OPTOELECTRONICS (I)

Chapter 6: Dispersion in Optical Fibers

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6. Dispersion in Optical Fibers

❖Dispersion: As a **pulse** of light propagates down a long fiber, it will generally broaden in time.

1. Intermodal dispersion

2. Intrarmodal (*chromatic*) dispersion

I. Material dispersion

II. Waveguide dispersion

3. Polarization-Mode dispersion (PMD)

۱. پاشندگی بین مدی

۲. پاشندگی درون مدی (رنگی)

۳. پاشندگی مد قطبش

❖ Intermodal dispersion: light distributed among several modes

❖ chromatic dispersion: light distributed over a range of wavelengths

❖ In multimode fibers, the dispersion is largely due to the different propagation speeds for the various modes.

❖Typical values of intermodal dispersion are ~ 50 ns/km, which limits the useful propagation range for a 100 Mb/s signal to ~ 100 m.

6. Dispersion in Optical Fibers

❖ There are two basic approaches to reducing dispersion:

I. Use a graded-index fiber : for multimode fibers

II. Use a single-mode fiber:

➢ Although single-mode fibers have no intermodal dispersion, they have other sources of dispersion.

6.1 Graded Index Fiber

$\boxed{v = c/n}$ $\qquad n(r) = n_1[1 - (r/a)^2\Delta]$ $\qquad \Delta = (n_1 - n_2)/n_1$

n_1: maximum core index, n_2: cladding index, a: core radius.

❖ The dispersion reduces by a factor of $\Delta/8$ compared to an equivalent step-index fiber.

If $\Delta = 0.01$, ⇨ 50 ns/km intermodal dispersion (for a step- index fiber).

⇩

50 ps/km

for graded-

index fiber

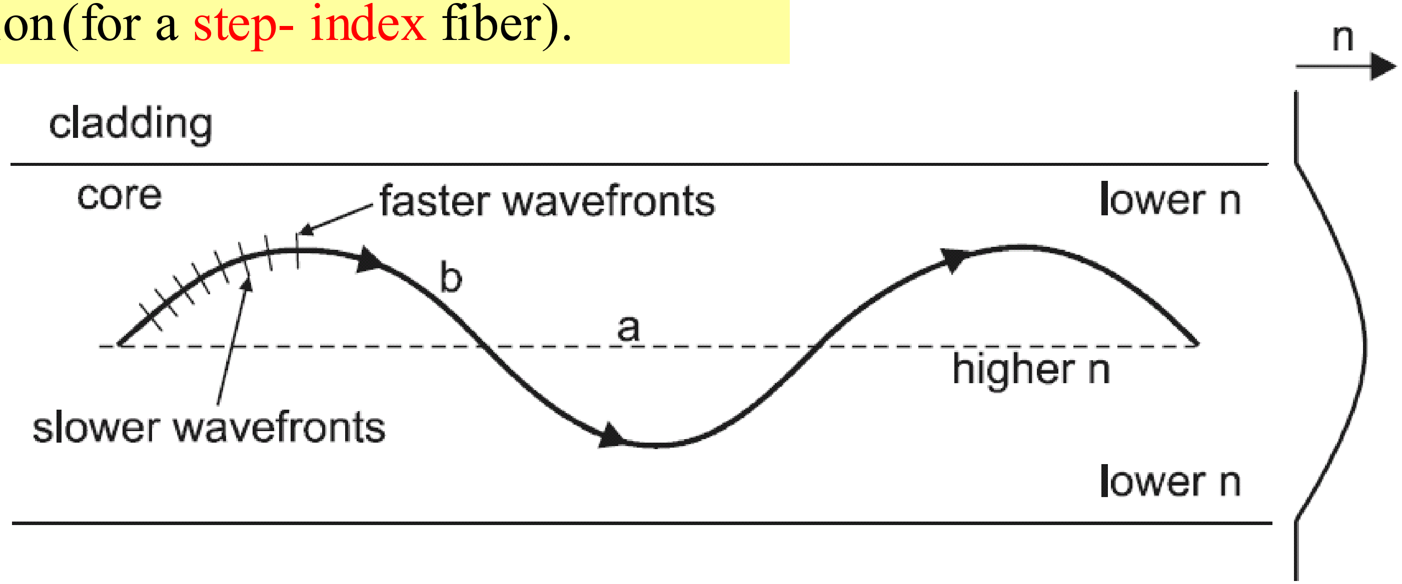


Figure 6-1 Ray propagation along **two paths** a and b in a graded-index fiber.

6.2 Intramodal (Chromatic) Dispersion

I. **Material dispersion**

II. **Waveguide dispersion**

I. Material dispersion

- n ⟹ n(λ) ⟹ varying speed for the different wavelength
- Material dispersion depends only on a property of the material (n).

Quantitatively: by calculating the time t for light of a particular wavelength λ to travel a distance L down the fiber.

υ_g: group velocity ⟹

$$t = \frac{L}{v_g} = L\frac{d\beta}{d\omega} = L\frac{d\beta}{d\lambda}\cdot\frac{d\lambda}{d\omega} \qquad (6\text{-}1)$$

λ: free-space wavelength

➢ Material Dispersion - (1)

$$t \stackrel{?}{=} \frac{L}{n/c}$$

$$\boxed{t = \frac{L}{v_g} = L\frac{d\beta}{d\omega} = L\frac{d\beta}{d\lambda}\cdot\frac{d\lambda}{d\omega}} \qquad (6\text{-}1)$$

$$\lambda = c/\nu = 2\pi c/\omega \Rightarrow \frac{d\lambda}{d\omega} = -2\pi\frac{c}{\omega^2} = -\frac{\lambda^2}{2\pi c} \qquad (6\text{-}2)$$

$$\boxed{\beta = nk_0 = n\frac{2\pi}{\lambda} \qquad \text{(plane wave assumption)}} \qquad (6\text{-}3)$$

$$\Rightarrow \frac{d\beta}{d\lambda} = \frac{2\pi}{\lambda}\frac{dn}{d\lambda} - \frac{2\pi}{\lambda^2}n = -\frac{2\pi}{\lambda^2}\left(n - \lambda\frac{dn}{d\lambda}\right) \qquad (6\text{-}4)$$

Substituting Eq. (2) and Eq. (4) into Eq. (1)

$$\Rightarrow \boxed{t = \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right)} \qquad (6\text{-}5)$$

➢ Material Dispersion - (2)

$$v_p = \frac{c}{n} \Rightarrow t = \frac{Ln}{c}$$

$$t = \frac{L}{c}\left(n - \lambda \frac{dn}{d\lambda}\right) \quad (6\text{-}5)$$

$$v_g = \frac{c}{n - \lambda \frac{dn}{d\lambda}} \quad (6\text{-}6)$$

➢ If a light pulse has a spectral width $\Delta\lambda$, the **different wavelength** components in the pulse will propagate with different delay times according to the $n(\lambda)$ and $dn/d\lambda$ for each wavelength.

➢ The spread in arrival times Δt for the **different wavelength** components:

$$\Delta t = \frac{dt}{d\lambda} \cdot \Delta\lambda \quad (6\text{-}7)$$

$$\frac{dt}{d\lambda} = \frac{L}{c}\left[\frac{dn}{d\lambda} - \frac{dn}{d\lambda} - \lambda \frac{d^2n}{d\lambda^2}\right] = -\frac{L}{c}\lambda \frac{d^2n}{d\lambda^2} \quad (6\text{-}8)$$

material dispersion

$$\Delta t = -\frac{L}{c}\lambda \frac{d^2n}{d\lambda^2}\,\Delta\lambda \quad (6\text{-}9)$$

➢ Material Dispersion - (3)

material dispersion

$$\Delta t = -\frac{L}{c}\lambda \frac{d^2 n}{d\lambda^2}\Delta\lambda \qquad (6\text{-}9)$$

➢ There are two ways to minimize material dispersion:

1. Use a nearly monochromatic light source (small). $\Rightarrow$ $\Delta\lambda \approx \cdot$ $\Rightarrow$ **Laser**
2. **Choose** a wavelength where $d^2n/d\lambda^2$ becomes very small. $\Rightarrow$ $\boldsymbol{\lambda_0 \approx 1300}$ **nm**

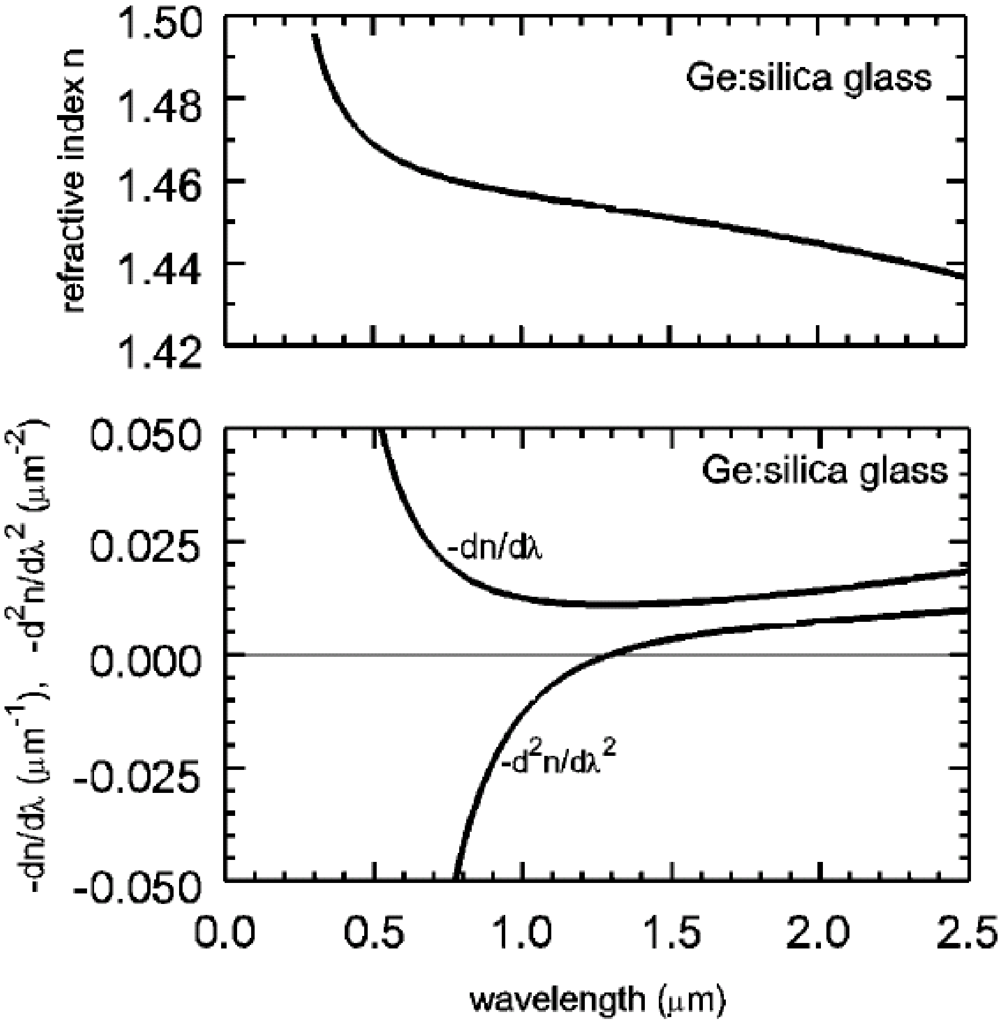
➢ The variation of n with wavelength arises from the interaction of the light with the electronic and vibrational **transitions** in the **glass**.

➢ For wavelengths in the visible and near infrared regions, the balance between these two types of transitions causes n to decrease with increasing λ.

➢ In silica glass, this occurs at $\lambda_0 \approx 1300$ nm, which is another reason (in addition to low attenuation) that the 1300 nm region was chosen for the second telecommunications window.

➢ Material Dispersion - (4)

Figure 6-2 Variation of refractive index with wavelength for silica glass in the visible and near IR regions.



The curvature $d^2n/d\lambda^2$ goes to zero at $\lambda_0 \approx 1300$ nm.

➢ Material Dispersion - (5)

material dispersion $\equiv \lambda, \Delta\lambda$

$$\Delta t = -\frac{L}{c}\lambda \frac{d^2 n}{d\lambda^2}\Delta\lambda \quad (6\text{-}9)$$

$$D_m \equiv \frac{1}{L}\frac{\Delta t}{\Delta\lambda} = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2} \quad \text{(material dispersion coefficient)} \quad (6\text{-}10)$$

which is only dependent on the *material property* $d^2n/d\lambda^2$.

➢ D_m is negative for $\lambda < \lambda_0$ and positive for $\lambda > \lambda_0$.

➢ A *negative D_m* implies that **longer wavelengths** have a shorter arrival time, that is, they travel faster.

➢ This is termed *normal dispersion* since it is what is normally encountered in the visible and near IR spectral regions.

➢ longer λ means decreasing n, which gives a greater $v_p = c/n$.

➢ Material Dispersion - (6)

- A *positive* D_m implies that longer wavelengths have longer arrival times, and thus **travel slower**.

- This is termed *anomalous dispersion*, and occurs in silica glass for λ >1300 nm.

- In this spectral region, the υ_g decreases with increasing λ, but the υ_p increases, since *n* continues to decrease with increasing λ.

- This difference in υ_g and υ_p behavior is one sense in which the dispersion is "anomalous," and has applications in soliton propagation in fibers.

Example 6-1

Calculate the dispersion coefficient D_m in ps/(nm · km) and the dispersion per unit length in ns/km or ps/km for each of the following:

(a) LED (light-emitting diode) light with spectral width of 40 nm, operating at wavelength 800 nm, where $d^2n/d\lambda^2 = 4 \times 10^{10}\ m^{-2}$.

(b) Laser light with spectral width of 0.2 nm, operating at wavelength 1500 nm, where $d^2n/d\lambda^2 = -2.7 \times 10^{9}\ m^{-2}$.

Solution: (a)

$\lambda = 800$ nm

$$D_m = -\frac{800 \times 10^{-9}}{3 \times 10^{8}}(4 \times 10^{10}) = -107 \times 10^{-6}\ \mathrm{s/m^2}$$

or

$$D_m = -107\ \frac{\mathrm{ps}}{\mathrm{nm \cdot km}}$$

The dispersion per unit length (dropping the minus sign) is:

$$\frac{\Delta t}{L} = \left(107\ \frac{\mathrm{ps}}{\mathrm{nm \cdot km}}\right) \cdot (40\ \mathrm{nm}) = 4.3\ \frac{\mathrm{ns}}{\mathrm{km}}$$

Example 6-1 (b)

Solution: (b)

For λ= 1500 nm

material dispersion coefficient (D_m):

$$D_m = -\frac{1500 \times 10^{-9}}{3 \times 10^{8}}(-2.7 \times 10^{9}) = 13.5 \times 10^{-6} \text{ s/m}^2 = 13.5 \ \frac{\text{ps}}{\text{nm} \cdot \text{km}}$$

The dispersion per unit length is:

$$\frac{\Delta t}{L} = \left(13.5 \ \frac{\text{ps}}{\text{nm} \cdot \text{km}}\right) \cdot (0.2 \text{ nm}) = 2.7 \ \frac{\text{ps}}{\text{km}}$$

The dramatic reduction in dispersion for the laser source illustrates its importance for high-speed optical communications.

➢ Waveguide Dispersion - (1)

➢ Waveguide dispersion can analyzed quantitatively by making the substitution $n \longrightarrow n_{\text{eff}}$ in each of Eqs. (6-3)–(6-10).

Total chromatic dispersion coefficient or **profile** dispersion (D_C):

$$D_c \equiv \frac{1}{L}\frac{\Delta t}{\Delta\lambda} = -\frac{\lambda}{c}\frac{d^2 n_{\text{eff}}}{d\lambda^2} \qquad (6\text{-}11)$$

$\boxed{\delta \equiv n_{\text{eff}} - n_2}$

$$D_c = -\frac{\lambda}{c}\frac{d^2 n_2}{d\lambda^2} - \frac{\lambda}{c}\frac{d^2\delta}{d\lambda^2} = D_m + D_w \qquad (6\text{-}12)$$

where D_w *is the waveguide dispersion coefficient.*

$$V \equiv \frac{2\pi a}{\lambda_0}\sqrt{n_1^2 - n_2^2} \qquad (4\text{-}9)$$

$$\boxed{D_w \simeq -\frac{V}{\lambda c}\frac{d^2(V\delta)}{dV^2}} \qquad (6\text{-}13)$$

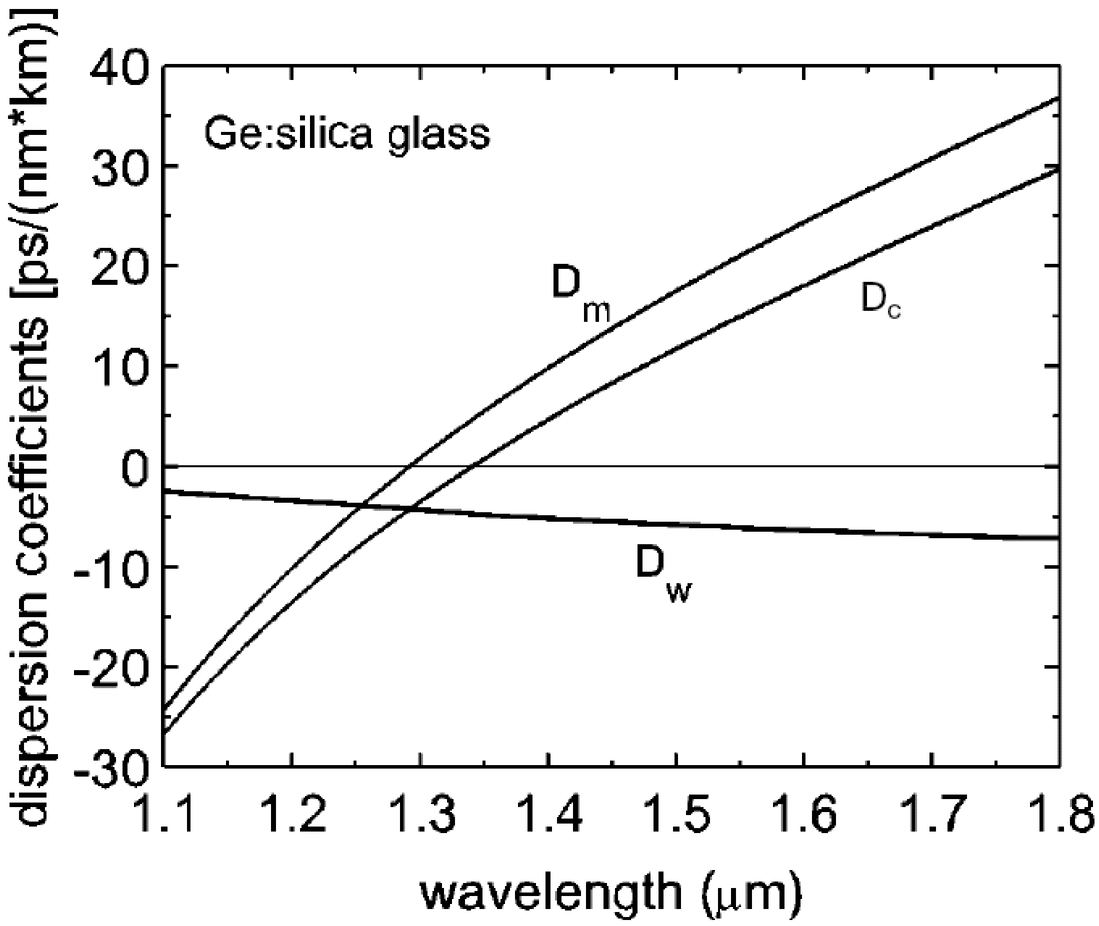
(waveguide dispersion coefficient)

➢ Waveguide Dispersion - (2)

D_c : Combined dispersion
D_m : material dispersion
D_w : waveguide dispersion

$$D_c = D_m + D_w$$

Figure 6-3 Dispersion coefficient D_c for single-mode fiber, showing contributions D_m from material dispersion and D_w from waveguide dispersion (core radius ≈ 4 m).



➢ Waveguide Dispersion - (3)

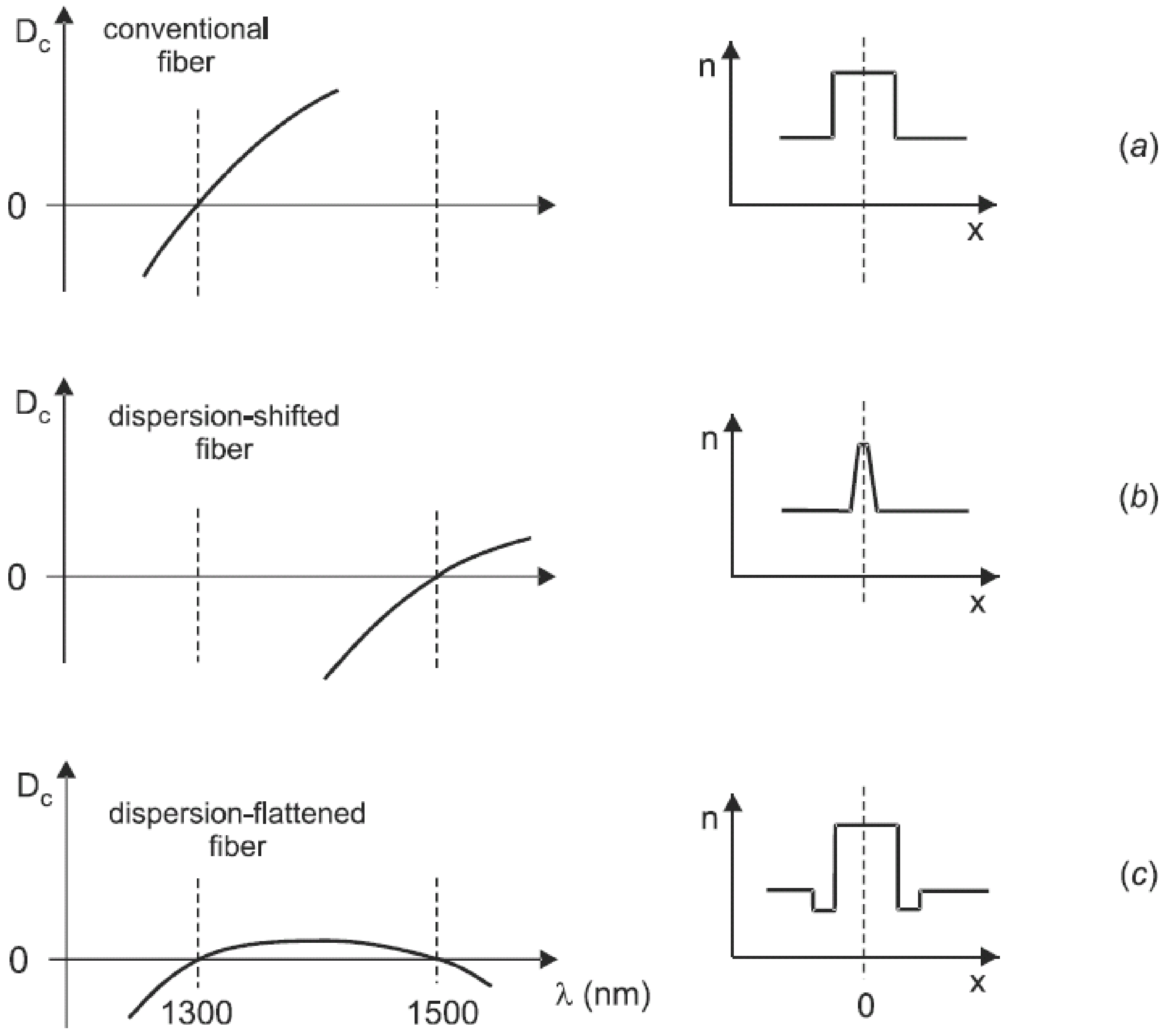


Figure 6-4

The refractive index profile can be tailored to produce different dispersion curves.

➢ Polarization-Mode Dispersion (PMD)-

➢ A third type of time-spreading mechanism, that of *polarization mode dispersion* (PMD), is a consequence of the light being distributed over different polarizations.

➢ For a perfectly uniform and symmetrical fiber, the propagation speed would be independent of polarization.

➢ In real fibers, depends slightly on polarization.

➢ The time spread of a pulse due to PMD is found to obey

polarization mode dispersion:

$$\boxed{\Delta t_{\mathrm{PMD}} \simeq D_{\mathrm{PMD}}\sqrt{L}} \qquad (6\text{-}14)$$

where D_{PMD} is the polarization mode dispersion coefficient. Typical values for communications fiber are 0.2-2 ps/km.

➢ Total Fiber Dispersion

➢ To determine the total time spread of a pulse, we must combine the various sources of fiber dispersion.

➢ The way that we combine them depends on whether they are correlated or uncorrelated.

➢ For example, *material* dispersion D_m *and waveguide dispersion* D_w *are* correlated because they both depend in a specified way on the wavelength. In this case, we add these dispersions directly. ($D_c = D_m + D_w$)

➢ *However, intermodal dispersion, chromatic dispersion and PMD do not share* any common origin, and are therefore uncorrelated.

➢ In this case, we must add the time spreads "in quadrature":

$$\Delta t_{\text{fiber}} = \sqrt{\Delta t^2_{\text{modal}} + \Delta t^2_{\text{chromatic}} + \Delta t^2_{\text{PMD}}} \qquad \text{(total fiber dispersion)} \qquad (6\text{-}15)$$

➢ Total Fiber Dispersion – (2)

➢ In many situations, one of these three terms dominates and the others can be neglected.

➢ For example, in **step-index multimode** fiber, the Δt^2_{modal} term usually dominates; it is zero, however, in single-mode fiber.

➢ The contribution from PMD can often be neglected, but can be significant in long fiber spans when very monochromatic light sources are used.

Problems (chap.6): 1 to 11

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