Lecture 7 - Dispersion and Chirp

General Dispersion Formula

- If we take into account more realistic source and fiber effects †
  - we include β_3
  - source with a generic spectral width σ_ω

$$\frac{\sigma(z)}{\sigma_0} = \left[\left(1 + \frac{C\beta_2 z}{2\sigma_0^{\,2}}\right)^2 + \left(1+V^2\right)\left(\frac{\beta_2 z}{2\sigma_0^{\,2}}\right)^2 + (1 + C^2 + V^2)^2 \frac{1}{2}\left(\frac{\beta_3 z}{4\sigma_0^{\,3}}\right)^2 \right]^{1/2}$$

Where $V = 2\sigma_0\sigma_\omega$

- This formula can be used to derive dispersion limits in several different transmission scenarios

†D. Marcuse, Applied Optics, Vol. 19, p. 1653, 1980 and Vol. 20, p. 3573, 1981.

Dispersion Limits

- First solution: use a single frequency laser, then spectral width is 0.1 nm and the limit is 167 Gbps km.
- Second solution: Use dispersion shifted fiber, so D~1 ps/nm km. This was done in Japan. Then, the limit is 2500 Gbps km

$$L < \frac{1}{4 \bullet 0.1nm \bullet 1ps/nm/kmB} = \frac{8.3GHz \bullet km}{B}$$

- Third solution: Use external modulators. Then

$$\sigma = 0.4B/17GHz/nm$$

$$L < \frac{17GHz/nm}{4 \bullet 0.4 \bullet 1ps/nm/kmB^2}$$

- Note: Nonlinearity and four wave mixing are big problems in fibers with low dispersion

Dispersion Bit Rate Limitations

Large Source Spectral Width (e.g., LED)

- Assume V >> 1, C = 0 and $\beta_3 = 0$, define the pulse broadening factor σ_D

$$\sigma = \left(\sigma_0^{\ 2} + \sigma_D^{\ 2}\right)^{1/2}$$

$$\sigma_D = |\beta_2| L \sigma_\omega = |D| L \sigma_\lambda$$

- Assume that the bit slot is T_B for a bit rate B
- Assume that the pulse width at the receiver must not be greater than 1/4 of T_B
- Assume that the initial pulse width is much smaller than the final pulse width ($\sigma \approx \sigma_D$)

$$BL \leq \frac{1}{4|D|\sigma_\lambda}$$

Dispersion Bit Rate Limitations

Large Source Spectral Width (e.g., LED) at the zero dispersion point (SMF at 1300 nm)

- Assume that D = 0 and $\sigma \approx \sigma_D$

$$BL \leq \frac{1}{|S|\sigma_\lambda^2 \sqrt{8}}$$

- Relation between maximum achievable distance and bit-rate

$$L_{\max} \propto \frac{1}{B}$$

In these systems, the maximum dispersion-limited distance is inversely proportional to the bit rate

Dispersion Bit Rate Limitations

Small Source Spectral Width (e.g., DFB laser +external modulation)

- Assume V << 1, C = 0 and $\beta_3 = 0$, and that $\sigma_0 = \sigma_D = (\beta_2 L/2)^{1/2}$ †
- Assume that the pulse width at the receiver must not be greater than 1/4 of T_B

$$\sigma = \left(|\beta_2| L\right)^{1/2}$$

$$L_{max} \propto \frac{1}{B^2}$$

$$B^2 L \leq \frac{1}{16|\beta_2|}$$

> In these systems, the maximum dispersion-limited distance is inversely proportional to the square of the bit rate

†G. P. Agrawal, Fiber-Optic Communication Systems, Wiley Series in Microwave and Optical Engineering, 1992

Dispersion Bit Rate Limitations

Small Source Spectral Width (e.g., DFB laser +external modulation) at the <u>zero dispersion point</u>

- Assume $V \ll 1$, $C = 0$ and $\beta_2 = 0$, and that $\sigma_0 = (\beta_3 L/4)^{1/3}$ †
- Assume that the pulse width at the receiver must not be greater than 1/4 of T_B

$$\sigma = \left(\frac{3}{2}\right)^{1/2} \left(|\beta_3| L / 4\right)^{1/3}$$

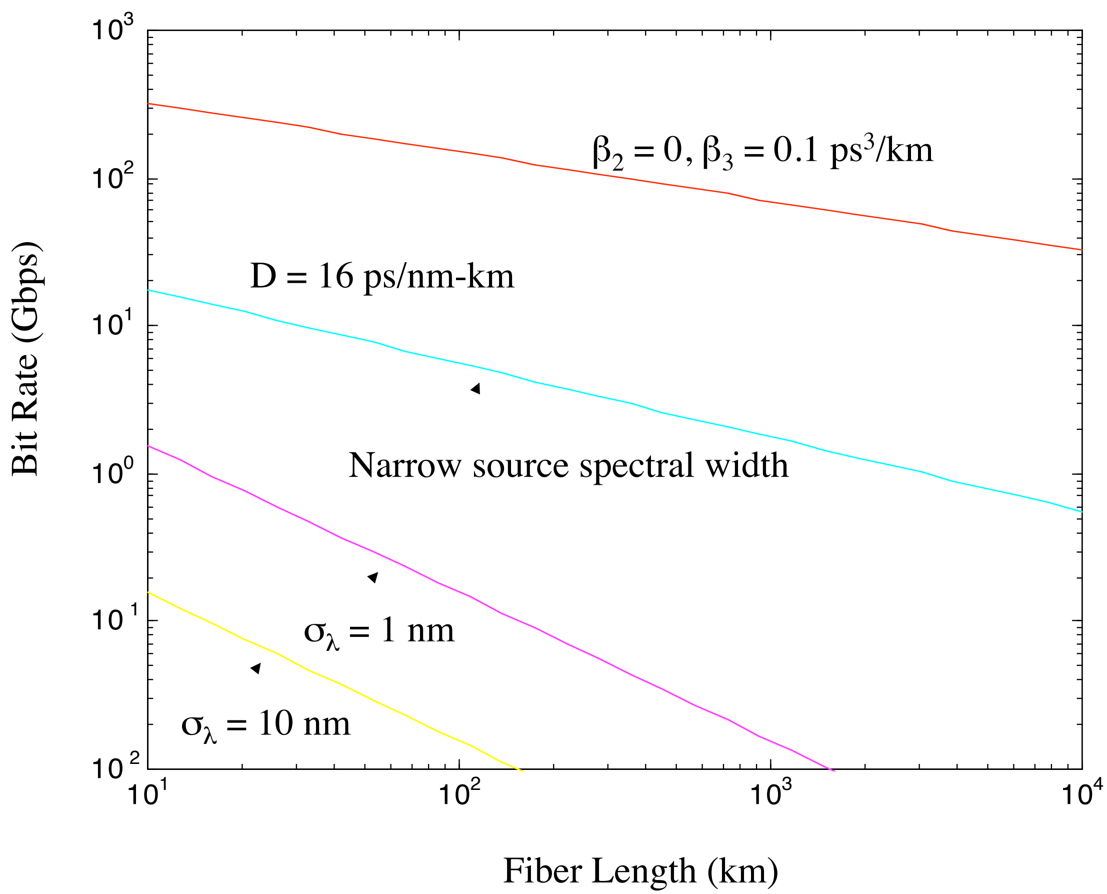
$$B^3 L \le \frac{(0.324)^3}{|\beta_3|}$$

$$L_{max} \propto \frac{1}{B^3}$$

In these systems, the maximum dispersion-limited distance is inversely proportional to the <u>third power</u> of the bit rate

†G. P. Agrawal, Fiber-Optic Communication Systems, Wiley Series in Microwave and Optical Engineering, 1992

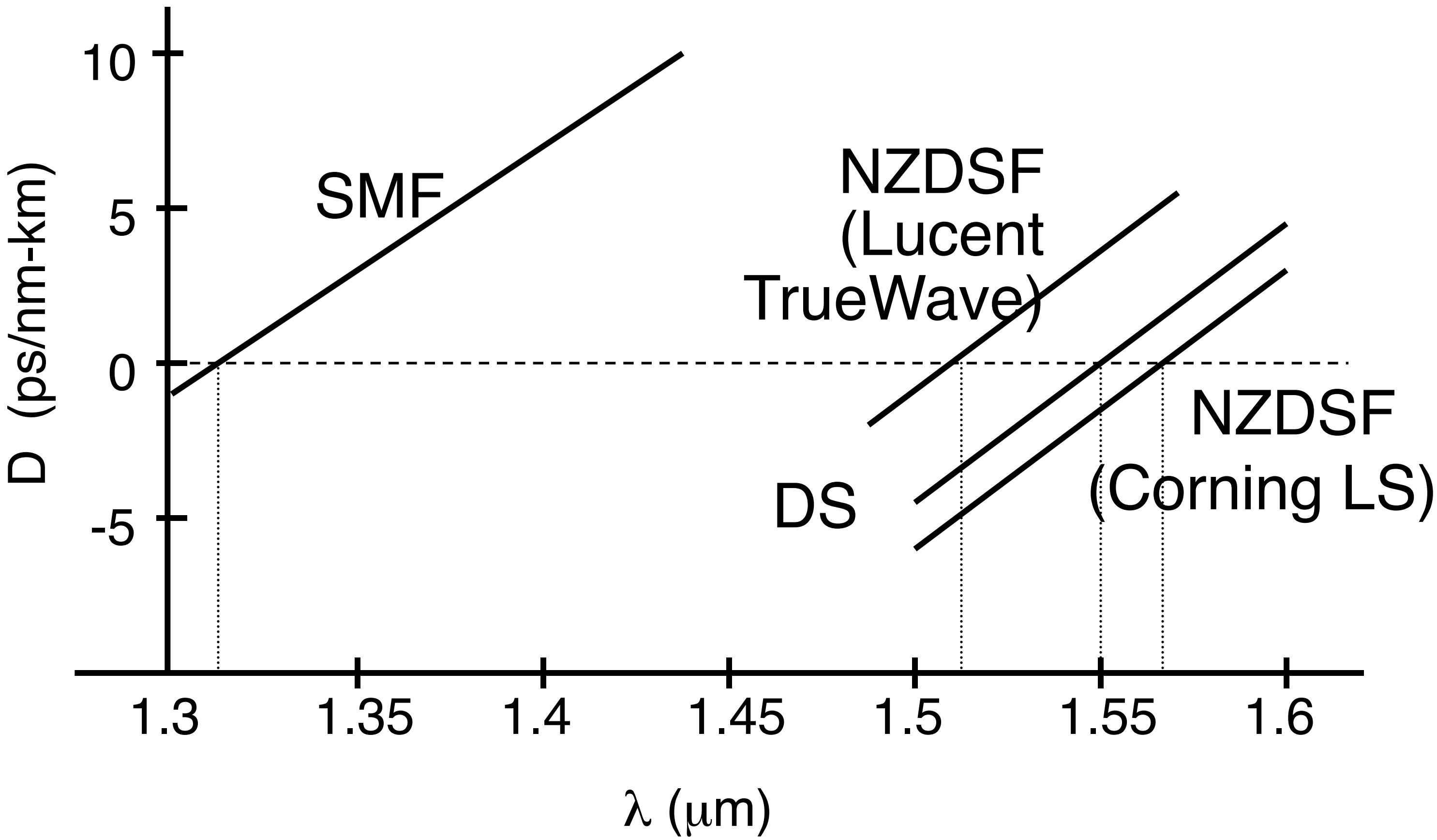
Dispersion Bit Rate Limitations



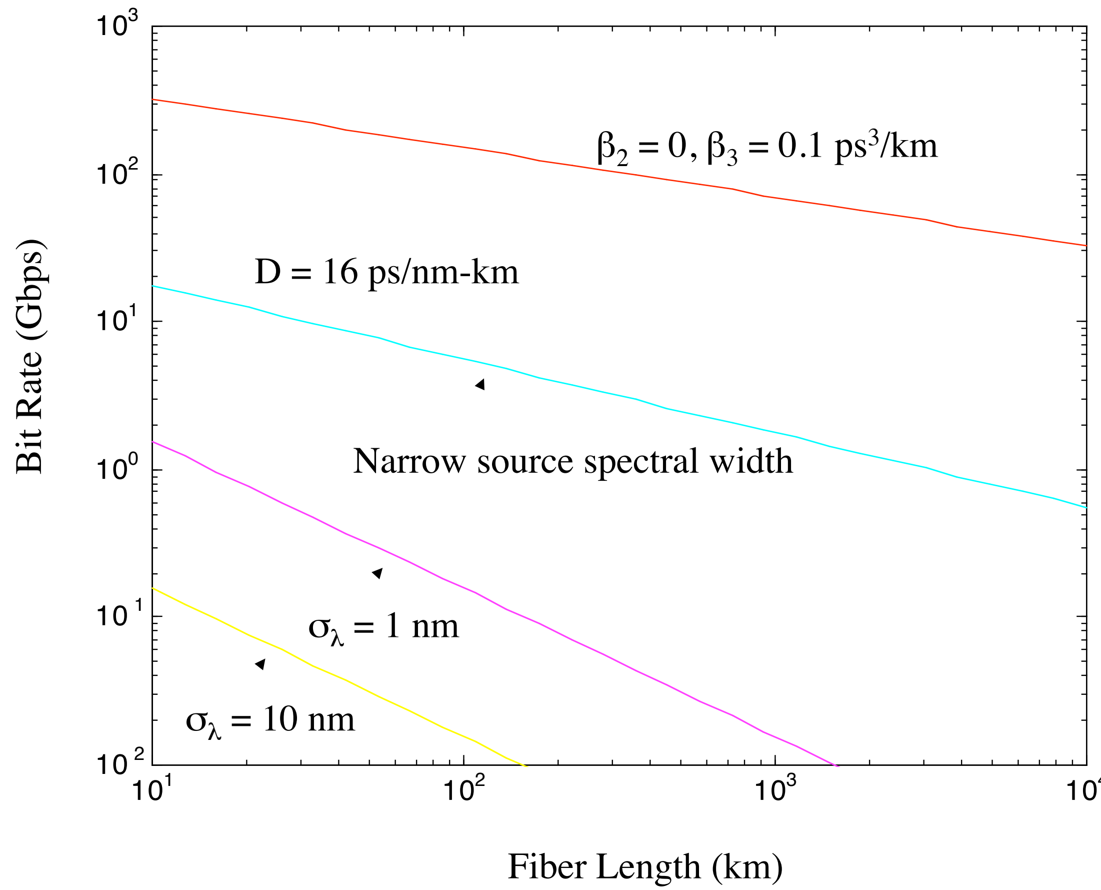
For standard SMF fibers, the limit at 10 Gbit/ is of the order of 100 km (400 km at 2.5 Gb/s)

Note that the limit at the zero dispersion points are extremely high. Unfortunately they cannot be reached due to other effects (fiber nonlinearity)

Commercial Fibers



Dispersion Bit Rate Limitations

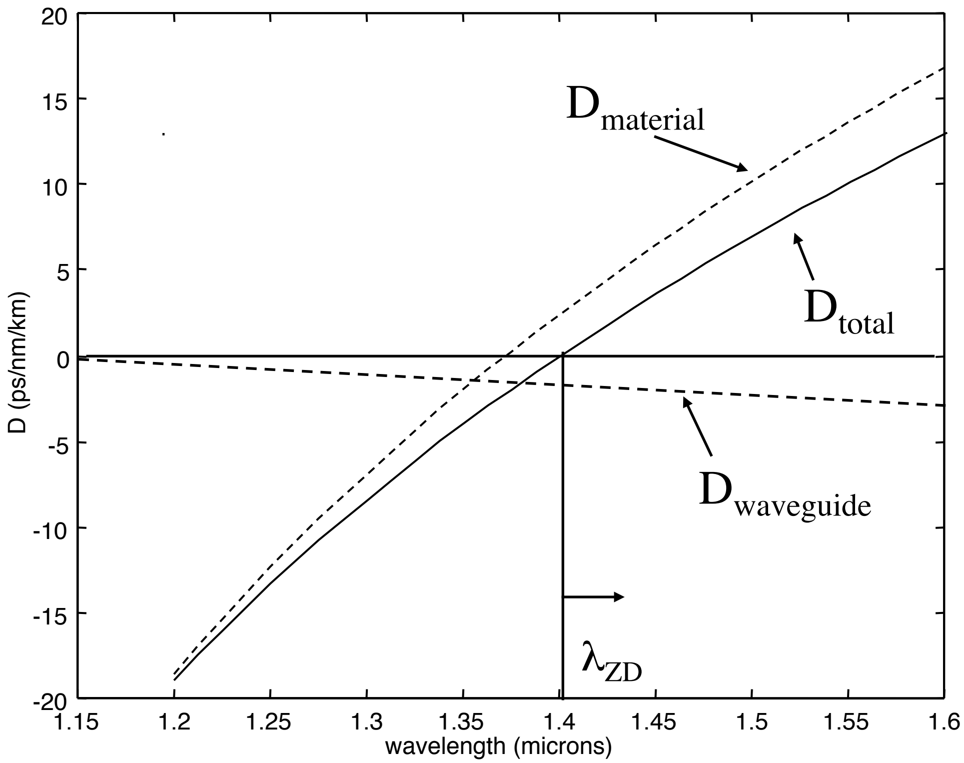


Total Fiber Dispersion

➢The waveguide geometry and design also introduces dispersion called "waveguide dispersion" which can be in the opposite sign as the material dispersion

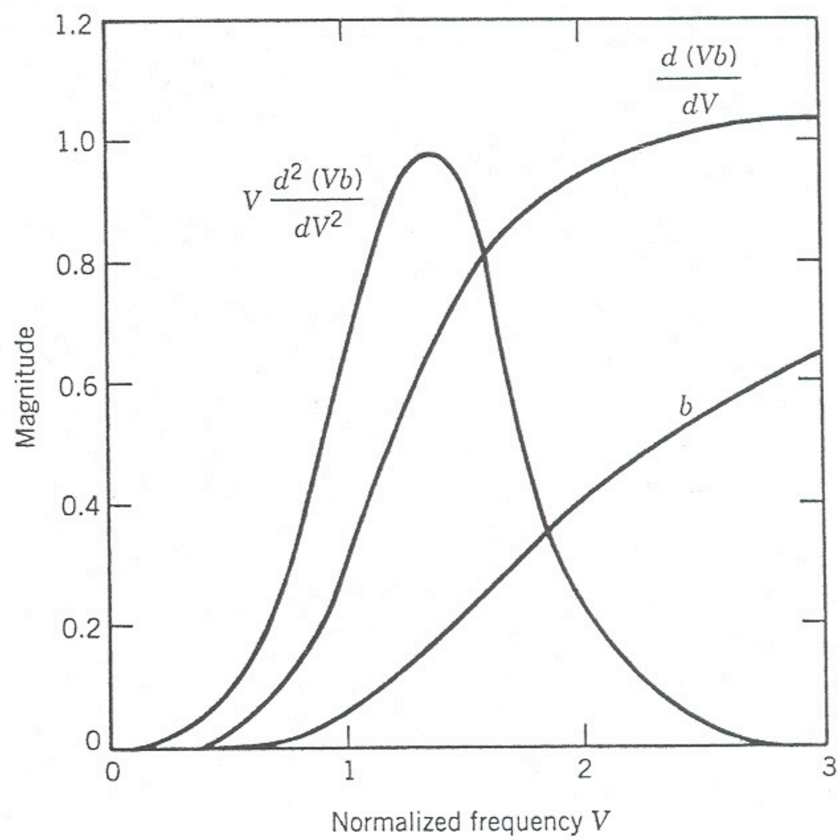
$$D_{total} = D_{material} + D_{waveguide}$$

Waveguide dispersion can be combined with material dispersion to shift the zero dispersion frequency



Waveguide Dispersion

- Waveguide dispersion D_W comes from the first and second derivatives of (Vb) with respect to V
- For the wavelength range considered, D_W is always negative.
- Therefore, sum of waveguide and material dispersion shifts zero-dispersion wavelength to a slightly longer wavelength



Waveguide dispersion

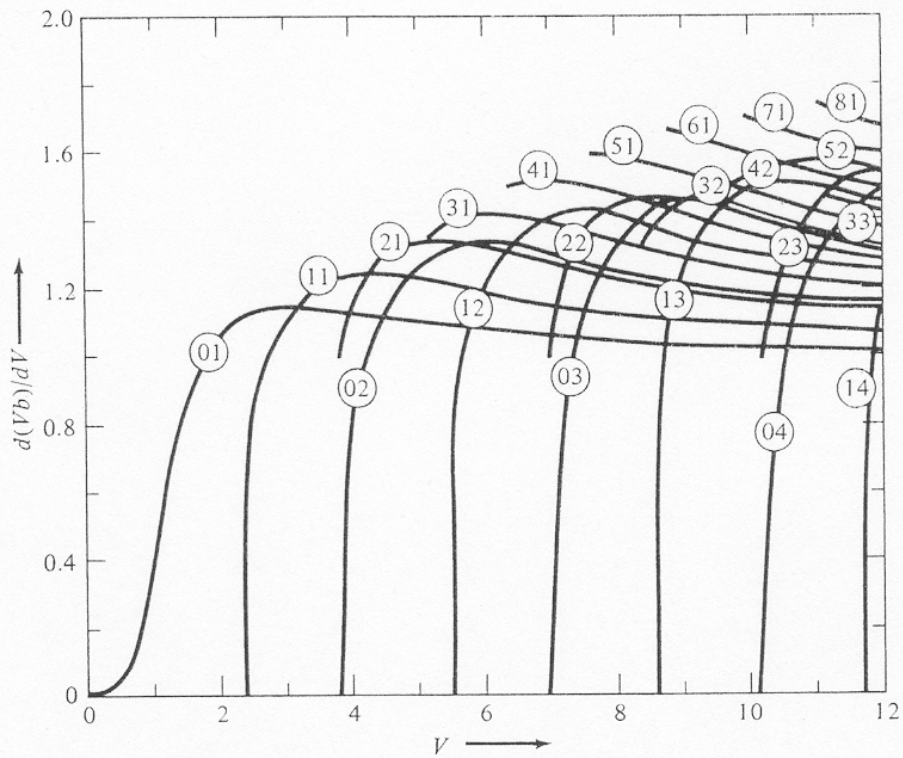
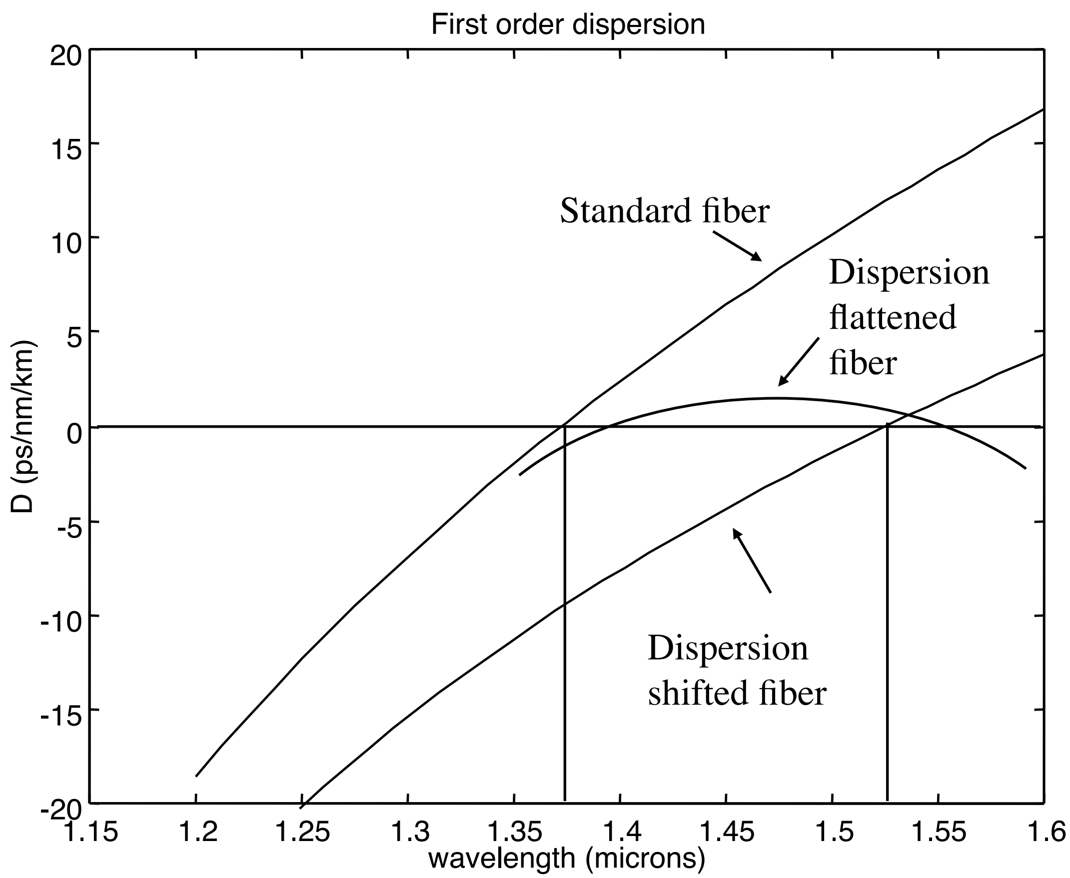


FIGURE 3-14
The group delay arising from waveguide dispersion as a function of the V number for a step-index optical fiber. The curve numbers jm designate the LP_{jm} modes. (Reproduced with permission from Gloge.[37])

Dispersion Shifted and Flattened Fibers



Fiber-Optic Communication Systems

Table 2.1 Characteristics of several commercial fibers

Fiber Type and Trade Name	A_{eff} (μm^2)	λ_{ZD} (nm)	D (C band) [ps/(km-nm)]	Slope S [ps/(km-nm^2)]
Corning SMF-28	80	1302–1322	16 to 19	0.090
Lucent AllWave	80	1300–1322	17 to 20	0.088
Alcatel ColorLock	80	1300–1320	16 to 19	0.090
Corning Vascade	101	1300–1310	18 to 20	0.060
Lucent TrueWave-RS	50	1470–1490	2.6 to 6	0.050
Corning LEAF	72	1490–1500	2 to 6	0.060
Lucent TrueWave-XL	72	1570–1580	−1.4 to −4.6	0.112
Alcatel TeraLight	65	1440–1450	5.5 to 10	0.058

Bandwidth Distance Product: Motivation for 1310nm Transmission

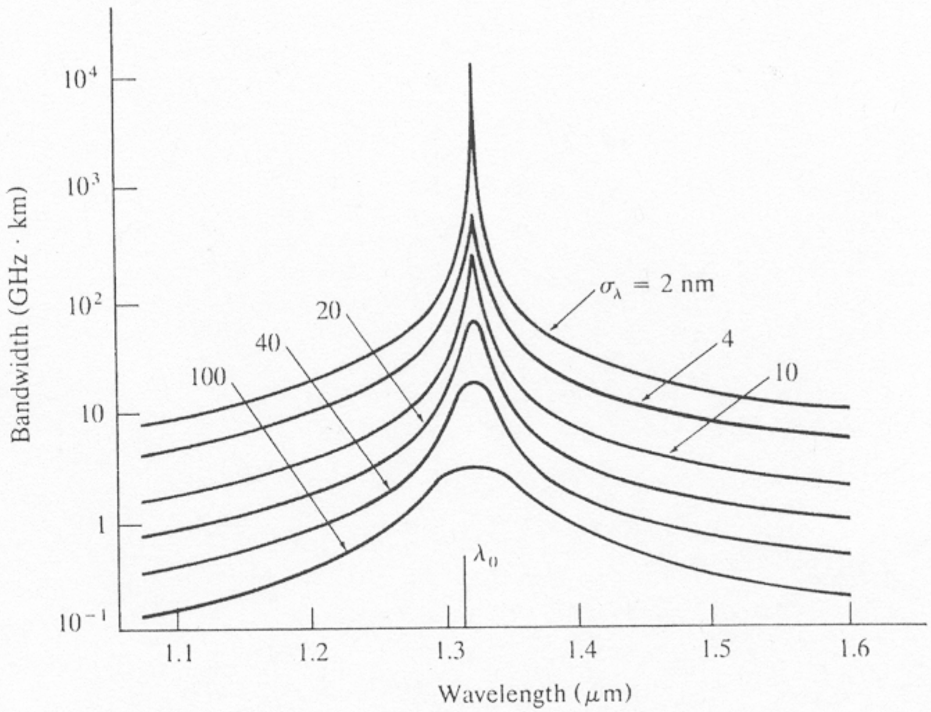


FIGURE 3-26
Examples of bandwidth versus wavelength for different source spectral widths σ_λ in a single-mode fiber having a dispersion minimum at 1300 nm. (Reproduced with permission from Reed, Cohen, and Shang,[56] © 1987, AT & T.)

Higher Order Dispersion

If the wavelength is chosen such that $D=0$ or $\beta_2=0$, there is still dispersion described by the higher order dispersion terms S or β_3

$$S = \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3$$

$$\beta_3 = \frac{d\beta_2}{d\omega}$$

The S parameters is relevant mostly for systems:

- Working close to a zero first order dispersion
- Using WDM (i.e. multiple wavelength)

Example:

A typical value of S for standard fiber at zero dispersion wavelength is $S=0.085\ ps/km\text{-}nm^2$. For dispersion-shifted fiber with $\lambda_{ZD}=1.55\ \mu m$, a typical value of S is $S=0.05\ ps/km\text{-}nm^2$.