The Wave Equation in Birefringent Media, Modes in Optical Fiber

Read: Kasap, Chapter 2
Homework#1 due Today

ECE 162C

Lecture #4

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Two primary limits to transmission

- Loss: Loss budget for loss limited transmission
- Dispersion: Dispersion budget for dispersion limited transmission.

Comparison to cable

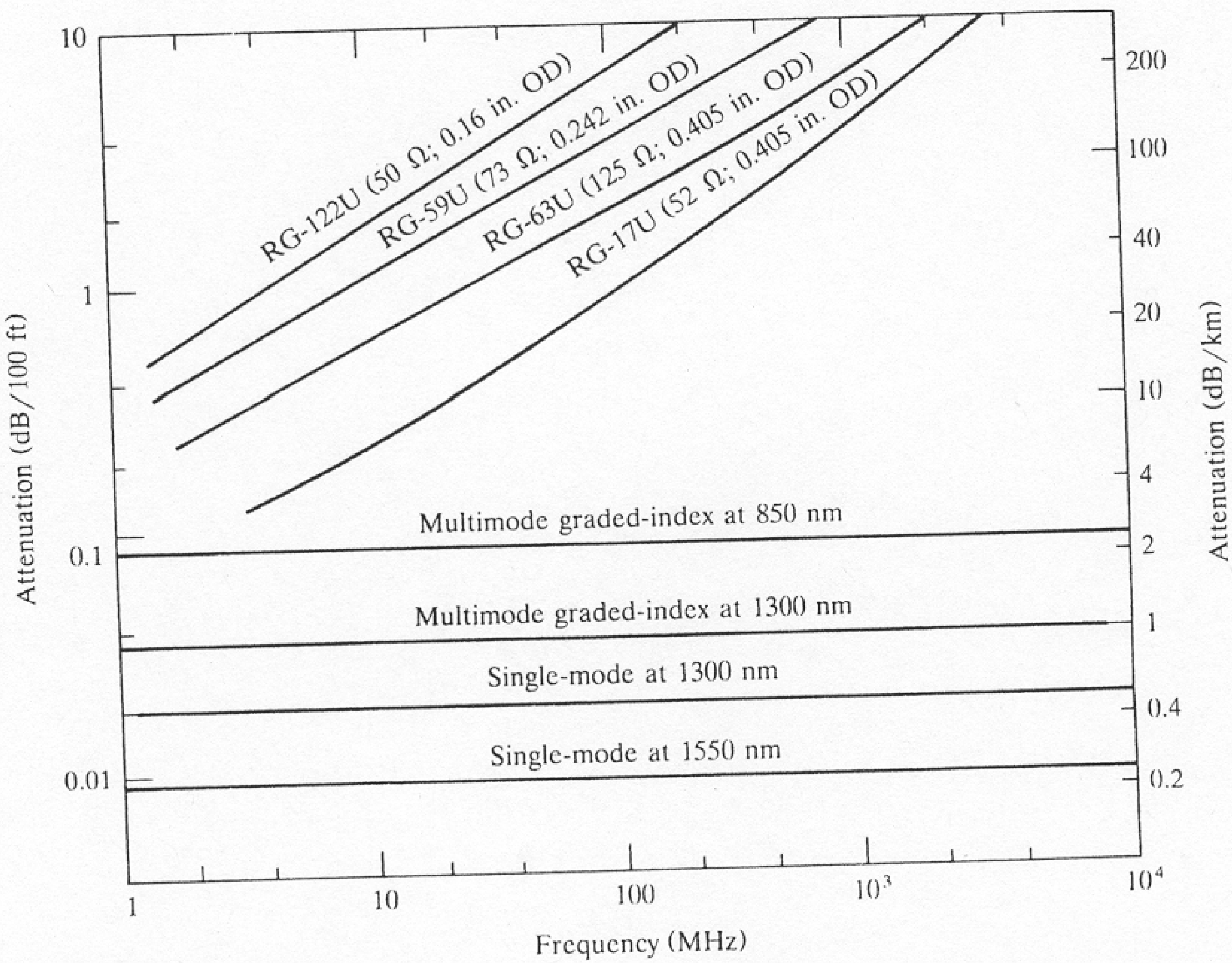


FIGURE 3-11
A comparison of the attenuation as a function of frequency or data rate of various coaxial cables and several types of high-bandwidth optical fibers.

E

Loss in early optical fibers
(now the O-H peaks around 1.4 μm are small)

$\alpha_R = C / \lambda^4$

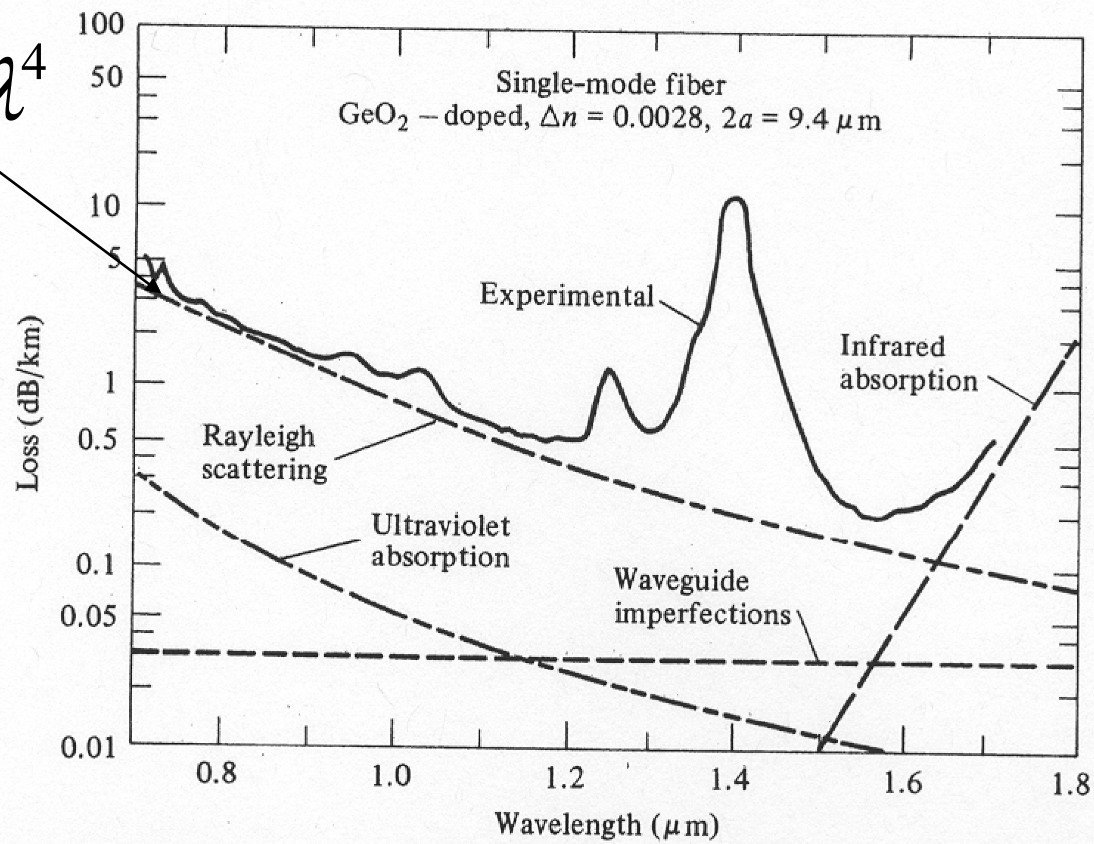


Figure 3-19 Observed loss spectrum of a germanosilicate single-mode fiber. Estimated loss spectra for various intrinsic materials effects and waveguide imperfections are also shown. (From Reference [20].)

Loss Budget

- p_{trans}=transmitter power
- p_{rec}=sensitivity of receiver

$$p_{rec} = p_{trans} e^{-\alpha L}$$

- Take 10 log of each side and express in dBm
- P_{trans}, P_{rec}

$$P_{rec} = P_{trans} - \alpha L$$

$$L_{\max} = \frac{P_{trans} - P_{rec}}{\alpha}$$

- Example:
- P_{trans}=10 dBm
- P_{rec}=-20 dBm
- L_{max}=30 dB/0.2 dB/km=150 km

Two primary limits to transmission

- Loss: Loss budget for loss limited transmission
- Dispersion: Dispersion budget for dispersion limited transmission.

Dispersion

- Multimode– different modes have different β
- Intramodal (i.e. group-velocity dispersion)
  - Material dispersion – silica refractive index is a function of wavelength
  - Waveguide dispersion – V parameter is a function of wavelength
- Polarization-Mode Dispersion – bifrefringence induced by perturbations

Multimode Dispersion

- For step index multimode fibers, the fiber bandwidth (in MHz km) is given by

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

- For graded index fibers, the fiber bandwidth in MHz km is given by

$$B < \frac{8c}{n_1 L\Delta^2}$$

Fiber-Optic Waveguides

- Step index fiber: Standard for single mode (small core size – 8 micron)
- Graded index fiber: Designed so all multimodes travel at the same velocity.

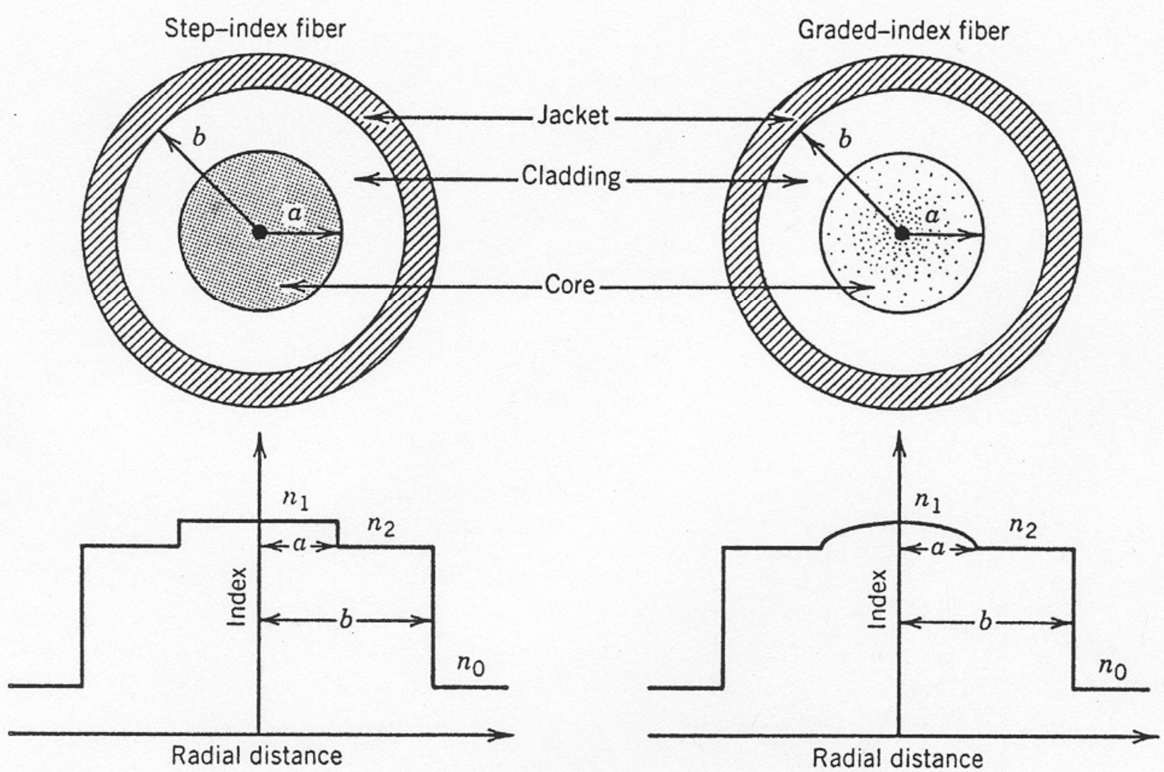


Figure 2.1: Cross section and refractive-index profile for step-index and graded-index fibers.

Group-Velocity Dispersion

- The index of the mode is dependent on the wavelength (i.e. the fiber is dispersive).
- Two components: material dispersion and waveguide dispersion.
- These contribute to phase index.
- The group index is given by

$$n_g = n + \omega \frac{\partial n}{\partial \omega}$$

$$D = -\frac{2\pi c}{\lambda^2}\frac{d^2\beta}{d\omega^2} = -\frac{2\pi c}{\lambda^2}\beta_2$$

Units are ps/(km-

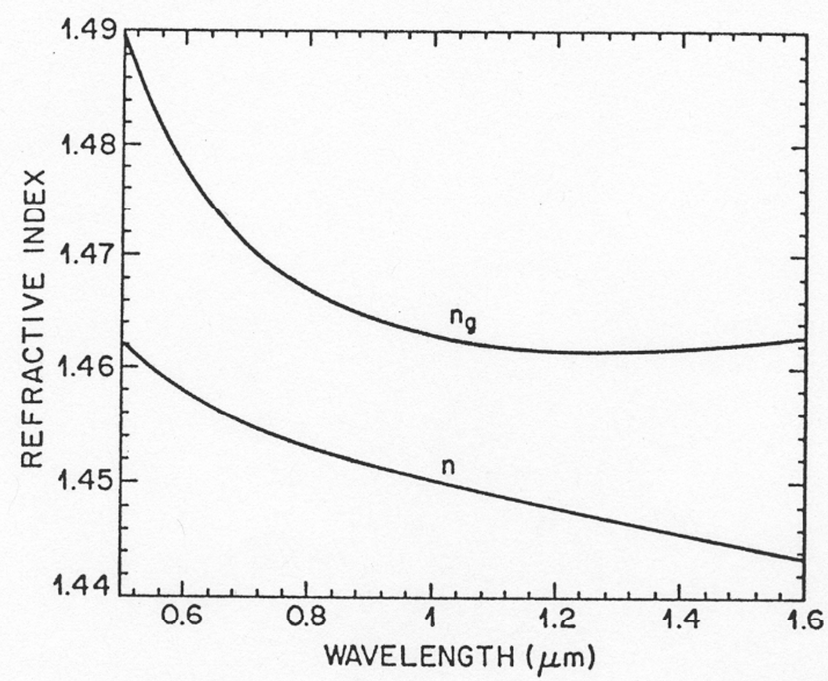


Figure 2.8: Variation of refractive index n and group index n_g with wavelength for fused silica.

Material Dispersion

- Refractive index change of silica with optical frequency is modeled with the Sellmeier Equation:

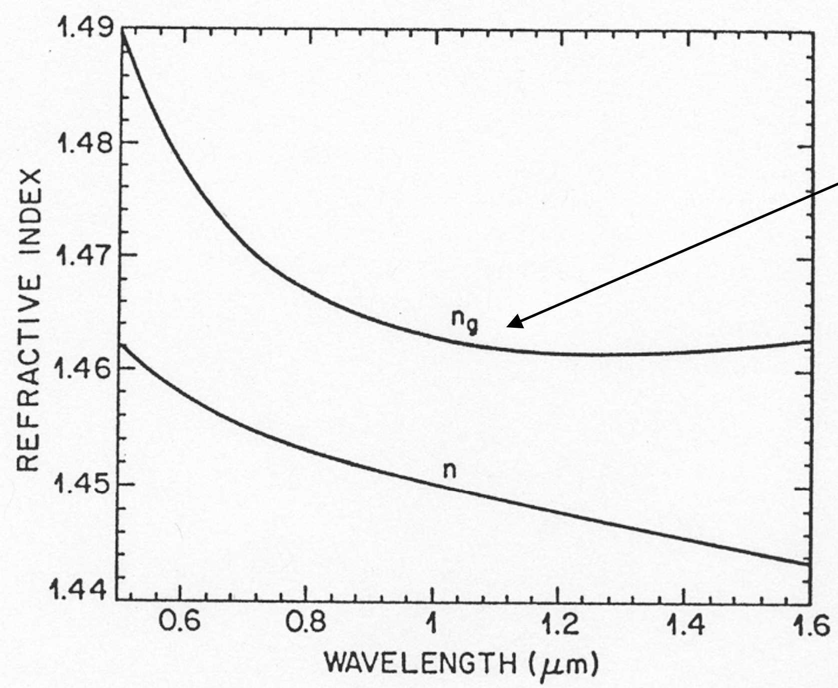
$$n^2(\omega) = 1 + \sum_{j=1}^{M} \frac{B_j \omega_j}{\omega_j^2 - \omega^2}$$

B_j is the strength of medium resonance j of the material

ω_j is the frequency of medium resonance j

Material Dispersion

- Material dispersion D_M is the slope of the n_g vs. λ (times 1/c)
- Therefore, looking at the figure we see that the slope hits zero at some wavelength – zero-dispersion wavelength

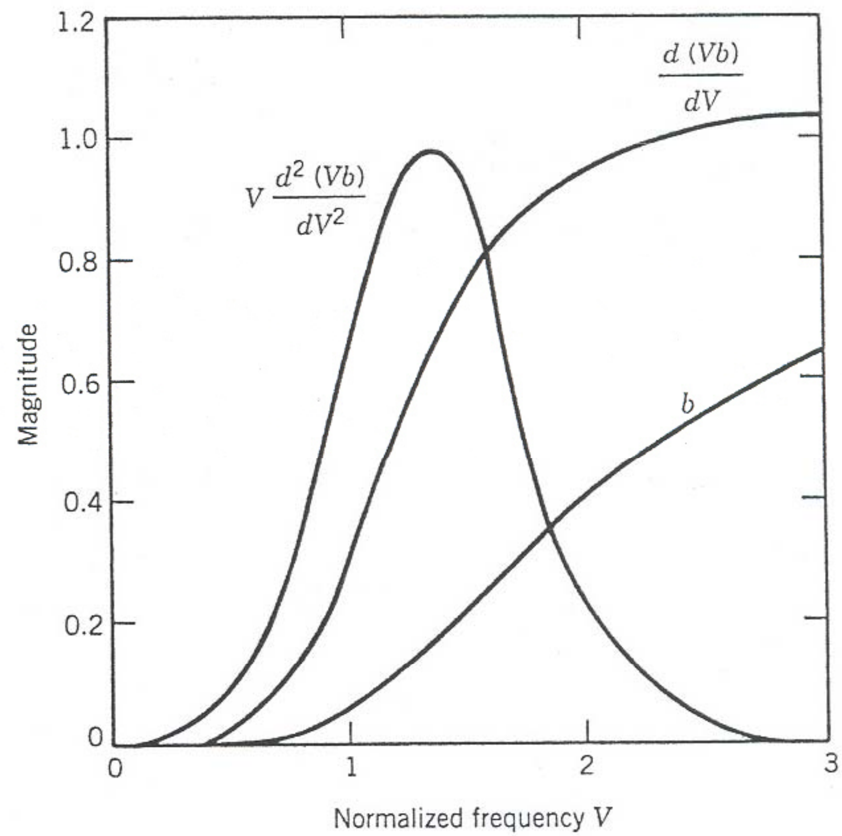


$\lambda_{zD} \sim 1.27\text{-}1.29\ \mu m$

Figure 2.8: Variation of refractive index n and group index n_g with wavelength for fused silica.

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

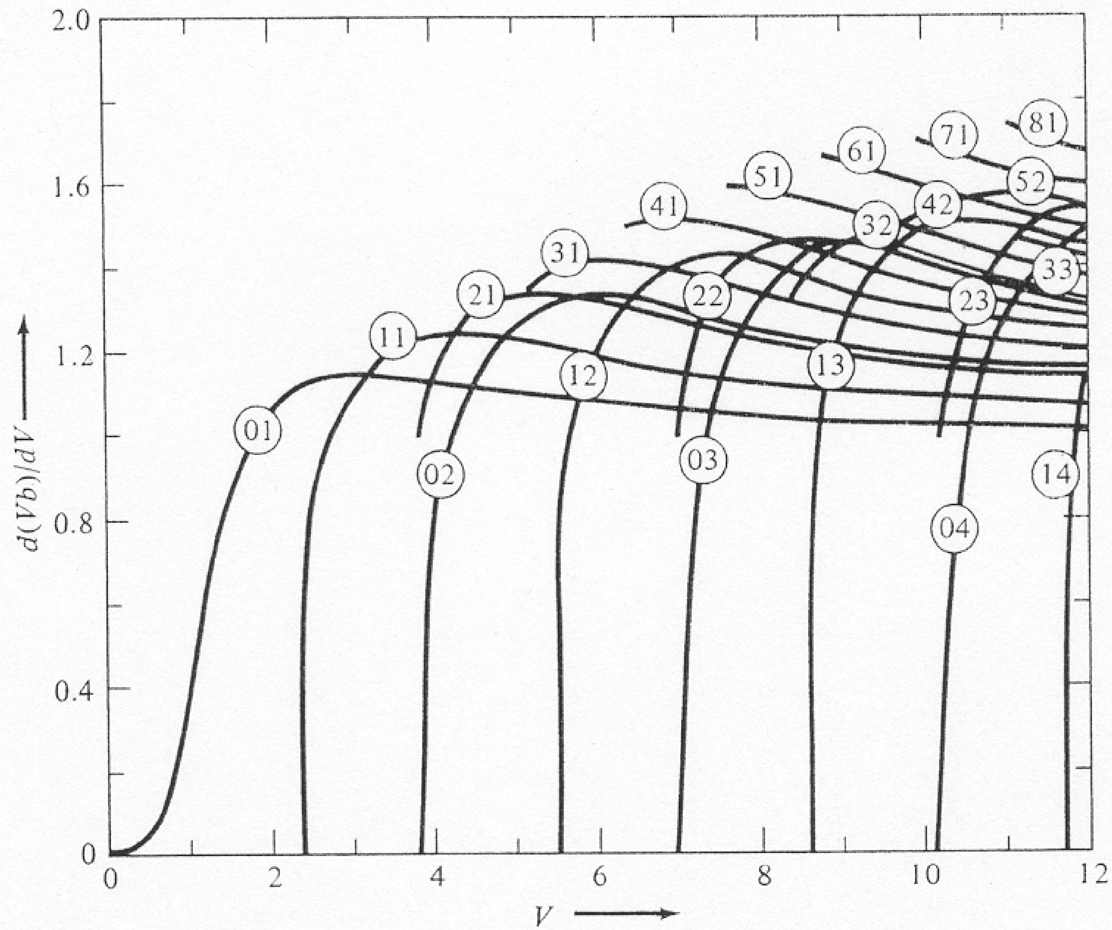
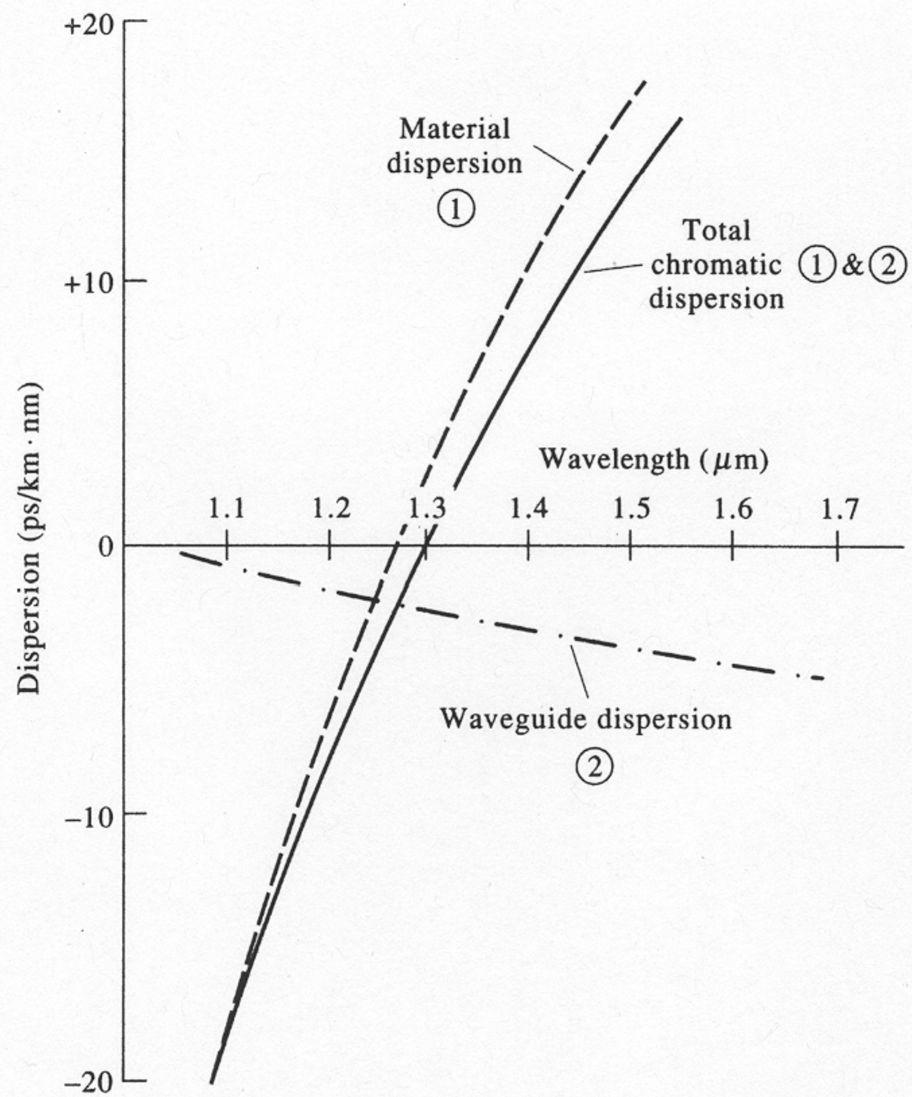


FIGURE 3-14
The group delay arising from waveguide dispersion as a function of the V number for a step-index optical fiber. The curve numbers jm designate the LP_{jm} modes. (Reproduced with permission from Gloge.[37])

Dispersion

$$\tau = DL\sigma$$

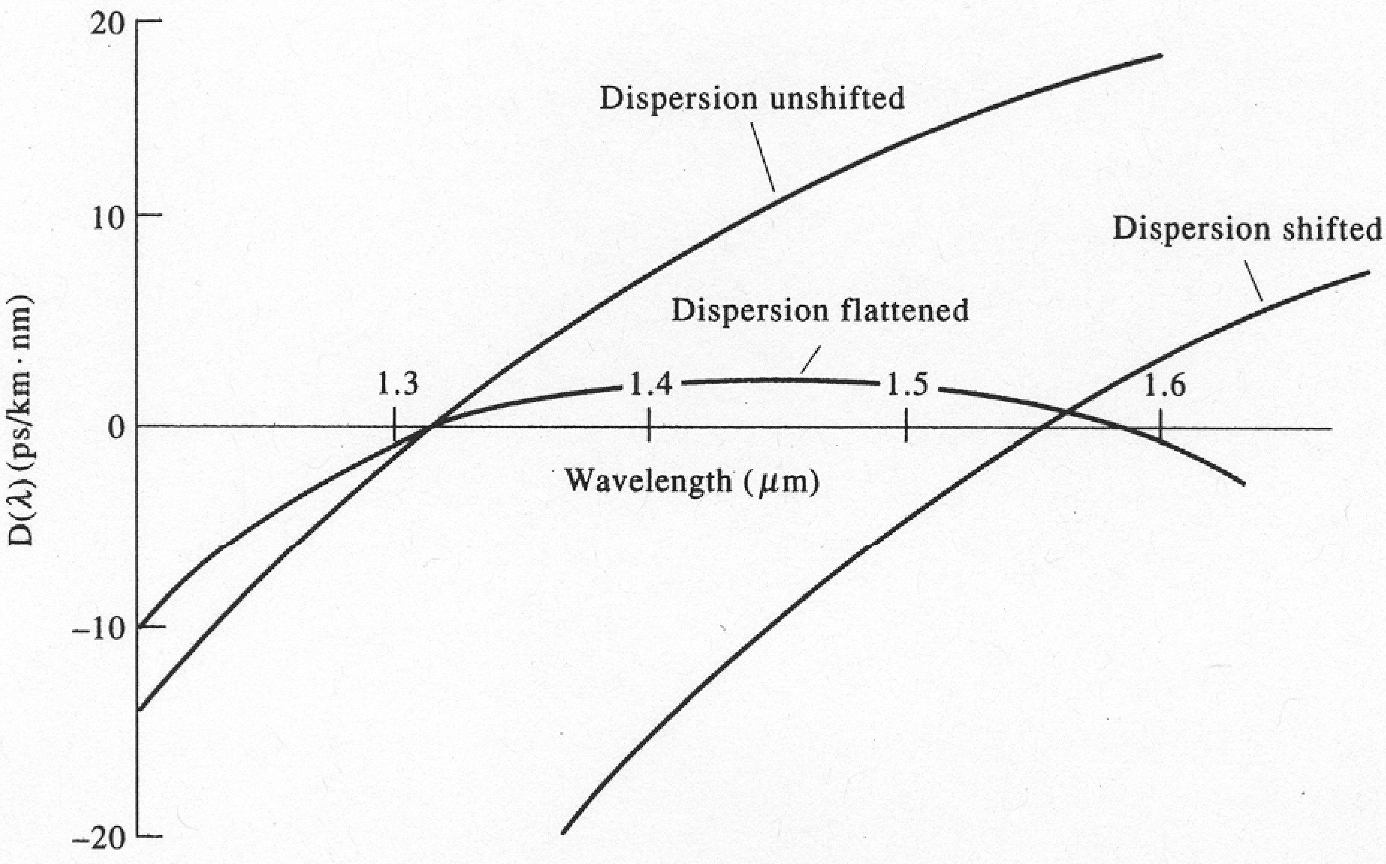
$$\Delta T = DL\Delta\lambda$$



(a)

D is dispersion parameter
L is the propagation length
σ is the spectral width

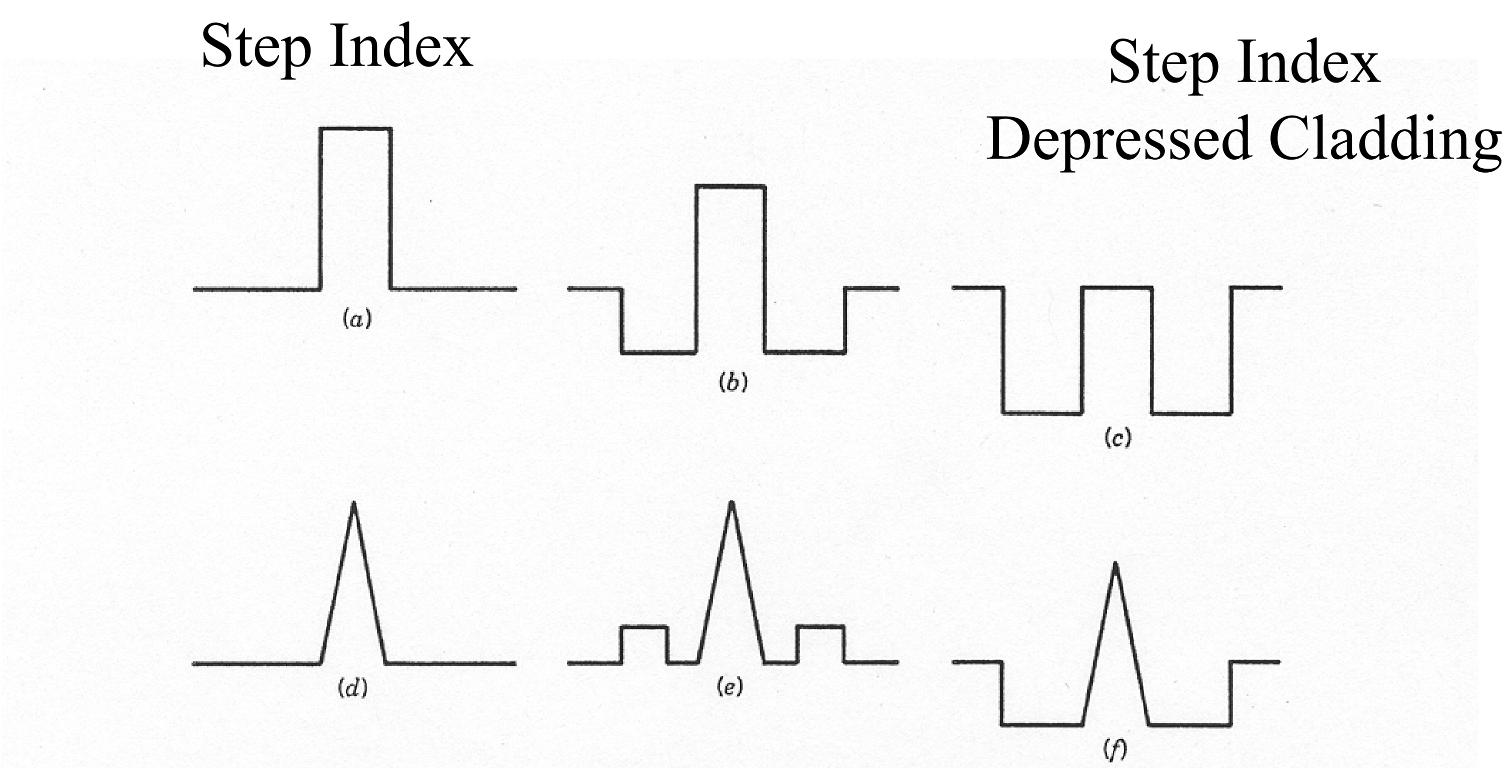
Dispersion (sum of material and waveguide dispersion)



(b)

Figure 3-10 Group velocity disperion of (a) dispersion-unshifted 1.3 μm fiber and (b) dispersion- flattened and dispersion-shifted fibers. (After Reference [1].)

Dispersion Shifted Fiber Designs



Dispersion Shifted Fiber Designs

Chirp

- Fourier transform of a pulse gives amplitudes and phase of the frequency components. Chirp is a property that describes how the phase changes with time.
- Instantaneous frequency is equal to the slope of the phase (divided by 2π). Therefore chirp can also be described as the frequency modulation.
- If chirp parameter C is zero, the pulse is transform-limited. If the product of the GVD parameter and chirp parameter ($\beta_2 C$) is positive, the pulse broadens faster. If negative, the pulse narrows to a minimum and then broadens.

$$\delta\omega(t) = -\frac{\partial \phi}{\partial t} = \frac{C}{T_0^2} t$$

$$\frac{T_1}{T_0} = \left[\left(1 + \frac{C\beta_2 z}{T_0^2} \right)^2 + \left(\frac{\beta_2 z}{T_0^2} \right)^2 \right]^{1/2}$$

Dispersion Budget

- Pulse spreading < Pulse width/4

$$\tau = DL\sigma < \tfrac{1}{4B}$$

$$L < \frac{1}{4BD\sigma}$$

- For Fabry Perot laser, spectral width ~ 2 nm
- So, for conventional fiber at 1.5 micron, D=15 ps/nm/km

$$L < \frac{1}{4 \bullet 2nm \bullet 15\,ps/nm/kmB} = \frac{8.3GHz \bullet km}{B}$$

- Gee, at 10 Gbit/s, this is just 0.8 km.

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

$$L < \frac{1}{4 \bullet 0.1 nm \bullet 1 ps/nm/kmB} = \frac{2.5 THz \bullet km}{B}$$

- Third solution: Use external modulators. Then

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

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

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

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

Dispersion Limits

- Multimode fiber:
  - Every mode has a different velocity: huge dispersion limit.
  - Solution: Graded index fiber: adjust the index profile so every mode travels at the same velocity. Big improvement- most multimode fiber today is graded index.
- Single mode fiber:
  - Only one mode so the dominant dispersion is due to material dispersion and waveguide dispersion
  - PMD Polarization mode dispersion: real fiber is not perfectly concentric and there is strain in the fiber and cabling so fiber does have birefringence i.e. PMD.

Polarization

- So called single mode fiber is not really single mode. There are two degenerate modes (for example, vertical and horizontal polarization).
- Fiber is in general birefringent due to core ellipticity or strain so the two polarizations travel at different velocities.
- The polarization evolves in time. The distance over which it repeats is the beat length.

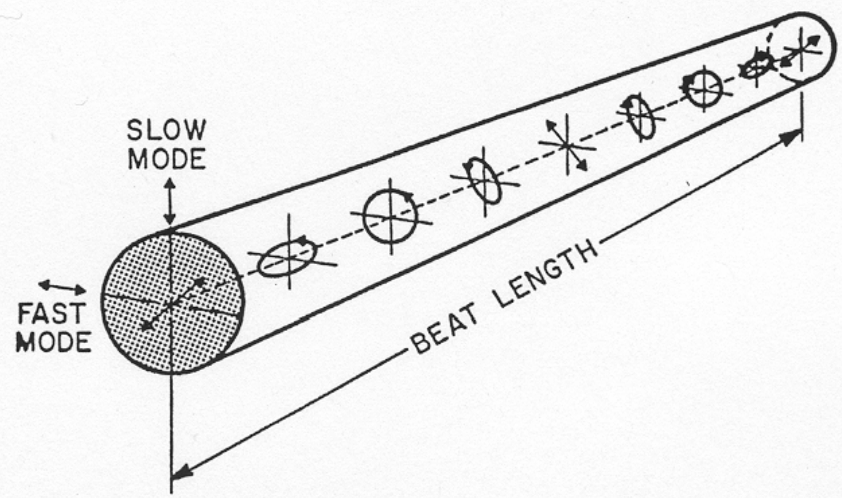


Figure 2.6: State of polarization in a birefringent fiber over one beat length. Input beam is linearly polarized at 45° with respect to the slow and fast axes.

Dispersion Summary

- Single mode condition required for high performance
- Multimode fiber used for low cost
- Dispersion is designable.
- 1.3 micron: zero of dispersion
- 1.55 micron: minimum loss
- Zero dispersion is not good because of nonlinearities

Material

- Gain and absorption (1 week)
- Lasers (2 weeks)
- Photodetectors (2 weeks)
- Modulators (2 weeks)