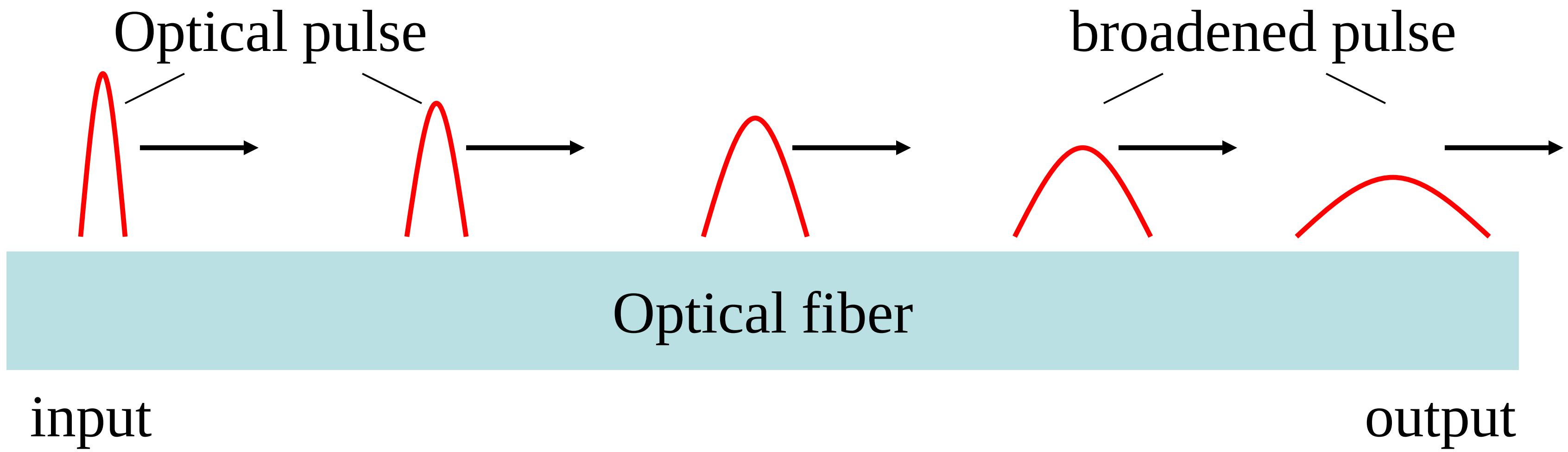
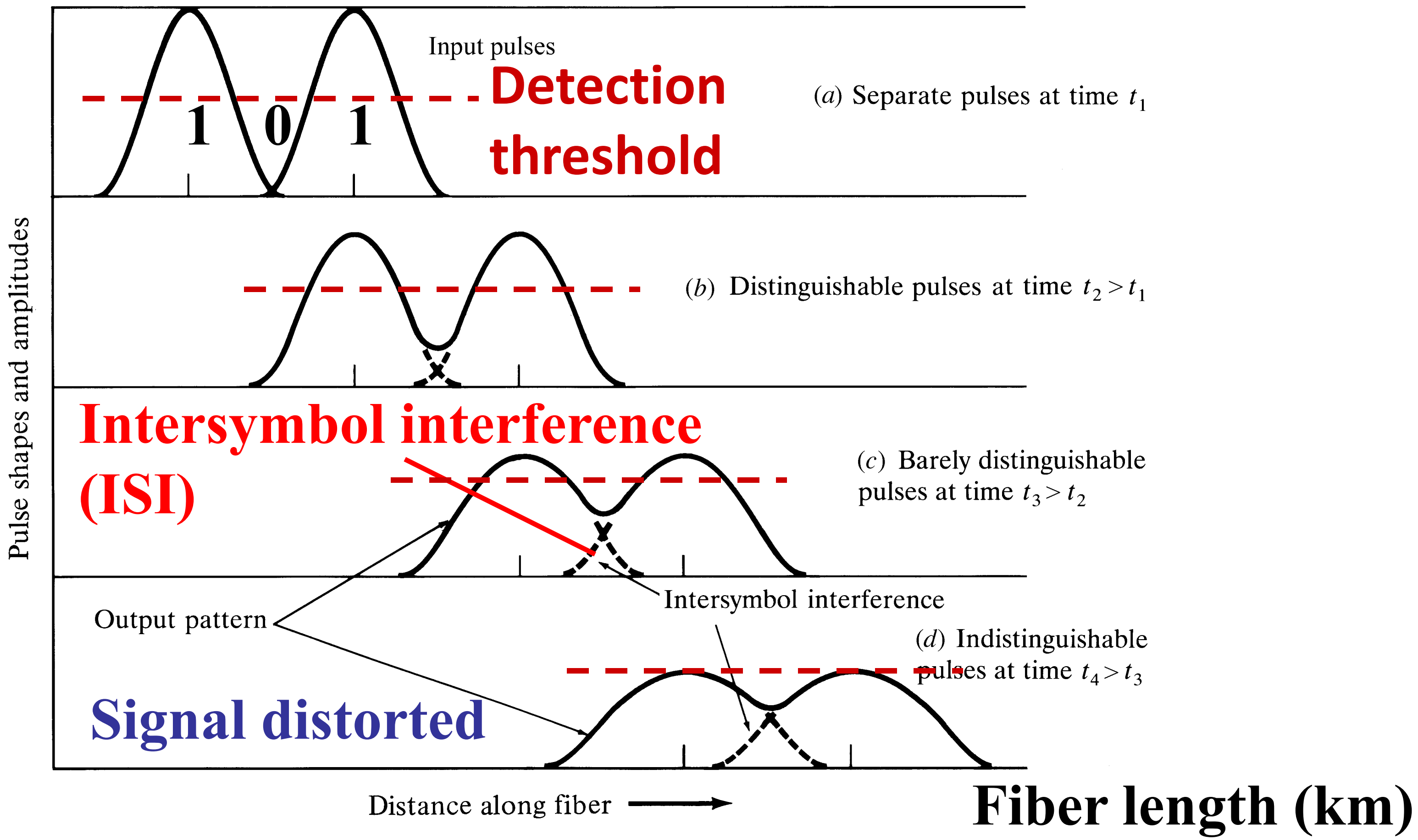
Fiber dispersion

- 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.

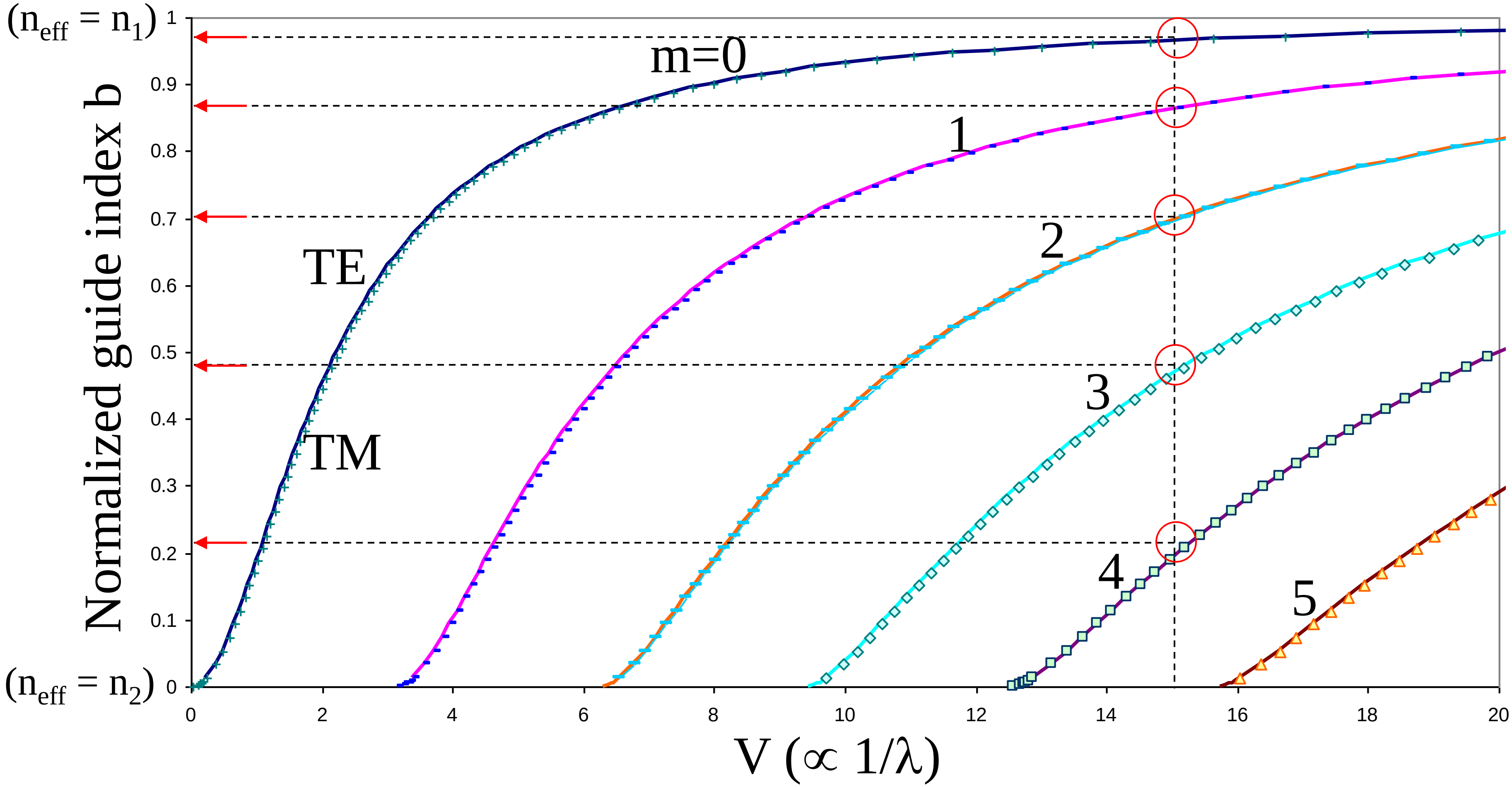
- An input waveform distorts during propagation because its energy is distributed among several modes, each traveling at a different speed.

- 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!

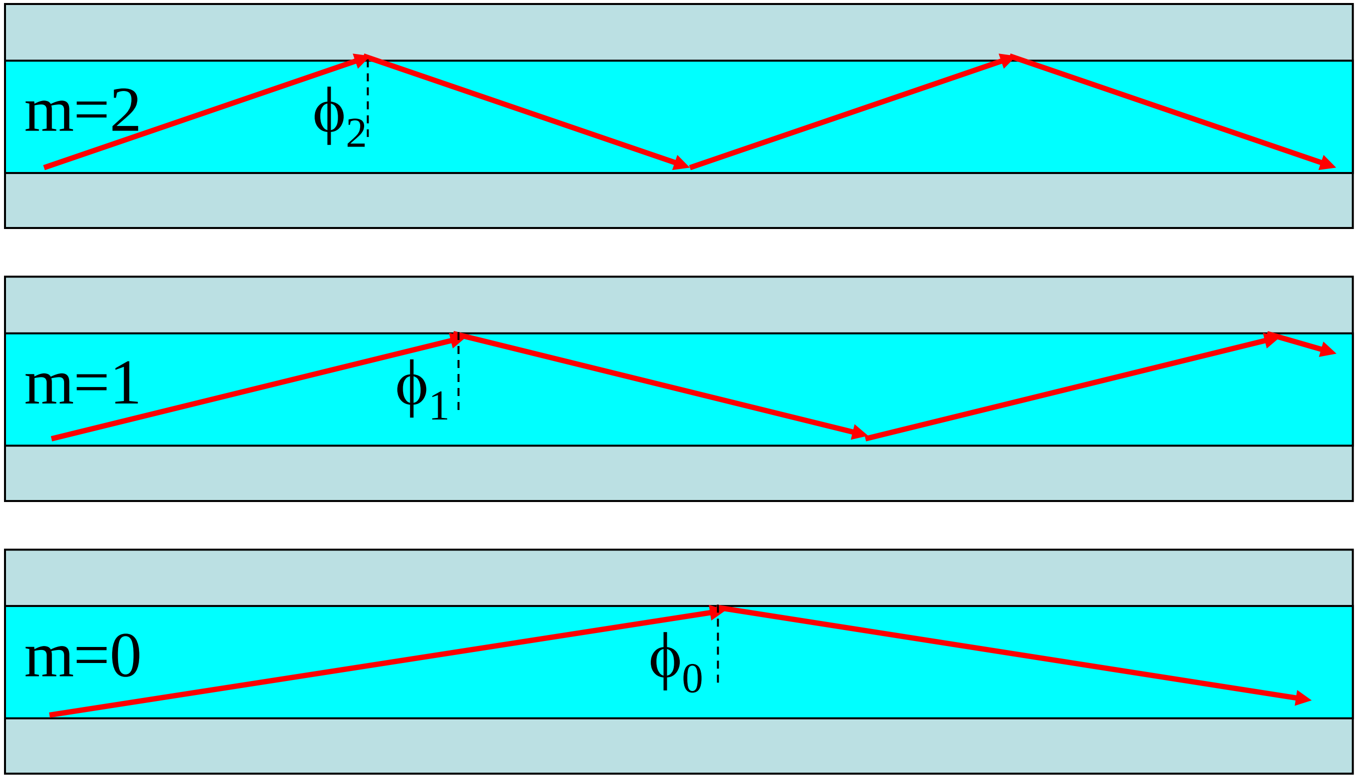
Modal dispersion as shown from the mode chart of a symmetric slab waveguide



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

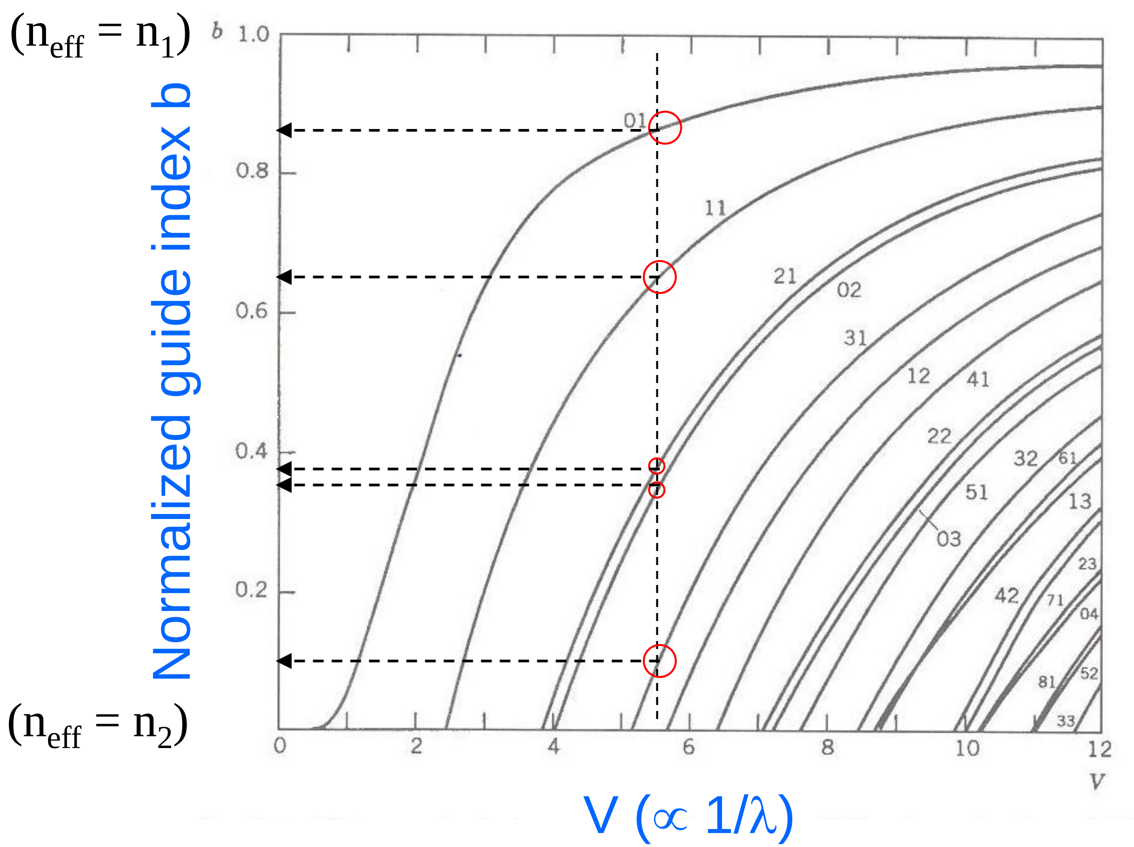
(note that m = 0 mode is the *slowest* mode)

Modal dispersion in multimode waveguides



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

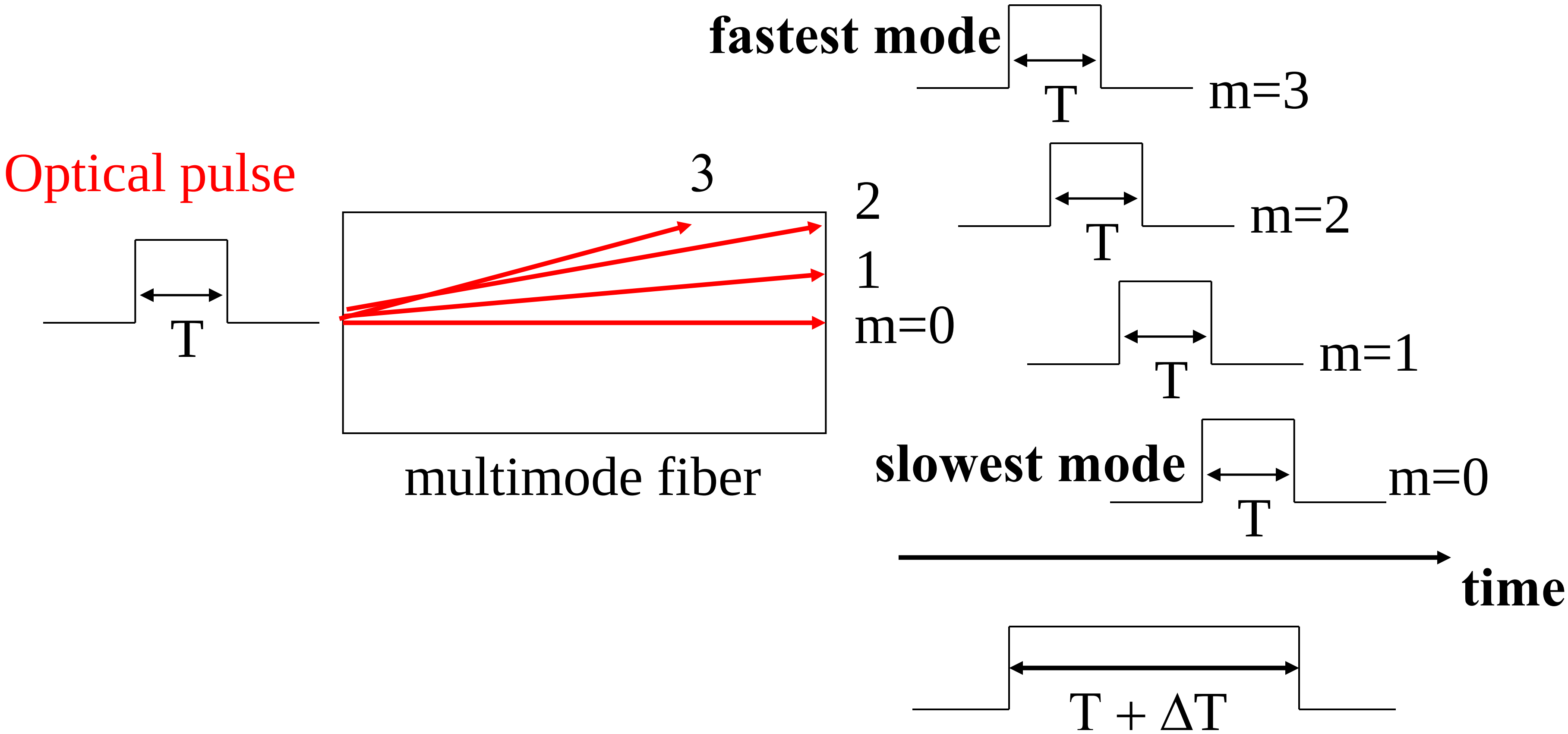
Modal dispersion as shown from the LP mode chart of a silica optical fiber



- 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

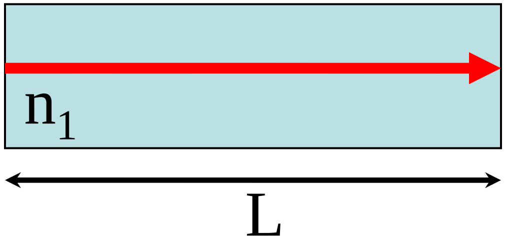


modal dispersion: different modes arrive at the receiver with different delays => pulse broadening

Estimated modal dispersion pulse broadening using phase velocity

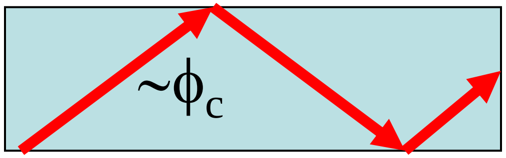
- A zero-order mode traveling near the waveguide axis needs time:

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



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

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



=> 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*)

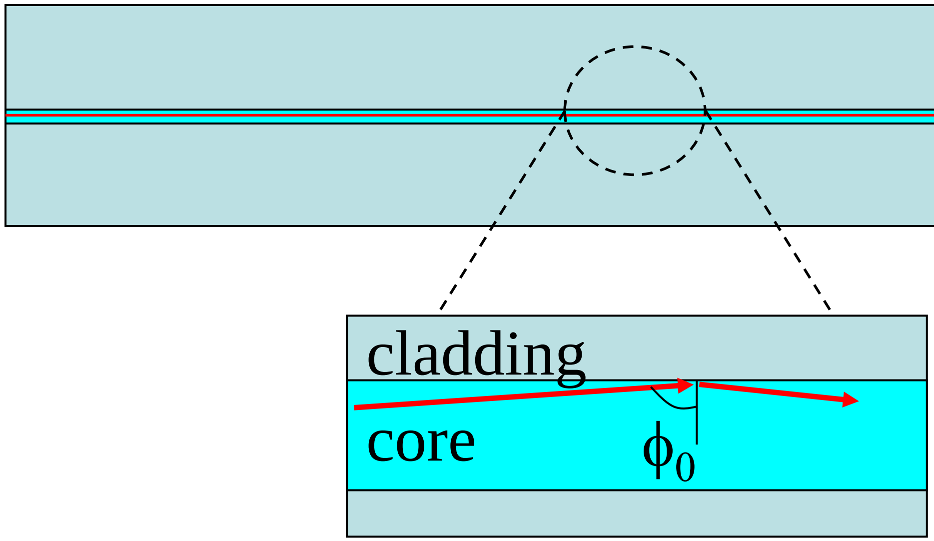
The capacity of optical communications systems is frequently measured in terms of the **bit rate-distance product**.

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

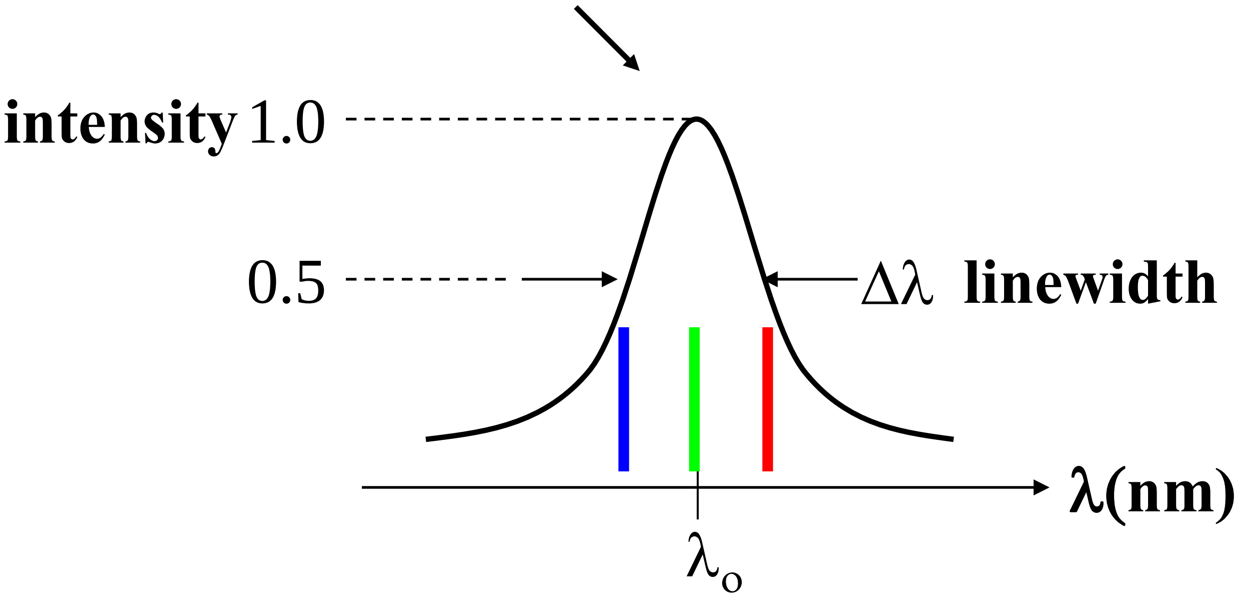


- The main advantage of *single*-mode fibers is to propagate *only one mode* so that *modal dispersion is absent.*

- 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 chromatic dispersion.

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

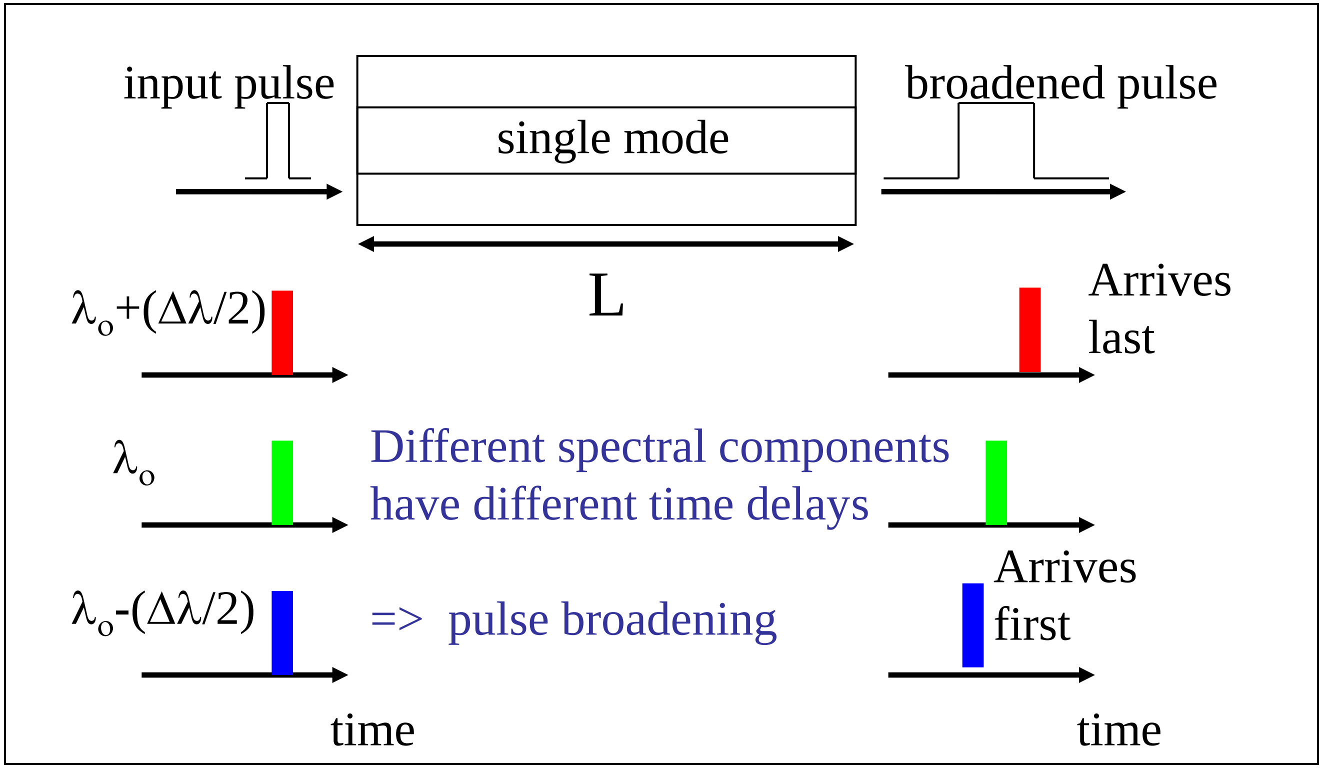
- Real sources emit over a range of wavelengths. This range is the *source linewidth* or *spectral width*.

- 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).

Dispersion in Single-mode Fibres

Single-mode fibres are far superior to multimode fibres in dispersion characteristics, because they avoid multipath effects, ie. energy of injected pulse is transported by a single-mode only.

However, some dispersion still exists.

Group velocity of fundamental mode is frequency dependent – hence different spectral components of the pulse travel at slightly different group velocities.

Group Velocity Dispersion (GVD)

Contribution: (i) material dispersion (ii) waveguide dispersion

Time delay for a specific spectral component at frequency ω arriving at output of fibre of length L is

$$T = \frac{L}{v_g}$$

where group velocity $v_g = \left(\frac{d\beta}{d\omega}\right)^{-1}$

$\frac{d\theta}{dt} = \omega = 2\pi f = \frac{2\pi c}{\lambda}$

Since $\beta = \bar{n}k_0 = \bar{n}\frac{\omega}{c}$

$$\Rightarrow v_g = \frac{c}{\bar{n}_g}$$

where Group Index $\bar{n}_g = \bar{n} + \omega\left(\frac{d\bar{n}}{d\omega}\right)$

Mode index

Frequency dependence of v_g causes pulse broadening because different spectral components of the pulse disperse during propagation and do not arrive simultaneously at the fibre output.

If $\Delta\omega$ is spectral width of the pulse $\Rightarrow$ pulse broadening for fibre length L is

$$\Delta T = \frac{dT}{d\omega}\Delta\omega = \frac{d}{d\omega}\left(\frac{L}{v_g}\right)\Delta\omega = L\frac{d^2\beta}{d\omega^2}\Delta\omega$$

In optical fibre communications, $\Delta\lambda$ is used instead of $\Delta\omega$.

If the frequency spread $\Delta\omega$ is determined by range of wavelengths $\Delta\lambda$ emitted by source, using $\omega = \dfrac{2\pi c}{\lambda}$

$$\Delta\omega = -\frac{2\pi c}{\lambda^2}\Delta\lambda$$

$\cancel{f = c}$

$2\pi f_1 - f_2 \delta\lambda = -\frac{2\pi c}{\lambda}(\lambda_1 - \lambda_2)$

$v_1 - v_2 = -$

$$\Rightarrow \Delta T = -\frac{2\pi c}{\lambda^2}\left(\frac{d^2\beta}{d\omega^2}\right)L\,\Delta\lambda$$

$$\Rightarrow \boxed{\Delta T = D\,L\,\Delta\lambda}$$

where <u>Dispersion parameter</u> $\quad D \equiv -\dfrac{2\pi c}{\lambda^2}\left(\dfrac{d^2\beta}{d\omega^2}\right)$

D is expressed in ps/km-nm

<u>Effect of dispersion on bit rate</u>

Using rough criterion that pulse broadening ΔT must be less than time allocated to a bit ie. $\dfrac{1}{B}$

Require $\Delta T < \dfrac{1}{B}$

$$\Rightarrow \boxed{B|D|L\,\Delta\lambda < 1}$$

- gives order of magnitude estimate of $B \cdot L$ product offered by single-mode fibre.

eg. For operation near $\lambda = 1.3\,\mu m$, $D \sim 1\,\text{ps/km}\cdot\text{nm}$

For semiconductor (multimode) laser of spectral width $\Delta\lambda = 2 - 4\,nm$

$$\Rightarrow B\,L \sim 100\,(\text{Gb/s})\cdot\text{km}$$

For semiconductor (single-mode) laser of spectral width $\Delta\lambda < 1\,nm$

$$\Rightarrow B\,L \sim 1\,(\text{Tb/s})\cdot\text{km}$$ for fibre.

Behaviour of dispersion parameter D

D varies with wavelength

$$D = -\frac{2\pi c}{\lambda^2}\left(\frac{d^2\beta}{d\omega^2}\right)$$

and $\beta = -\dfrac{\overline{n}\omega}{c}$ where $\overline{n}$ is the mode index

$$\Rightarrow D = -\frac{2\pi}{\lambda^2}\left(2\frac{d\,\overline{n}}{d\omega} + \omega\frac{d^2\overline{n}}{d\omega^2}\right)$$

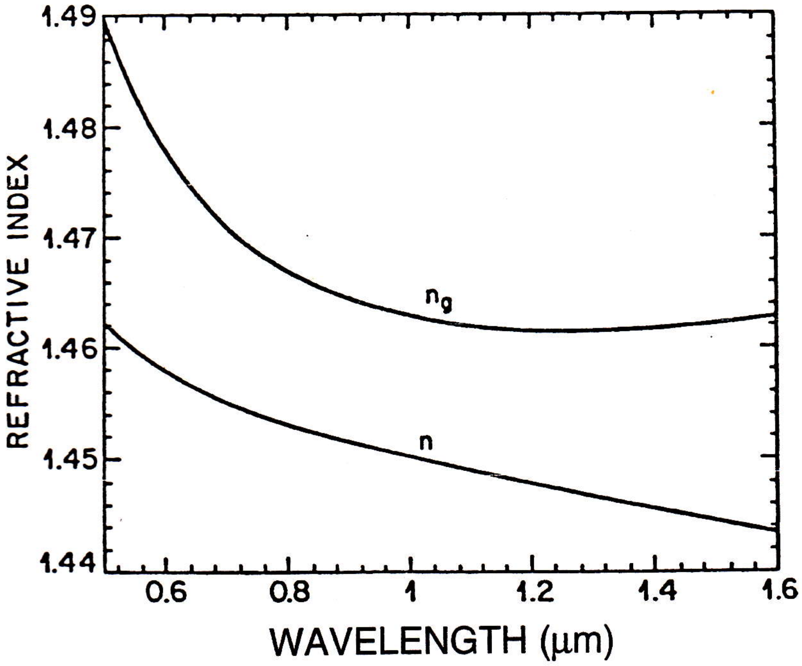
This can be decomposed into two additive terms.

D_M - material dispersion — due to refractive index of silica changing with optical freq. ω

D_W - waveguide dispersion — due to normalised propagation constant b changing with optical freq ω (Proportion of field in core & cladding changes with ω & V)

Material Dispersion

Occurs because refractive index of silica changes with optical frequency ω



Wavelength dependence of n and group index n_g for fused silica

$$D_M \propto \frac{dn_g}{d\lambda}$$

It turns out that $\frac{dn_g}{d\lambda} = 0$ at $\lambda = 1.276\,\mu m \equiv \lambda_{ZD}$

ie. zero material dispersion wavelength $D_M = 0$ at $\lambda = \lambda_{MZD}$

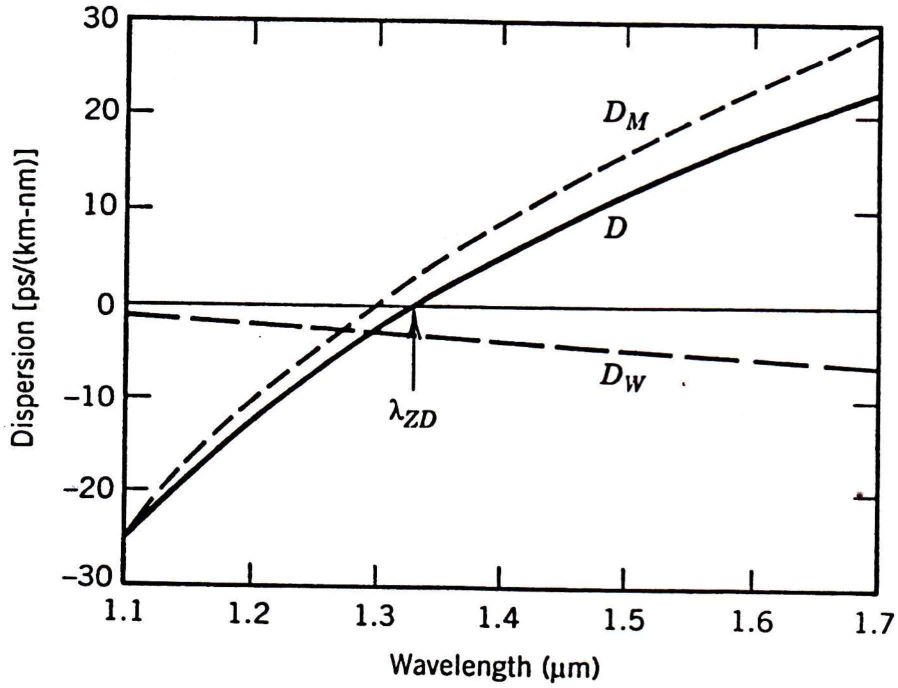
<u>Note</u> $D_M < 0$ below λ_{MZD} and $D_M > 0$ above λ_{MZD}

Waveguide Dispersion

Occurs because propagation constant *b* depends on optical frequency ω and on the V parameter of the fibre.

It turns out that $D_W < 0$ in the entire range 0-1.6 μm.

Since $D_M > 0$ for $\lambda > \lambda_{MZD}$, it is possible to cancel the waveguide & material dispersion at a specific λ to get total dispersion $D = D_M + D_W = 0$



Total dispersion $D = 0$ at $\lambda_{ZD} = 1.31\,\mu m$.

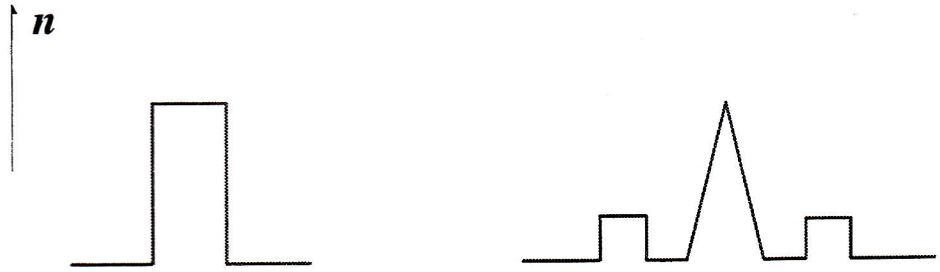
At the low-fibre-loss wavelength of $\lambda = 1.55\,\mu m$,
$D = 15 - 18\ ps/(km \cdot nm)$

This is relatively high and limits the performance of 1.55 μm systems.

Dispersion-shifted Fibres

The waveguide contribution D_W depends on fibre parameters such as core radius a, index difference Δ.

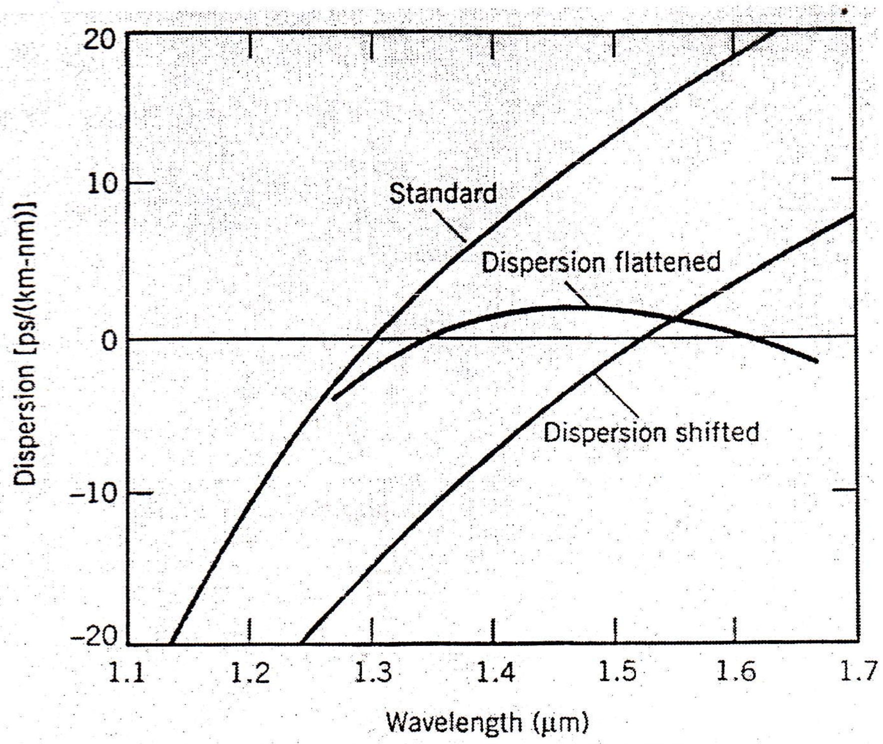
Hence can design fibre index profile so that λ_{ZD} is shifted to 1.55 μm.



Standard Fibre *Dispersion-shifted Fibre*

It is also possible to tailor the waveguide contribution so that the total dispersion is reduced over a range 1.3-1.6 μm → dispersion flattened fibres.

The design of dispersion modified fibres uses multiple cladding layers & tailored refractive index profile.



Typical fibre characteristics

Single-mode fibre

Corning SMF-28

NA = 0.13
$\Delta = 0.36\%$
Spot size diameter = 9.3 μm
$\lambda_{ZD} = 1.312$ μm

Dispersion-shifted fibre

Corning SMF-DS

NA = 0.17
$\Delta = 0.90\%$
Spot size diameter = 8.1 μm
$\lambda_{ZD} = 1.550$ μm

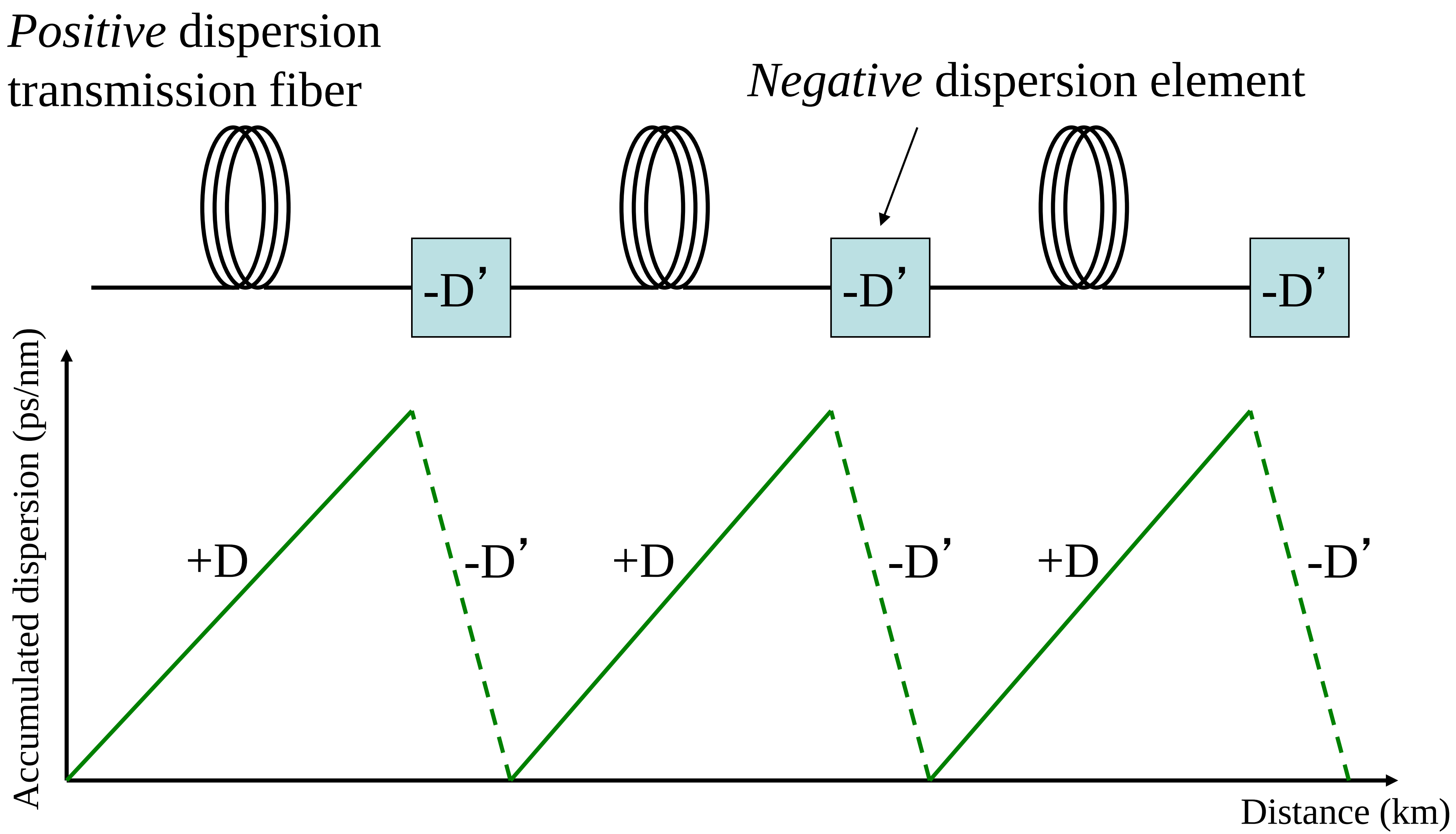
Chromatic Dispersion Compensation

- 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}).

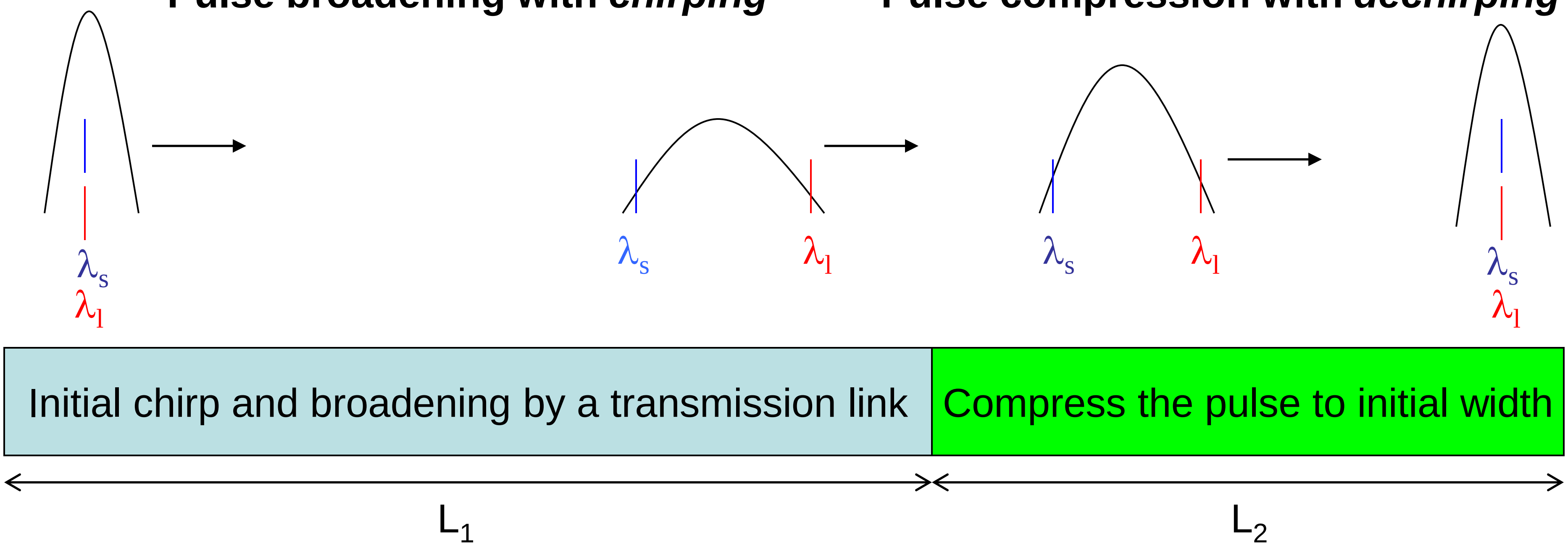


• In a *dispersion-managed* system, positive dispersion transmission fiber *alternates with negative dispersion compensation elements*, such that the *total* dispersion is *zero* end-to-end.

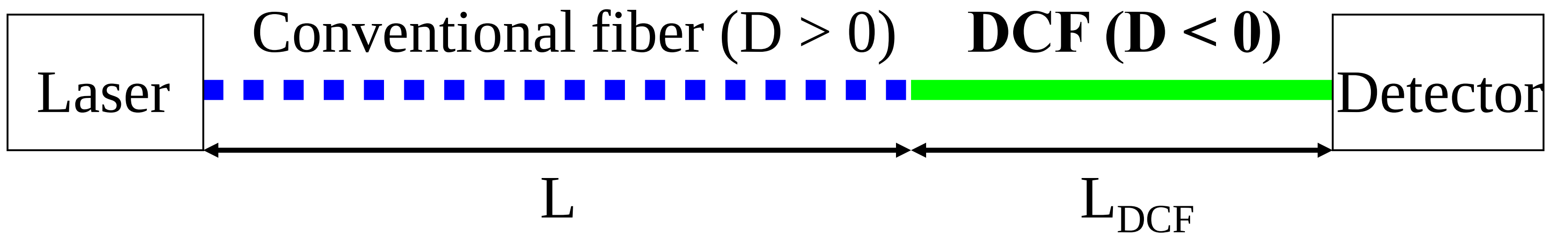
Dispersion-Compensating Fiber

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

Pulse broadening with *chirping* **Pulse compression with *dechirping***



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

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

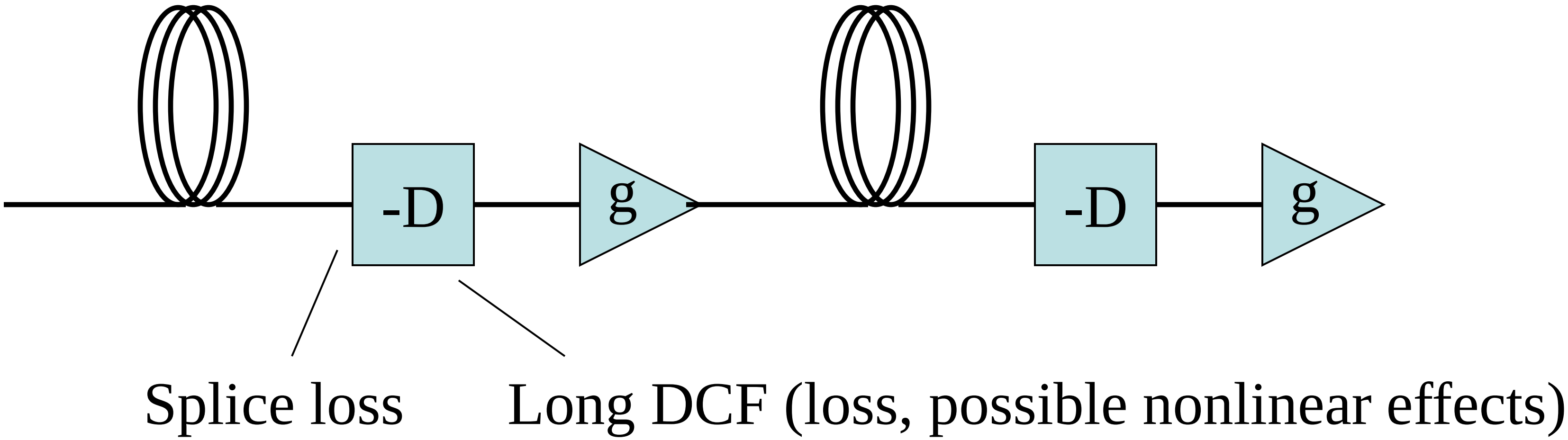
*Typically, **only one wavelength can be compensated exactly.** Better CD compensation requires **both *dispersion* and *dispersion slope* compensation**.

Disadvantages in using DCF

- *Added loss* associated with the increased fiber span

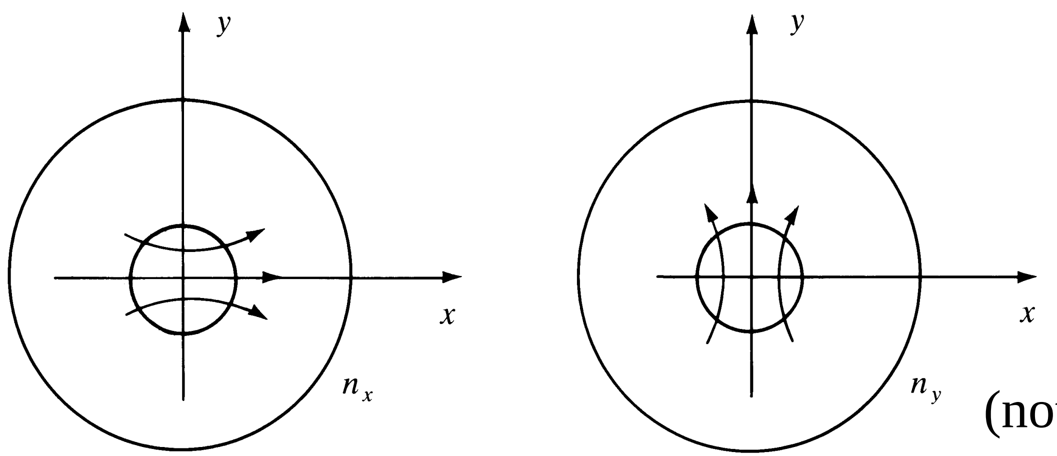
- *Nonlinear effects* may degrade the signal over the long length of the fiber if the signal is of sufficient intensity.

- 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***.

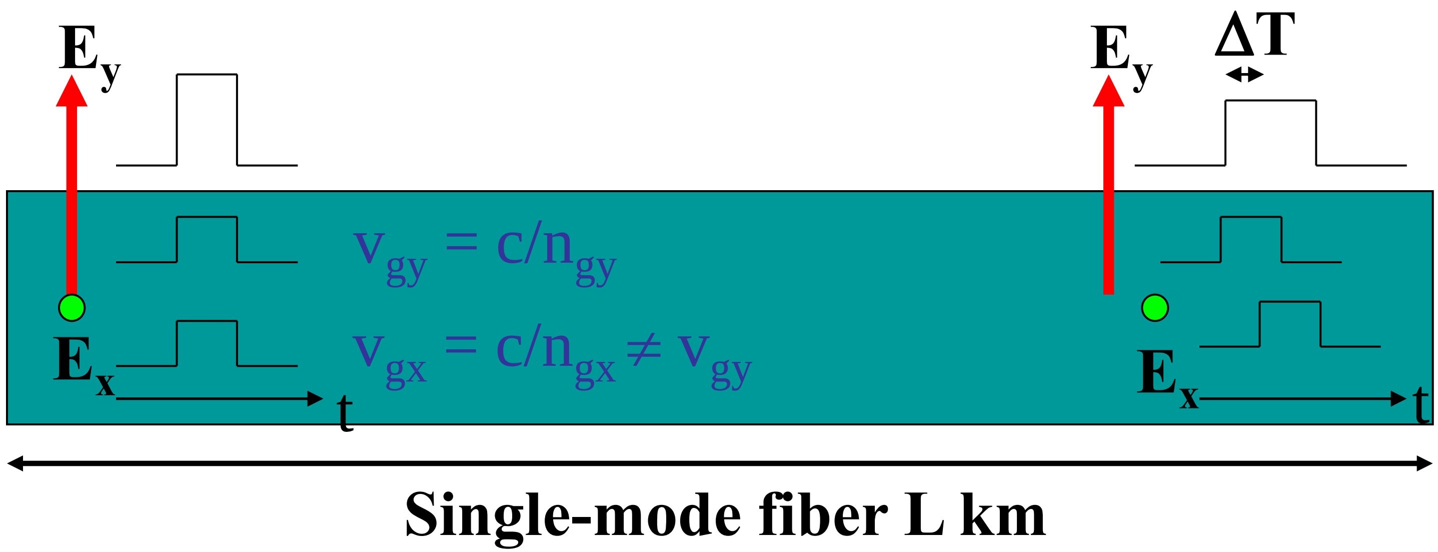


Horizontal mode

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**.



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*****.**

$$B = n_x - n_y$$

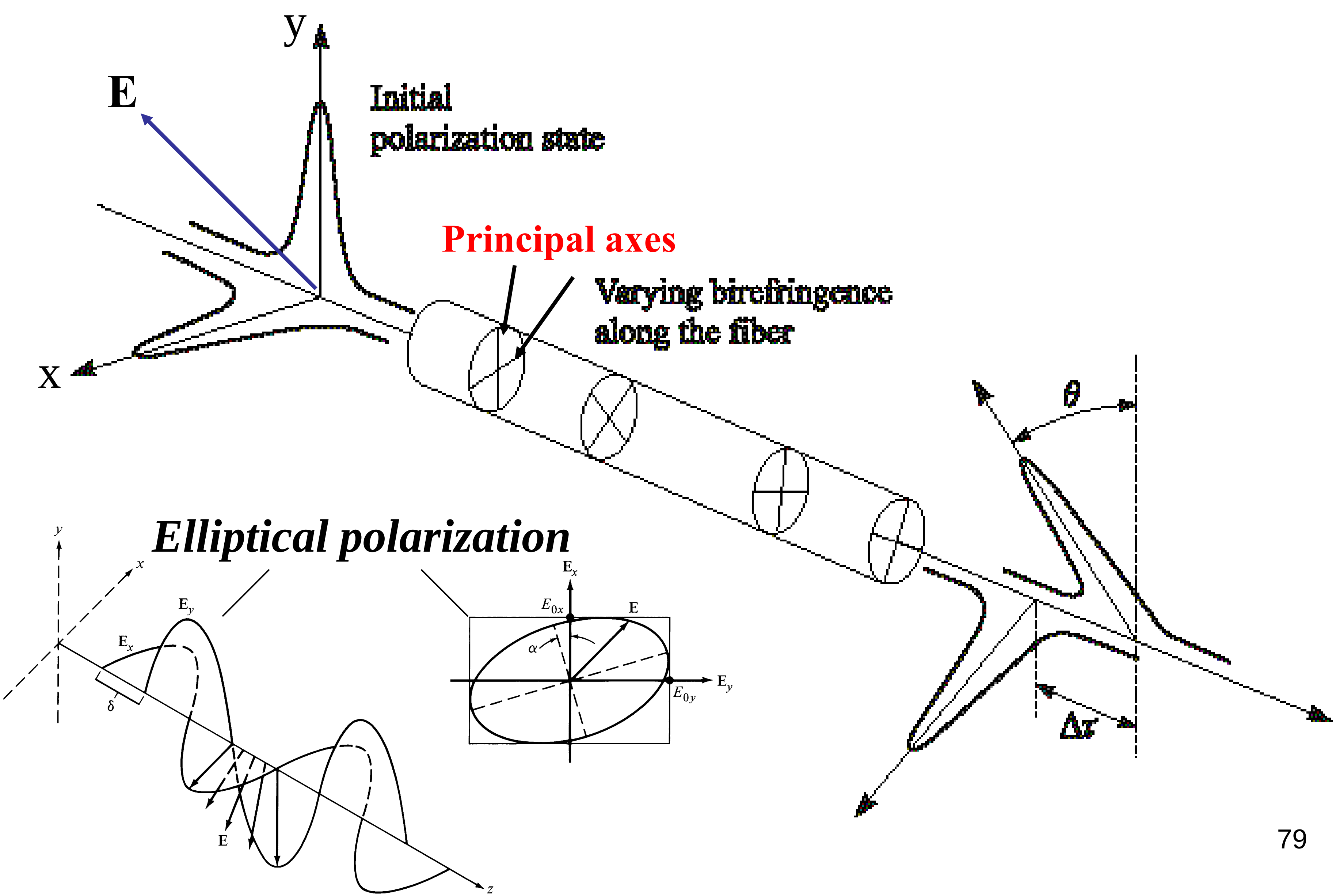
(~ 10^{-6} - 10^{-5} for single-mode fibers)

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

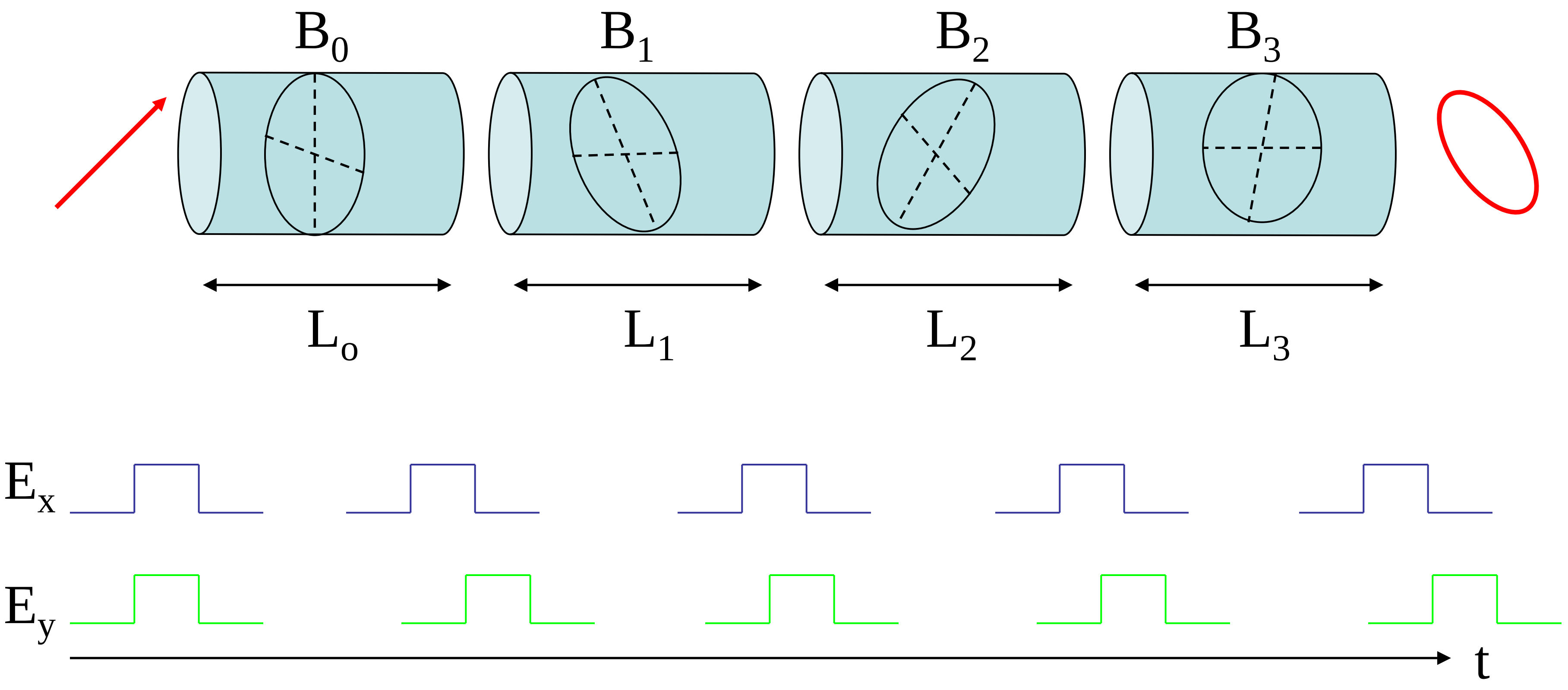


• The polarization state of light propagating in fibers with ***randomly varying birefringence*** will generally be ***elliptical and would quickly reach a state of arbitrary polarization***.

*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*!

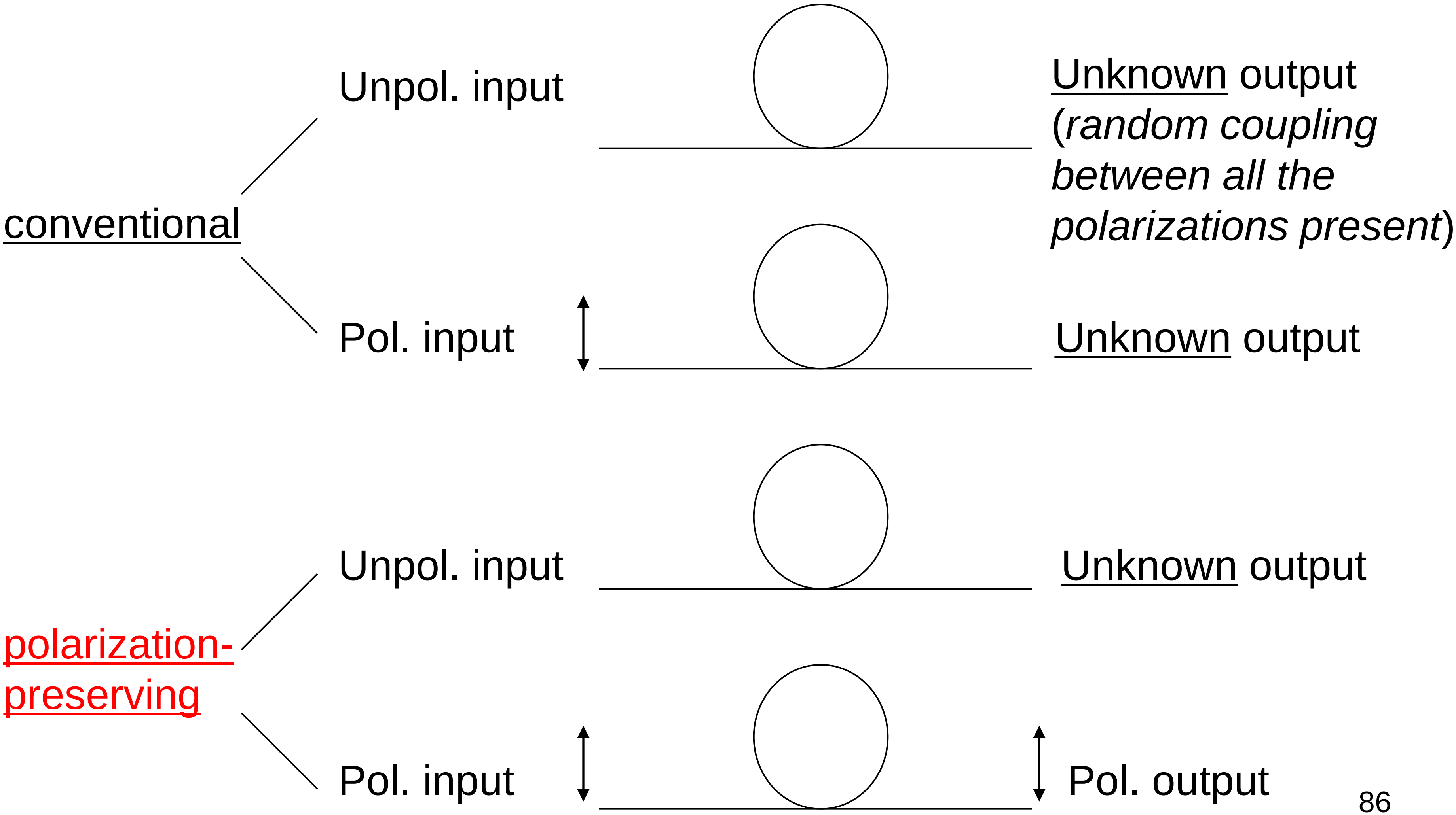
• PMD is of lesser concern in lower data rate systems. At lower transmission speeds (***up to and including 10 Gb/s***), networks have higher tolerances to all types of dispersion, including PMD.

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



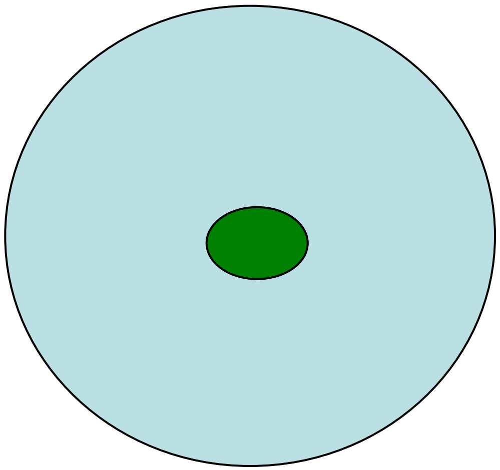
Polarization-preserving fibers

- The fiber birefringence is enhanced in single-mode *polarization-preserving* (*polarization-maintaining*) fibers, which are designed to maintain the polarization of the launched wave.

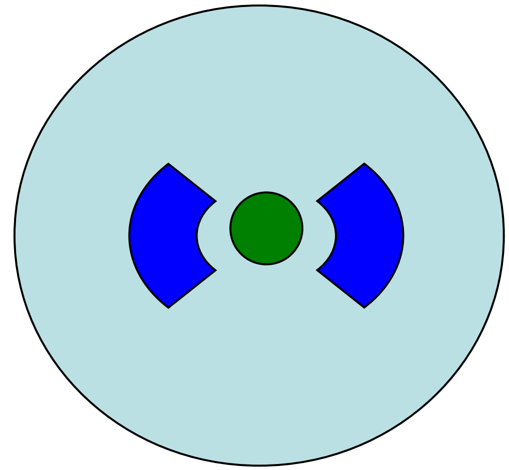
- *Polarization is preserved* because the two possible waves have significantly different propagation characteristics. This keeps them from exchanging energy as they propagate through the fiber.

- Polarization-preserving fibers are constructed by designing *asymmetries* into the fiber. Examples include fibers with elliptical cores (which cause waves polarized along the *major* and *minor* axes of the ellipse to have different effective refractive indices) and fibers that contain nonsymmetrical stress-producing parts.

Polarization-preserving fibers



<u>Elliptical-core fiber</u>



<u>bow-tie fiber</u>

- 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