Chapter 5

Single-Mode Fibers – Basics

- How a single-mode fiber works（工作原理）
- Attenuation（衰减）
- Dispersion & bandwidth（色散与带宽）

5.1 How a Singlemode Fiber Works

◆ The principle of action

for fundamental mode LP_{01}， Cutoff number: $V_c = 0$

for LP_{11}， Cutoff number: $V_c = 2.405$

Singlemode operation: *（单模工作）*

$$V < 2.405 \quad \text{or} \quad \lambda > \lambda_c$$

where:

$$V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2} \approx \frac{\pi d n}{\lambda}\sqrt{2\Delta}, \qquad \Delta = \frac{n_1 - n_2}{n}$$

$$\lambda_c = \frac{\pi d \sqrt{n_1^2 - n_2^2}}{2.405}$$

Decrease d: <10um←50/62.5um,and even 1000um

Increase λ: >1300nm←650nm

Decrease Δ: <0.4%←1-2%

Smaller critical propagation angle and NA!

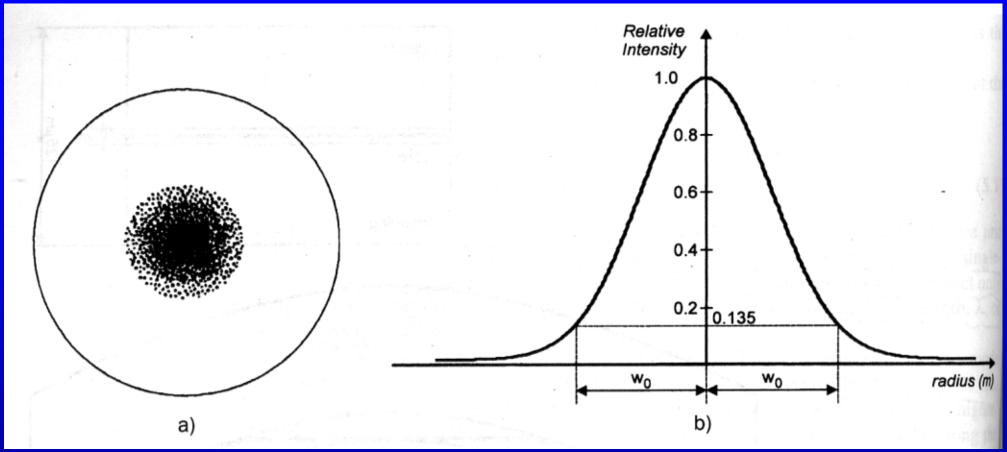
◆ Gaussian Beam （高斯光束）

-> A beam of light does not have strict cross-sectional boundaries.

-> The most popular model used in singlemode fiber is Gaussian curve:

$$I(r) = I(0)e^{-\frac{2r^2}{w_0^2}}$$

where $2w_0$ is the mode-field diameter.（模场直径）

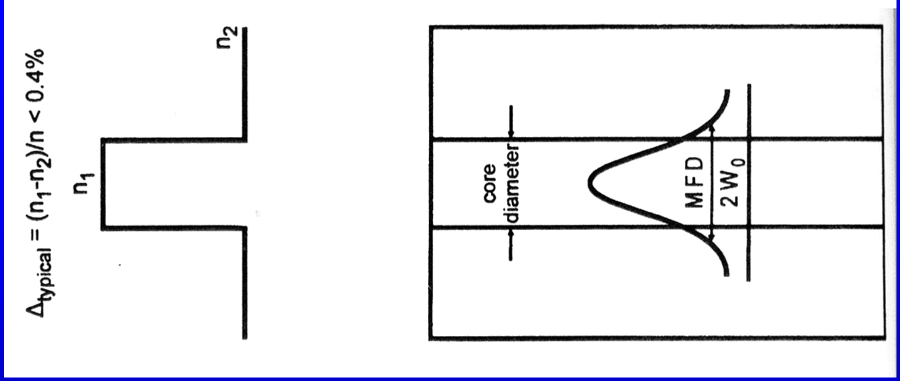


◆ Core, Cladding, and Mode Field Diameter（模场直径）

-> Manufactures use the mode-field diameter, MFD, rather than the core diameter.

-> The essential portion of the light (typically, about 20%) is carried by the cladding.

-> The refractive index profile might be too complex to precisely detect the border between the core and the cladding.



Typical dimensions of MFD and the core diameters in step-index single-mode fibers are 9.3 and 8.3 um.

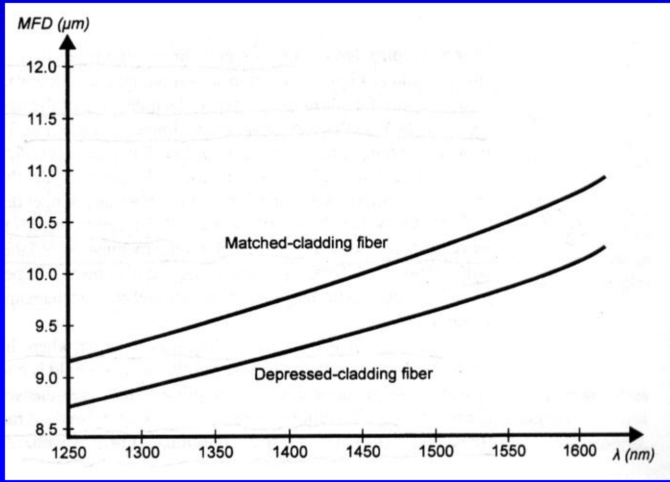
-> The fiber's effective refractive index is the combination of the core and cladding refractive index.（有效折射率）

-> The mode-field diameter depends on operating wavelength.

Longer wavelength →

Larger MFD →

Worse Confinement



-> If two fibers have different mode-field diameters, one will have extra insertion loss:（插入损耗）

$$Loss_{CoulingMFD}(dB) = -10\log[4/(MFD_1/MFD_2 + MFD_2/MFD_1)^2]$$

Closer MFD → Better Matching → Less Insertion Loss

◆ Cutoff wavelength（截止波长）

-> Cutoff wavelength written as the refractive index:

$$\lambda_c = \{\pi d\sqrt{[(n_1)^2 - (n_2)^2]}\}/2.405$$

correct in page 143.

-> Cutoff wavelength written as the numerical aperture:（数值孔径）

$$\lambda_c = 1.306 d\,NA$$

correct in page 144.

-> The optical fiber can be singlemode or multimode, which depends on the operation wavelength.

5.2 Attenuation（衰减）

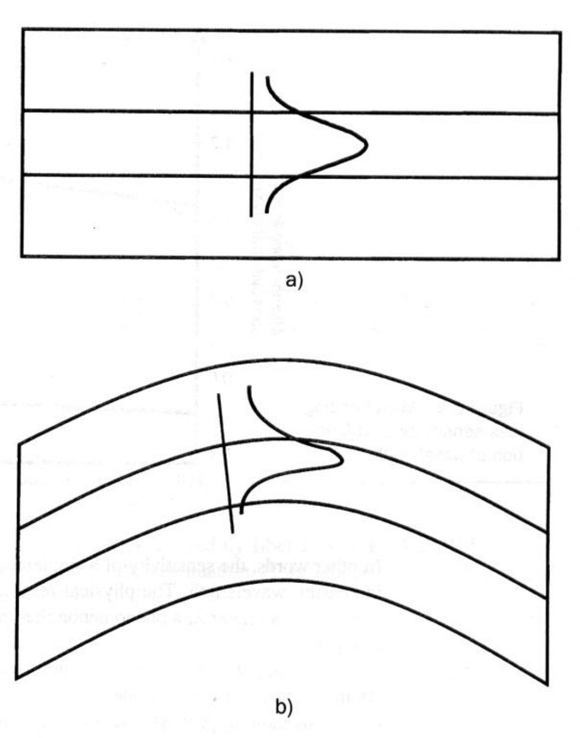
◆ Bending loss（弯曲损耗）

- Macrobending loss（宏弯损耗）

-> Change of the mode field

- A longer “tail” appears at the outer side of the cladding (*depending on wavelength*)

-> Traveling velocity analysis (-> loss)



A singlemode fiber is more sensitive to bending than is a multimode fiber!

-> Properties of Macrobending Loss

i. changing in exponential form with bending radius（指数形改变）

ii. relate to operation wavelength

iii. depend on parameter Δ or NA

ii & *iii*： less normolized MFD, less bending loss, MAC=MFD/λ_c

- Microbending Loss： （微弯损耗）

-> Mechanism is the same of multimode fiber : *stress induced by cabling process, or thermal stress.（成缆工艺，热应力）*

-> Dependence on wavelength： *Larger wavelength, more micro-bending loss (**because the MFD increases**)*

◆ Scattering（散射）

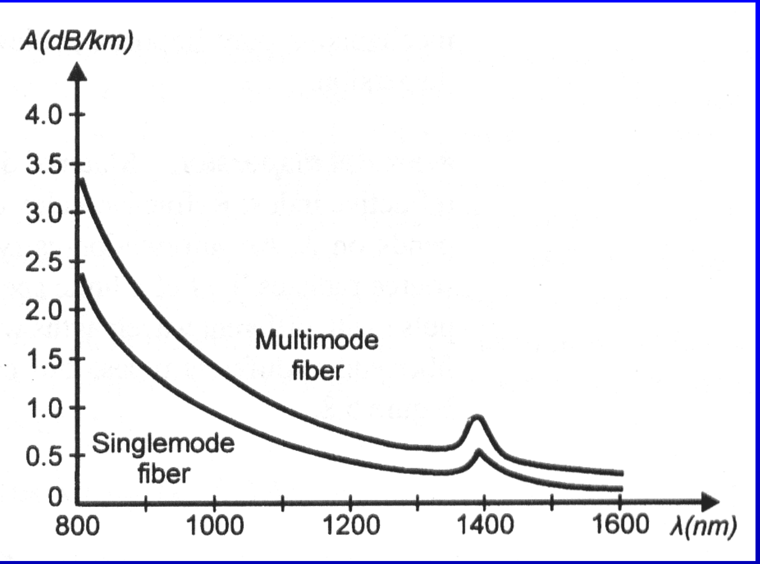
-> Mechanism : Small changes in the core's refractive index

-> Scattering loss determines the spectral dependence

◆ Absorption（吸收）

-> Mechanism
The absorption by SiO_2, and imperfections (e.g. OH^-)

-> <u>Less absorption loss !</u>
(Smaller MFD of LP_{01} in SMF;
Another important advantage of SMF, except for the absence of inter-modal dispersion)



5.3 Dispersion and Bandwidth

Dispersion in a singlemode fiber : (no intermodal dispersion)

chromatic dispersion + polarization-mode dispersion **（色度色散+偏振模色散）**

◆ Chromatic Dispersion

(material dispersion + waveguide dispersion)（材料色散+波导色散）

-> Pulse signal bandwidth： $\Delta\lambda << \lambda_0$

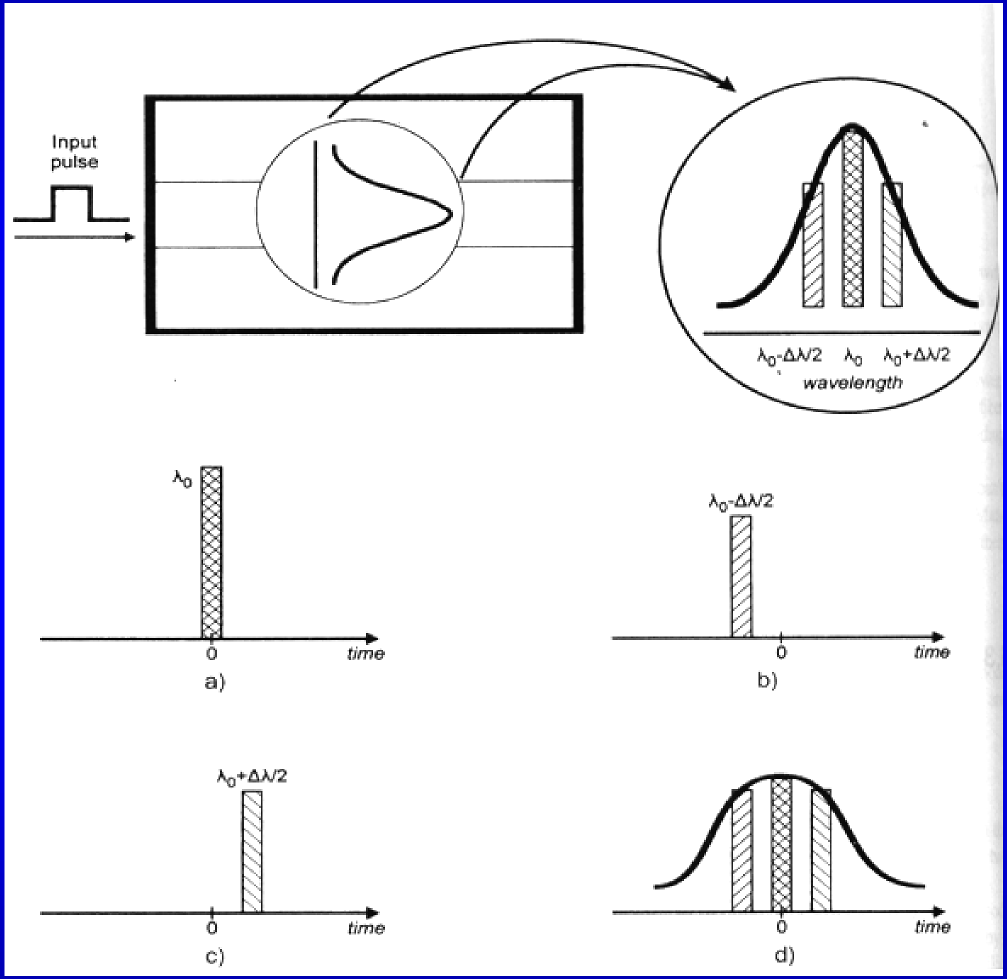
-> Signal spreading： $\Delta t = t(\lambda_0 + \frac{\Delta\lambda}{2}) - t(\lambda_0 - \frac{\Delta\lambda}{2})$

$$= \left.\frac{dt}{d\lambda}\right|_{\lambda=\lambda_0} \Delta\lambda$$

-> Dispersion characteristics: (unit： ps /nm.km)

$$D(\lambda) = \frac{1}{L}\frac{dt}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) \qquad \text{or,} \qquad \Delta t = LD(\lambda_0)\Delta\lambda$$

- Material Dispersion （材料色散）



(a) Pulse fraction delivered by λ_0 component.

(b) Pulse fraction delivered by λ_0-Δλ/2;

(c) Pulse fraction delivered by λ_0+Δλ/2;

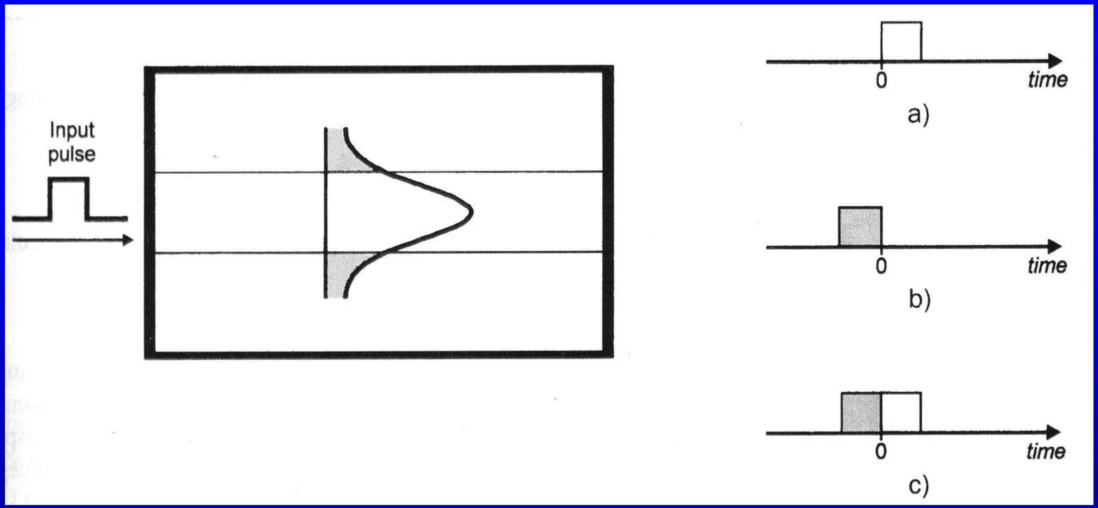
(d) Output pulse.

● Waveguide Dispersion （波导色散）

-> Waveguide dispersion is one of major components of chromatic dispersion in singlemode fibers. （占重要部分）

-> Pure waveguide dispersion occurs merely from restricting light within a certain structure.

-> Waveguide dispersion depends on the mode-field distribution between the core and the cladding. (Dependent on wavelength !)



- Chromatic dispersion in a singlemode fiber

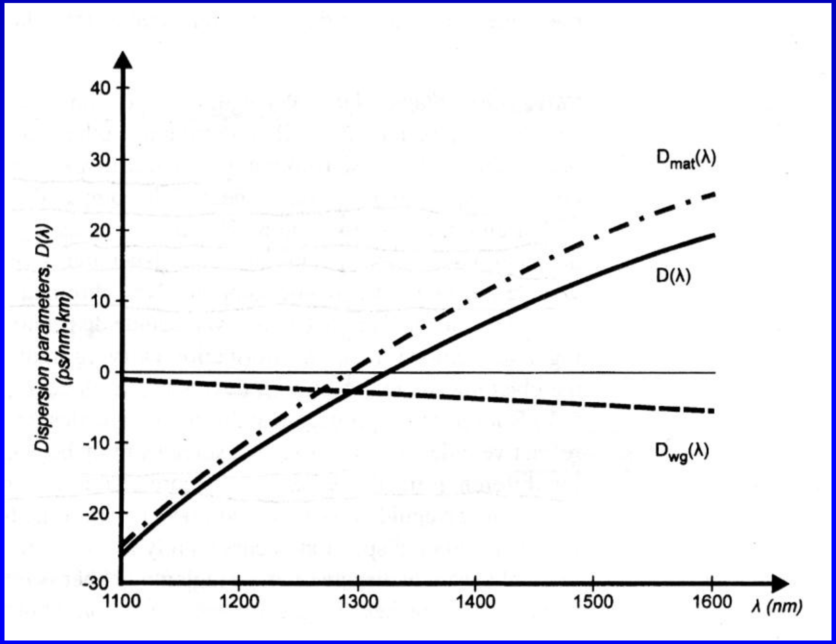
$$D = D_{mat} + D_{wg}$$

Basic Properties:

(1) $D_{mat} < 0$, when λ<1300nm;

$D_{mat} > 0$, when λ>1300nm.

(2) $D_{wg} < 0$ and $|D_{wg}|$ increase with λ.



-> The material and waveguide dispersion cancel with each other, which results in a zero-dispersion wavelength occurs around 1310nm.

（零色散波长）

Question:

How to explain $D_{wg} < 0$ in the single-mode fiber ?

It means: $$\frac{d}{d\lambda}\left(\frac{1}{v_g}\right) < 0 \quad \Rightarrow \quad \frac{dv_g}{d\lambda} > 0$$

or, V_g *increase with* λ.

Indeed, the guided mode will spread to cladding with increasing of wavelength λ.

From the structure of optical fiber, one can learn that

$$c/n_2 > c/n_1 \longrightarrow \lambda \uparrow, \quad V_g \uparrow$$

Example:

Dispersion of singlemode optical fibers

$$\lambda_0 = 1.31\mu m, \quad \Delta\lambda = 1nm, \quad L = 1km$$

$$D = -2\,ps/nm \cdot km$$

$$|\Delta t| = D\Delta\lambda L = 0.002ns$$

Comparing to multimode optical fiber：

Step-index： $\Delta t \sim 5.6ns/km$

Graded-index： $\Delta t \sim 0.21ns/km$

◆ Conventional, Dispersion-Shifted, and Dispersion-Flattened Fibers （常规，色散位移，色散平坦光纤）

One has learned：

$\lambda \sim 1.31\mu m \qquad D \approx 0$

$\lambda \sim 1.55\mu m \qquad D \sim 15\, ps/nm \cdot km$ （*but, with minimum attenuation!*）

Problem： How to decrease the dispersion around $\lambda \sim 1.55\mu m$

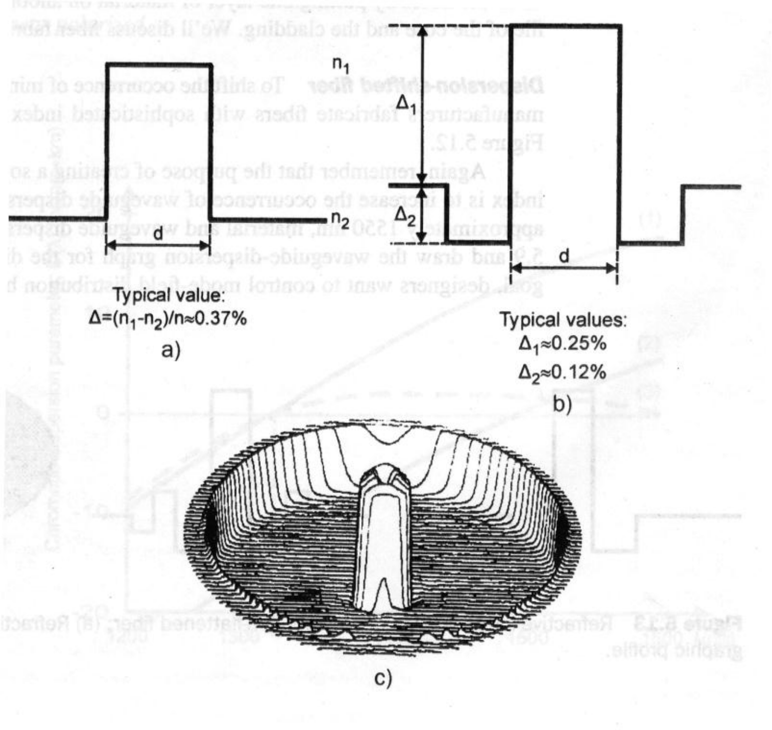
$$D = D_{mat} + D_{wg}$$

D_{mat}： is difficult to be changed

D_{wg}： depends on fiber structure， which can be changed

Effective way： —> change fiber structure $D_{wg} \approx -D_{mat}$

- Conventional Fibers : zero-dispersion wavelength is around 1300 nm.



a) matched cladding fiber

(匹配包层光纤)

b) depressed cladding fiber

(凹陷包层光纤)

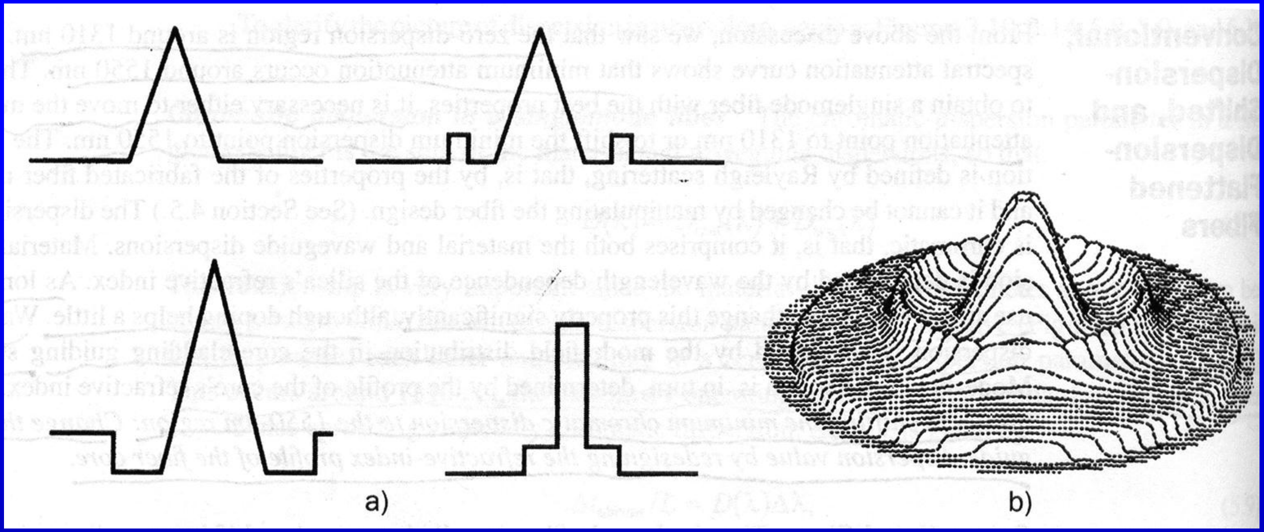
-> to reduce coupling to *cladding* modes

- Dispersion-Shifted Fibers (色散位移光纤)

-> To shift the minimum dispersion, designers can control ***mode-field distribution*** by changing the profiles of the core and cladding.

-> The triangular-shaped core refractive index is the most popular.

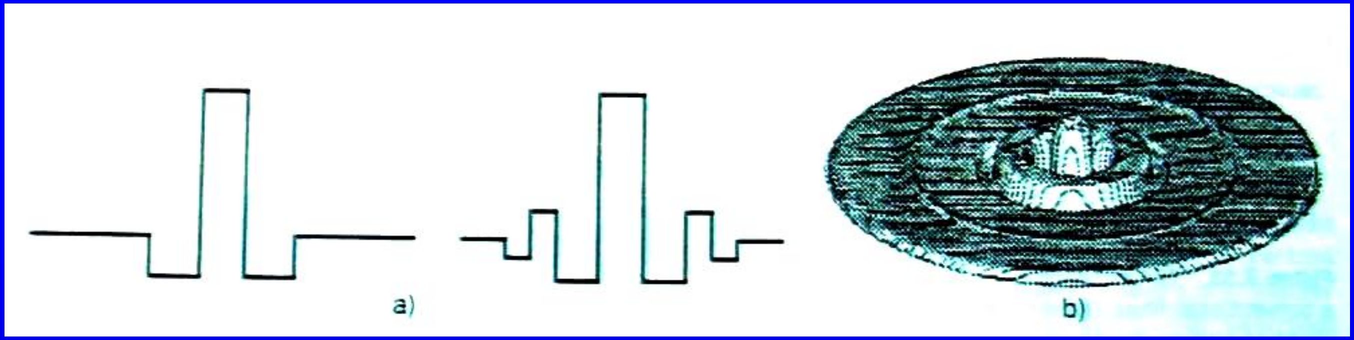
（三角形芯层折射率分布）



- Dispersion-Flattened Fibers (色散平坦光纤)

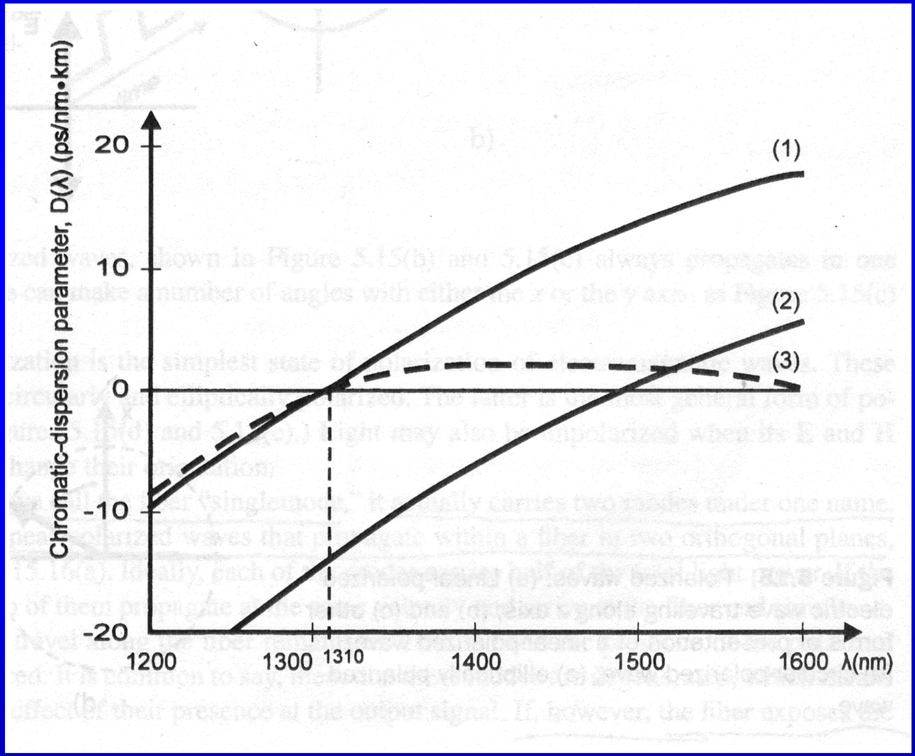
  -> WDM system need the zero-dispersion property distributed along a region of wavelengths.

  -> In 1988, it is made out by Philips Ltd..（飞利浦公司）



Chromatic-Dispersion Parameters

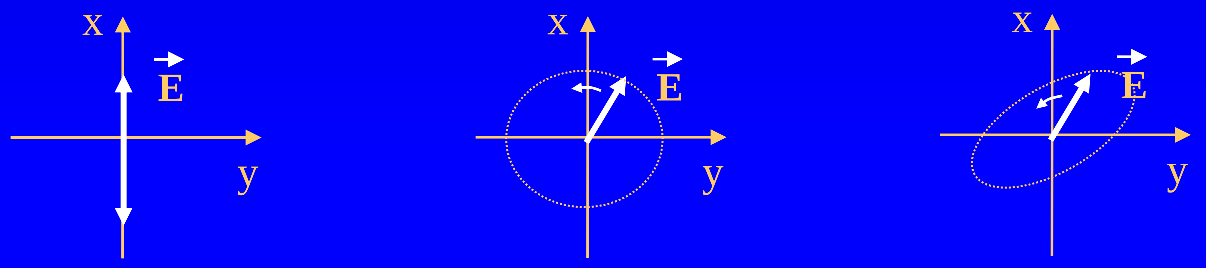
for (1) conventional, (2) dispersion-shifted, (3) dispersion-flattened fibers



◆ Polarization-Mode Dispersion (PMD)（偏振模色散）

-> Ideal circular optical fibers: *(without birefringence 没有双折射）*

(1) Fundamental mode is linear polarized; （线偏振）
(2) Propagation in optical fiber is independent on polarization

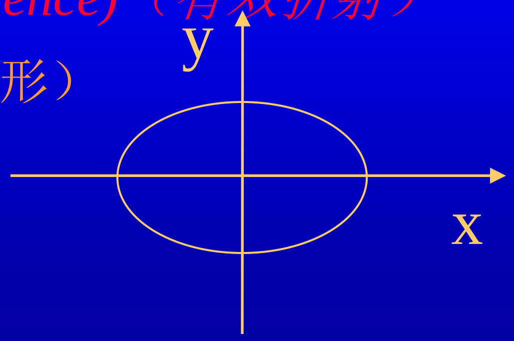


(a) (b) (c)

-> Real optical fiber: *(with birefringence)（有双折射）*

(1) existence of non-circularity; （非圆形）

(2) close to elliptic shape.（椭圆形）



Input arbitrary polarized pulse:

$$\vec{E} = E(\hat{x}\cos\theta + \hat{y}\sin\theta)$$

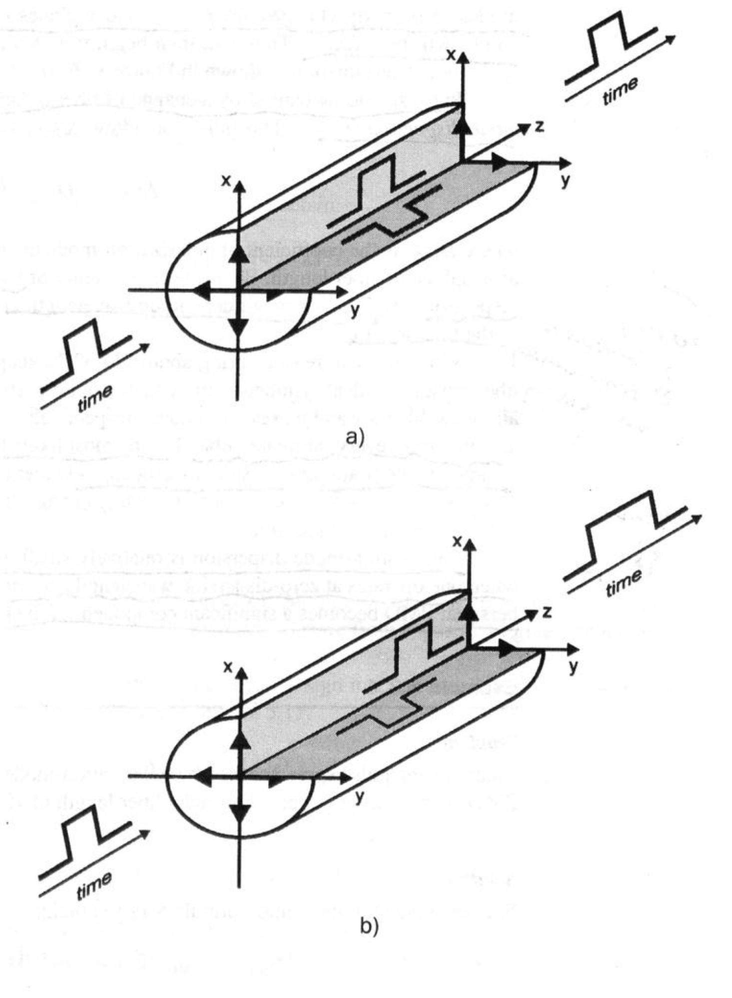
LP_{01}： HE_{11}*2

Excite two linear-polarizations of signal pulse to propagate with different velocities（不同速度）

$$\beta_x \neq \beta_y$$

Pulse spreading（脉冲展宽）

Polarization Mode Dispersion (PMD)



-> Causes of PMD

Some asymmetry induced by the stress from fabrication, cabling process, external force, bending, etc.（引入非对称）

-> PMD is a stochastic process！ （随机过程）

$$\Delta t_{PMD} \approx D_{PMD}\sqrt{L}$$

（statistical result）（统计结果）

-> D_{PMD} does not depend on operation wavelength！

-> D_{PMD} does depend on the square root of the fiber length！

◆ Bandwidth of a Singlemode Fiber（带宽）

$$BR < \frac{1}{4\Delta t}$$

-> SMF： $\Delta t = D(\lambda)\Delta\lambda L \quad \Rightarrow \quad BR = 1/(4D\Delta\lambda L)$

：Example-1：

$$\lambda_0 = 1310\ nm, \quad \Delta\lambda = 1nm, \quad BR_{chrom}\big|_{1300nm} = ?$$

$$D = -2\ ps/nm\cdot km$$

$$BR_{chrom} \times L = 1/(4\times 2\ ps/nm\cdot km \times 1nm) = 125Gbps\cdot km$$

$$\Rightarrow BR_{chrom} = 1.25Gbps \quad (for\ \ 100km\ \text{link})$$

：Example-2：

$$D_{PMD} = 0.5\ ps/\sqrt{km}, \quad BR_{chrom}\big|_{1300nm} = ?$$

$$BR_{PMD} = 1/(4\times\Delta t) = 1/(4\times 5\ ps) = 50Gbps \quad (for\ 100km)$$

Homework

- 5.5, 5.6, 5.13, 5.17, 5.18

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