Lecture 6. Transmission Characteristics of Optical Fibers

- Fiber attenuation
- Fiber dispersion
- Group velocity
- Material dispersion
- Waveguide dispersion
- Chromatic dispersion compensation
- Polarization mode dispersion
- Polarization-maintaining fibers

Reading: Senior 3.1-3.4, 3.6, 3.8-3.13
Keiser 3.1 – 3.3

Transmission characteristics of optical fibers

- The transmission characteristics of most interest: **attenuation (*loss*)** and **bandwidth**.

- Now, *silica-based* glass fibers have losses about 0.2 dB/km (i.e. 95% launched power remains after 1 km of fiber transmission). This is essentially the *fundamental lower limit* for attenuation in silica-based glass fibers.

- **Fiber bandwidth** is limited by the *signal dispersion* within the fiber. Bandwidth determines the number of bits of information transmitted in a given time period. Now, fiber bandwidth has reached many 10's Gbit/s over many km's per wavelength channel.

Attenuation

- Signal attenuation within optical fibers is usually expressed in the logarithmic unit of the decibel.

The decibel, which is used for comparing two *power* levels, may be defined for a particular optical wavelength as the *ratio* of the output optical power P_o from the fiber to the input optical power P_i.

$$\text{Loss (dB)} = -10 \log_{10} (P_o/P_i) = 10 \log_{10} (P_i/P_o)$$

$$(P_o \le P_i)$$

*In *electronics*, $\text{dB} = 20 \log_{10} (V_o/V_i)$

*The logarithmic unit has the advantage that the operations of *multiplication* (*and division*) reduce to *addition* (*and subtraction*).

In numerical values: $P_o/P_i = 10^{[-Loss(dB)/10]}$

The attenuation is usually expressed in decibels per unit length (i.e. dB/km):

$$\gamma L = -10 \log_{10} (P_o/P_i)$$

γ (dB/km): signal attenuation per unit length in decibels

L (km): fiber length

dBm

- dBm is a specific unit of power in decibels when the reference power is 1 mW:

$$\text{dBm} = 10 \log_{10} (\text{Power}/1\ \text{mW})$$

e.g. 1 mW = 0 dBm; 10 mW = 10 dBm; 100 μW = - 10 dBm

=> Loss (dB) = input power (dBm) - output power (dBm)

e.g. Input power = 1 mW (0 dBm), output power = 100 μW (-10 dBm)

$$\Rightarrow \text{loss} = -10 \log_{10} (100\ \mu\text{W}/1\ \text{mW}) = 10\ \text{dB}$$

OR 0 dBm – (-10 dBm) = 10 dB

The dBm Unit

Example 3.2 As Sec. 1.3 describes, optical powers are commonly expressed in units of *dBm*, which is the decibel power level referred to 1 mW. Consider a 30-km long optical fiber that has an attenuation of 0.4 dB/km at 1310 nm. Suppose we want to find the optical output power P_{out} if 200 μW of optical power is launched into the fiber. We first express the input power in dBm units:

$$P_{in}(\text{dBm}) = 10\log\left[\frac{P_{in}(\text{W})}{1\,\text{mW}}\right]$$
$$= 10\log\left[\frac{200\times10^{-6}\ \text{W}}{1\times10^{-3}\,\text{W}}\right] = -7.0\ \text{dBm}$$

From Eq. (3.1*c*) with $P(0) = P_{in}$ and $P(z) = P_{out}$ the output power level (in dBm) at $z = 30$ km is

$$P_{out}(\text{dBm}) = 10\log\left[\frac{P_{out}(\text{W})}{1\,\text{mW}}\right]$$
$$= 10\log\left[\frac{P_{in}(\text{W})}{1\,\text{mW}}\right] - \alpha z$$
$$= -7.0\ \text{dBm} - (0.4\ \text{dB/km})\,(30\ \text{km})$$
$$= -19.0\ \text{dBm}$$

In unit of watts, the output power is

$$P(30\ \text{km}) = 10^{-19.0/10}(1\ \text{mW}) = 12.6\times10^{-3}\ \text{mW}$$
$$= 12.6\ \mu\text{W}$$

e.g. When the mean optical power launched into an 8 km length of fiber is 120 μW, the mean optical power at the output is 3 μW.

Determine:

(a) the overall signal attenuation (or loss) in decibels through the fiber assuming there are no *connectors* or *splices*

(b) the signal attenuation per kilometer for the fiber

(c) the overall signal attenuation for a 10 km optical link using the same fiber with *splices* (i.e. fiber connections) at 1 km intervals, each giving an attenuation of 1 dB

(d) the output/input power ratio in (c).

(a) signal attenuation = $-10 \log_{10}(P_o/P_i) = 16$ dB

(b) 16 dB / 8 km = 2 dB/km

(c) the loss incurred along 10 km fiber = 20 dB.

With a total of 9 *splices* (i.e. fiber connections) along the link, each with an attenuation of 1 dB, the loss due to the splices is 9 dB.

=> the overall signal attenuation for the link = 20 + 9 dB = 29 dB.

(d) $P_o/P_i = 10^{(-29/10)} = 0.0013$

fiber attenuation mechanisms:

1. Material absorption
2. Scattering loss
3. Bending loss
4. Radiation loss (due to mode coupling)
5. Leaky modes

1. Material absorption losses in silica glass fibers

• Material absorption is a loss mechanism related to both *the material composition* and the *fabrication process* for the fiber. The optical power is lost as *heat* in the fiber.

• The light absorption can be *intrinsic* (due to the material components of the glass) or *extrinsic* (due to impurities introduced into the glass during fabrication).

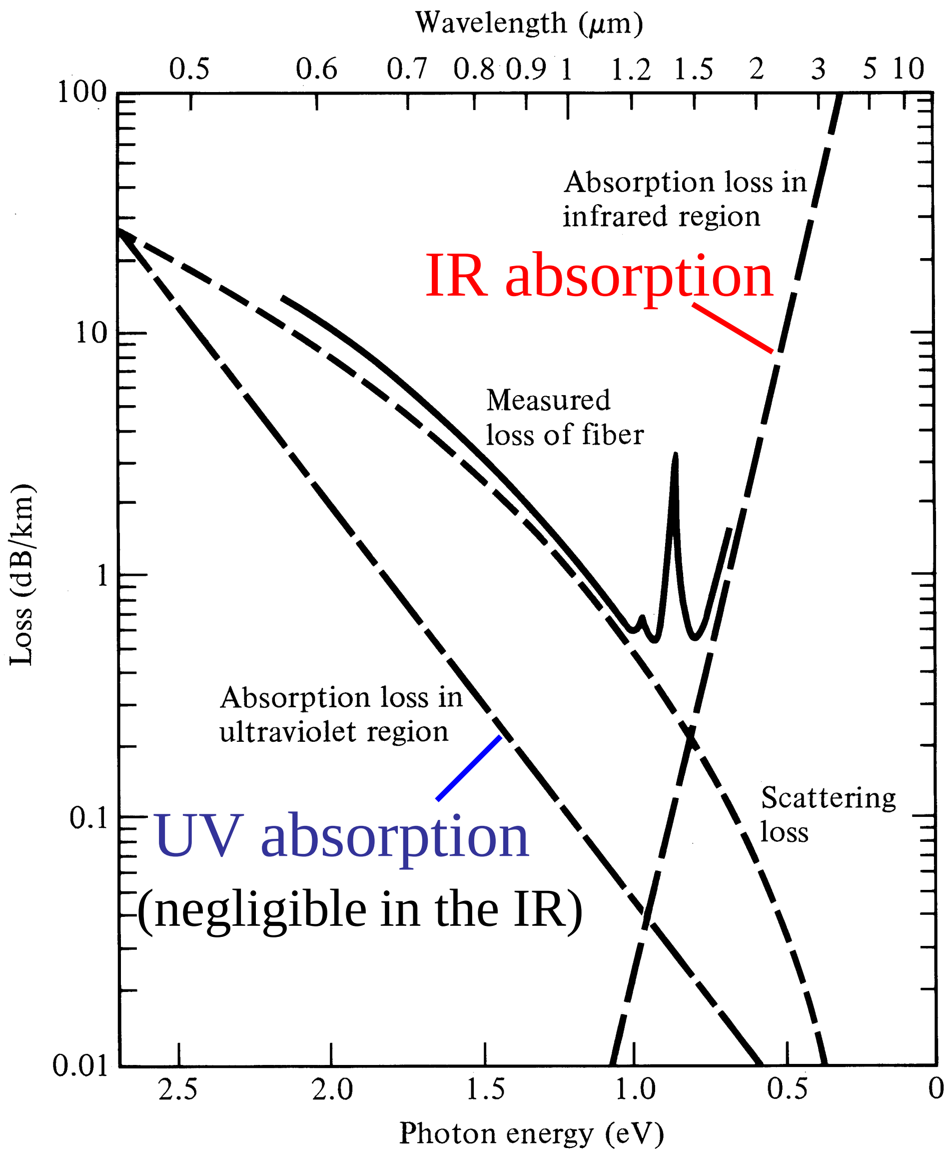
Intrinsic absorption

- Pure silica-based glass has *two* major intrinsic absorption mechanisms at optical wavelengths:

(1) a *fundamental UV absorption* edge, the peaks are centered in the *ultraviolet wavelength region*. This is due to the *electron transitions* within the glass molecules. The tail of this peak may extend into the the shorter wavelengths of the fiber transmission spectral window.

(2) A fundamental *infrared and far-infrared absorption edge*, due to *molecular vibrations* (such as Si-O). The tail of these absorption peaks may extend into the longer wavelengths of the fiber transmission spectral window.

Fundamental fiber attenuation characteristics



Extrinsic absorption

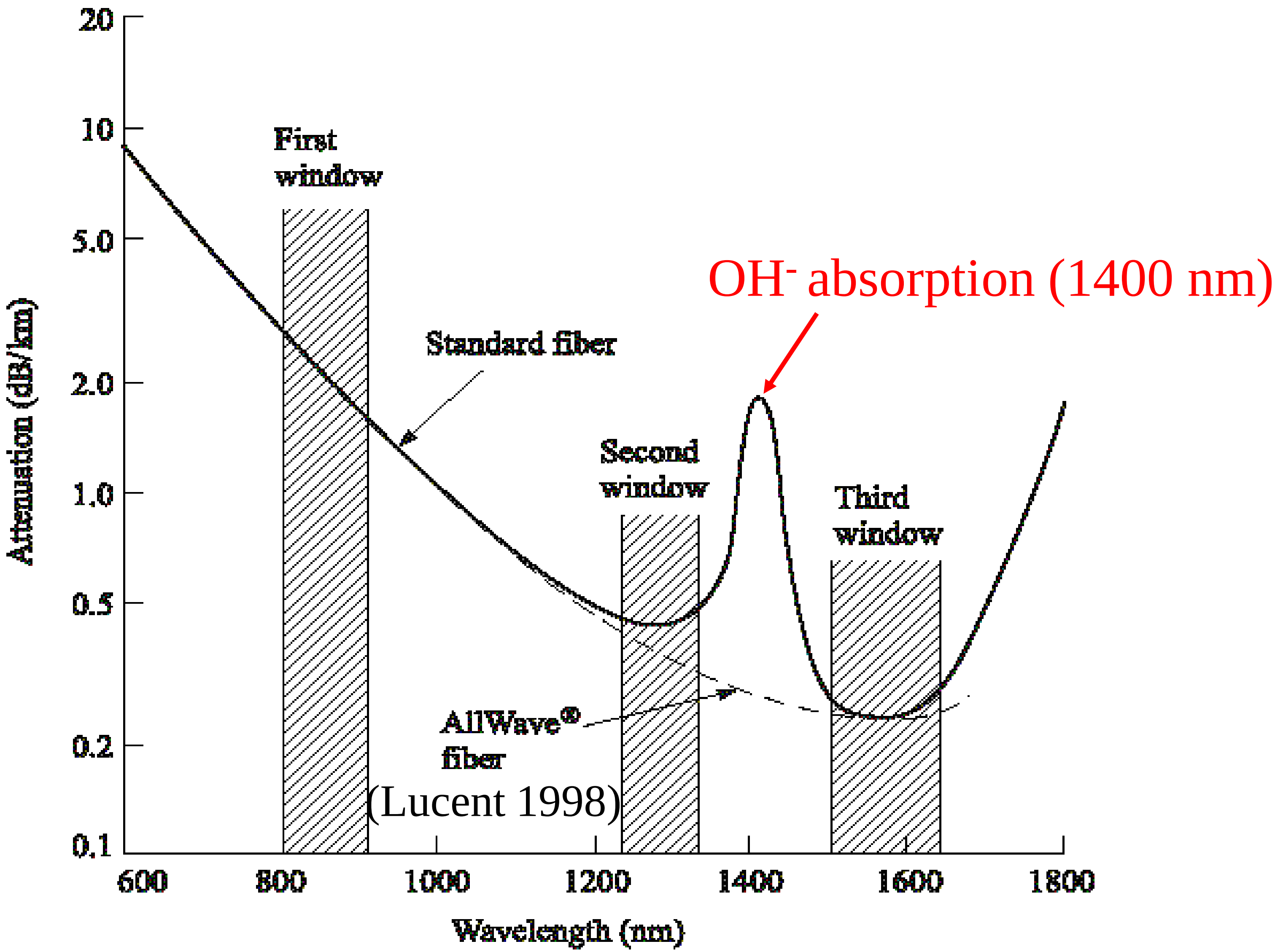
- Major extrinsic loss mechanism is caused by absorption due to water (*as the hydroxyl or OH^- ions*) introduced in the glass fiber during *fiber pulling by means of oxyhydrogen flame*.

- These OH^- ions are bonded into the glass structure and have absorption peaks (due to *molecular vibrations*) at 1.38 μm.

- Since these OH^- absorption peaks are sharply peaked, narrow spectral windows exist around 1.3 μm and 1.55 μm which are essentially unaffected by OH^- absorption.

- The lowest attenuation for typical silica-based fibers occur at wavelength 1.55 μm at about 0.2 dB/km, approaching the *minimum possible attenuation* at this wavelength.

1400 nm OH^- absorption peak and spectral windows



OFS AllWave fiber: example of a "low-water-peak" or "full spectrum" fiber. Prior to 2000 the fiber transmission bands were referred to as "windows."

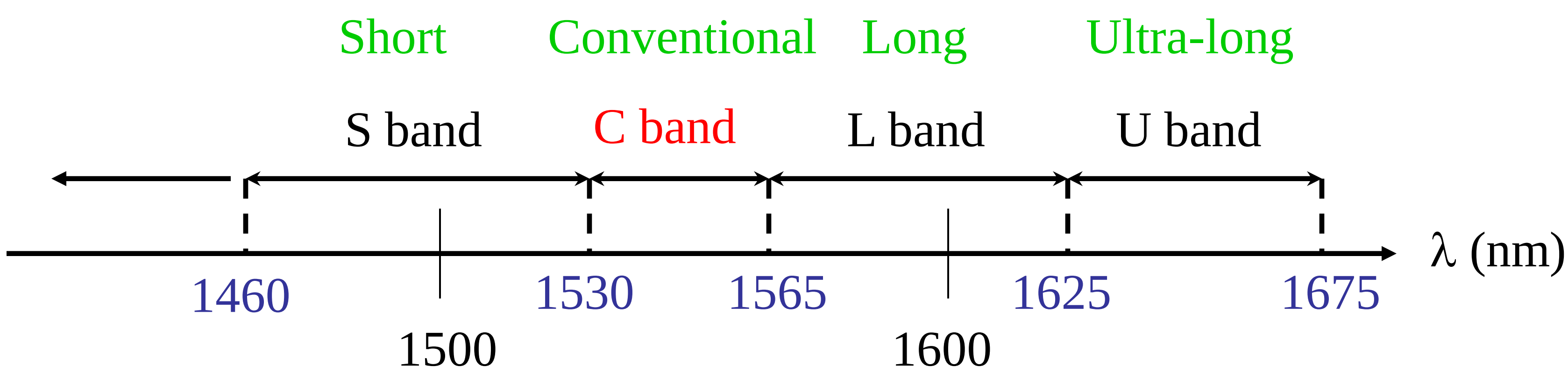
Three major spectral windows where fiber attenuation is low

The 1st window: 850 nm, attenuation 2 dB/km

The 2nd window: 1300 nm, attenuation 0.5 dB/km

The 3rd window: 1550 nm, attenuation 0.3 dB/km

1550 nm window is today's standard **long-haul** communication wavelengths.



Absorption Losses of Impurities

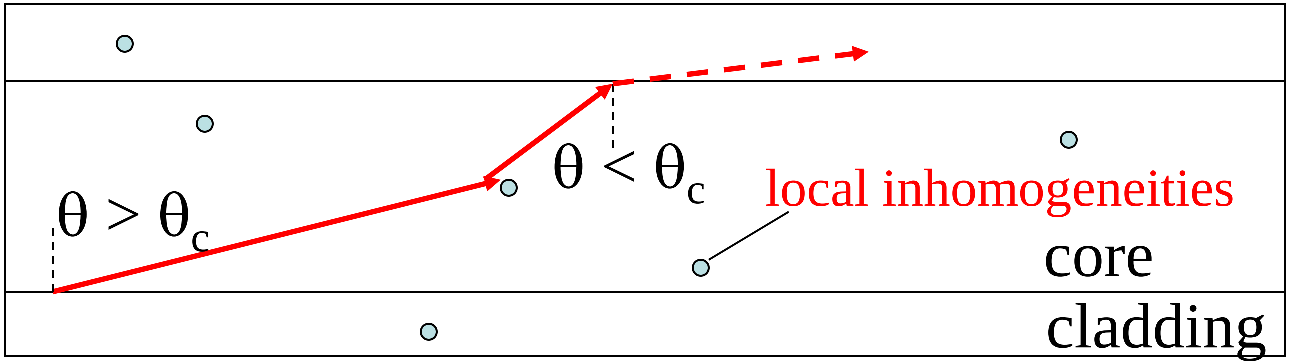
Table 3.1 *Examples of absorption loss in silica glass at different wavelengths due to 1 ppm of water-ions and various transition-metal impurities*

Impurity	*Loss due to 1 ppm of impurity (dB/km)*	*Absorption peak (nm)*
Iron: Fe^{2+}	0.68	1100
Iron: Fe^{3+}	0.15	400
Copper: Cu^{2+}	1.1	850
Chromium: Cr^{2+}	1.6	625
Vanadium: V^{4+}	2.7	725
Water: OH^-	1.0	950
Water: OH^-	2.0	1240
Water: OH^-	4.0	1380

2. Scattering loss

Scattering results in attenuation (*in the form of radiation*) as the scattered light may not continue to satisfy the total internal reflection in the fiber core.

One major type of scattering is known as *Rayleigh scattering*.



Silica glass is amorphous.

The scattered ray can escape by refraction according to Snell's Law.

• *Rayleigh scattering* results from random *inhomogeneities* that are small in size compared with the wavelength.

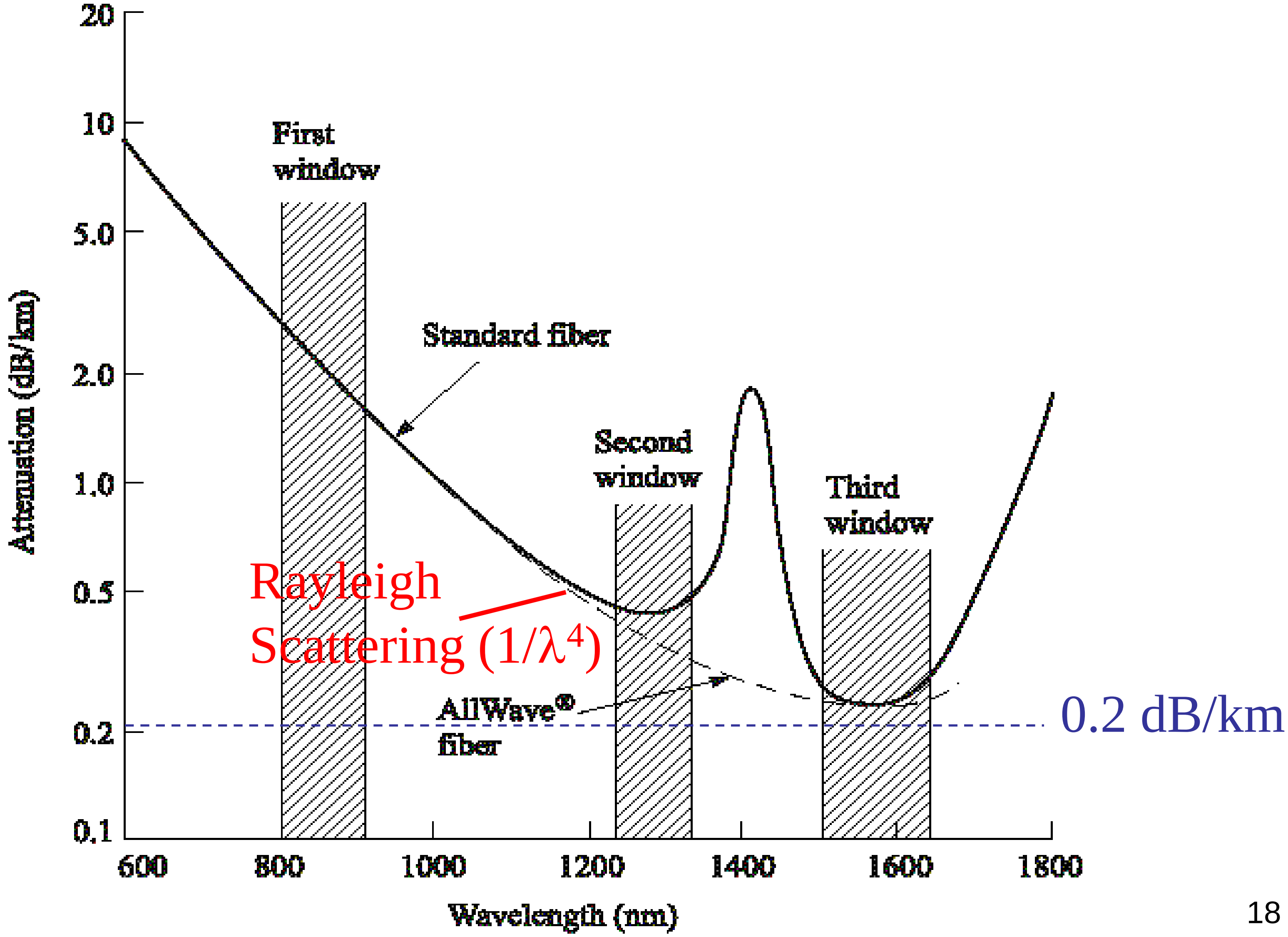
$$\circ \quad \ll \quad \lambda$$

• These inhomogeneities exist in the form of *refractive index fluctuations* which are frozen into the *amorphous* glass fiber upon fiber pulling. Such fluctuations *always exist and cannot be avoided* !

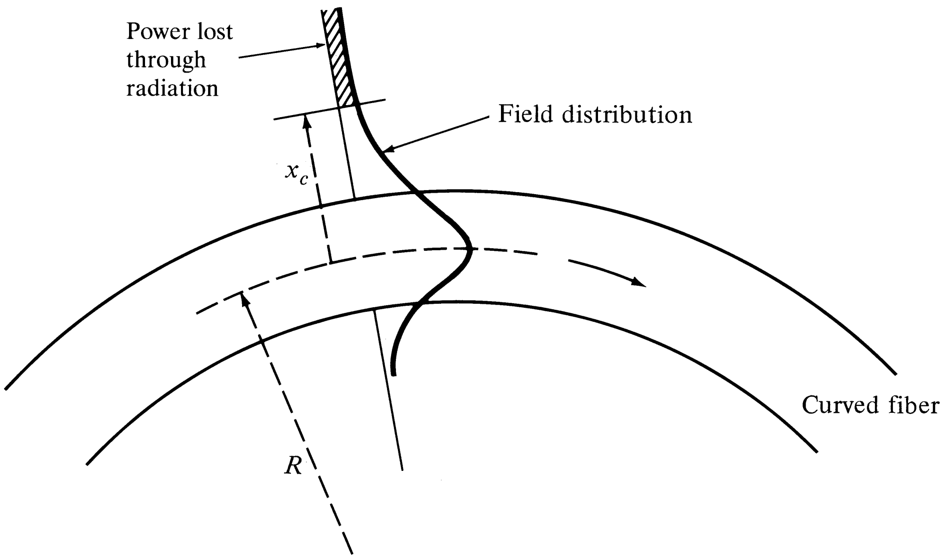
Rayleigh scattering results in an attenuation (dB/km) $\propto 1/\lambda^4$

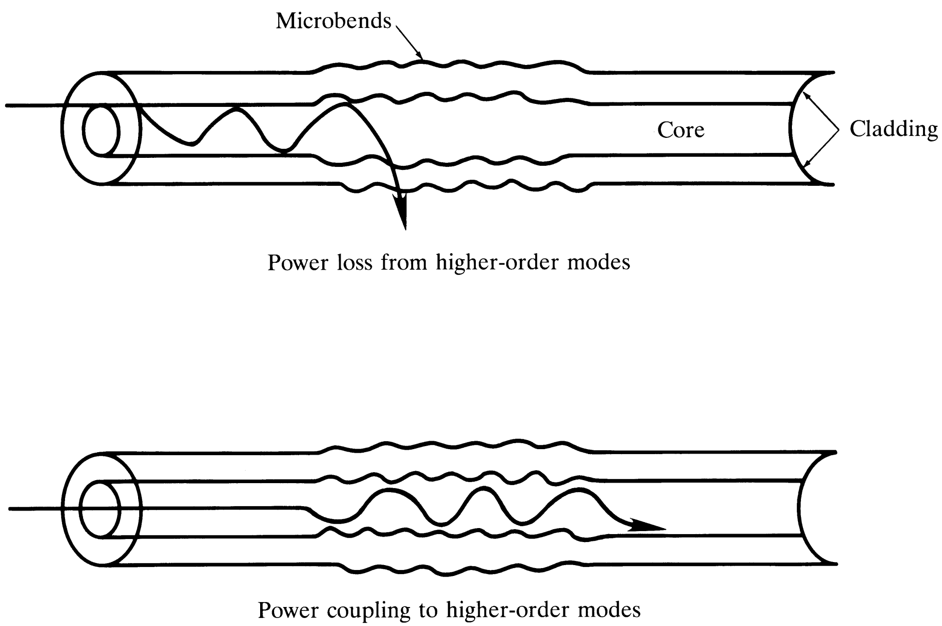
Where else do we see Rayleigh scattering?

Rayleigh scattering is the dominant loss in today's fibers



Fiber bending loss and mode-coupling to higher-order modes





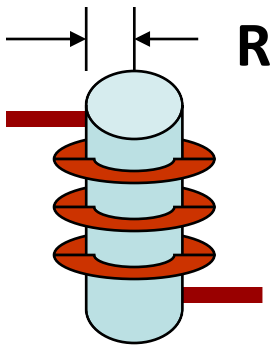
"macrobending"

(*how do we measure bending loss*?)

"microbending" – power coupling to higher-order modes that are more lossy.

Bending Losses in Fibers (1)

- Optical power escapes from tightly bent fibers
- Bending loss increases at longer wavelengths
  - Typical losses in 3 loops of standard 9-μm single-mode fiber (from: *Lightwave*; Feb 2001; p. 156):
  - 2.6 dB at 1310 nm and 23.6 dB at 1550 nm for R = 1.15 cm
  - 0.1 dB at 1310 nm and 2.60 dB at 1550 nm for R = 1.80 cm
- Progressively tighter bends produce higher losses
- Bend-loss insensitive fibers have been developed and now are recommended
- Improper routing of fibers and incorrect storage of slack fiber can result in violations of bend radius rules



Test setup for checking bend loss: N fiber loops on a rod of radius R

Bending Losses in Fibers (2)

The total number of modes that can be supported by a curved fiber is less than in a straight fiber.

$$M_{\text{eff}} = M_\infty \left\{ 1 - \frac{\alpha + 2}{2\alpha\Delta} \left[\frac{2a}{R} + \left(\frac{3}{2n_2 kR} \right)^{2/3} \right] \right\}$$

Example 3.6 Consider a graded-index multimode fiber for which the index profile $\alpha = 2.0$, the core index $n_1 = 1.480$, the core-cladding index difference $\Delta = 0.01$, and the core radius $a = 25\ \mu\text{m}$. If the radius of curvature of the fiber is $R = 1.0$ cm, what percentage of the modes remain in the fiber at a 1300-nm wavelength?

Solution: From Eq. (3.7) the percentage of modes at a given curvature R is

$$\frac{M_{\text{eff}}}{M_\infty} = 1 - \frac{\alpha + 2}{2\alpha\Delta} \left[\frac{2a}{R} + \left(\frac{3}{2n_2 kR} \right)^{2/3} \right]$$

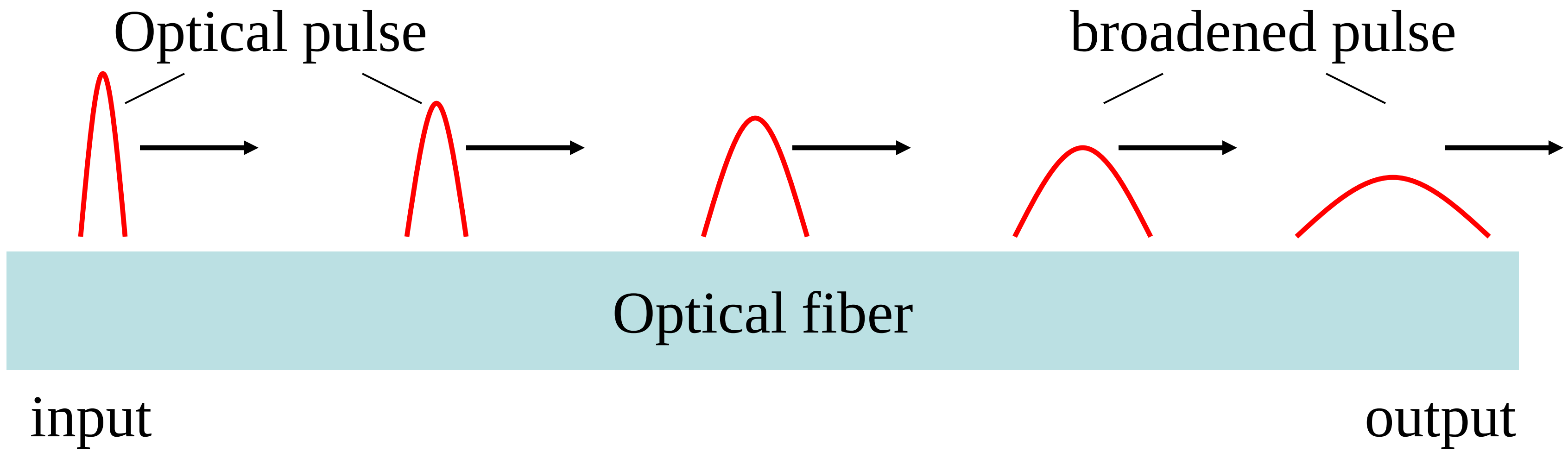
$$= 1 - \frac{1}{.01} \left[\frac{2(25)}{10000} + \left(\frac{3(1.3)}{2(1.465)2\pi(10000)} \right)^{2/3} \right]$$

$$= 0.42$$

Thus 42 percent of the modes remain in this fiber at a 1.0-cm bend radius.

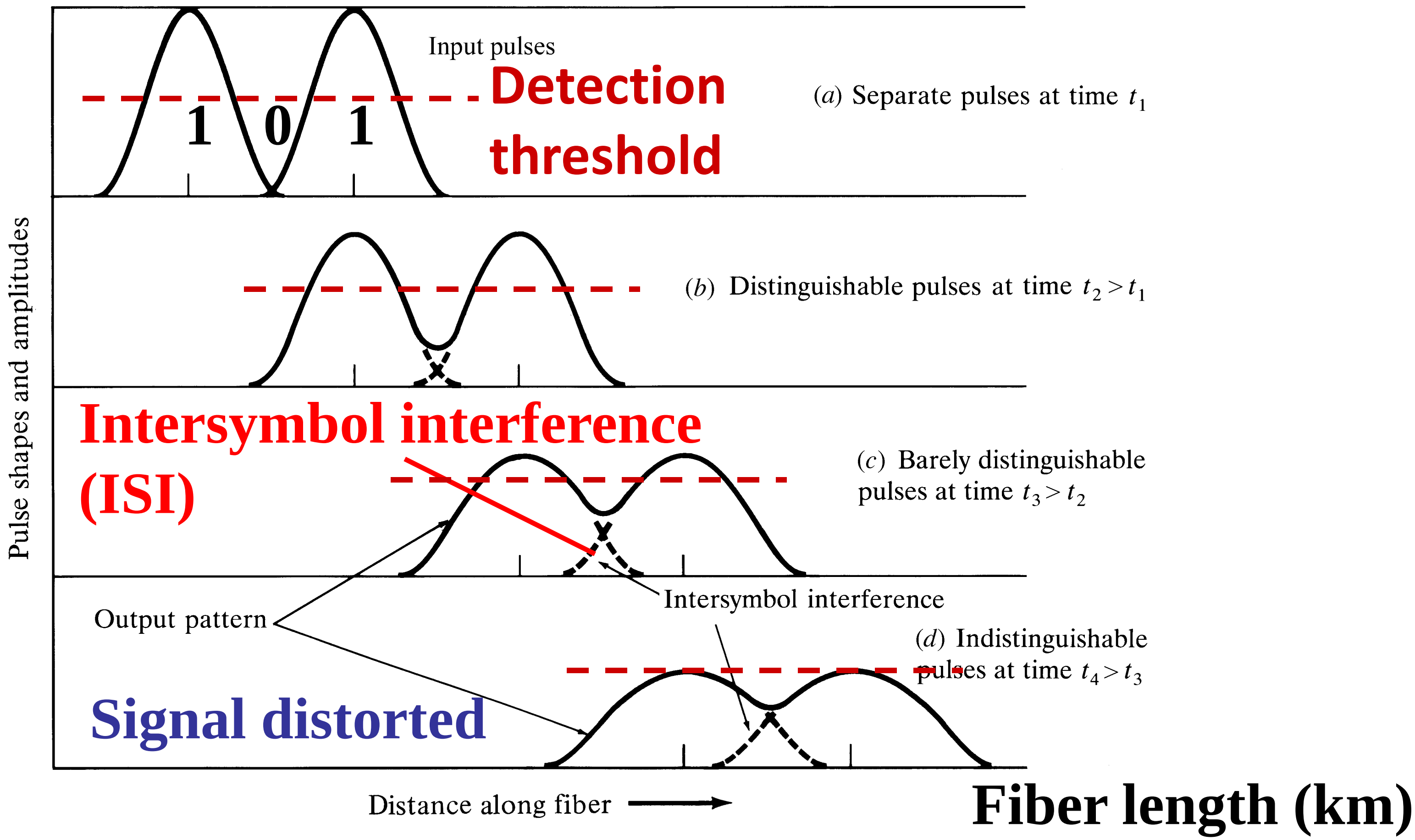
Fiber dispersion

- Fiber dispersion results in *optical pulse broadening* and hence *digital signal degradation*.



Dispersion mechanisms: 1. Modal (or *intermodal*) dispersion
2. Chromatic dispersion (CD)
3. Polarization mode dispersion (PMD)

Pulse broadening limits fiber bandwidth (data rate)



- An *increasing number of errors* may be encountered on the digital optical channel as the ISI becomes more pronounced.

1. Modal dispersion

- When numerous waveguide modes are propagating, they all travel with different net velocities with respect to the waveguide axis.

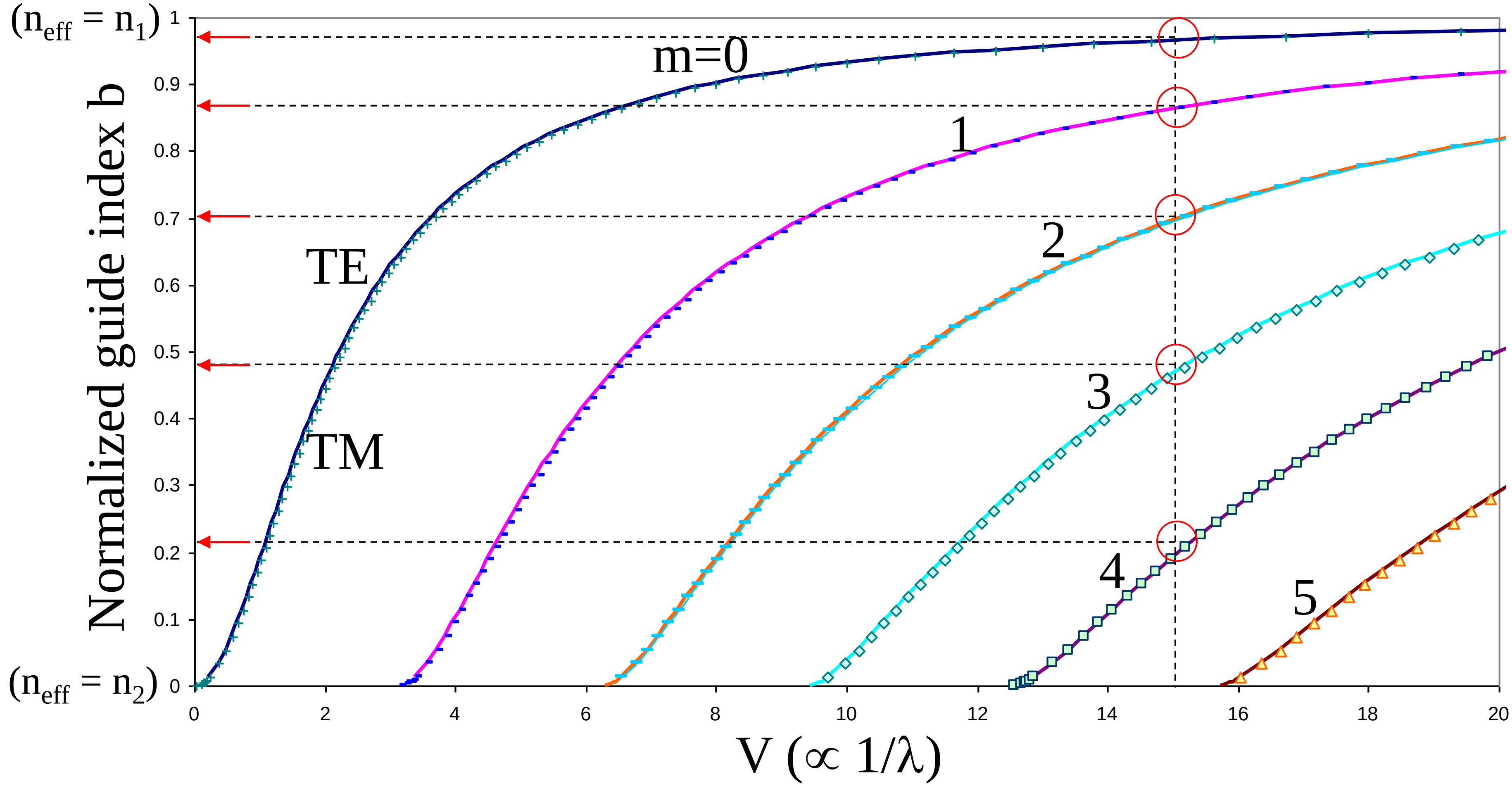
- An input waveform distorts during propagation because its energy is distributed among several modes, each traveling at a different speed.

- Parts of the wave arrive at the output before other parts, spreading out the waveform. This is thus known as multimode (modal) dispersion.

- Multimode dispersion does *not* depend on the source linewidth (even a *single* wavelength can be simultaneously carried by *multiple modes* in a waveguide).

- Multimode dispersion would *not* occur if the waveguide allows *only* one mode to propagate - the advantage of *single*-mode waveguides!

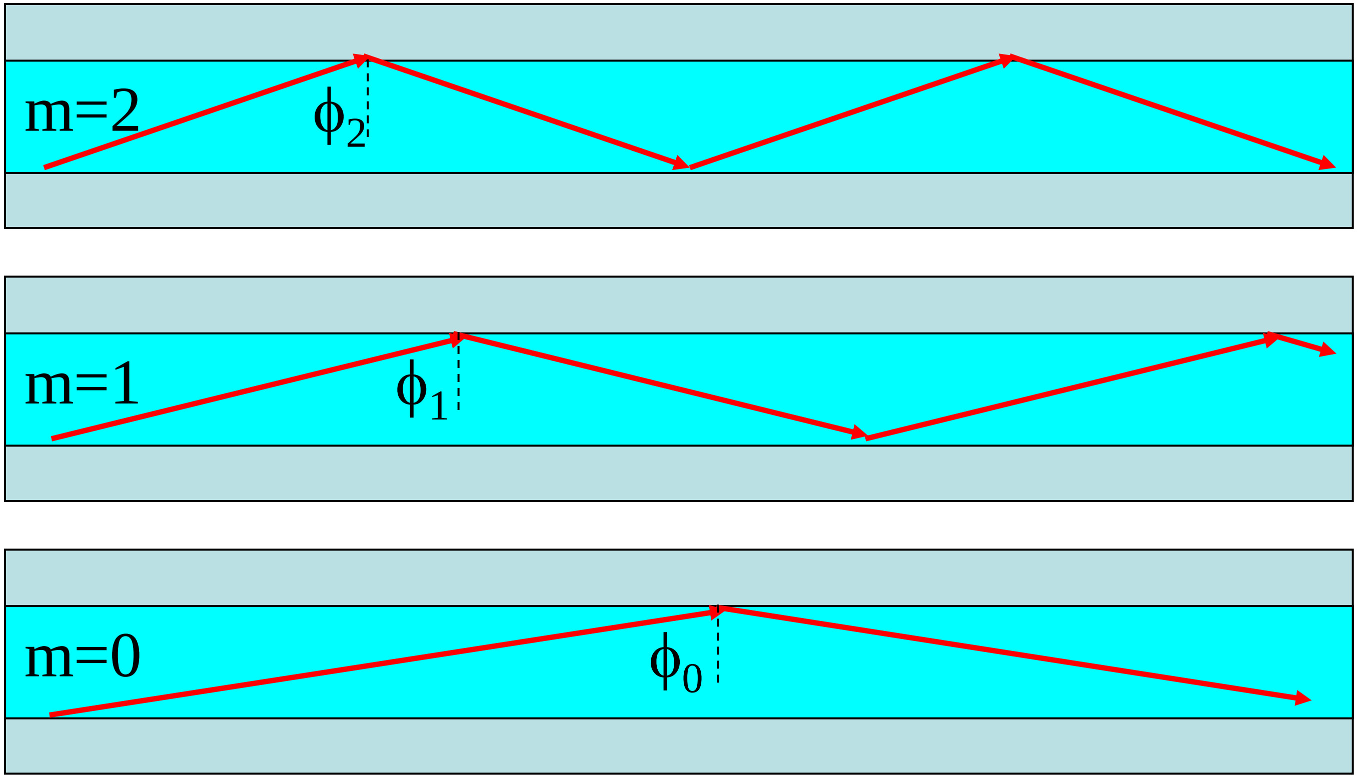
Modal dispersion as shown from the mode chart of a symmetric slab waveguide



- Phase velocity for mode m $= \omega/\beta_m = \omega/(n_{eff}(m)\, k_0)$

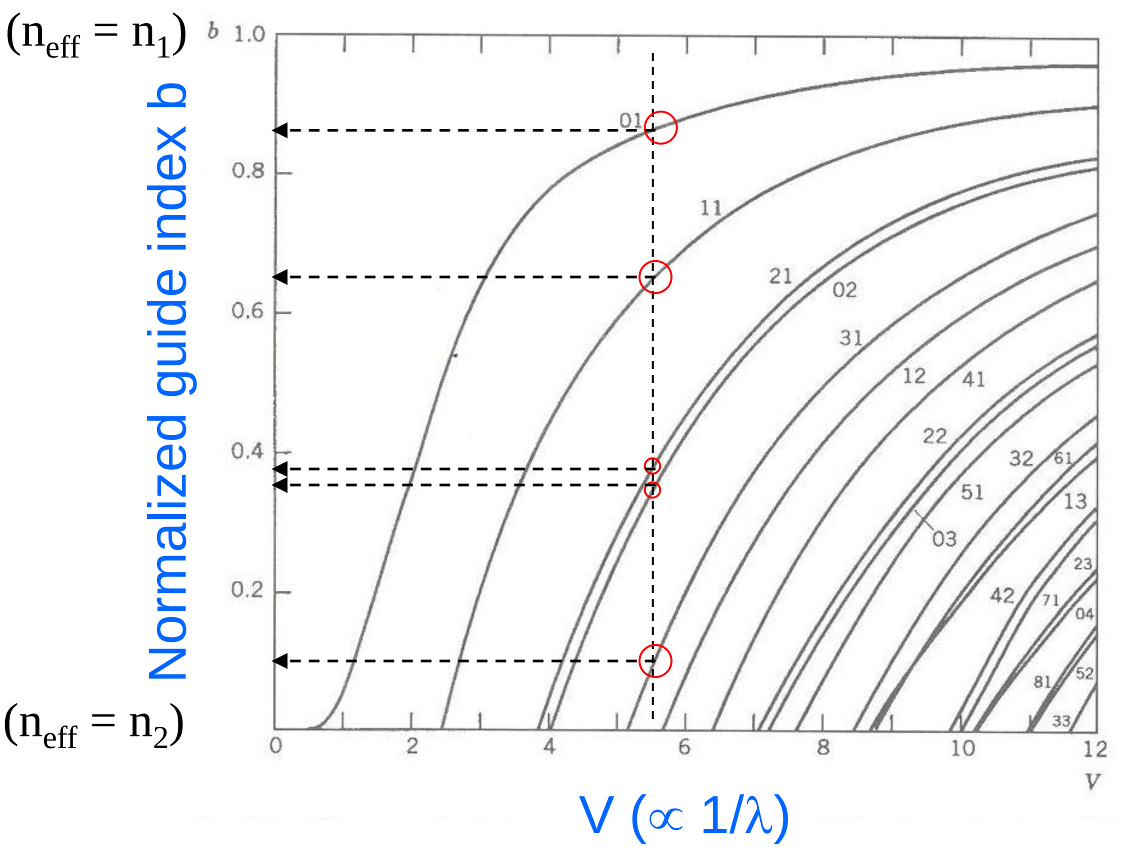
(note that m = 0 mode is the *slowest* mode)

Modal dispersion in multimode waveguides



The carrier wave can propagate along all these different "zig-zag" ray paths of *different path lengths*.

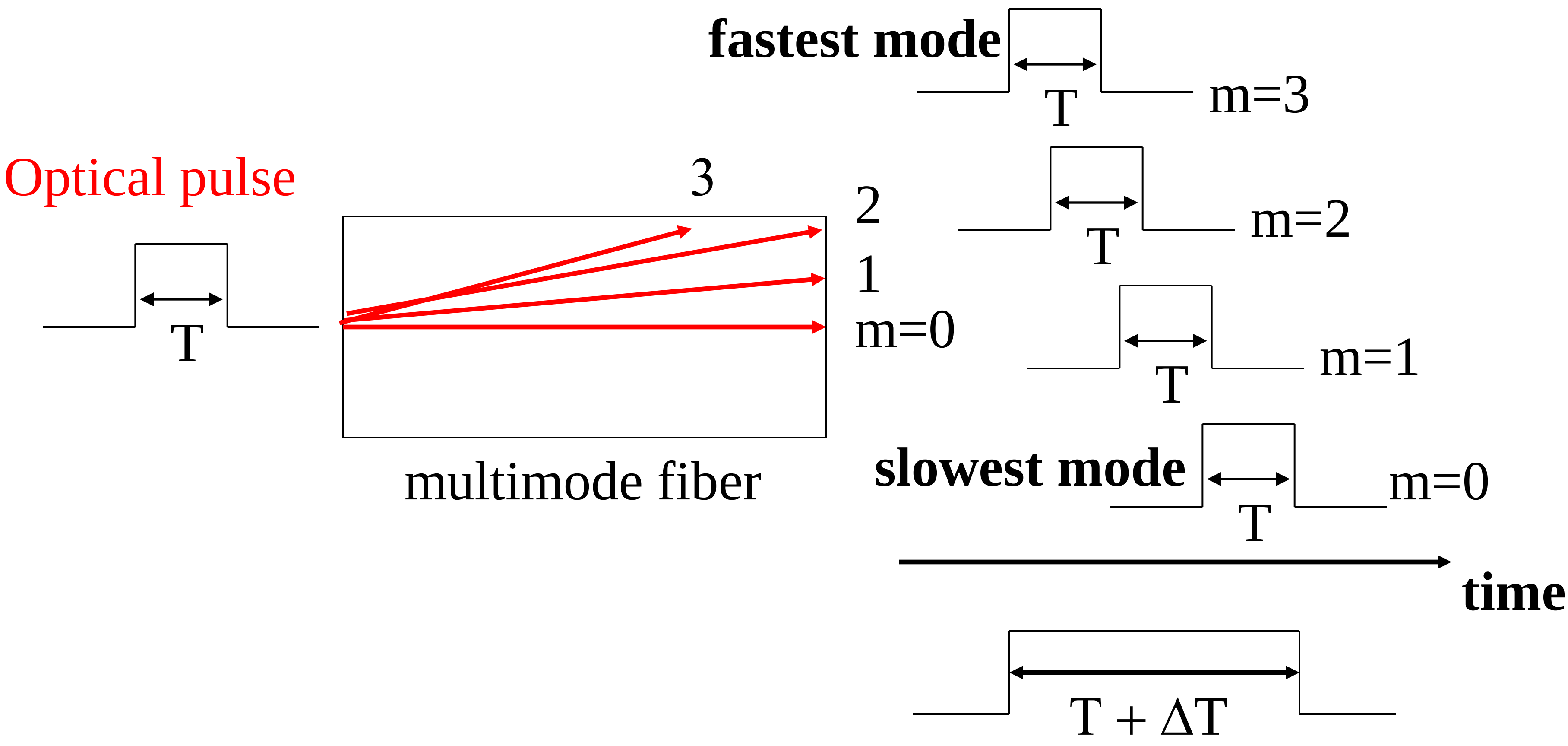
Modal dispersion as shown from the LP mode chart of a silica optical fiber



- Phase velocity for LP mode = $\omega/\beta_{lm} = \omega/(n_{eff}(lm)\ k_0)$

(note that LP_{01} mode is the *slowest* mode)

Modal dispersion results in pulse broadening

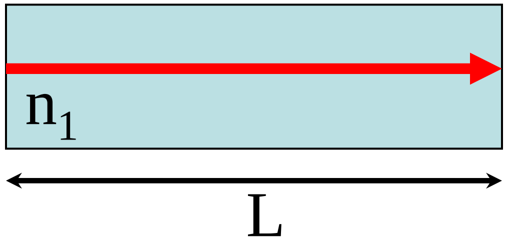


modal dispersion: different modes arrive at the receiver with different delays => pulse broadening

Estimated modal dispersion pulse broadening using phase velocity

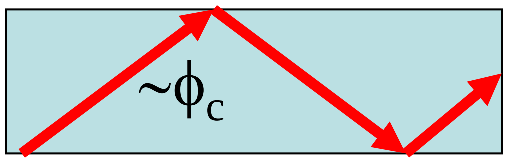
- A zero-order mode traveling near the waveguide axis needs time:

$t_0 = L/v_{m=0} \approx Ln_1/c$ $\quad\quad$ $(v_{m=0} \approx c/n_1)$



- The highest-order mode traveling near the critical angle needs time:

$t_m = L/v_m \approx Ln_2/c$ $\quad\quad$ $(v_m \approx c/n_2)$



=> the *pulse broadening* due to modal dispersion:

$$\Delta T \approx t_0 - t_m \approx (L/c)(n_1 - n_2)$$

$$\approx (L/2cn_1)\, NA^2 \qquad (n_1 \sim n_2)$$

e.g. How much will a light pulse spread after traveling along 1 km of a step-index fiber whose NA = 0.275 and n_{core} = 1.487?

How does modal dispersion restricts fiber bit rate?

Suppose we transmit at a low bit rate of 10 Mb/s

=> Pulse duration = $1 / 10^7$ s = 100 ns

Using the above e.g., each pulse will spread up to ≈ 100 ns (i.e. ≈ pulse duration !) every km

⇒The broadened pulses overlap! (**Intersymbol interference** (ISI))

*Modal dispersion limits the bit rate of a fiber-optic link to ~ 10 Mb/s.
(a coaxial cable supports this bit rate easily!)

Bit-rate distance product

• We can relate the pulse broadening ΔT to the *information-carrying capacity* of the fiber measured through the bit rate B.

• Although a precise relation between B and ΔT depends on many details, such as the pulse shape, it is intuitively clear that ΔT *should be less than the allocated bit time slot* given by 1/B.

$\Rightarrow$An *order-of-magnitude* estimate of the supported bit rate is obtained from the condition $B\Delta T < 1$.

$\Rightarrow$***Bit-rate distance product*** (limited by modal dispersion)

$$BL < 2c\, n_{core} / NA^2$$

This condition provides a rough estimate of a fundamental limitation of step-index multimode fibers.

(the *smaller is the NA, the larger is the bit-rate distance product*)

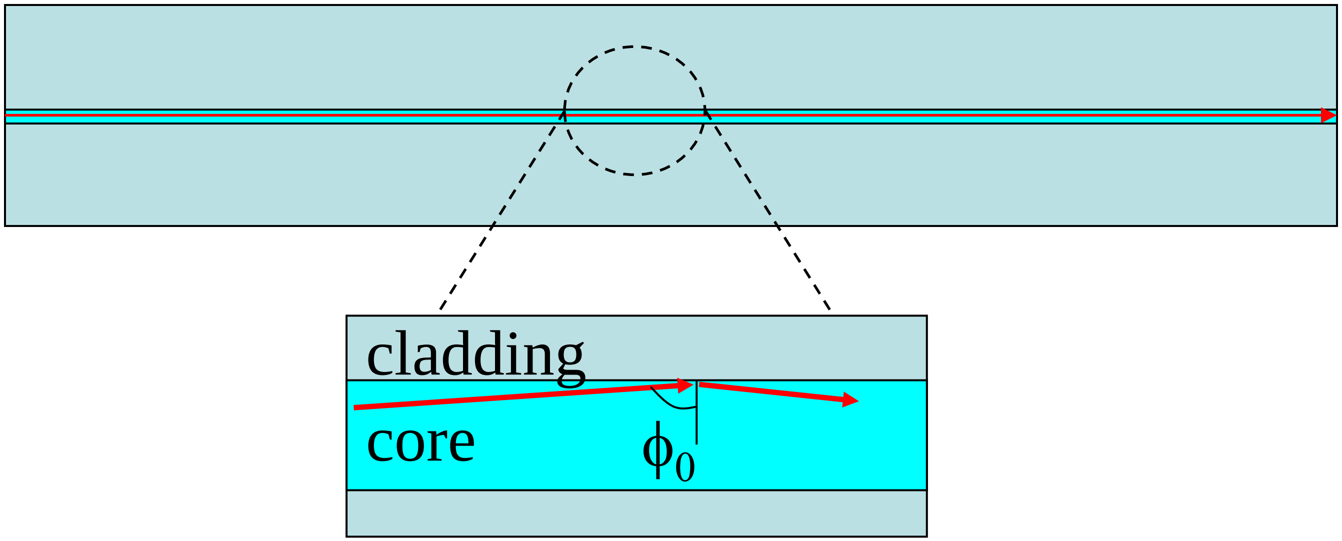
The capacity of optical communications systems is frequently measured in terms of the **bit rate-distance product**.

e.g. If a system is capable of transmitting 10 Mb/s over a distance of 1 km, it is said to have a *bit rate-distance* product of
10 (Mb/s)-km.

This may be suitable for some *local-area networks (LANs)*.

Note that the same system can transmit 100 Mb/s along 100 m, or
1 Gb/s along 10 m, or 10 Gb/s along 1 m, or 100 Gb/s along 10 cm,
1 Tb/s along 1 cm

Single-mode fiber eliminates modal dispersion

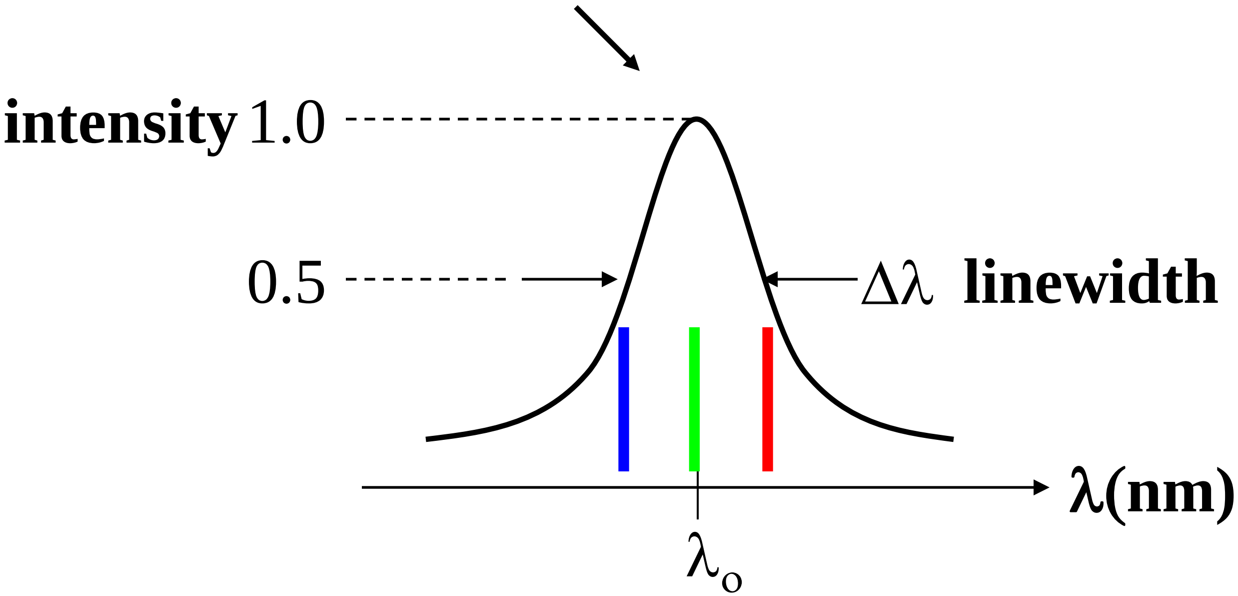


- The main advantage of *single*-mode fibers is to propagate *only one mode* so that *modal dispersion is absent*.

- However, *pulse broadening does not disappear altogether*. The *group velocity* associated with the fundamental mode is *frequency dependent* within the pulse *spectral linewidth* because of <u>chromatic dispersion</u>.

2. Chromatic dispersion

• Chromatic dispersion (CD) may occur in *all* types of optical fiber. The optical pulse broadening results from the *finite spectral linewidth of the optical source and the modulated carrier*.



*In the case of the semiconductor laser $\Delta\lambda$ corresponds to only a fraction of % of the centre wavelength λ_o. For LEDs, $\Delta\lambda$ is likely to be a significant percentage of λ_o.

Spectral linewidth

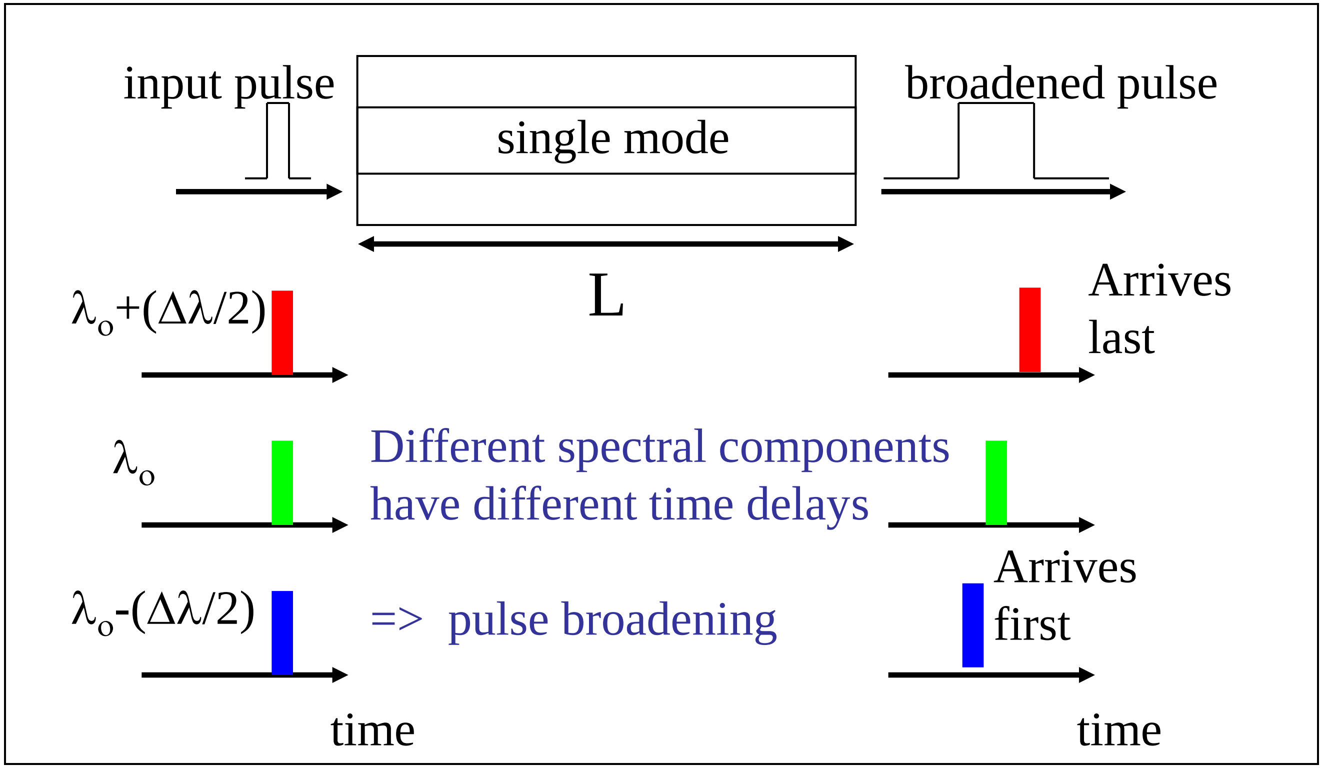
- Real sources emit over a range of wavelengths. This range is the *source linewidth* or *spectral width*.

- The smaller is the linewidth, the smaller is the spread in wavelengths or frequencies, the more *coherent* is the source.

- An *ideal* perfectly coherent source emits light at a *single* wavelength. It has *zero* linewidth and is *perfectly* monochromatic.

Light sources	**Linewidth (nm)**
Light-emitting diodes	20 nm – 100 nm
Semiconductor laser diodes	1 nm – 5 nm
Nd:YAG solid-state lasers	0.1 nm
HeNe gas lasers	0.002 nm

- Pulse broadening occurs because there may be *propagation delay differences* among the *spectral components* of the transmitted signal.



Chromatic dispersion (CD): Different spectral components of a *pulse* travel at different *group velocities*. This is known as *group velocity dispersion* (GVD).

Phase velocity, group velocity and dispersion

- For a *monochromatic* (i.e. single wavelength) plane optical wave traveling in the z direction, the electric field can be written as

$$\mathbf{E} = \boldsymbol{E} \exp i(kz - \omega t)$$

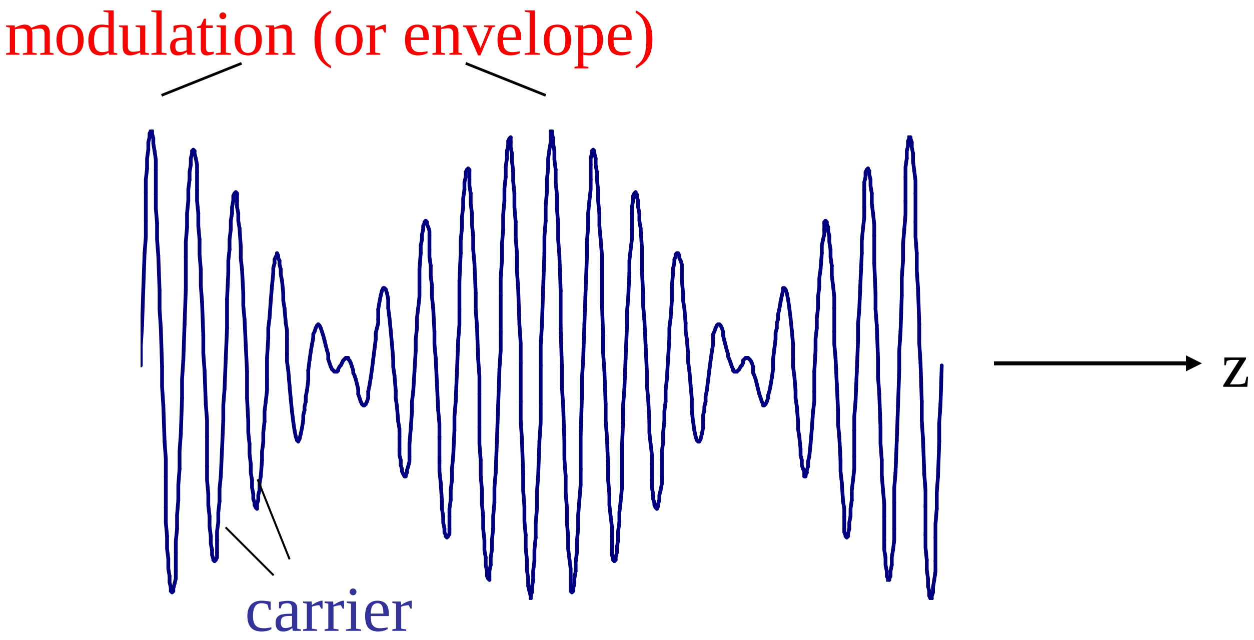
where $\boldsymbol{E}$ is a constant vector independent of space and time. We see a sinusoidal wave whose phase varies with z and t

$$\phi = kz - \omega t$$

For a point of constant phase on the space- and time-varying field, ϕ = constant and thus $k dz - \omega dt = 0$. If we track this point of constant phase, we find that it is moving with a velocity of

$$v_p = dz/dt = \omega/k \qquad \text{phase velocity}$$

- In reality, a *group of waves* with *closely similar wavelengths* (*or frequencies*) always combine to form a *packet of wave*.



- For example, we consider a *wave packet* that is composed of two plane waves of equal real amplitude ***E***. The frequencies and propagation constants of the two component plane waves are:

$$\omega_1 = \omega_o + d\omega,\ k_1 = k_o + dk$$
$$\omega_2 = \omega_o - d\omega,\ k_2 = k_o - dk$$

- The space- and time-dependent *total real* field of the wave packet is given by

complex conjugate

$$\boldsymbol{E}_{packet} = \boldsymbol{E} \exp i(k_1 z - \omega_1 t) + \text{c.c.} + \boldsymbol{E} \exp i(k_2 z - \omega_2 t) + \text{c.c.}$$

$$= 2\boldsymbol{E} \{\cos [(k_o + dk)z - (\omega_o + d\omega)t] + \cos [(k_o - dk)z - (\omega_o - d\omega)t]\}$$

$$= 4\boldsymbol{E} \cos (zdk - td\omega) \cos (k_o z - \omega_o t)$$

- The resultant wave packet has a *carrier*, which has a frequency ω_o and a propagation constant k_o, and an *envelope* cos $(zdk - td\omega)$.

- Therefore, a fixed point on the envelope is defined by $zdk - td\omega$ = constant, and it travels with a velocity

$$v_g = dz/dt = d\omega/dk \qquad \text{group velocity}$$

Remarks on group velocity

- Because the *energy* of a harmonic wave is proportional to the square of its field amplitude, the energy carried by a wave packet that is composed of many frequency components is concentrated in regions *where the amplitude of the envelope is large*.

- Therefore, *the energy in a wave packet is transported at group velocity v_g*.

- The constant-phase wavefront travels at the phase velocity, but the group velocity is the velocity at which *energy* (and *information*) travels.

Any information signal is a wave packet, and thus travels at the **group velocity**, *not at the phase velocity*.

Light pulse in a dispersive medium

When a *light pulse* with a spread in frequency $\delta\omega$ and a spread in propagation constant δk propagates in a *dispersive* medium $n(\lambda)$, the group velocity:

$$v_g = (d\omega/dk) = (d\lambda/dk)\,(d\omega/d\lambda)$$

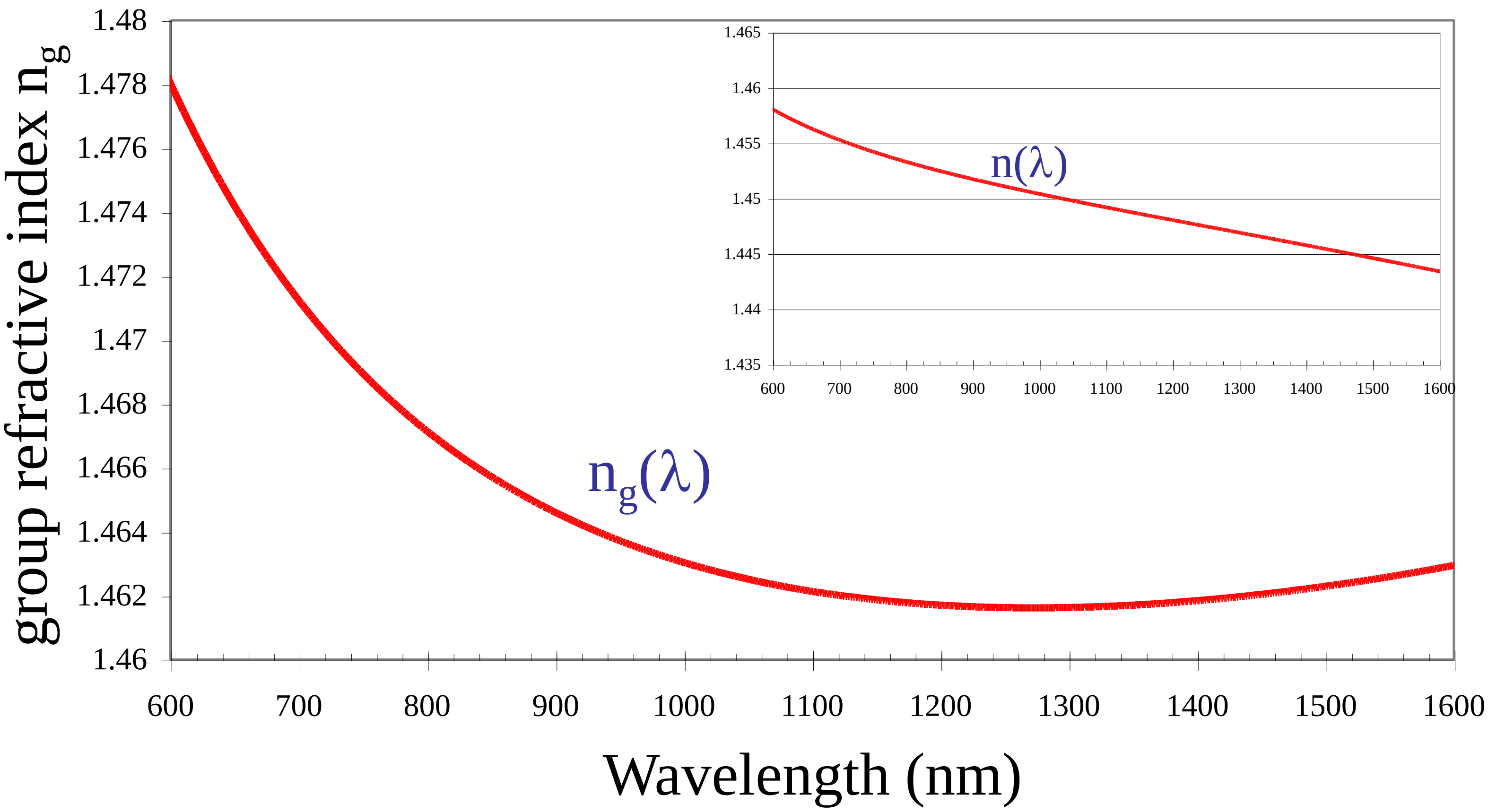
$$k = n(\lambda)\,2\pi/\lambda \qquad \Rightarrow \qquad dk/d\lambda = (2\pi/\lambda)\,[(dn/d\lambda) - (n/\lambda)]$$

$$\omega = 2\pi c/\lambda \qquad \Rightarrow \qquad d\omega/d\lambda = -2\pi c/\lambda^2$$

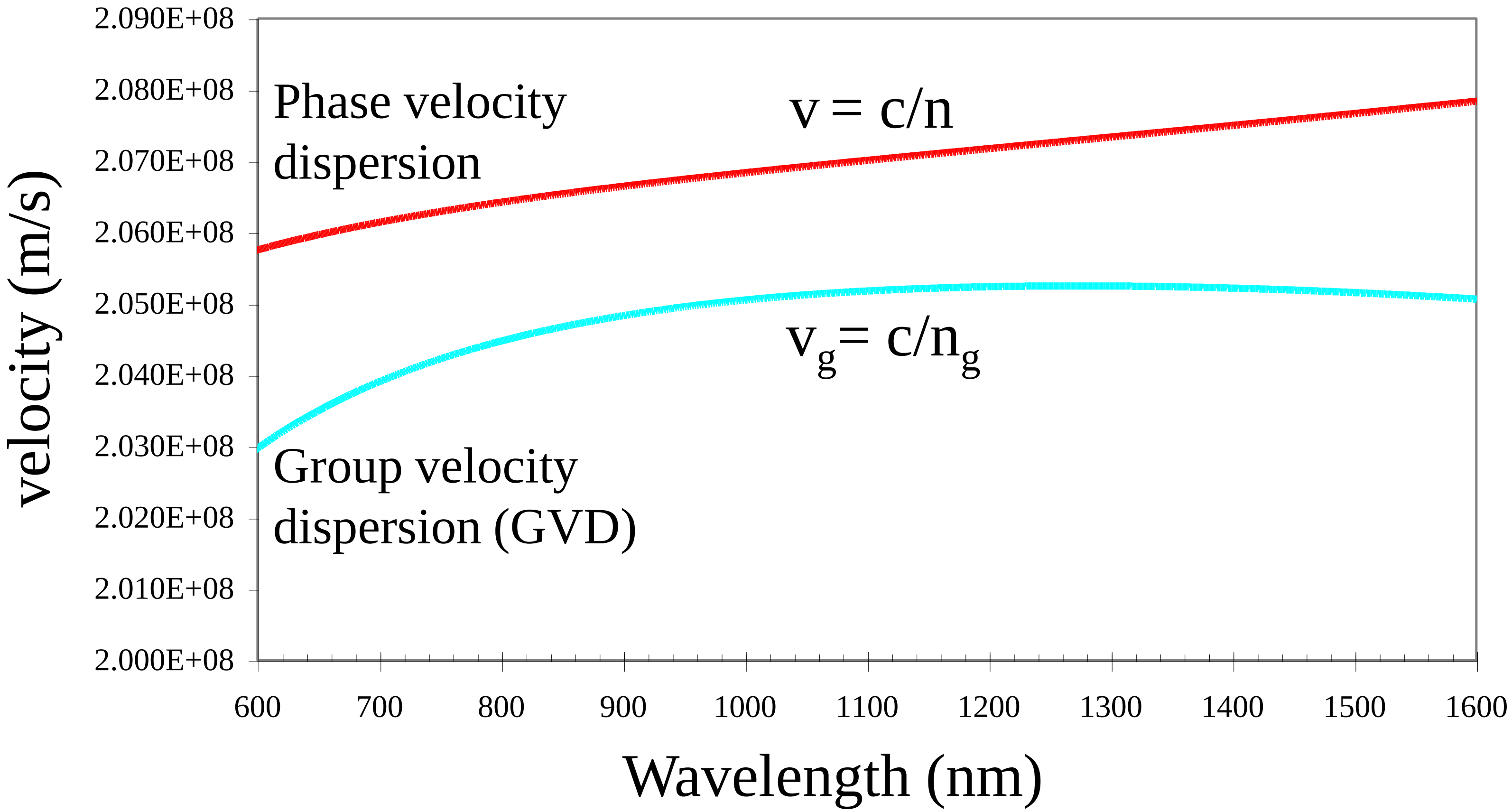
Hence $\quad v_g = c\,/\,[n - \lambda(dn/d\lambda)] = c\,/\,n_g$

Define the **group refractive index** $n_g = n - \lambda(dn/d\lambda)$

Group refractive index n_g vs. λ for fused silica



Phase velocity c/n and group velocity c/n_g vs. λ for fused silica



Group-Velocity Dispersion (GVD)

Consider a light pulse propagates in a dispersive medium of length L

- A specific spectral component at the frequency ω (or wavelength λ) would arrive at the output end of length L after a *time delay*:

$$T = L/v_g$$

- If $\Delta\lambda$ is the *spectral width* of an optical pulse, the extent of *pulse broadening* for a material of length L is given by

$$\Delta T = (dT/d\lambda)\,\Delta\lambda = [d(L/v_g)/d\lambda]\,\Delta\lambda$$

$$= L\,[d(1/v_g)/d\lambda]\,\Delta\lambda$$

Hence the pulse broadening due to a *differential time delay*:

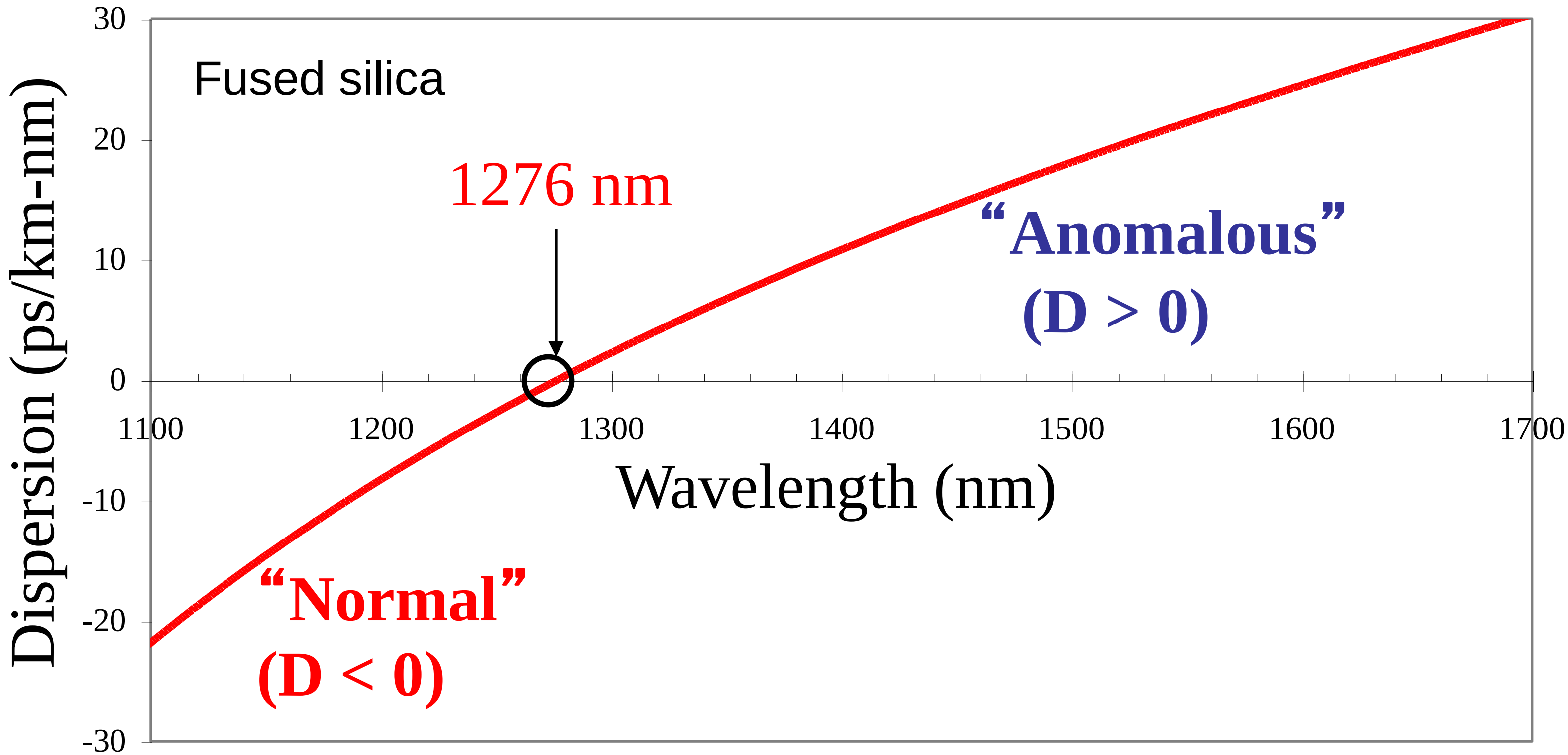
$$\Delta T = L\, D\, \Delta\lambda$$

where $D = d(1/v_g)/d\lambda$ is called the *dispersion parameter* and is expressed in units of ps/(km-nm).

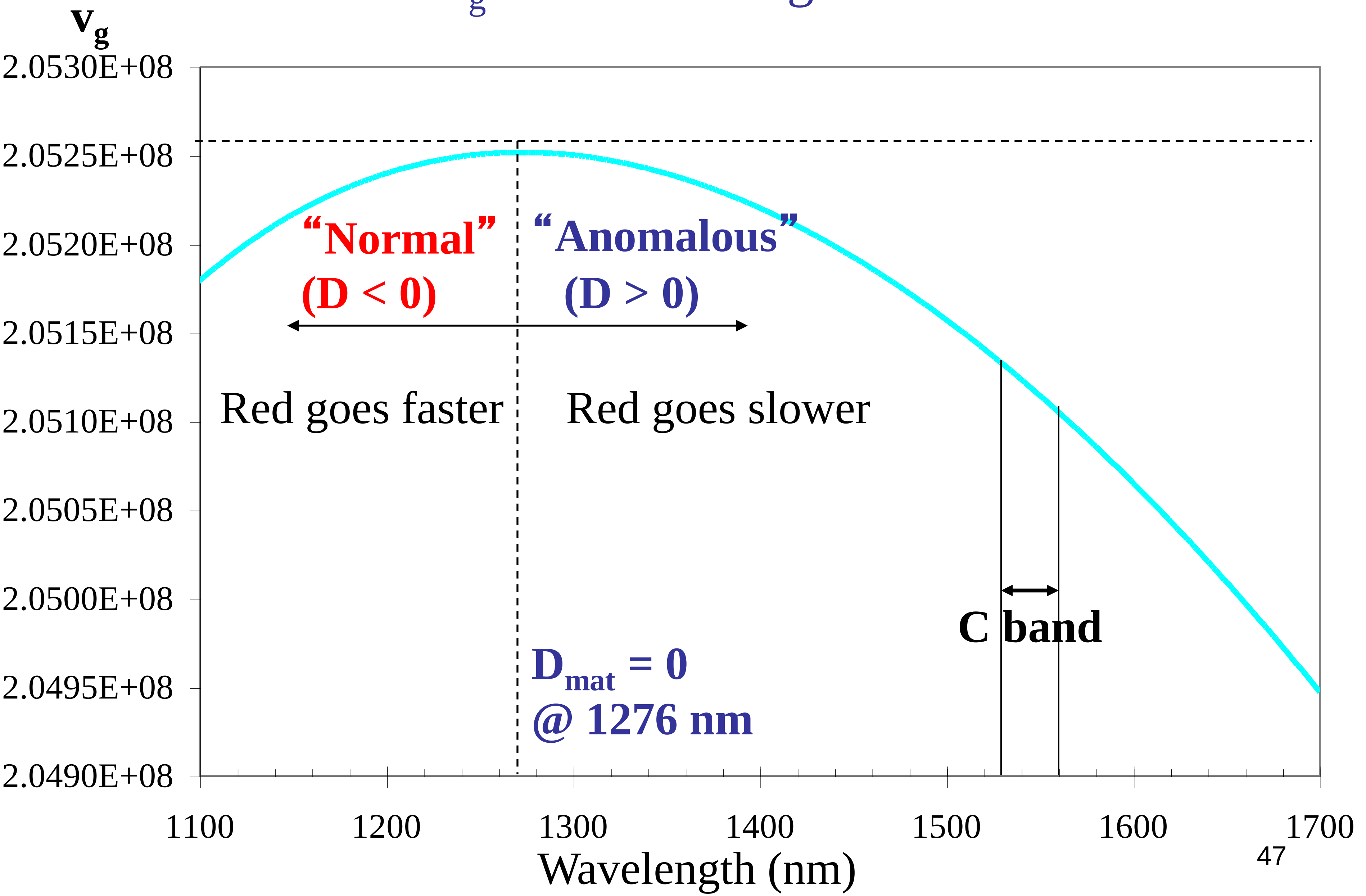
$$D = d(1/v_g)/d\lambda = c^{-1}\, dn_g/d\lambda = c^{-1}\, d[n - \lambda(dn/d\lambda)]/d\lambda$$

$$= -c^{-1}\, \lambda\, d^2n/d\lambda^2$$

Dispersion parameter $D = -(\lambda/c)\, d^2n/d\lambda^2$



Variation of v_g with wavelength for fused silica



Zero-dispersion wavelength

Material dispersion $D_{mat} = 0$ at $\lambda \sim 1276$ nm for fused silica.

This λ is referred to as the ***zero-dispersion wavelength*** $\boldsymbol{\lambda_{ZD}}$.

Chromatic (or *material*) dispersion $D(\lambda)$ can be zero;
or
negative => longer wavelengths travel *faster* than shorter wavelengths;
or
positive => shorter wavelengths travel *faster* than longer wavelengths.

In fact there are <u>two</u> mechanisms for chromatic dispersion in a fiber:

(a) Silica refractive index *n is wavelength dependent* (i.e. $n = n(\lambda)$)

=> different wavelength components travel at different speeds in silica

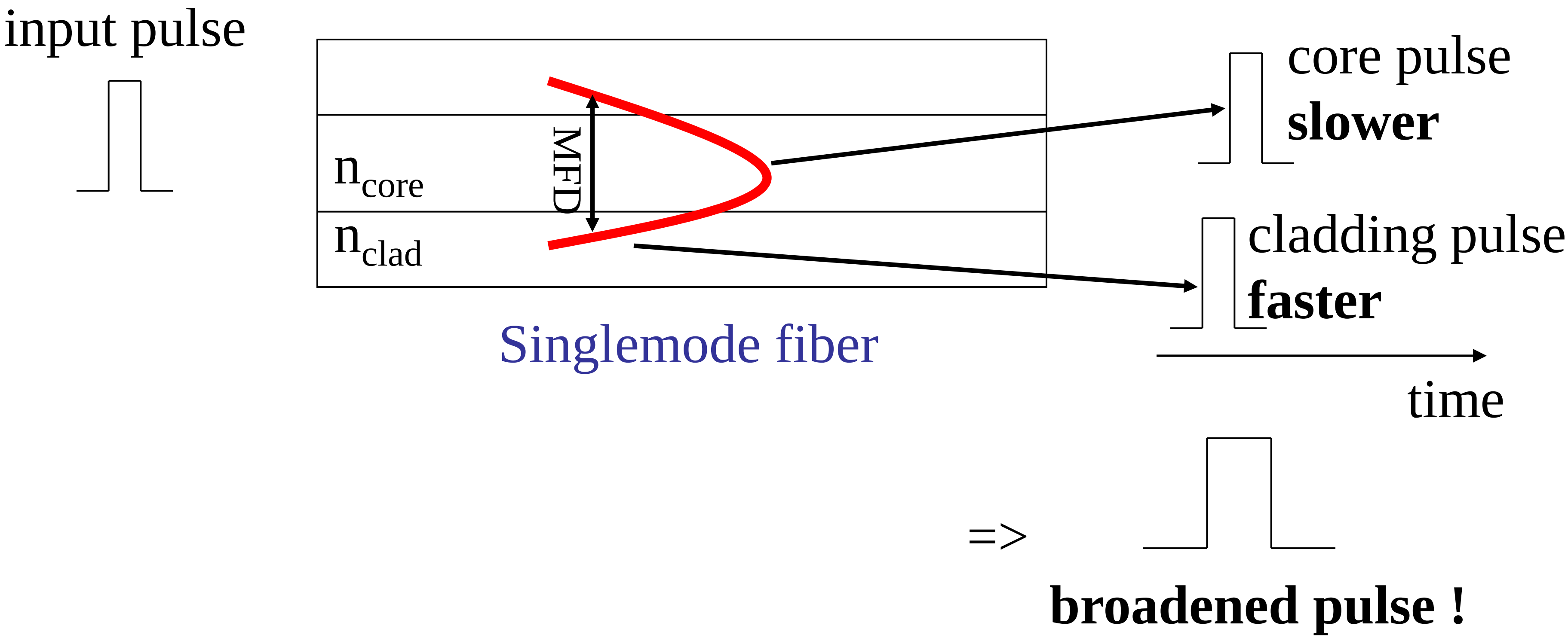
This is known as **<u>material dispersion</u>**.

(b) Light energy of a mode propagates *partly in the core and partly in the cladding of a fiber.* The mode power distribution between the core and the cladding *depends on λ.* (*Recall the mode field diameter*)

This is known as **<u>waveguide dispersion</u>.**

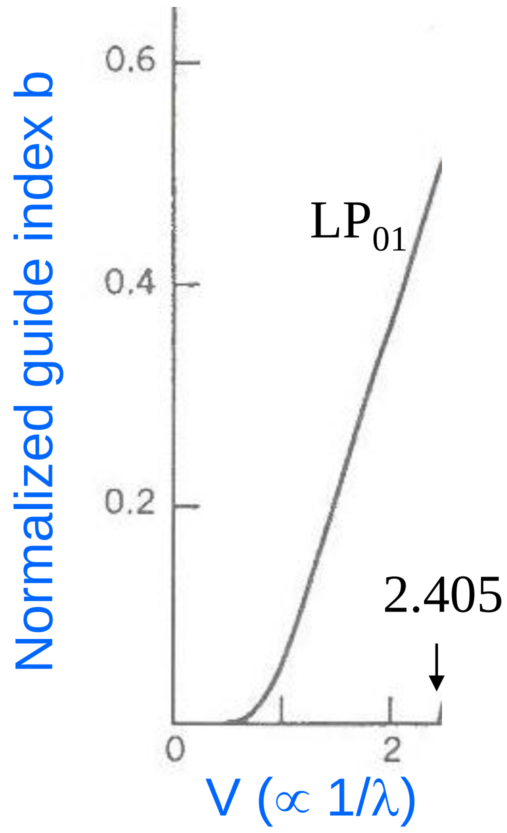
$$\Rightarrow D(\lambda) = D_{mat}(\lambda) + D_{wg}(\lambda)$$

Waveguide dispersion in a single-mode fiber



Waveguide dispersion depends on the *mode field distribution in the core and the cladding*. (given by the fiber V number)

Waveguide dispersion of the LP_{01} mode



- Different wavelength components λ of the LP_{01} mode see different effective indices n_{eff}

Derivation of waveguide dispersion-induced pulse broadening

- Consider an optical pulse of linewidth $\Delta\lambda$ ($\Delta\omega$) and a corresponding spread of propagation constant $\Delta\beta$ propagating in a waveguide

Group velocity $\quad v_{g,eff} = d\omega/d\beta$

Waveguide propagation constant

or $\quad v_{g,eff}^{-1} = d\beta/d\omega$

Waveguide effective index

$$= d/d\omega\,(c^{-1}\,\omega\, n_{eff})$$

$$= c^{-1}\,(n_{eff} + \omega\, dn_{eff}/d\omega)$$

$$= c^{-1}\,(n_{eff} - \lambda\, dn_{eff}/d\lambda) = c^{-1}\, n_{g,eff}$$

Time delay after a waveguide of length L: $\tau = L/v_{g,eff}$

Or *time delay per unit length*: $\tau/L = v_{g,eff}^{-1}$

- If $\Delta\lambda$ is the spectral width of an optical pulse, the extent of *pulse broadening* for a waveguide of length L is given by

$$\Delta\tau = (d\tau/d\lambda)\,\Delta\lambda = [d(L/v_{g,eff})/d\lambda]\,\Delta\lambda$$

$$= L\,[d(1/v_{g,eff})/d\lambda]\,\Delta\lambda$$

$$= L\,D_{wg}\,\Delta\lambda$$

- $D_{wg} = d(1/v_{g,eff})/d\lambda$ is called the *waveguide dispersion parameter* and is expressed in units of ps/(km-nm).

$$D_{wg} = d(1/v_{g,eff})/d\lambda = c^{-1}\,dn_{g,eff}/d\lambda = c^{-1}\,d[n_{eff} - \lambda\,dn_{eff}/d\lambda]/d\lambda$$

$$= -c^{-1}\,\lambda\,d^2n_{eff}/d\lambda^2$$

- Recall $v_{g,eff} = (d\beta/d\omega)^{-1}$ and note that the propagation constant β is a *nonlinear* function of the V number, $V = (2\pi a/\lambda)\ NA = a\ (\omega/c)\ NA$

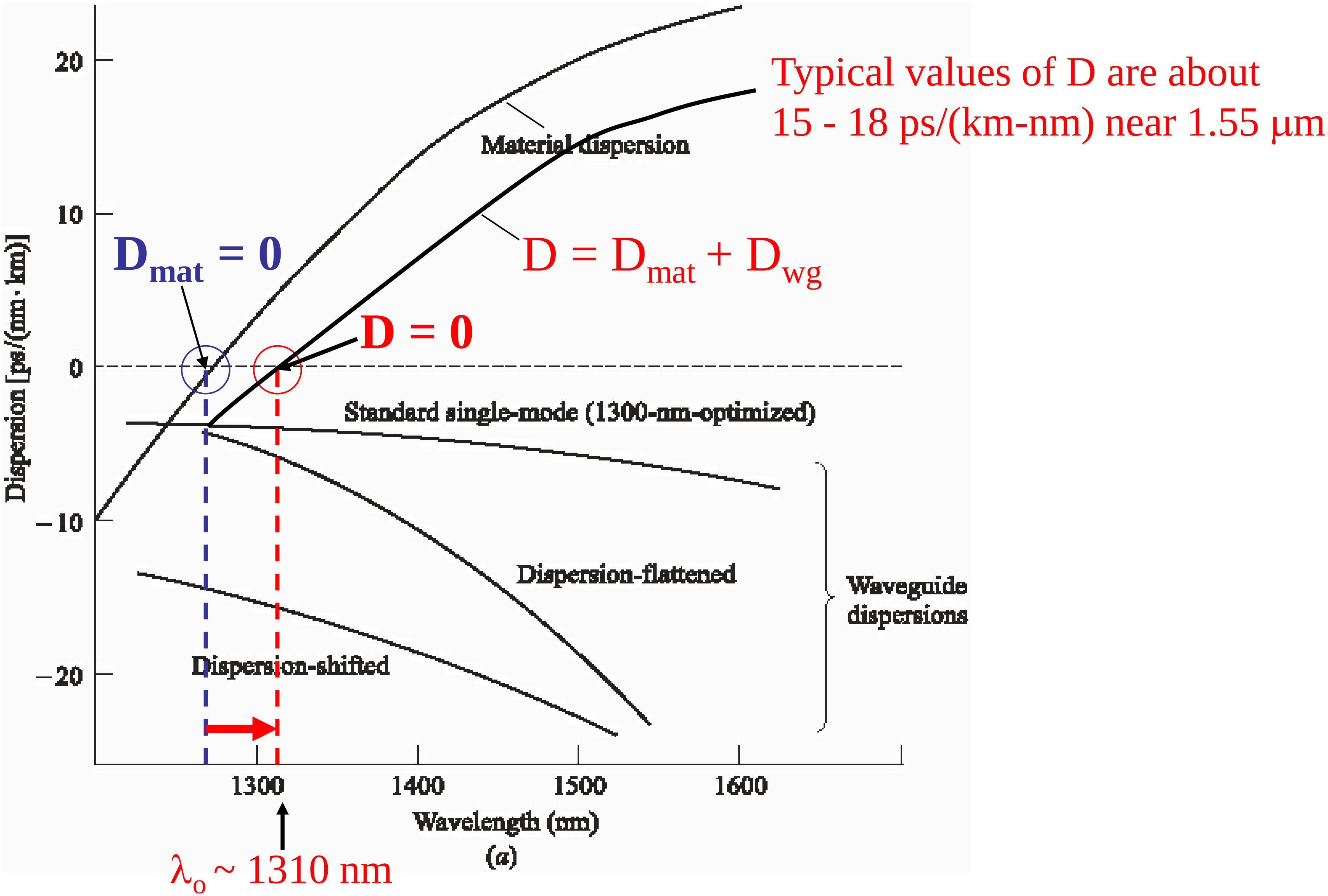
- *In the absence of material dispersion* (i.e. when NA is independent of ω), V is directly proportional to ω, so that

$$1/v_{g,eff} = d\beta/d\omega = (d\beta/dV)\ (dV/d\omega) = (d\beta/dV)\ (a\ NA/c)$$

- The pulse broadening associated with a source of spectral width $\Delta\lambda$ is related to the time delay $L/v_{g,eff}$ by $\Delta T = L\ |D_{wg}|\ \Delta\lambda$. The *waveguide dispersion parameter* D_{wg} is given by

$$D_{wg} = d/d\lambda\ (1/v_{g,eff}) = -(\omega/\lambda)\ d/d\omega\ (1/v_{g,eff}) = -(1/(2\pi c))\ V^2\ d^2\beta/dV^2$$

⇒*The dependence of D_{wg} on λ may be controlled by altering the <u>core radius</u>, the <u>NA</u>, or the <u>V number</u>.*



- $D_{wg}(\lambda)$ compensate some of the $D_{mat}(\lambda)$ and shifts the λ_{ZD} from about 1276 nm to a *longer* wavelength of about **1310 nm.**

Chromatic dispersion in low-bit-rate systems

Broadening of the light pulse due to Chromatic Dispersion:

$$\Delta T = D\,L\,\Delta\lambda$$

Consider the maximum pulse broadening equals to the bit time period 1/B, then the *dispersion-limited distance*:

$$L_D = 1 / (D\,B\,\Delta\lambda)$$

e.g. For D = 17 ps/(km•nm), B = <u>2.5 Gb/s</u> and $\Delta\lambda$ = 0.03 nm

$$\Rightarrow L_D = 784 \text{ km}$$

(It is known that dispersion limits a 2.5 Gbit/s channel to roughly 900 km! Therefore, chromatic dispersion is *not* much of an issue in low-bit-rate systems deployed in the early 90s!)

- **When upgrading** from *2.5- to 10-Gbit/s* systems, most technical challenges are less than four times as complicated and the cost of components is usually much less than four times as expensive.

- However, *when increasing the bit rate by a factor of 4, the effect of chromatic dispersion increases by a factor of 16!*

Consider again the dispersion-limited distance:

$$L_D = 1 / (D\ B\ \Delta\lambda)$$

Note that spectral width $\Delta\lambda$ is proportional to the modulation of the lightwave!
i.e. Faster the modulation, more the frequency content, and therefore wider the spectral bandwidth => $\Delta\lambda \propto B$

$$\Rightarrow \quad L_D \propto 1 / B^2$$

Chromatic dispersion in high-bit-rate systems

e.g. In standard single-mode fibers for which D = 17 ps/(nm•km) at a signal wavelength of 1550 nm (assuming from the same light source as the earlier example of 2.5 Gbit/s systems), the maximum transmission distance before significant pulse broadening occurs for 10 Gbit/s data is:

$$L_D \sim 784 \text{ km} / 16 \sim 50 \text{ km!}$$

(A more exact calculation shows that 10-Gbit/s (40-Gbit/s) would be limited to approximately 60 km (4 km!).)

This is why chromatic dispersion compensation must be employed for systems operating at 10 Gbit/s (now at 40 Gbit/s and beyond.)

Zero-dispersion slope

If $D(\lambda)$ is *zero* at a specific $\lambda = \lambda_{ZD}$, can we eliminate pulse broadening caused by chromatic dispersion?

There are higher-order effects! The derivative

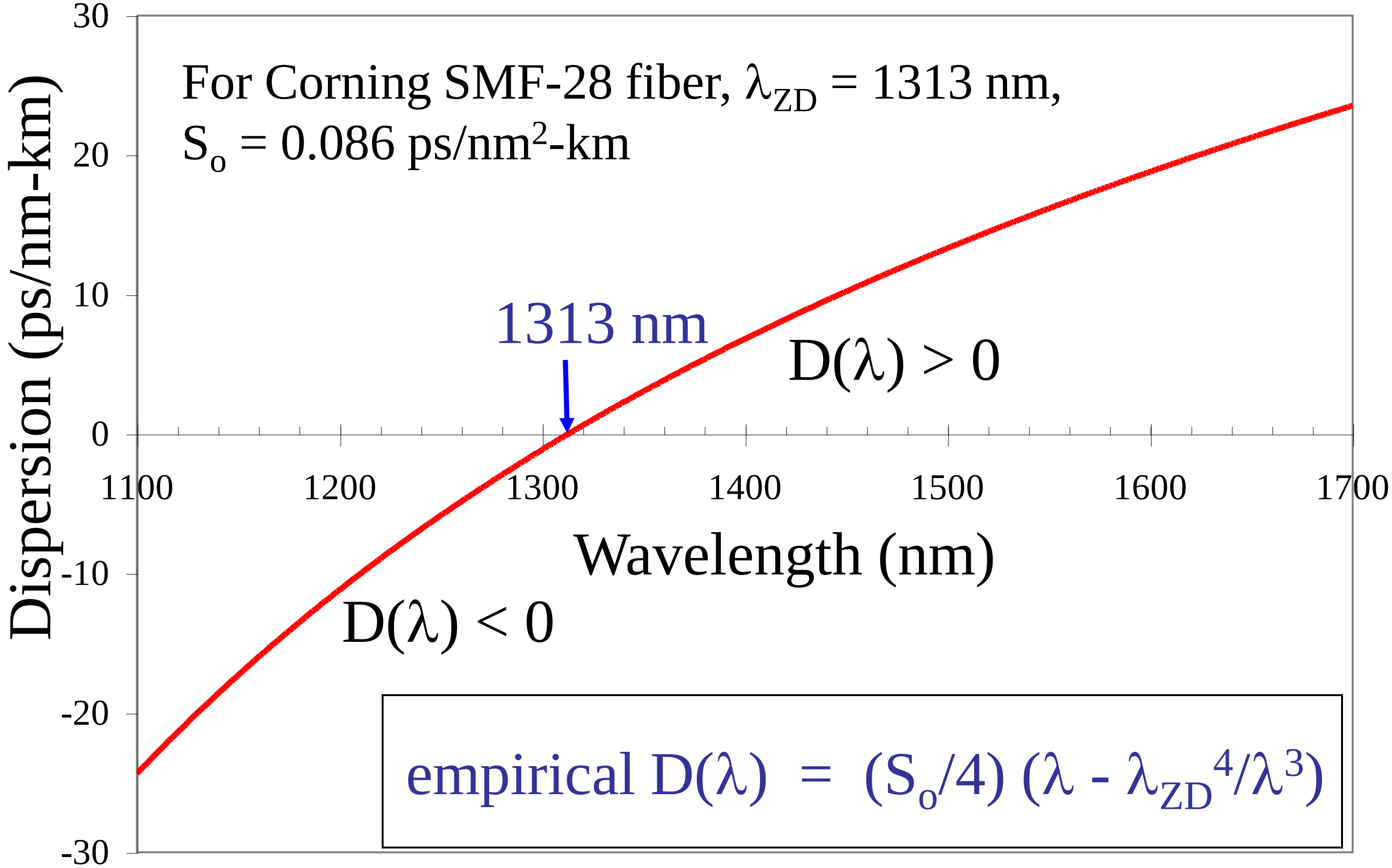
$$dD(\lambda)/d\lambda = S_o$$

needs to be accounted for when the first-order effect is zero (i.e. $D(\lambda_{ZD}) = 0$) .

S_o is known as the zero-dispersion slope measured in **ps/(km-nm²)**.

The chromatic pulse broadening near λ_{ZD}:

$$\Delta T = L\, S_o\, |\lambda - \lambda_{ZD}|\, \Delta\lambda$$



- Now it becomes clear that at $\lambda = \lambda_{ZD}$, the dispersion slope S_o becomes the bit rate limiting factor.

We can estimate the limiting bit rate by noting that for a source of spectral width $\Delta\lambda$, the effective value of dispersion parameter becomes

$$D = S_o \Delta\lambda$$

=> The limiting *bit rate-distance product* can be given as

$$BL\,|S_o|\,(\Delta\lambda)^2 < 1 \qquad (B\,\Delta T < 1)$$

*For a *multimode* semiconductor laser with $\Delta\lambda = 2$ nm and a *dispersion-shifted fiber* with $S_o = 0.05$ ps/(km-nm^2) at $\lambda = 1.55$ µm, the BL product approaches 5 (Tb/s)-km. Further improvement is possible by using *single-mode* semiconductor lasers.

Dispersion comparison for a non-dispersion-shifted fiber

Example 3.14 A manufacturer's data sheet states that a non-dispersion-shifted fiber has a zero-dispersion wavelength of 1310 nm and a dispersion slope of 0.092 ps/(nm^2 · km). Compare the dispersions for this fiber at wavelengths of 1280 nm and 1550 nm.

Solution: Using Eq. (3.47) we find that

$$D(1280) = \frac{\lambda S_0}{4}\left[1-\left(\frac{\lambda_0}{\lambda}\right)^4\right]$$

$$= \frac{(1280)(0.092)}{4}\left[1-\left(\frac{1310}{1280}\right)^4\right]$$

$$= -2.86 \text{ ps/(nm} \cdot \text{km)}$$

$$D(1550) = \frac{\lambda S_0}{4}\left[1-\left(\frac{\lambda_0}{\lambda}\right)^4\right]$$

$$= \frac{(1550)(0.092)}{4}\left[1-\left(\frac{1310}{1550}\right)^4\right]$$

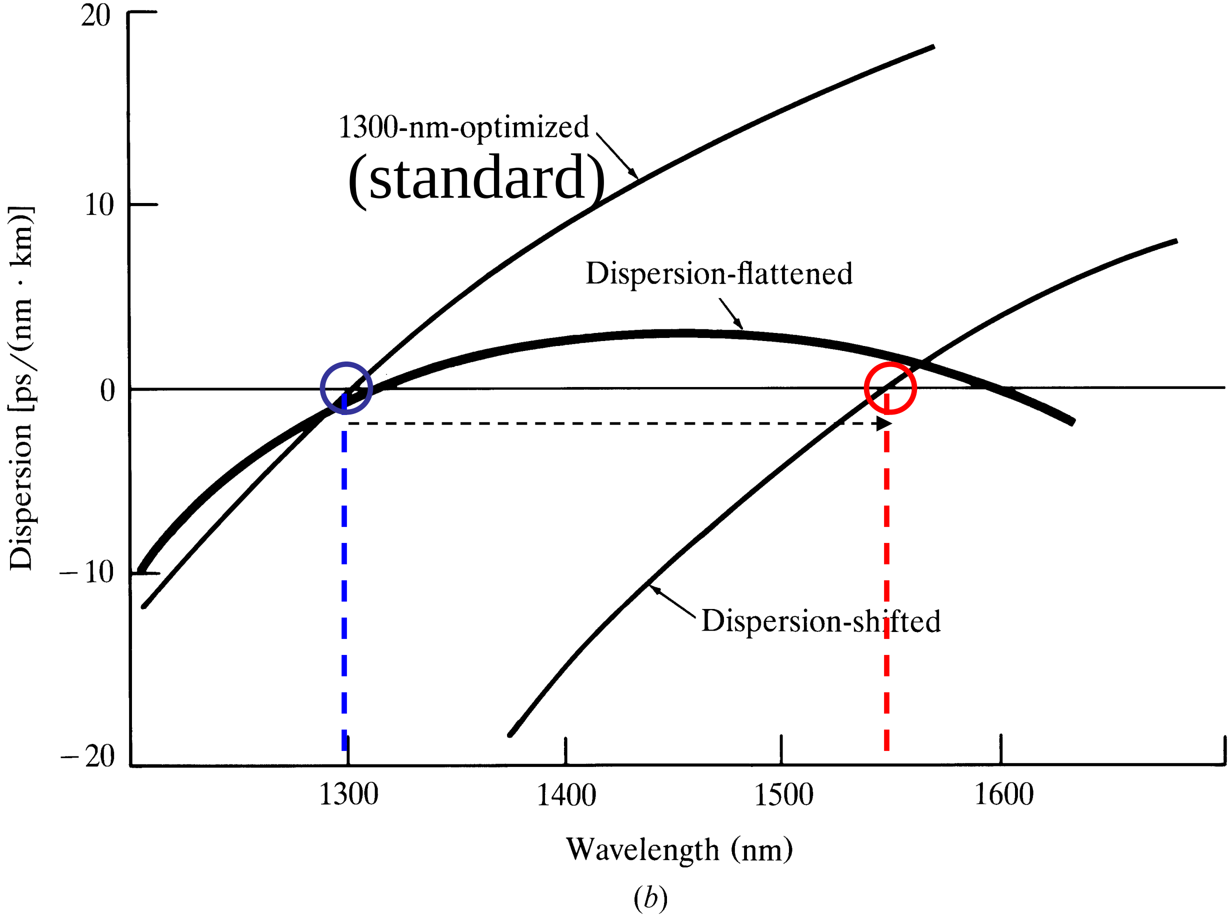
$$= 17.5 \text{ ps/(nm} \cdot \text{km)}$$

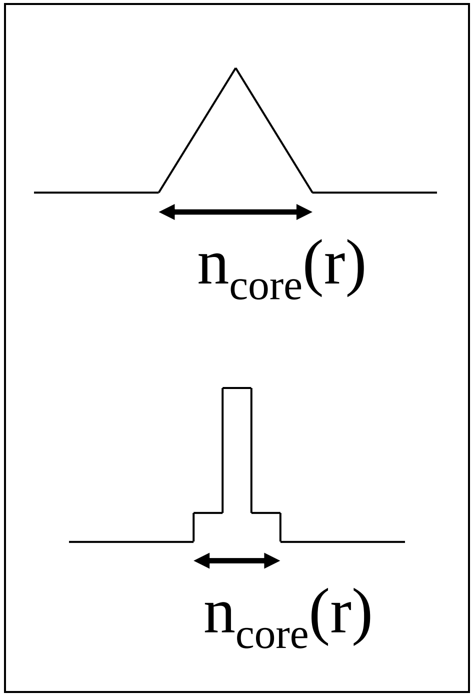
Dispersion tailored fibers

1. As the waveguide contribution D_{wg} depends on the fiber parameters such as the core radius *a* and the index difference Δ, it is *possible to design the fiber such that λ_{ZD} is shifted* into the neighborhood of 1.55 μm. Such fibers are called ***dispersion-shifted fibers***.

2. It is also possible to tailor the waveguide contribution such that the *total dispersion D is relatively small over a wide wavelength range* extending from 1.3 to 1.6 μm. Such fibers are called ***dispersion-flattened fibers***.

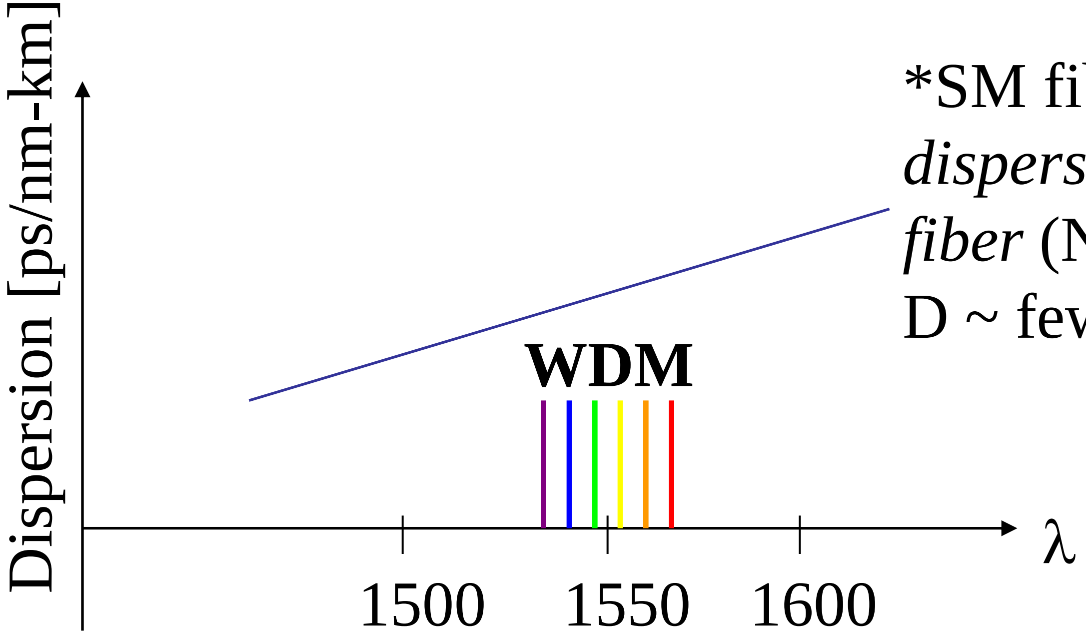
Dispersion-shifted and flattened fibers





- The design of dispersion-modified fibers often involves the use of multiple cladding layers and a <u>tailoring of the refractive index profile</u>.

- Since ***dispersion slope*** S > 0 for singlemode fibers => different ***wavelength-division multiplexed (WDM)*** channels have different *dispersion values*.



*SM fiber or *non-zero dispersion-shifted fiber* (NZDSF) with D ~ few ps/(km-nm)

*In fact, for WDM systems, *small amount of chromatic dispersion must be present* to prevent the impairment of **fiber nonlinearity** (i.e. power-dependent interaction between wavelength channels.)

Chromatic Dispersion Compensation

- Chromatic dispersion is ***time independent*** in a *passive* optical link
$\Rightarrow$allow compensation along the entire fiber span
(**Note** that recent developments focus on *reconfigurable* optical link, which makes chromatic dispersion *time dependent*!)

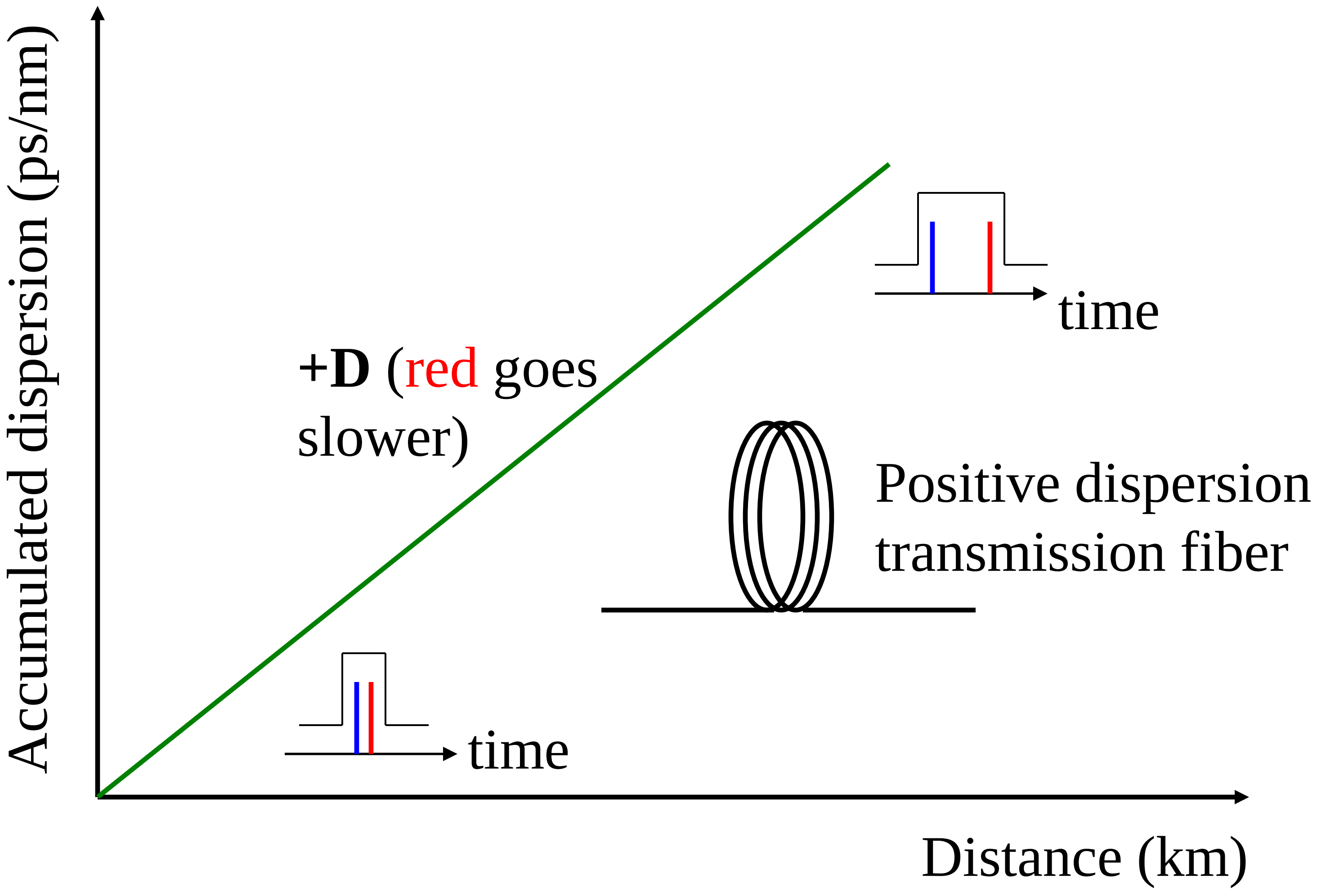
Two basic techniques: (1) **dispersion-compensating fiber DCF**

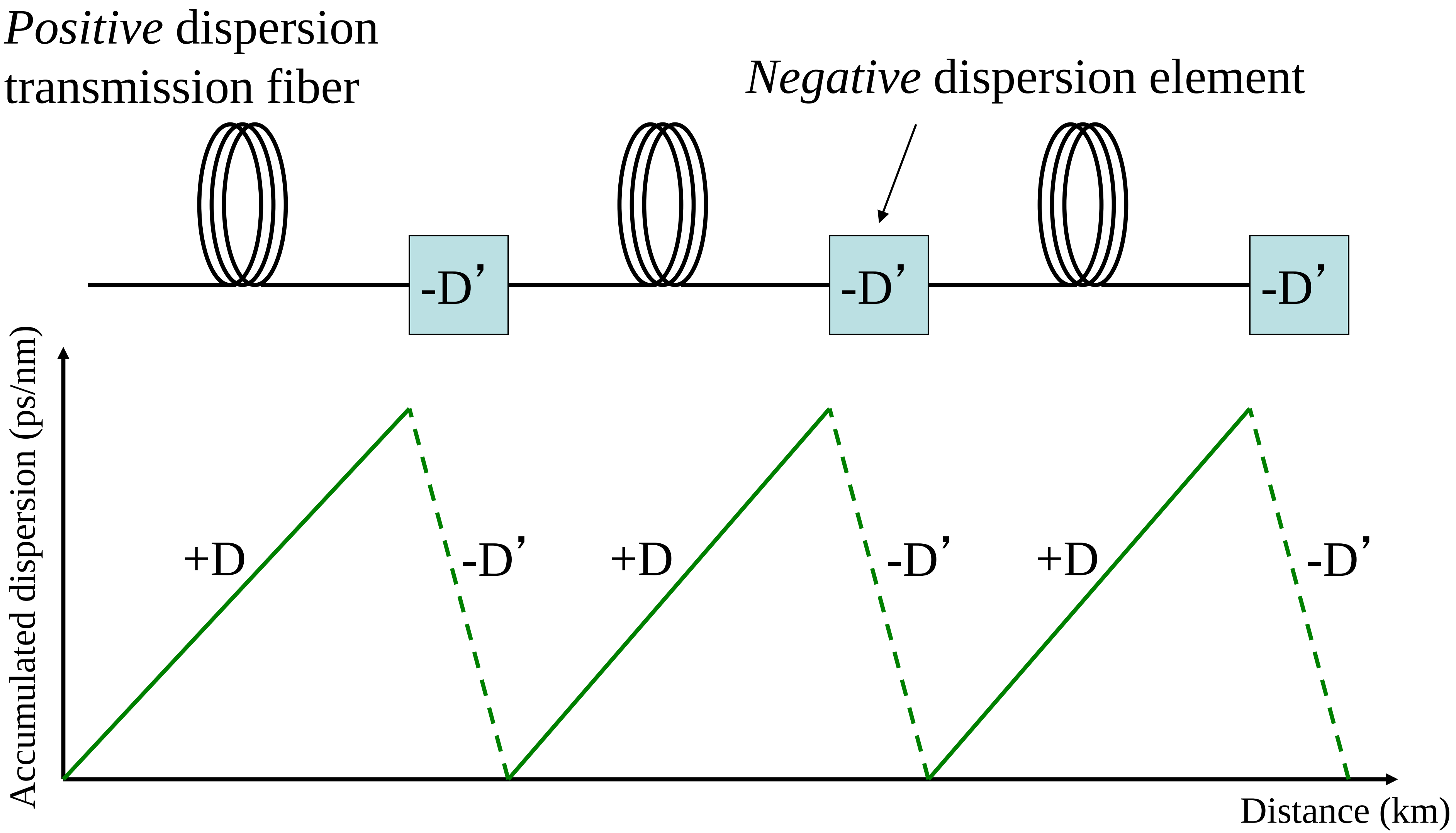
(2) dispersion-compensating **fiber grating**

- **The basic idea for DCF**: the ***positive dispersion*** in a conventional fiber (say ~ 17 ps/(km-nm) in the 1550 nm window) can be compensated for by inserting a ***fiber with negative dispersion*** (*i.e. with large -ve* D_{wg}).

Chromatic dispersion accumulates *linearly* over distance

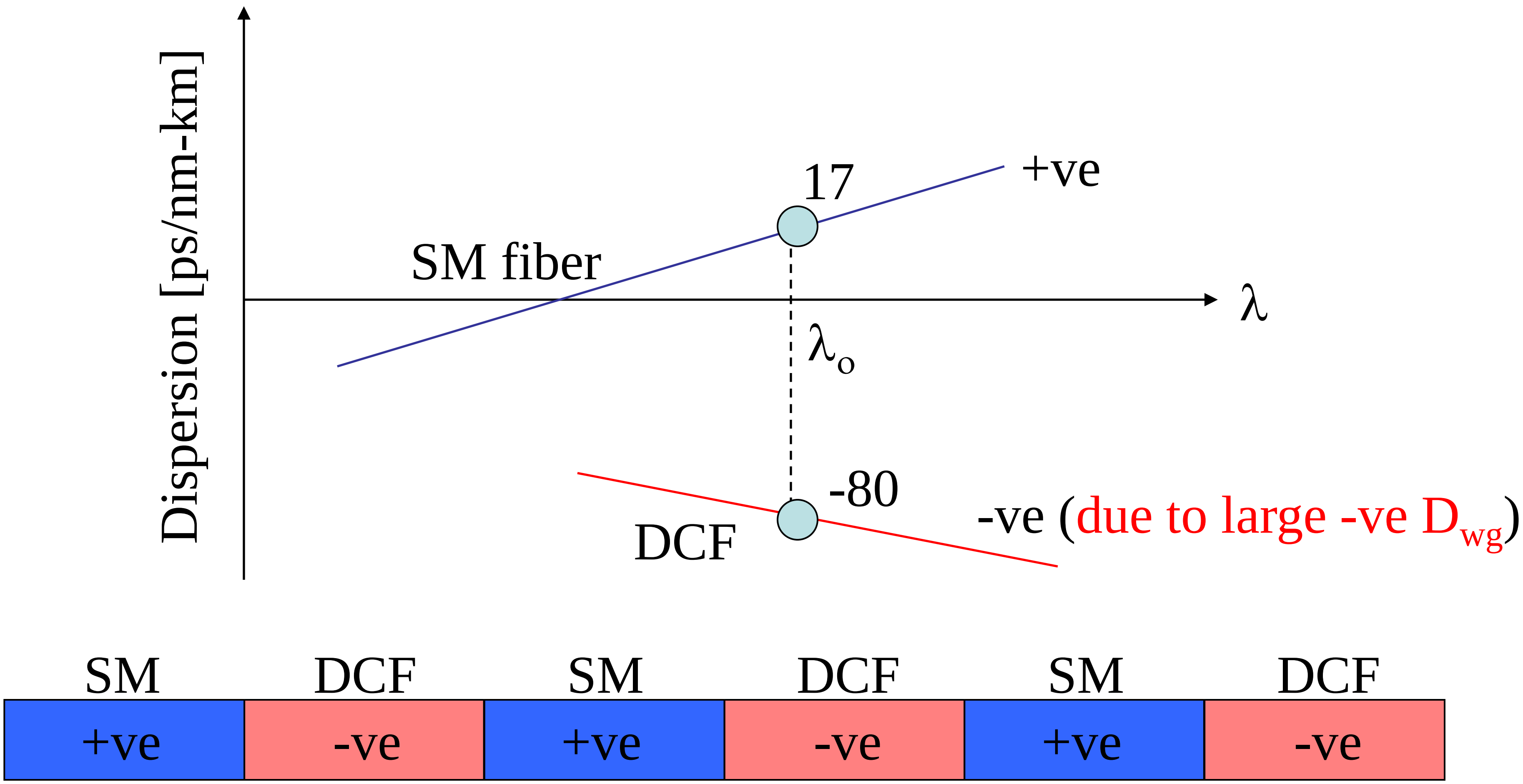
(recall $\Delta T = D\ L\ \Delta\lambda$)





- In a *dispersion-managed* system, positive dispersion transmission fiber *alternates with negative dispersion compensation elements*, such that the *total* dispersion is *zero* end-to-end.

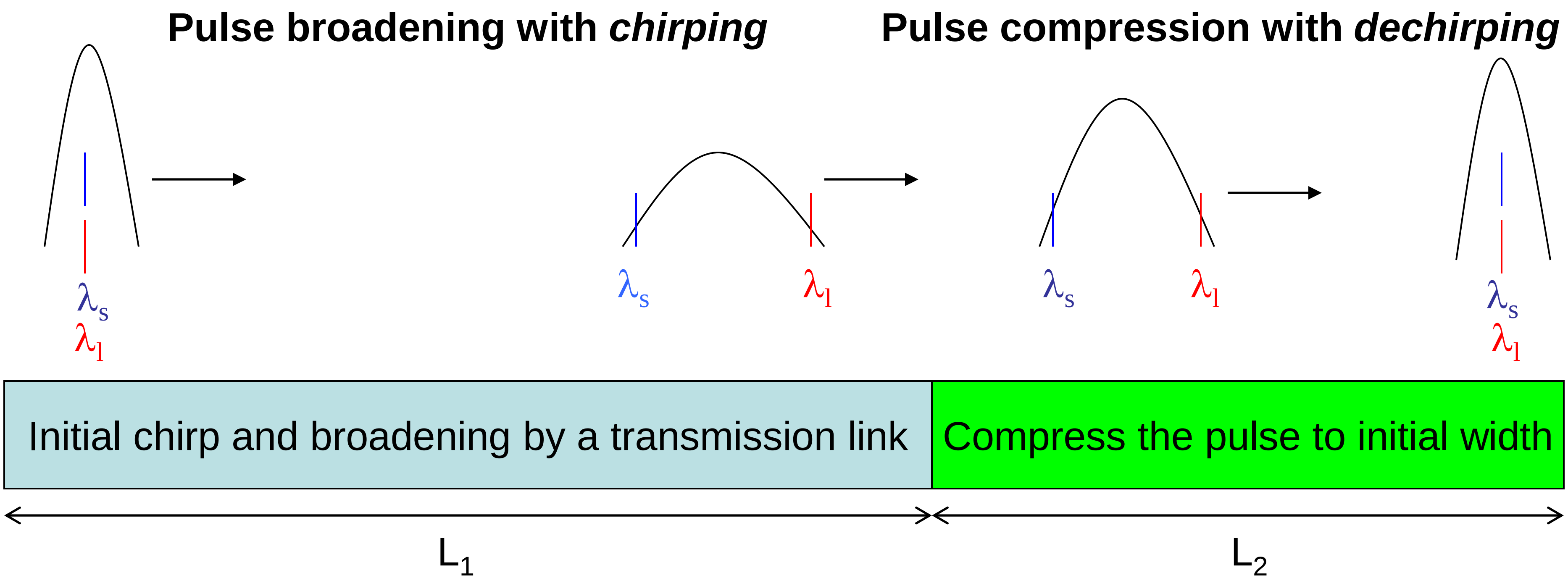
Fixed (passive) dispersion compensation



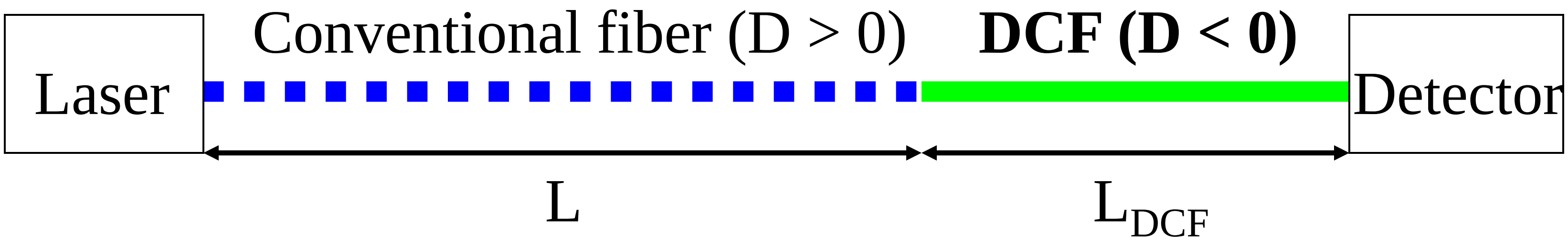
*DCF is a length of fiber producing -ve dispersion *four to five times* as large as that produced by conventional SMF.

Dispersion-Compensating Fiber

The concept: using a span of fiber to *compress* an initially chirped pulse.



Dispersion compensated channel: $D_2 L_2 = - D_1 L_1$



e.g. What DCF is needed in order to compensate for dispersion in a conventional single-mode fiber link of 100 km?

Suppose we are using Corning SMF-28 fiber,

=> the dispersion parameter D(1550 nm) ~ 17 ps/(km-nm).

$\Rightarrow$ Pulse broadening $\Delta T_{chrom} = D(\lambda)\, \Delta\lambda\, L \sim 17 \times 1 \times 100 = 1700$ ps.

assume the semiconductor (diode) laser linewidth $\Delta\lambda \sim 1$ nm.

$\Rightarrow$The DCF needed to compensate for 1700 ps with a large *negative-dispersion* parameter

i.e. we need $\Delta T_{chrom} + \Delta T_{DCF} = 0$

$$\Rightarrow \Delta T_{DCF} = D_{DCF}(\lambda)\, \Delta\lambda\, L_{DCF}$$

suppose typical ratio of $L/L_{DCF} \sim 6 – 7$, we assume $L_{DCF} = 15$ km

$$=> D_{DCF}(\lambda) \sim -113 \text{ ps/(km-nm)}$$

*Typically, **only one wavelength can be compensated exactly.** Better CD compensation requires **both *dispersion* and *dispersion slope* compensation**.

Compensating the dispersion slope produces the additional requirement:

$$L_2\, dD_2/d\lambda = - L_1\, dD_1/d\lambda$$

$\Rightarrow$ The compensating fiber must have a ***negative*** dispersion slope, and that the *dispersion* and *slope* values need to be compensated for a given length.

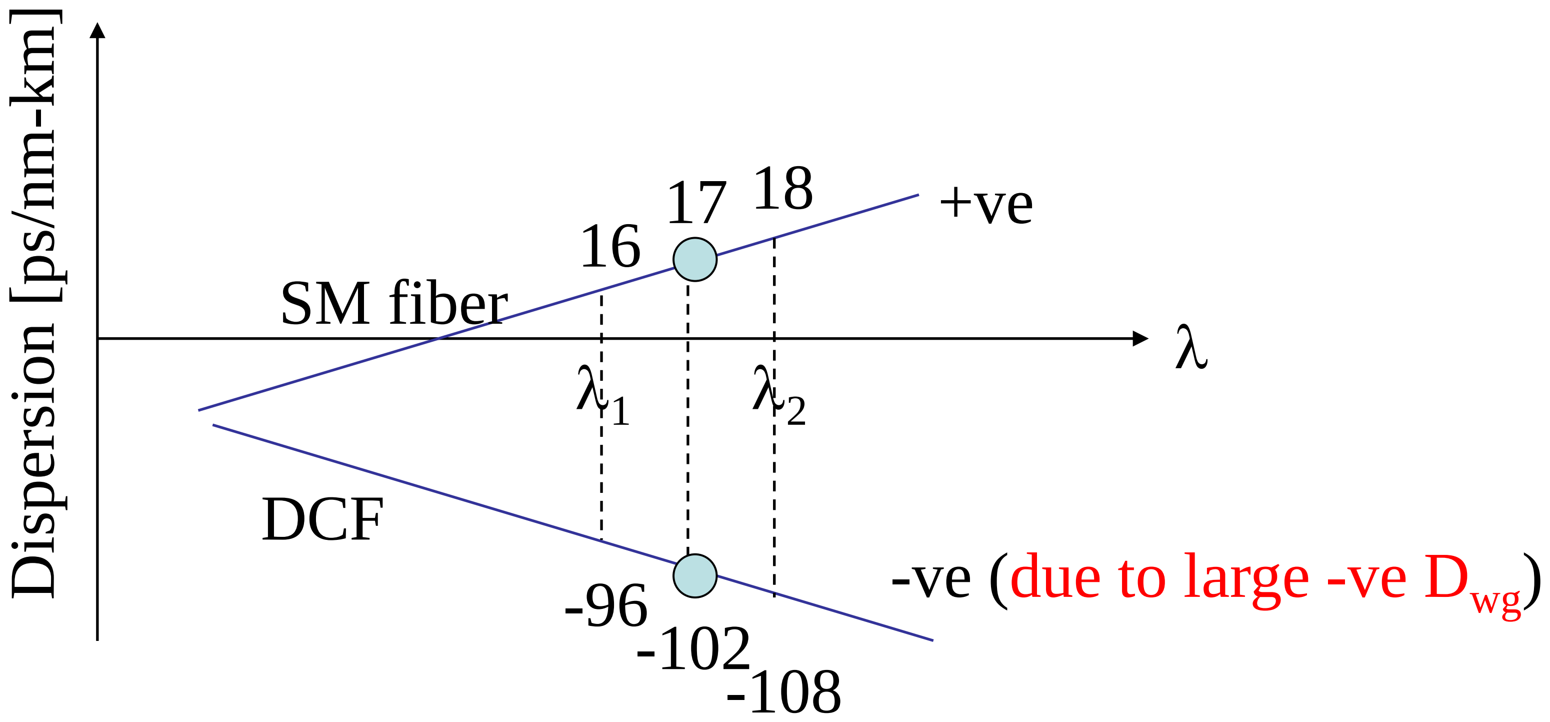
$$D_2\, L_2 = - D_1\, L_1$$

$$L_2\, dD_2/d\lambda = - L_1\, dD_1/d\lambda$$

=> Dispersion and slope compensation: $D_2 / (dD_2/d\lambda) = D_1 / (dD_1/d\lambda)$

(In practice, two fibers are used, one of which has negative slope, in which the pulse wavelength is at zero-dispersion wavelength λ_{zD}.)

Dispersion slope compensation



Within the spectral window (λ_1, λ_2), $D_{DCF}/D_{SM} = -6$

$S_{DCF} = -12/(\lambda_2 - \lambda_1)$; $S_{SM} = 2/(\lambda_2 - \lambda_1)$ => $S_{DCF}/S_{SM} = -6$

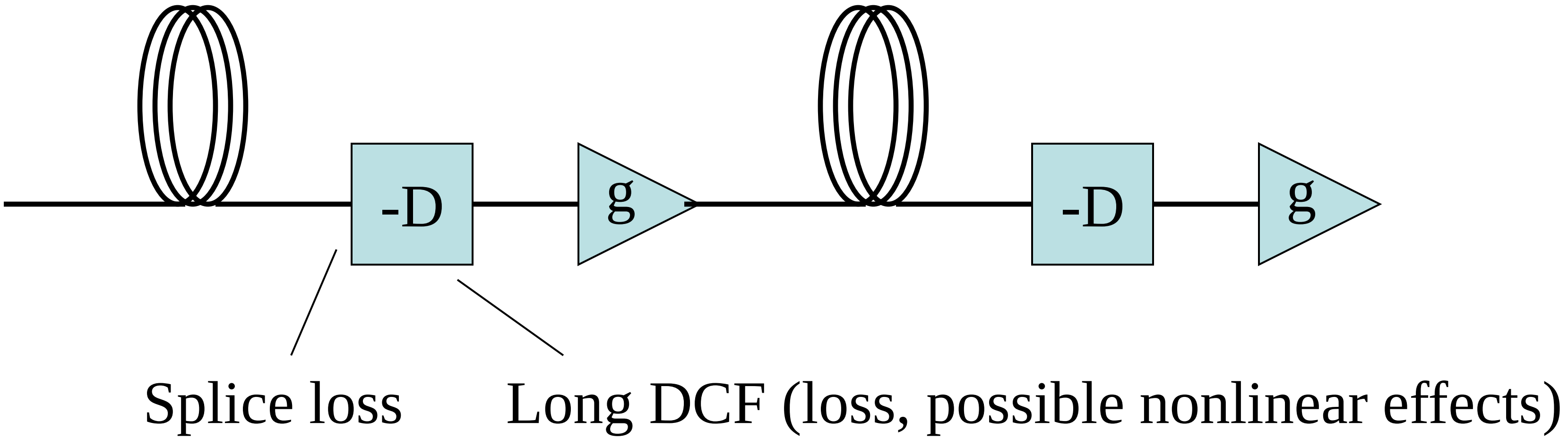
=> Dispersion slope compensation: $(D_{SM}/S_{SM}) / (D_{DCF}/S_{DCF}) = 1$

Disadvantages in using DCF

- *Added loss* associated with the increased fiber span

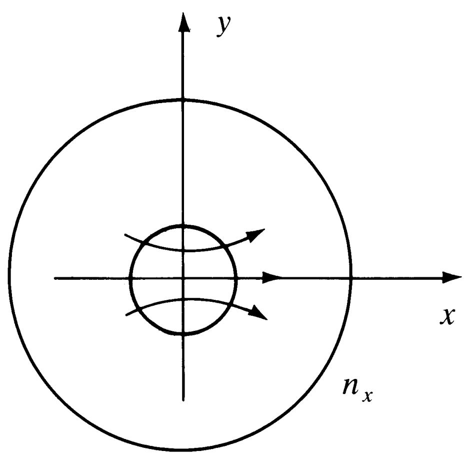
- *Nonlinear effects* may degrade the signal over the long length of the fiber if the signal is of sufficient intensity.

- Links that use DCF often require an *amplifier* stage to compensate the added loss.

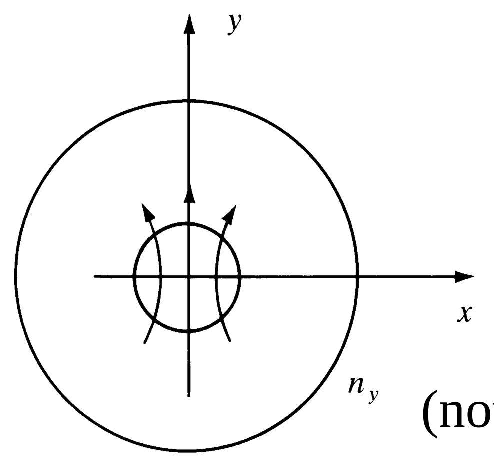


3. Polarization Mode Dispersion (PMD)

- In a single-mode optical fiber, the optical signal is carried by the ***linearly polarized*** "fundamental mode" LP_{01}, which has ***two polarization components that are orthogonal***.



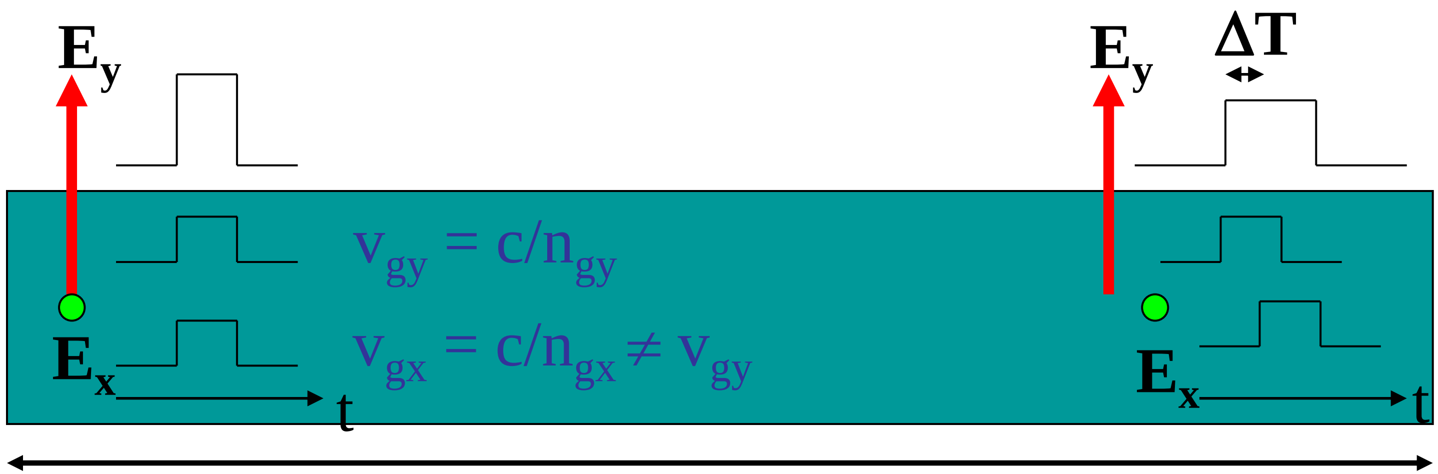
Horizontal mode



Vertical mode

(note that x and y are chosen arbitrarily)

- In a ***real* fiber (i.e. $n_{gx} \neq n_{gy}$)**, the two orthogonal polarization modes propagate at ***different group velocities***, resulting in pulse broadening – **polarization mode dispersion**.



Single-mode fiber L km

1.** ***Pulse broadening due to the orthogonal polarization modes (*The time delay between the two polarization components is characterized as the* ***differential group delay (DGD).****)*

2. ***Polarization varies*** along the fiber length

- The *refractive index difference* is known as ***birefringence*****.**

$$B = n_x - n_y$$

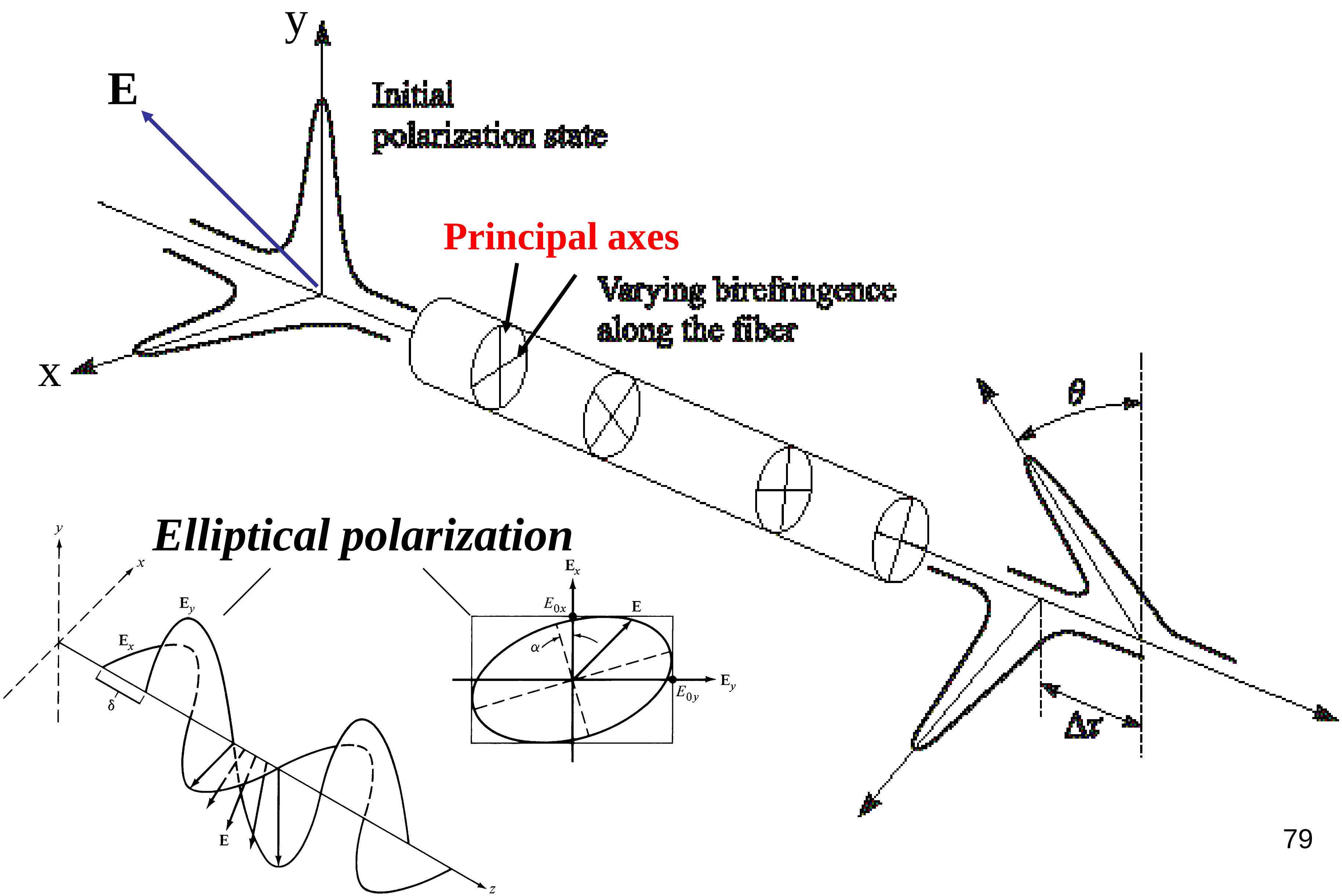
(~ 10^{-6} - 10^{-5} for single-mode fibers)

assuming $n_x > n_y$ => y is the *fast axis*, x is the *slow axis*.

*B varies ***randomly*** because of *thermal and mechanical stresses over time* (due to *randomly varying* environmental factors in submarine, terrestrial, aerial, and buried fiber cables).

=> ***PMD is a statistical process*** **!**

Randomly varying birefringence along the fiber

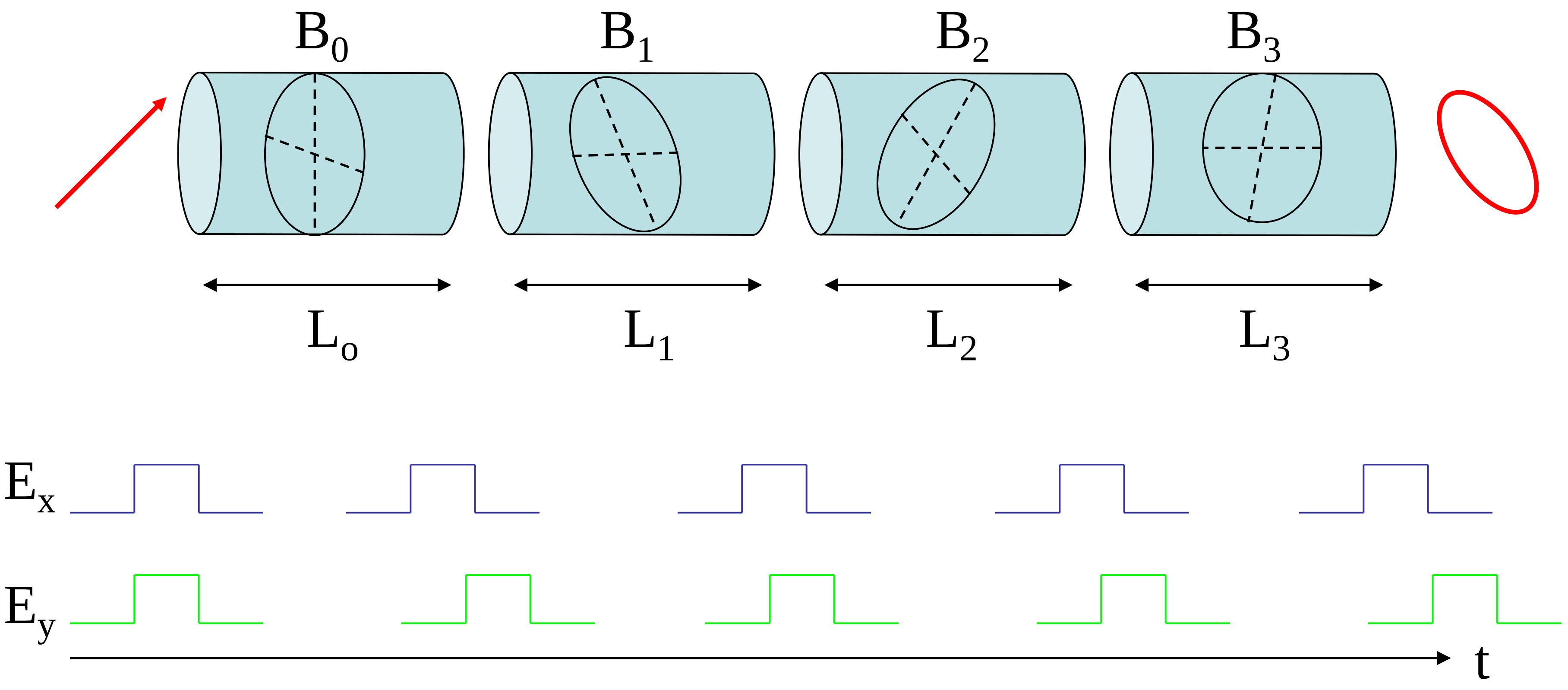


• The polarization state of light propagating in fibers with ***randomly varying birefringence*** will generally be ***elliptical and would quickly reach a state of arbitrary polarization***.

*However, the final polarization state is *not* of concern for most lightwave systems as ***photodetectors are insensitive to the state of polarization***.
(**Note**: recent technology developments in "*Coherent Optical Communications*" do require polarization state to be analyzed.)

• A simple model of PMD divides the fiber into a large number of segments. Both the *magnitude of birefringence B* and the *orientation of the principal axes* remain constant in each section but *changes randomly from section to section*.

A simple model of PMD



Randomly changing differential group delay (DGD)

- Pulse broadening caused by a *random* change of fiber polarization properties is known as polarization mode dispersion (PMD).

PMD pulse broadening	$\Delta T_{PMD} = D_{PMD} \sqrt{L}$

D_{PMD} is the PMD parameter (coefficient) measured in **ps/√km**.

√L models the "random" nature (like "random walk")

* D_{PMD} does not depend on wavelength (first order) ;

*Today's fiber (since 90's) PMD parameter is 0.1 - 0.5 ps/√km.

(*Legacy fibers deployed in the 80's have* D_{PMD} *> 0.8 ps/√km*.)

e.g. Calculate the pulse broadening caused by PMD for a singlemode fiber with a PMD parameter D_{PMD} ~ 0.5 ps/√km and a fiber length of 100 km. (i.e. $\Delta T_{PMD} = 5$ ps)

Recall that pulse broadening due to chromatic dispersion for a 1 nm linewidth light source was ~ 15 ps/km, which resulted in 1500 ps for 100 km of fiber length.

=> **PMD** pulse broadening is ***orders of magnitude less*** than chromatic dispersion !

*PMD is relatively small compared with chromatic dispersion. But when one operates at zero-dispersion wavelength (or *dispersion compensated wavelengths*) with narrow spectral width, PMD can become a significant component of the total dispersion.

So why do we care about PMD?

Recall that chromatic dispersion can be compensated to ~ 0, (at least for single wavelengths, namely, by designing proper -ve waveguide dispersion)

but there is no simple way to eliminate PMD completely.

=> *It is PMD that limits the fiber bandwidth after chromatic dispersion is compensated*!

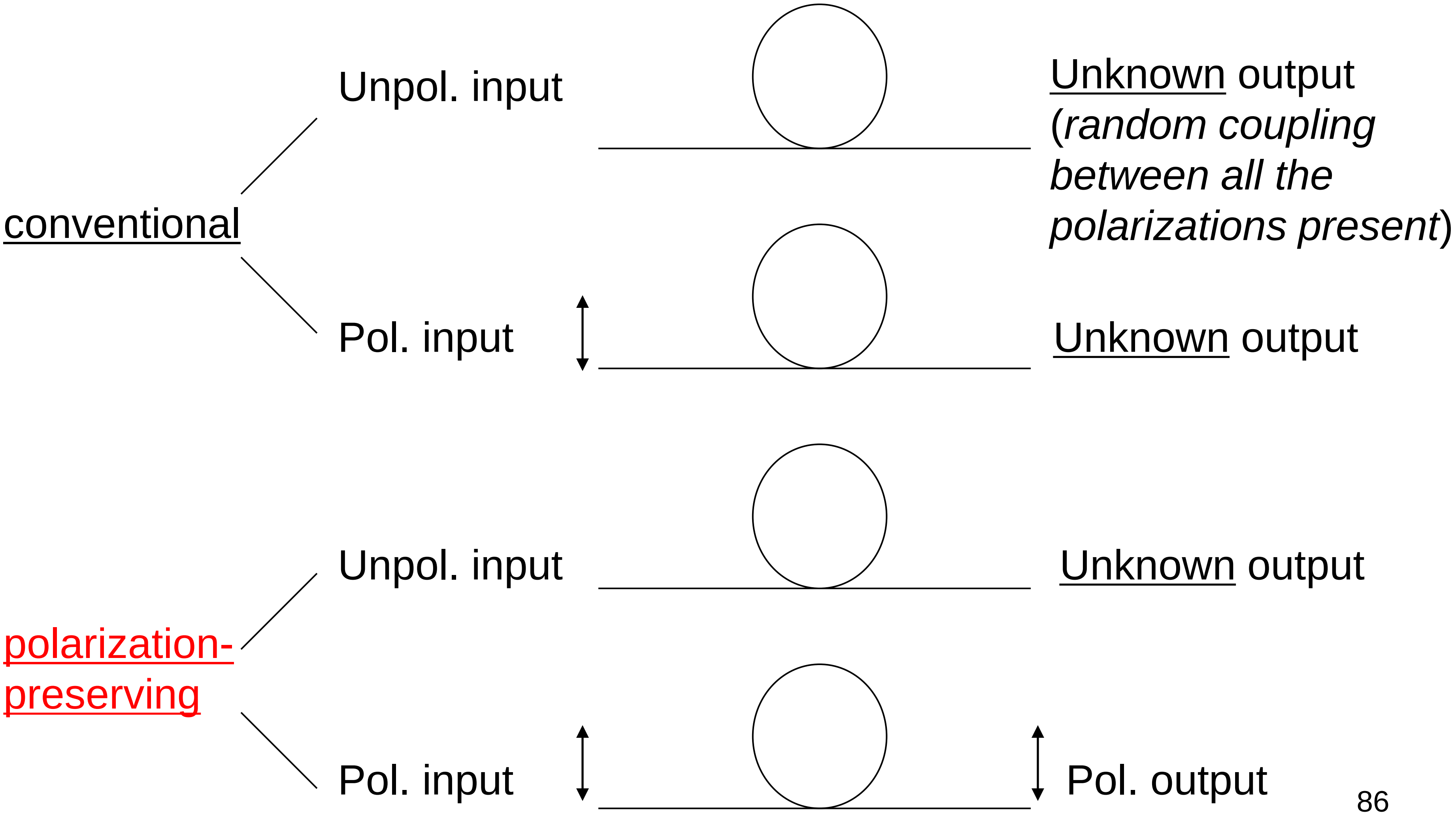
- PMD is of lesser concern in lower data rate systems. At lower transmission speeds (***up to and including 10 Gb/s***), networks have higher tolerances to all types of dispersion, including PMD.

As data rate increases, the dispersion tolerance reduces significantly, creating a need to control PMD as much as possible at the current **40 Gb/s** system.

e.g. The pulse broadening caused by PMD for a singlemode fiber with a PMD parameter of 0.5 ps/√km and a fiber length of 100 km => **5 ps**.

However, this is comparable to **the 40G bit period = 25 ps !**

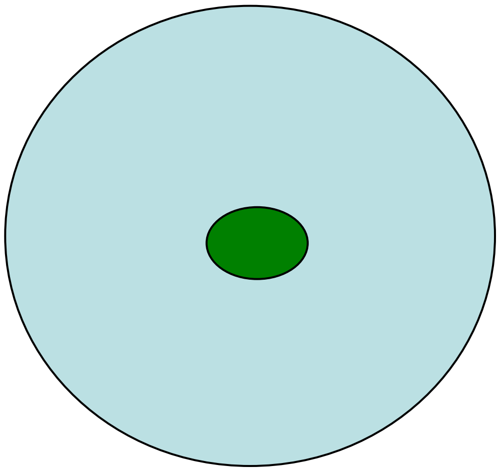
Polarizing effects of conventional / polarization-preserving fibers



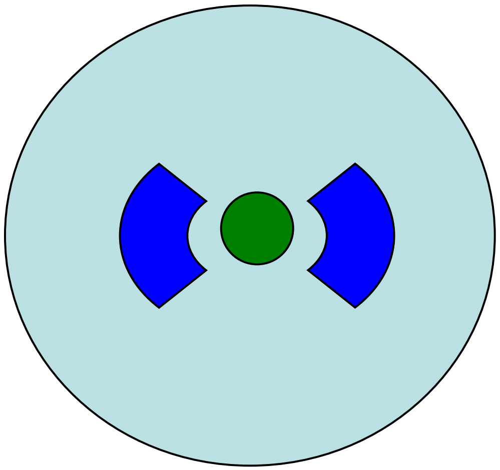
Polarization-preserving fibers

- The fiber birefringence is enhanced in single-mode *polarization-preserving* (*polarization-maintaining*) fibers, which are designed to maintain the polarization of the launched wave.
- *Polarization is preserved* because the two possible waves have significantly different propagation characteristics. This keeps them from exchanging energy as they propagate through the fiber.
- Polarization-preserving fibers are constructed by designing *asymmetries* into the fiber. Examples include fibers with <u>elliptical cores</u> (which cause waves polarized along the *major* and *minor* axes of the ellipse to have different effective refractive indices) and fibers that contain <u>nonsymmetrical stress-producing parts</u>.

Polarization-preserving fibers



Elliptical-core fiber



bow-tie fiber

- The shaded region in the bow-tie fiber is highly doped with a material such as boron. Because the thermal expansion of this doped region is so different from that of the pure silica cladding, a *nonsymmetrical stress* is exerted on the core. This produces a large *stress-induced birefringence*, which in turn *decouples the two orthogonal modes of the singlemode fiber*.

Multimode Fiber Transmission Distances

- **The possible transmission distances when using fibers with different core sizes and bandwidths for Ethernet, Fibre Channel, and SONET/SDH applications.**

Table 3.3 *Transmission distances in meters in multimode fibers using an 850-nm VCSEL*

		50-μm core		*62.5-μm core*	
Application	Data rate (Gb/s)	500 MHz.km	2000 MHz.km	160 MHz.km	200 MHz.km
Ethernet	1	550	860	220	275
	10	82	300	26	33
Fibre Channel	1	500	860	250	300
	2	300	500	120	150
	10	82	300	26	33
SONET/SDH	10	85	300	25	33

Examples of Specialty Fibers

Table 3.4 *Examples of specialty fibers and their applications*

Specialty fiber type	*Application*
Erbium-doped fiber	Gain medium for optical fiber amplifiers
Photosensitive fibers	Fabrication of fiber Bragg gratings
Bend-insensitive fibers	Tightly looped connections in device packages
Termination fiber	Termination of open optical fiber ends
Polarization-preserving fibers	Pump lasers, polarization-sensitive devices, sensors
High-index fibers	Fused couplers, short-λ sources, DWDM devices
Photonic crystal fibers	Switches; dispersion compensation

ITU-T Recommendations for Fibers (2)

ITU-T rec. no.	*Title and description*
G.655 (Edition 5, Nov. 2009)	Title: *Characteristics of a Non-Zero Dispersion-Shifted Single-Mode Optical Fiber and Cable* Description: For applications in long-haul links; describes single-mode optical fiber with chromatic dispersion greater than zero throughout the 1530-to-1565-nm wavelength range
G.656 (Edition 2, Dec. 2006)	Title: *Characteristics of a Fiber and Cable with Non-Zero Dispersion for Wideband Optical Transport* Description: Low chromatic dispersion fiber for expanded WDM applications; can be used for both CWDM and DWDM systems throughout the wavelength region between 1460 and 1625 nm
G.657 (Edition 2, Nov. 2009)	Title: *Characteristics of a bending loss insensitive single-mode optical fiber and cable for the access network* Description: Addresses use of single-mode fiber for broadband access networks; includes issues such as sensitivity to tight bending conditions for in-building use

ITU-T Recommendations for Fibers (1)

Table 3.2 *Recommendations for fibers used in telecom, access, and enterprise networks*

ITU-T rec. no.	*Title and description*
G.651.1 (Edition 1, July 2007); Addendum (Dec. 2008)	Title: *Characteristics of a 50/125 μm multimode graded index optical fiber cable for the optical access network*
	Description: Gives the requirements of a silica 50/125 μm multimode graded index optical fiber cable for use in the 850-nm or 1300-nm regions, either individually or simultaneously
G.652 (Edition 8, Nov. 2009)	Title: *Characteristics of a Single-Mode Optical Fiber and Cable*
	Description: Discusses single-mode fiber optimized for O-band (1310-nm) use, but which also can be used in the 1550-nm region
G.653 (Edition 6, Dec. 2006)	Title: *Characteristics of a Dispersion-Shifted Single-Mode Optical Fiber and Cable*
	Description: Discusses single-mode optical fiber with the zero-dispersion wavelength shifted into the 1550 nm region. Describes chromatic dispersion for the 1460-to-1625-nm range for CWDM applications
G.654 (Edition 7, Dec. 2006)	Title: *Characteristics of a Cut-Off Shifted Single-Mode Optical Fiber and Cable*
	Description: Undersea applications; discusses single-mode optical fiber with a zero-dispersion wavelength around 1300 nm and with cutoff wavelength shifted to around 1550 nm