Unit-2

Lecture -5

Intramodal dispersion and intermodal dispersion, Material Dispersion, Waveguide Dispersion in Single mode and Multi Mode Fiber

Intramodal Dispersion

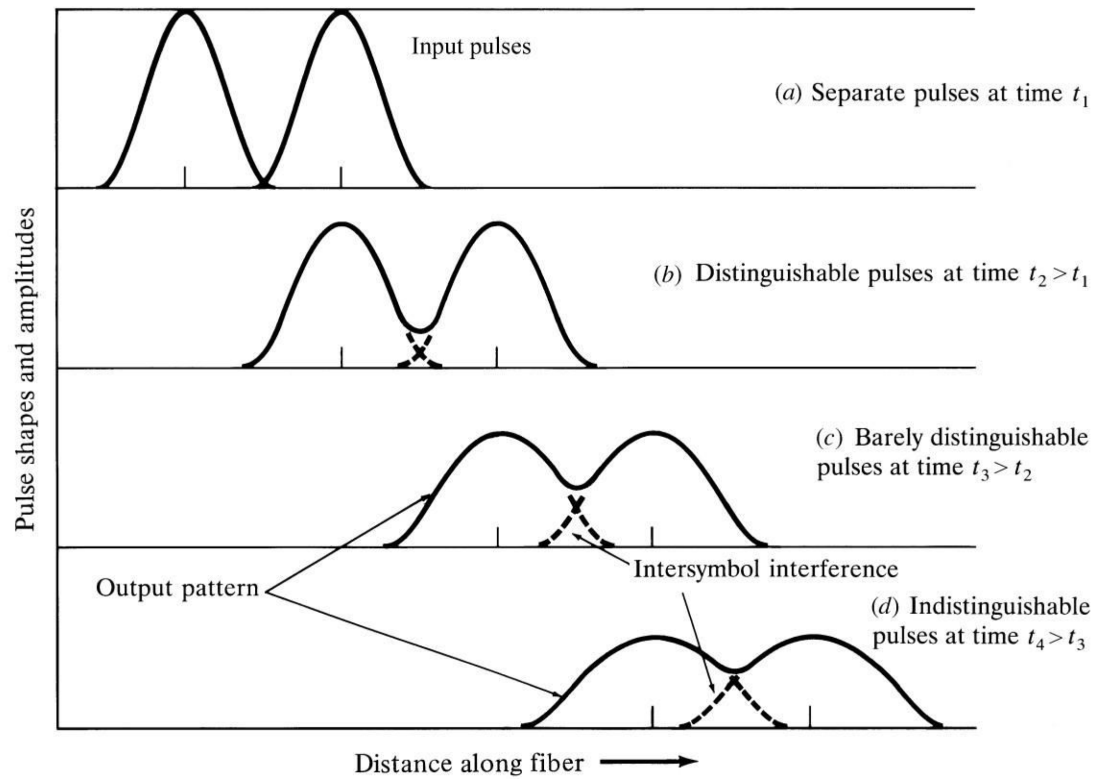
- As we have seen from Input/output signal relationship in optical fiber, the output is proportional to the delayed version of the input signal, and the delay is inversely proportional to the group velocity of the wave. Since the propagation constant, $\beta(\omega)$, is frequency dependent over band width $\Delta\omega$ sitting at the center frequency ω_c, at each frequency, we have one propagation constant resulting in a specific delay time. 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

How to characterize dispersion?

- Group delay per unit length can be defined as:

$$\frac{\tau_g}{L} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda} \qquad [3\text{-}15]$$

- If the spectral width of the optical source is not too wide, then the delay difference per unit wavelength along the propagation path is approximately $\frac{d\tau_g}{d\lambda}$. For spectral components which are $\delta\lambda$ apart, symmetrical around center wavelength, the total delay difference $\delta\tau$ over a distance L is:

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

$$= \left|\frac{d\tau}{d\omega}\right|\delta\omega = \frac{d}{d\omega}\left(\frac{L}{V_g}\right)\delta\omega = L\left(\frac{d^2\beta}{d\omega^2}\right)\delta\omega \qquad [3\text{-}16]$$

- $\beta_2 \equiv \frac{d^2\beta}{d\omega^2}$ is called **GVD parameter,** and shows how much a light pulse broadens as it travels along an optical fiber. The more common parameter is called **Dispersion,** and can be defined as the delay difference per unit length per unit wavelength as follows:

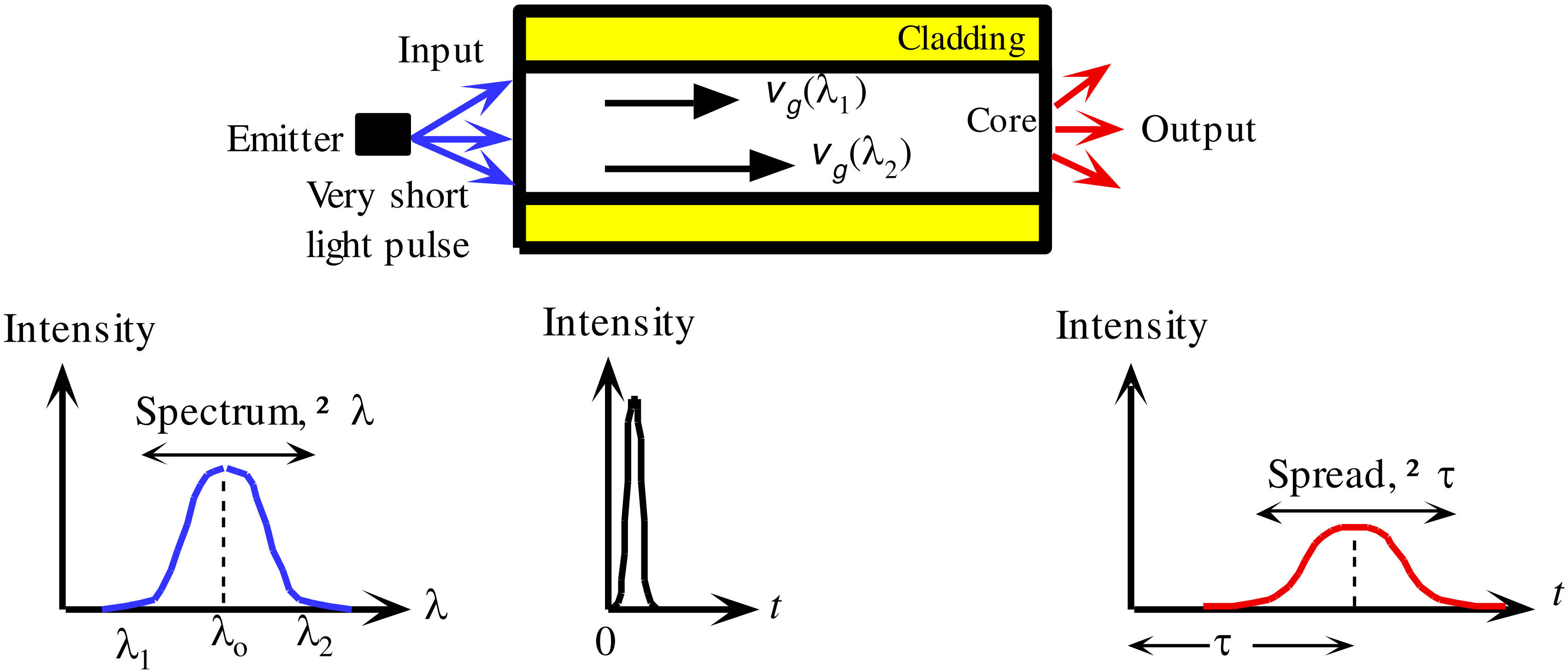
$$D_g = \frac{1}{L}\frac{d\tau}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2 \qquad \text{[3-17]}$$

- In the case of optical pulse, if the spectral width of the optical source is characterized by its rms value of the Gaussian pulse σ_λ , the pulse spreading over the length of L, σ_g can be well approximated by:

$$\sigma_g \approx \left|\frac{d\tau_g}{d\lambda}\right|\sigma_\lambda = DL\sigma_\lambda \qquad \text{[3-18]}$$

- *D* has a typical unit of [ps/(nm.km)].

Material Dispersion



All excitation sources are inherently non-monochromatic and emit within a spectrum, ²λ, 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.

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:

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

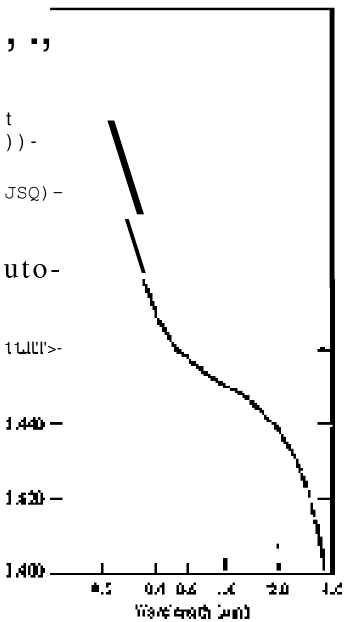
$$= \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right) \qquad [3\text{-}19]$$

- 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 Diagrams



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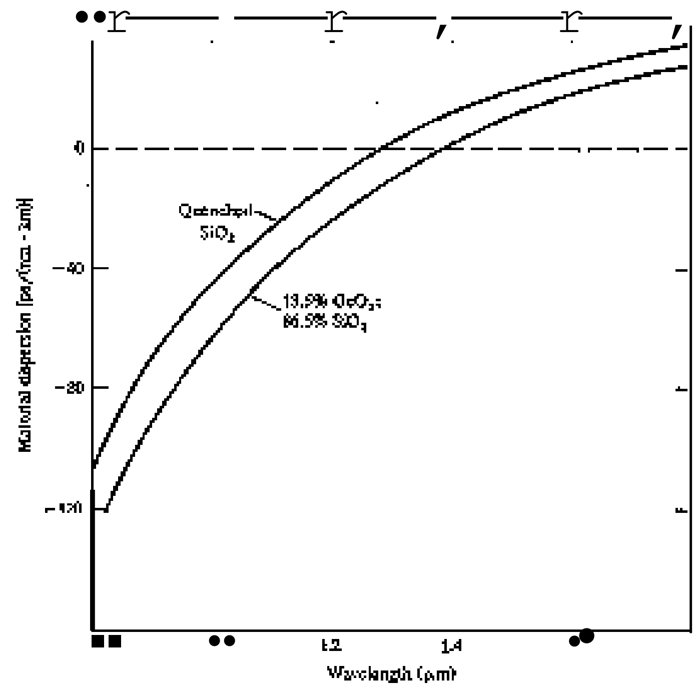

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Waveguide Dispersion

- Waveguide dispersion is due to the dependency of the group velocity of the fundamental mode as well as other modes on the *V* number, (see Fig 2-18 of the textbook). In order to calculate waveguide dispersion, we consider that *n* is not dependent on wavelength. Defining the normalized propagation constant *b* as:

$$b = \frac{\beta^2/k^2 - {n_2}^2}{{n_1}^2 - {n_2}^2} \approx \frac{\beta/k - n_2}{n_1 - n_2} \qquad [3\text{-}21]$$

- solving for propagation constant:

$$\beta \approx n_2 k(1 + b\Delta) \qquad [3\text{-}22]$$

- Using *V* number:

$$V = ka({n_1}^2 - {n_2}^2)^{1/2} \approx kan_2\sqrt{2\Delta} \qquad [3\text{-}23]$$

Waveguide Dispersion

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

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2\Delta\frac{d(Vb)}{dV}\right] \quad [3\text{-}24]$$

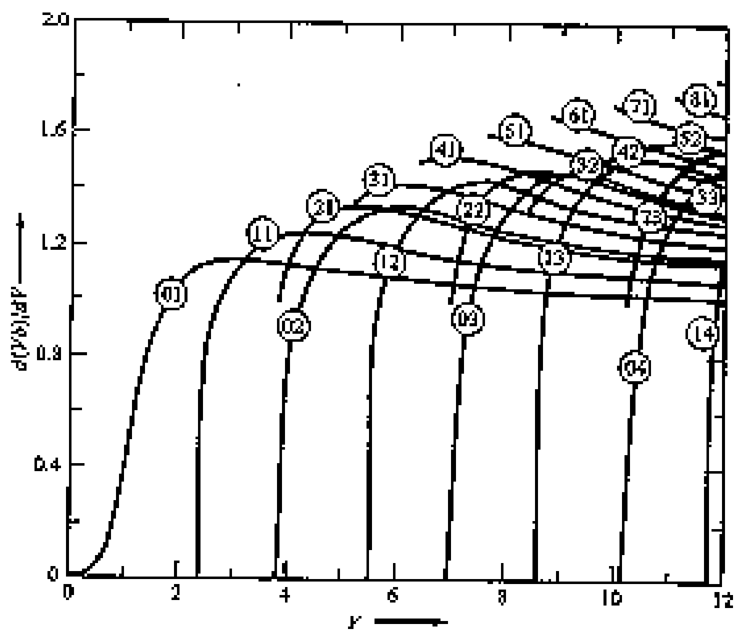

FIGURE 3-14
The group delay arising from waveguide dispersion as a function of the V number for a step-index optical fiber. The curve numbers $j\mu$ designate the $LP_{j\mu}$ modes. (Reproduced with permission from Gloge.[37])

Waveguide dispersion 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:

$$\sigma_{wg\,\lambda} \approx \left|\frac{d\tau_{wg}}{d\lambda}\right| \sigma_{\lambda} = L\sigma \; \left|D_{wg}(\lambda)\right| = \frac{n_2 L \Delta \sigma_{\lambda}}{c\lambda} V \frac{d^2(Vb)}{dV^2} \qquad [3\text{-}25]$$

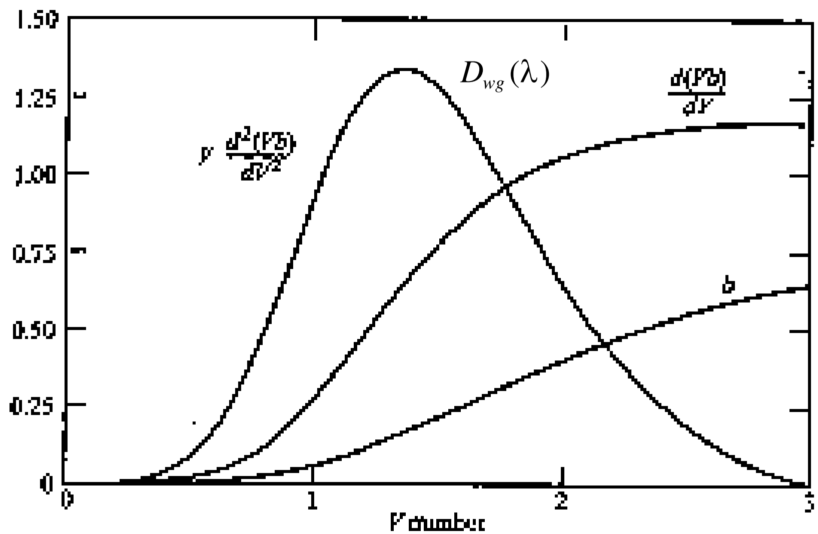

FIGURE 3-15
The waveguide parameter b and its derivatives $d(Vb)/dV$ and $V\, d^2(Vb)/dV^2$ plotted as a function of the V number for the HE_{11} mode.