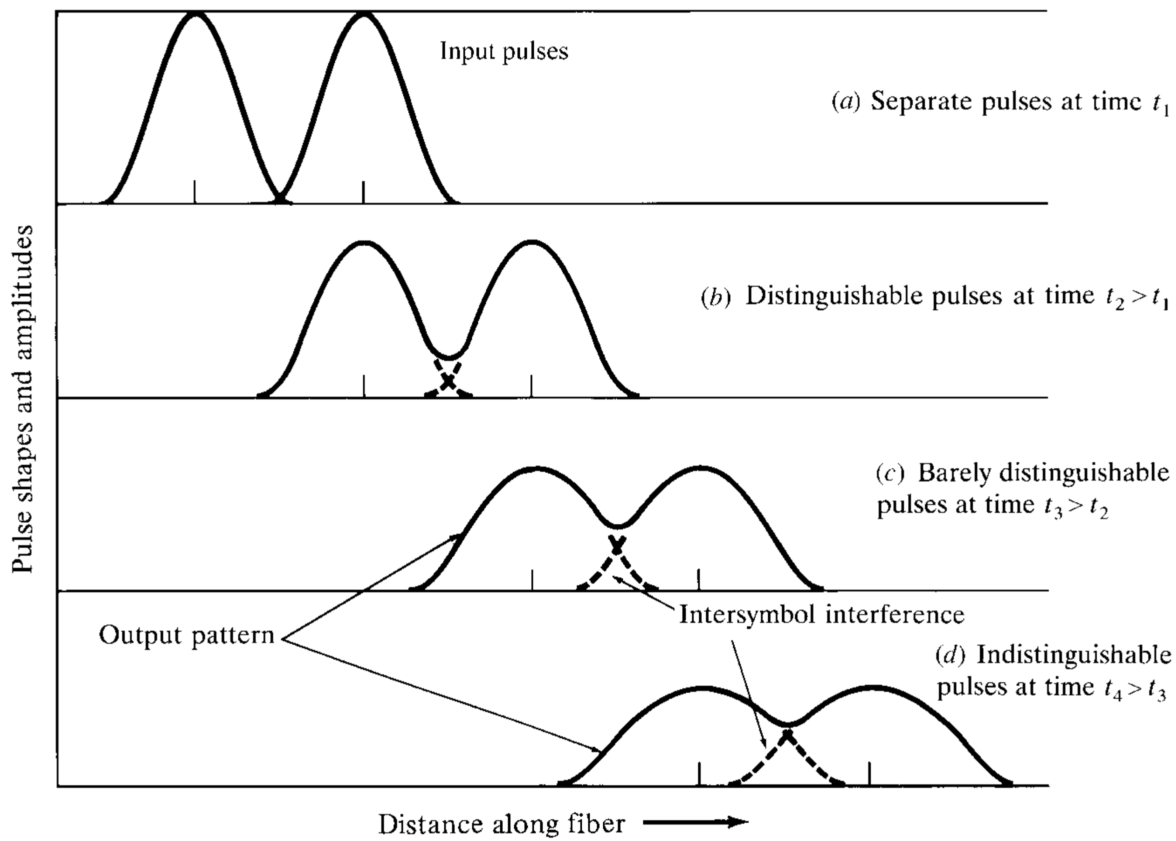
Signal Distortion in Fibers

Optical signal weakens from attenuation mechanisms and broadens due to distortion effects.

Eventually these two factors will cause **neighboring pulses to overlap**.

After a certain amount of overlap occurs, the receiver can no longer distinguish the individual adjacent pulses and error arise when interpreting the received signal.

Distortion in fiber



Origin of distortion

- Intermodal delay
- Intramodal dispersion

  causes of intramodal distortion
  - Material dispersion(chromatic dispersion)
  - Waveguide dispersion
- Polarization mode Dispersion

Group Velocity

Modal delay

Intermodal (multimode) Dispersion

- The fastest and slowest modes possible in such a fiber will be the axial ray, and the ray propagating at the critical angle θ_c ($\sin\theta_c = n_2/n_1$)

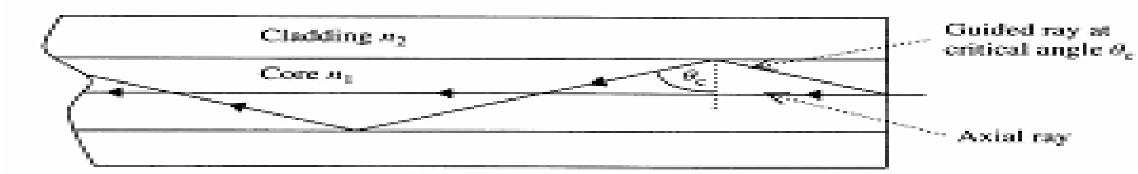


Figure 3.10 The origin of modal dispersion

Intermodal (Multimode) Dispersion

- In a multimode fiber, generally

$$t_{\min} = \frac{\text{distance}}{\text{velocity}} = \frac{L}{c/n_1} = \frac{Ln_1}{c}$$

$$t_{\max} = \frac{L/\sin\theta_c}{c/n_1} = \frac{L}{c}\frac{n_1}{\sin\theta_c}$$

or

$$t_{\max} = \frac{L/\sin\theta_c}{c/n_1} = \frac{L}{c}\frac{n_1^2}{n_2}$$

Intermodal Delay

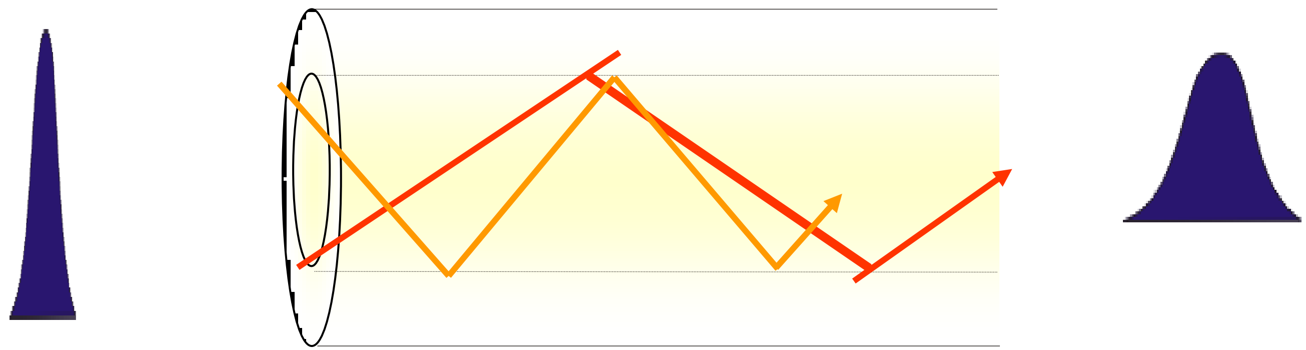
$$\Delta T = \frac{L n_1^2}{c n_2} \Delta$$

Typically the fiber capacity is specified in terms of the bit rate-distance product BL, that is, the bit rate times the possible transmission distance L. In order for neighboring signal pulses to remain distinguishable at the receiver, the pulse spread should be less than 1/B, which is the width of a bit period. For example, a stringent requirement for a high-performance link might be $\Delta T \leq 0.1/B$

In general, we need to have $\Delta T < 1/B$. This inequality gives the bit rate-distance product

$$BL < \frac{n_2}{n_1^2} \frac{c}{\Delta}$$

Dispersion



The root-mean-square (rms) value of the time delay is a useful parameter for assessing the effect of modal delay in a multimode fiber. If it is assumed that the light rays are uniformly distributed over the acceptance angles of the fiber, then the rms impulse response due to intermodal dispersion in a stepindex multimode fiber can be estimated from the following equation

$$\sigma_s \approx \frac{L n_1 \Delta}{2\sqrt{3}c} \approx \frac{L(NA)^2}{4\sqrt{3}n_1 c}$$

In graded index fiber this delay difference will decrease and calculated with following formula

$$\sigma_s = \frac{L n_1 \Delta^2}{20\sqrt{3}c}$$

Group Delay

- Group delay per unit length

$$\frac{\tau_g}{L} = \frac{1}{V_g} = \frac{1}{c}\frac{d\beta}{dk} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}$$

- Group Velocity

$$V_g = c\left(\frac{d\beta}{dk}\right)^{-1} = \left(\frac{\partial\beta}{\partial\omega}\right)^{-1}$$

- Delay Difference

$$\delta\tau = \frac{d\tau_g}{d\lambda}\delta\lambda = -\frac{L}{2\pi c}\left(2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right)\delta\lambda$$

- Pulse spreading rms

$$\sigma_g = \frac{d\tau_g}{d\lambda}\sigma_\lambda = -\frac{L\sigma_\lambda}{2\pi c}\left(2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right)$$

$$D = \frac{1}{L}\frac{d\tau_g}{d\lambda}$$

Dispersion

Intramodal Dispersion or Chromatic Dispersion

This takes place within a single mode.

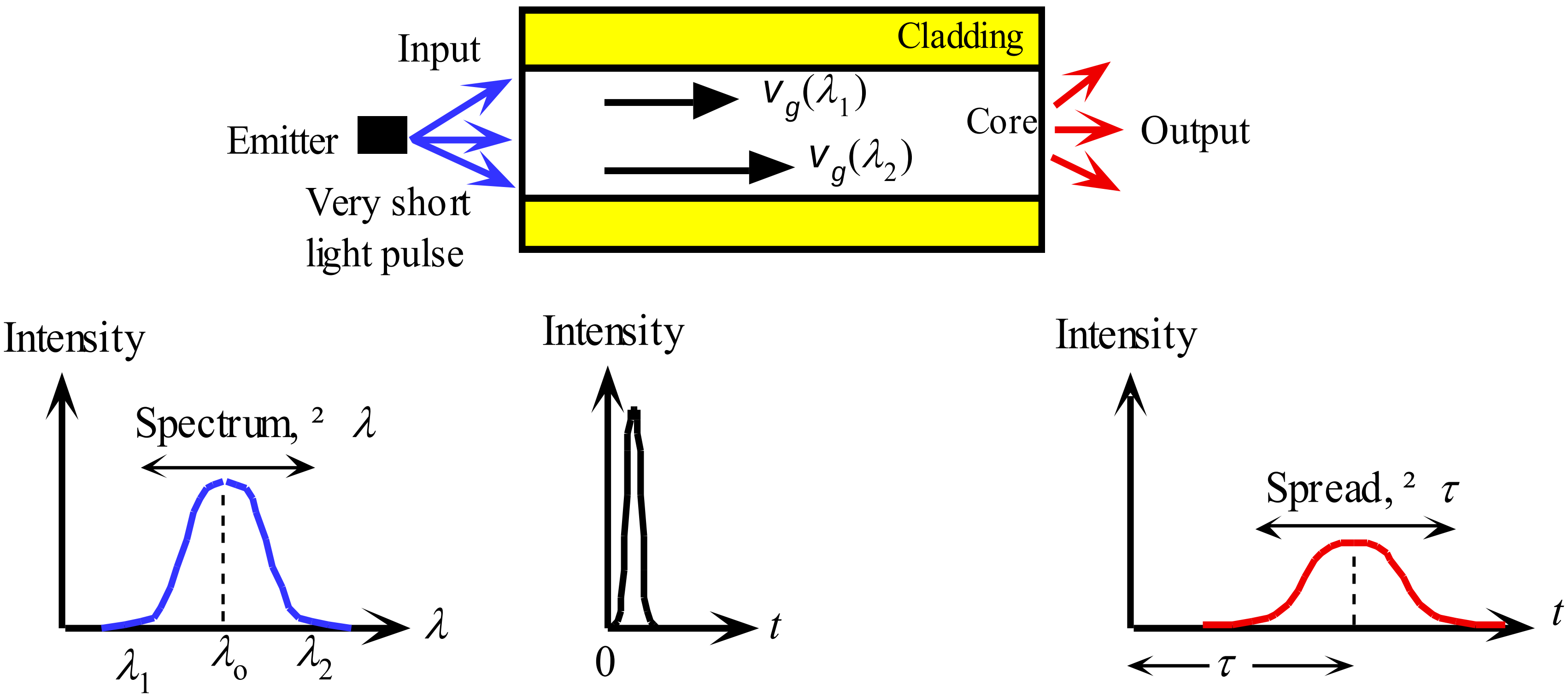
Intramodal dispersion depends on the **wavelength**, its effect on signal distortion **increases** with the **spectral width** of the light source.

Spectral width is approximately 4 to 9 percent of a central wavelength.

Two main causes of intramodal dispersion are as:

1. **Material Dispersion**
2. **Waveguide Dispersion**

Material Dispersion



All excitation sources are inherently non-monochromatic and emit within a spectrum, $^{2}\ \lambda$, of wavelengths. Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of n_1. The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.

Intramodal Dispersion or Chromatic Dispersion

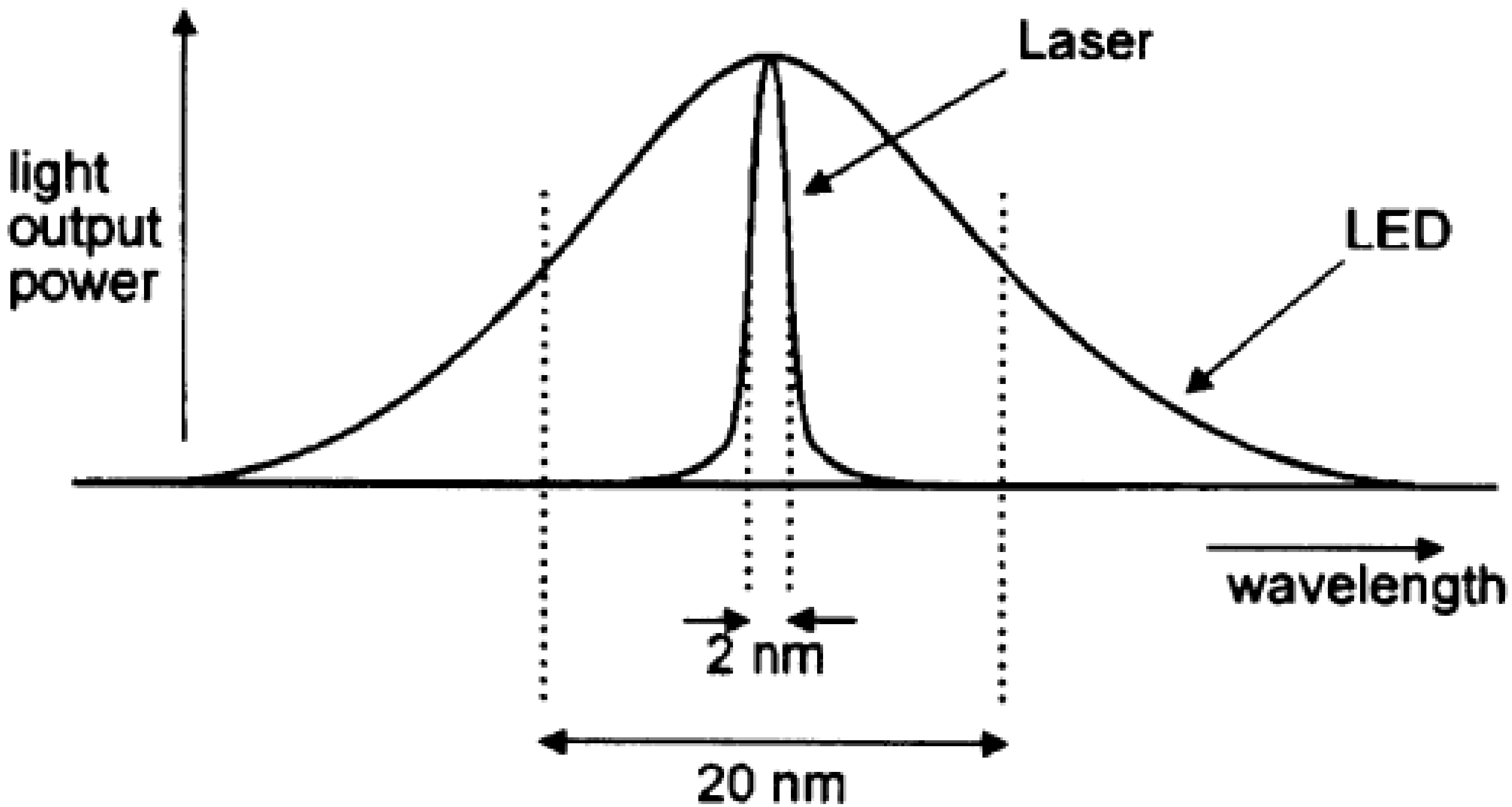
Material Dispersion:

This refractive index property causes a wavelength dependence of the group velocity of a given mode; that is,

Pulse spreading occurs even when different wavelength follow the same path.

Material dispersion can be reduced:

- Either by choosing sources with narrower spectral output widths OR
- By operating at longer wavelengths.



LASER source will produce far less **spectral dispersion or intramodal dispersion** than an LED source since it is more nearly monochromatic

Material Dispersion

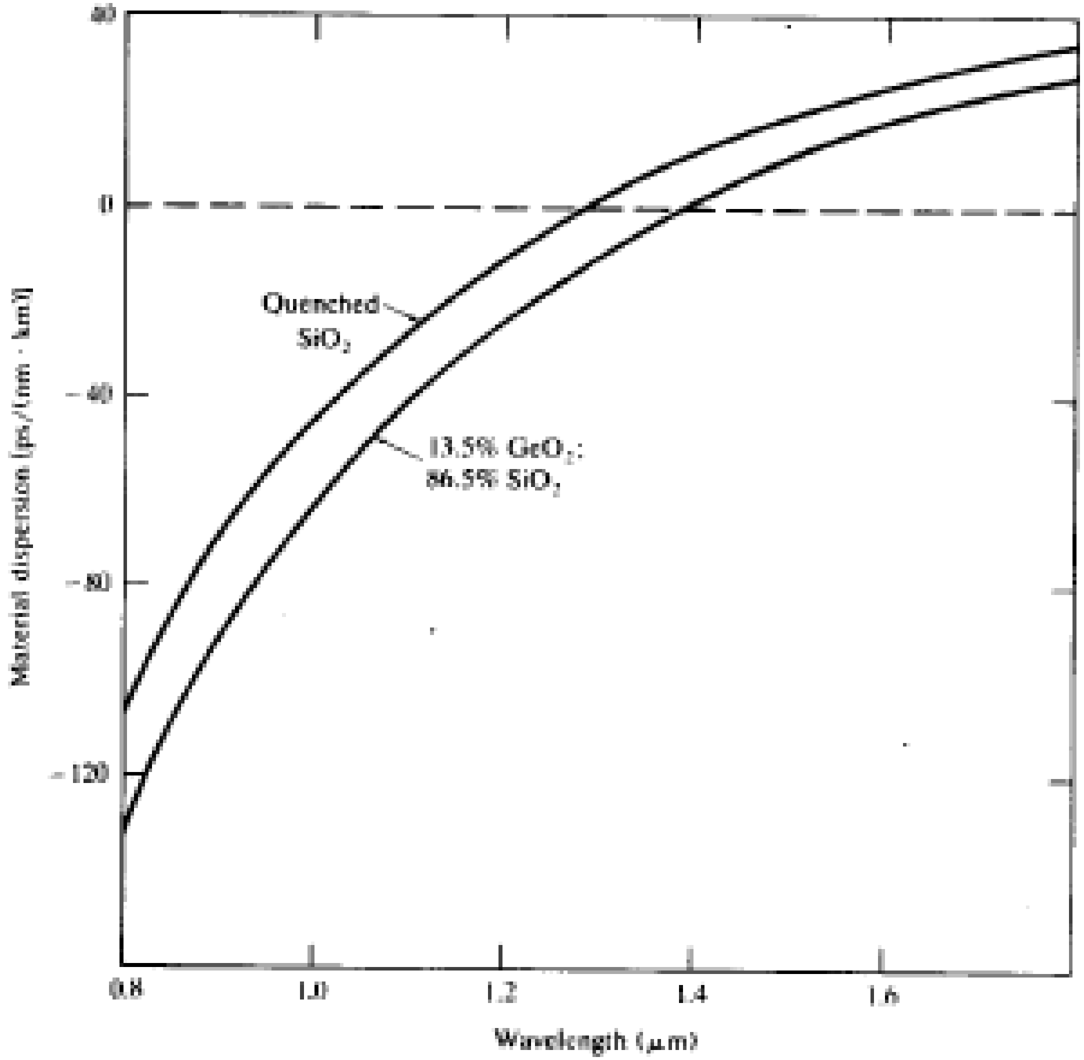
- The refractive index of the material varies as a function of wavelength, $n(\lambda)$
- Material-induced dispersion for a plane wave propagation in homogeneous medium of refractive index *n*:

$$\tau_{mat} = L\frac{d\beta}{d\omega} = -\frac{\lambda^2}{2\pi c}L\frac{d\beta}{d\lambda} = -\frac{\lambda^2}{2\pi c}L\frac{d}{d\lambda}\left[\frac{2\pi}{\lambda}n(\lambda)\right]$$
$$= \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right) \qquad [3\text{-}19]$$

- The pulse spread due to material dispersion is therefore:

$$\sigma_g \approx \left|\frac{d\tau_{mat}}{d\lambda}\right|\sigma_\lambda = \frac{L\sigma_\lambda}{c}\left|\lambda\frac{d^2n}{d\lambda^2}\right| = L\sigma_\lambda\left|D_{mat}(\lambda)\right| \qquad [3\text{-}20]$$

$D_{mat}(\lambda)$ is material dispersion



Material dispersion as a function of optical wavelength for pure silica and 13.5 percent GeO_2/ 86.5 percent SiO_2.

Intramodal Dispersion or Chromatic Dispersion

Waveguide Dispersion:

It causes pulse spreading because only part of the optical power propagation along a fiber is confined to core.

Dispersion arises because the fraction of light power propagating in the cladding travels faster than the light confined to core.

Single mode fiber confines only 80 percent of the power in the core for V values around 2.

The amount of waveguide dispersion depends on the fiber design.

Waveguide Dispersion

- Waveguide dispersion is due to the dependency of the group velocity of the fundamental mode as well as other modes on the *V* number, In order to calculate waveguide dispersion, we consider that *n* is not dependent on wavelength. Defining the normalized propagation constant *b* as:

$$b = \frac{\beta^2 / k^2 - n_2^{\ 2}}{n_1^{\ 2} - n_2^{\ 2}} \approx \frac{\beta / k - n_2}{n_1 - n_2} \qquad [3\text{-}29]$$

- solving for propagation constant:

$$\beta \approx n_2 k (1 + b\Delta) \qquad [3\text{-}31]$$

- Using *V* number:

$$V = ka(n_1^{\ 2} - n_2^{\ 2})^{1/2} \approx k a n_2 \sqrt{2\Delta} \qquad [3\text{-}33]$$

Waveguide Dispersion

- Delay time due to waveguide dispersion can then be expressed as:

$$\tau_{wg} = \frac{1}{c}\frac{d\beta}{dk} \approx \frac{d}{dk}\left(n_2 k(1+b\Delta)\right)$$

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2\Delta\frac{d(kb)}{dk}\right]$$

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2\Delta\frac{d(Vb)}{dV}\right]$$

Signal Distortion in single mode fibers

- For single mode fibers, waveguide dispersion is in the same order of material dispersion. The pulse spread can be well approximated as:

$$\sigma_{wg} \approx \left| \frac{d\tau_{wg}}{d\lambda} \right| \sigma_\lambda = \left| \underbrace{\frac{d \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d(Vb)}{dV} \right]}{d\lambda}}_{D_{wg}(\lambda)} \right| \sigma_\lambda \qquad [3\text{-}25]$$

$$= L\sigma_\lambda \left| D_{wg}(\lambda) \right|$$

$$= \frac{n_2 L \Delta \sigma_\lambda}{c\lambda} V \frac{d^2(Vb)}{dV^2}$$

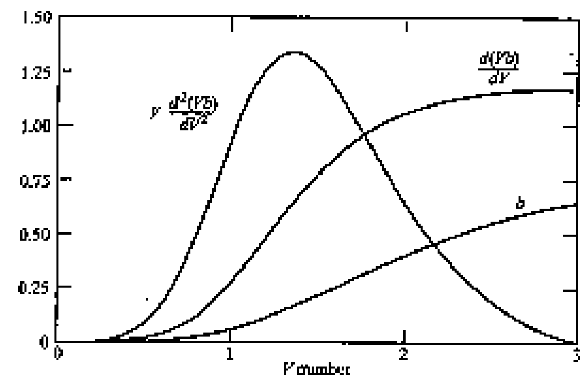


FIGURE 3-15
The waveguide parameter b and its derivatives $d(Vb)/dV$ and $V\,d^2(Vb)/dV^2$ plotted as a function of the V number for the HE_{11} mode.

Polarization Mode dispersion

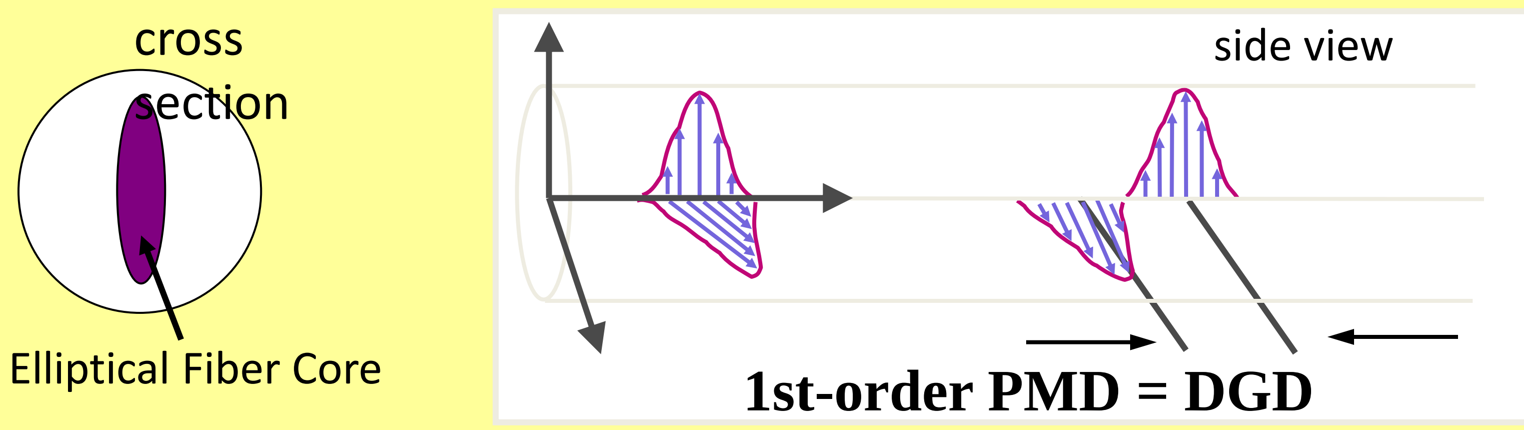
- The effects of fiber-birefringence on the polarization states of an optical are another source of pulse broadening. **Polarization mode dispersion** (PMD) is due to slightly different velocity for each polarization mode because of the lack of perfectly symmetric & anisotropicity of the fiber. If the group velocities of two orthogonal polarization modes are v_{gx} and v_{gy} then the differential time delay $\Delta\tau_{pol}$ between these two polarization over a distance L is

$$\Delta\tau_{pol} = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right| \qquad [3\text{-}26]$$

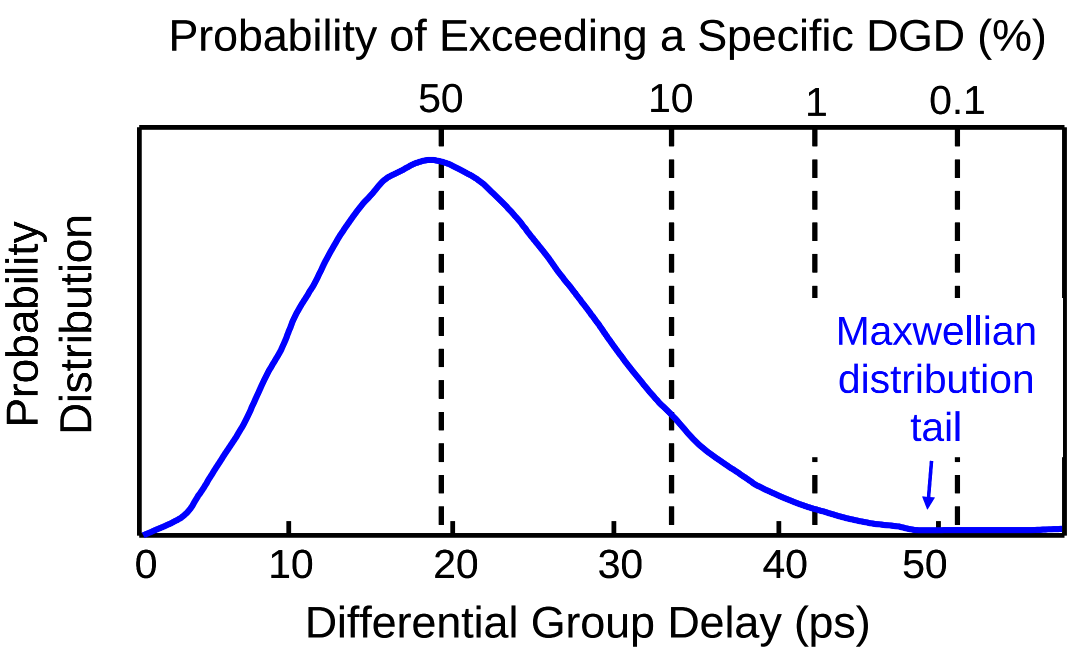
- The rms value of the differential group delay can be approximated as:

$$\langle \Delta\tau_{pol} \rangle \approx D_{PMD}\sqrt{L} \qquad [3\text{-}27]$$

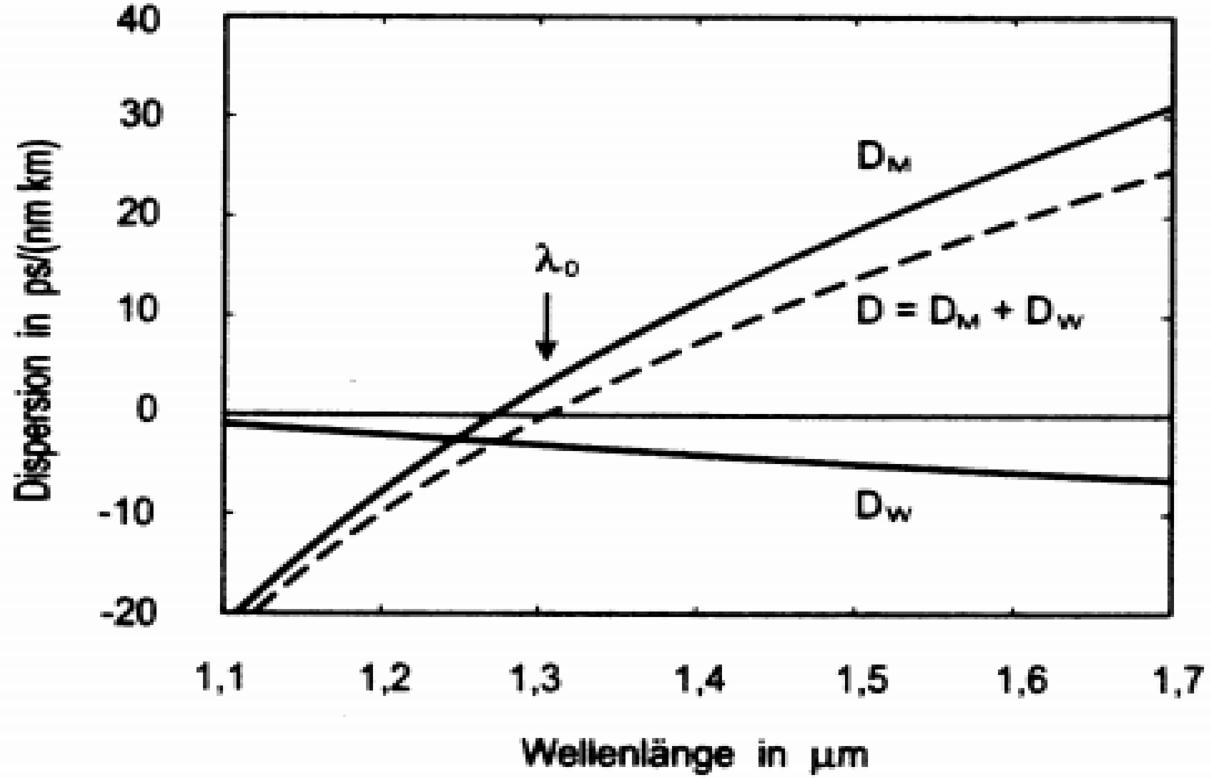
Polarization Mode Dispersion (PMD)



The 2 polarization modes propagate at different speeds.



- PMD induces randomly changing degradations.
- Critical limitation at ≥ 10 Gbit/s *payload* data rates.



40
30
20
10
0
-10
-20
Dispersion in ps/(nm km)
D_M
λ_0
$D = D_M + D_W$
D_W
1,1
1,2
1,3
1,4
1,5
1,6
1,7
Wellenlänge in µm

Dispersion Calculation

If t_{mod}, t_{CD}, and t_{PMD} are the modal, chromatic, and polarization mode dispersion times

Then

Then total dispersion t_T can be calculated by the relationship.

$$t_T = \sqrt{(t_{\mathrm{mod}})^2 + (t_{\mathrm{CD}})^2 + (t_{\mathrm{PMD}})^2}$$

Note that $t_{mod} = 0$ for single-mode fibers.

Where

$$\mathbf{t_{cd} = |D_{CD}|\, L\, \Delta\lambda}$$

$$\mathbf{t_{PMD} = D_{PMD}\,(\text{fiber length})^{1/2}}$$

Dispersion compensation example

Transmission fiber

Positive dispersion
(Negative dispersion)

Negative dispersion
(Positive dispersion)

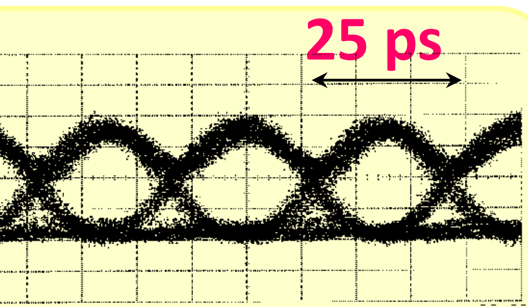
Longer wavelength ⇨ Slow (Fast)

Shorter wavelength ⇨ Fast (Slow)

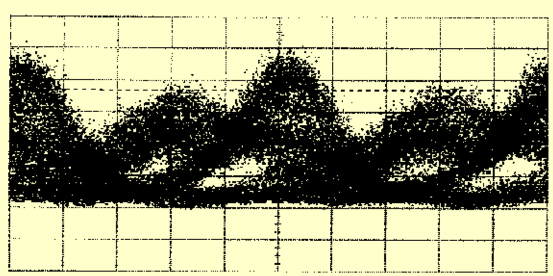
Longer wavelength ⇨ Fast (Slow)

Shorter wavelength ⇨ Slow (Fast)

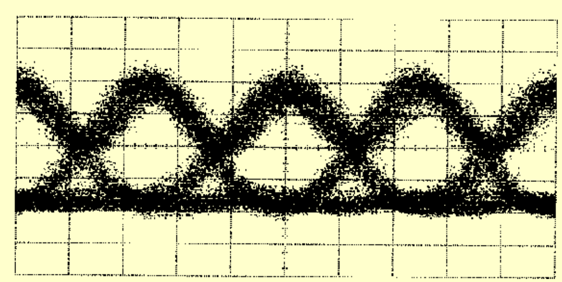
40 Gb/s optical signal



Transmitter output



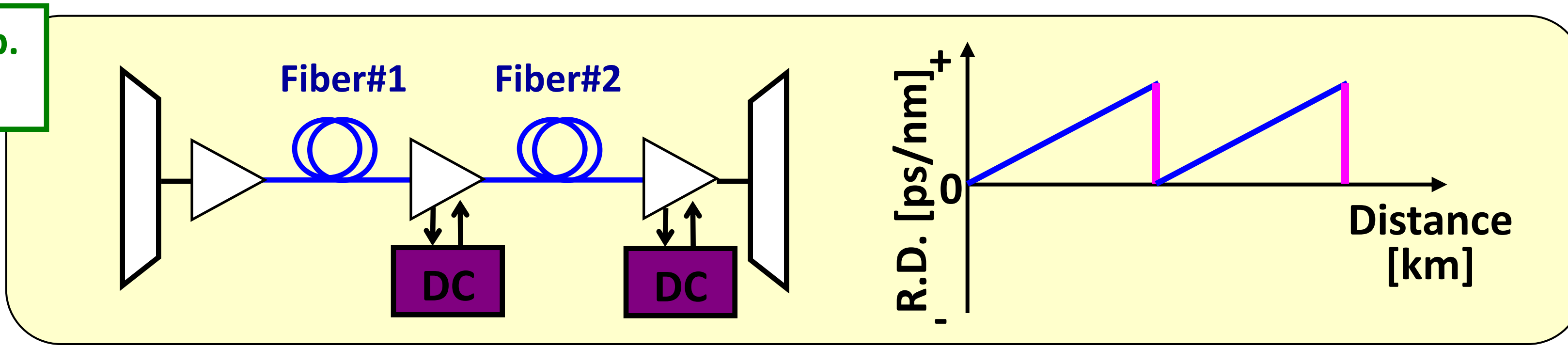
After fiber transmission



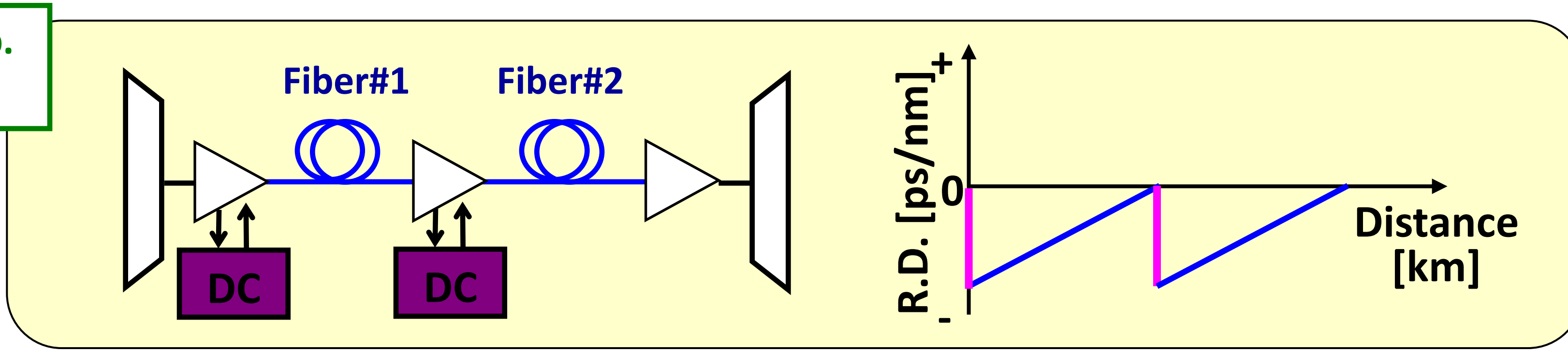
After dispersion comp.

DC allocations and dispersion maps

Post-comp.



Pre-comp.



Post- & Pre-comp.