Chapter 2.4

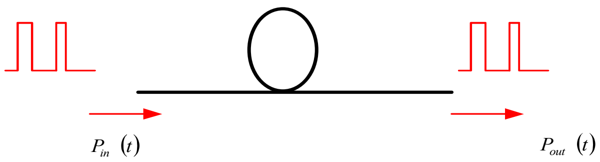
Fiber dispersion and the measurement methods

Except the fiber loss, there is another important fiber parameter, it is the fiber dispersion.

Dispersion is the spreading out of light pulses as they travel along a fiber. It occurs because the speed of light through a fiber depends on its wavelength and the propagation mode.

The differences in speed is slight, but like loss, they accumulate with distance.

In fiber communication systems, the signal is transmitted in the form of light pulse.

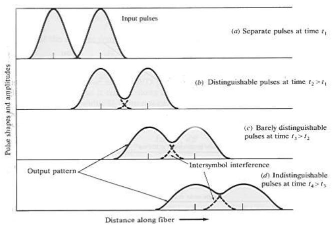


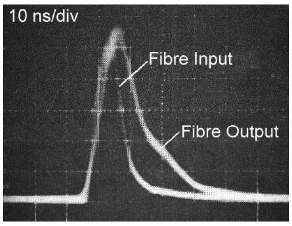
Fiber dispersion → Pulse spreading →

Interference between different temporal signals →

Increasing error rate → Decreased transmission rate

→ Shortened distance between repeater stations





The influence of dispersion on fiber communication systems and the corresponding compensation methods 、

[色散对光通信系统的影响及补偿色散的方法]

- Fiber dispersion limits transmission bandwidth of fiber communication systems
- The higher the transmission rate, more obvious the influence of dispersion on the system is.
- The dispersion can be compensated by suitable fiber design or introducing extra dispersion compensation modules.
- The influences resulted from dispersion can be also partly reduced by suitable source selection.

Therefore, the dispersion is worth investigating.

The types of dispersion

There are four main types of dispersion:

(1) Modal dispersion
from multimode transmission

This type of dispersion is not caused by the different frequencies, it is resulted from the different group velocities of different guided modes

(2) Material dispersion
from the dependence of refractive index on wavelength

(3) Waveguide dispersion
from variations in waveguide properties with wavelength

These two types of dispersion are related to light frequency thus called as chromatic dispersion [色度色散]

(4) Polarization-mode dispersion
from transmission of two different polarizations of light (mainly in SMF)

In the simplest sense, dispersion measures the pulse spreading per unit distance in nanoseconds or picoseconds per kilometer.
Total pulse spreading, Δt, is

$$\Delta t = \text{dispersion (ns/km)} \times \text{distance (km)}$$

In another form:

$$\Delta t_{\text{total}} = \sqrt{(\Delta t_{\text{modal}})^2 + (\Delta t_{\text{chromatic}})^2 + (\Delta t_{\text{polarization-mode}})^2}$$

In multimode fiber, the polarization-mode dispersion is small enough that it doesn't matter, thus the case simplified to:

$$\Delta t_{\text{total}} = \sqrt{(\Delta t_{\text{modal}})^2 + (\Delta t_{\text{chromatic}})^2}$$

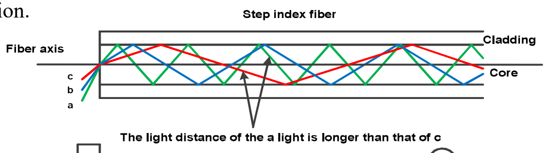
In single mode fiber, there is no modal dispersion, so the equation becomes:

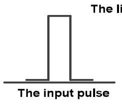
$$\Delta t_{\text{total}} = \sqrt{(\Delta t_{\text{chromatic}})^2 + (\Delta t_{\text{polarization-mode}})^2}$$

(1) Modal dispersion

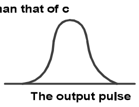
In the multimode fiber, many guided modes are allowed.

The different group velocities of the guided modes as a result of different optical paths lead to the time delay between different guided modes, i.e. dispersion.





$$\Delta t_{\text{modal}} = \frac{L\Delta n_1}{cn_2}$$



Δ is the difference of refractive indexes

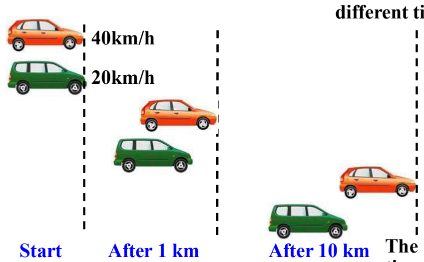
The modal dispersion can be reduced or removed by using graded or single mode fiber.

(2) Chromatic dispersion and wavelength

What is chromatic dispersion?

There is an example

The difference in speed between the two cars (or two components of light) causes them to arrive the end at different times



Start
0 min diff

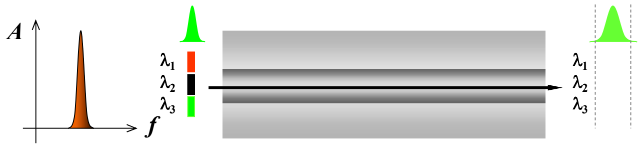
After 1 km
1.5 min diff

After 10 km
15 min diff

The longer the distance , the more time difference between them

色度色散

Common light source has a pulsed bandwidth of >0.001 nm



Chromatic dispersion is pulse spreading that arises by that the velocity of light through a fiber depends on its wavelength.
It is measured in units of picoseconds (of pulse spreading) per nanometer (of spectral width of the optical signal)per kilometer (of fiber length).

$$\Delta t_{\text{chromatic}} = \text{chromatic dispersion(ps/nm/km)} \times \Delta\lambda(\text{nm}) \times \text{fiber length(km)}$$

色度色散的计算

For example:

For a single mode fiber, the chromatic dispersion is 17 ps/nm/km, the spectral width of a common laser diode is 6 nm, the transmission distance is 10 km, the total pulse spreading caused by chromatic dispersion is:

$$\Delta t_{\text{chromatic}} = 17\text{ps/nm/km} \times 6\text{nm} \times 10\text{km} = 1020\text{ps}$$

For a pulse with 1 Gbps transmission rate of data, the pulse width is ~1 ns. If the pulse spreading is 20% of the pulse width, the system can not work. Thus, 1020 ps is too large for 1Gbps speed. But for it is ok 155 Mbps speed system, because it's pulse width is 6.5 ns and 20% of the pulse width is 1300 ps.

色度色散的计算

Question:

For a light source with a spectral width of 0.02 nm, it transmit in a single mode fiber with the chromatic dispersion of 17 ps/nm/km, and the transmission distance is 100 km.
What is the total pulse spreading caused by chromatic dispersion?
What is the maximum transmission rate of data of the system in 100 km?

$$\Delta t_{\text{chromatic}} = 17\text{ps/nm/km} \times 0.02\text{nm} \times 100\text{km} = 34\text{ps}$$

$$t_{\text{pulsewidth}} = \Delta t_{\text{chromatic}} / 0.2 = 170\text{ps}$$

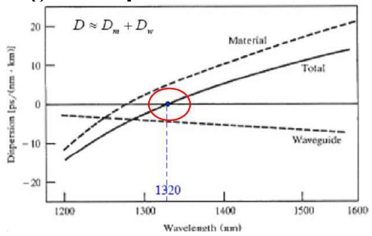
$$V = 1/170 = 5.8\text{Gbps}$$

色度色散的计算

In single mode fiber systems, the chromatic dispersion is the largest type of dispersion.

[单模光纤中，色度色散是影响最大的色散]

The chromatic dispersion is the sum of two components, i.e., material and waveguide dispersions.



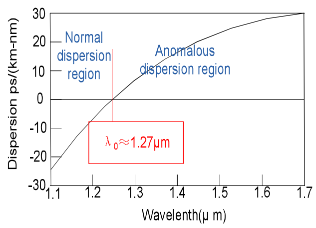
To understand chromatic dispersion, we need to look at both material and waveguide dispersions

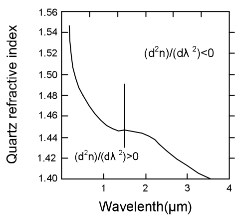
色度色散——材料色散

•**Material dispersion** (no-chirped)±都会展宽; (chirped)+展宽,-压缩

It is arises from the change in material's refractive index with wavelength.

The higher the refractive index, the slower light travels.





Normal dispersion region: the longer wavelength components transmit faster (negative material dispersion value)
Anomalous dispersion region: the shorter wavelength components transmit faster (positive material dispersion value)
In either normal or anomalous dispersion region, the pulse would be spread.

色度色散——材料色散

A closer look at material dispersion

Group delay is defined as the time that light travels a unit distance along the fiber axis.

Therefore

$$\text{Group velocity} = \frac{d\omega}{d\beta}$$

$$\text{Group delay} = \frac{d\beta}{d\omega}$$

$$\beta = \boxed{nk} + \boxed{nkb\Delta}$$

Material **Waveguide**

$$D = \frac{d(\text{group delay})}{d\lambda}$$

色度色散——相速度和群速度

Phase velocity and the group velocity

•At the end of the 19th Century, it was found that different measurement methods lead to different refractive indexes of the medium.

•In 1885, Michelson measured the ratio of light speed in vacuum to that in water according to $n=c/v$. The ratio is just the refractive index of the water 1.33 matching well with that measured by Foucault in 1860.

Michelson measured the ratio of light speed in vacuum to that in carbon disulfide to be 1.758. However, the measured value according to refraction law is 1.64.

There is a significant difference between them, why?

色度色散——相速度

* phase velocity $\upsilon_p \rightarrow$

the tranmission velocity of equiphase surface

$$E = E_0 \cos(\omega t - \beta z + \varphi_0)$$

$$\text{equiphase surface equation: } \theta = \omega t - \beta z + \varphi_0 = \text{const}$$

$$\text{perfect differential: } d\theta = \omega dt - \beta dz = 0$$

Phases at（z, t）and（z+dz, t+dt）are the same

$$\text{thus} \quad \upsilon_p = \frac{dz}{dt} = \frac{\omega}{\beta}$$

$$\upsilon_p = \frac{\mathrm{d}z}{\mathrm{d}t} = \frac{\omega}{\beta} = \frac{c}{n}$$

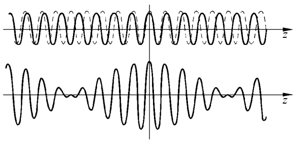
c is the light speed in vaccum

In vacuum, monochromatic 单色光 lights transmit at a same phase speed c, polychromatic light can be regarded as the superposition of some monochromatic lights, thus the phase speed of polychromatic light in vacuum is equal to that of monochromatic light in vacuum.

In medium, monochromatic lights transmit at different phase velocities, thus the phase velocity of polychromatic light is complex.

＊ Group velocity υ_g

Supposing a polychromatic 多色光 light contains two monochromatic lights with the similar frequencies and an equal amplitude



$$E_1 = E_0 \cos(\omega_1 t - \beta_1 z)$$
$$E_2 = E_0 \cos(\omega_2 t - \beta_2 z)$$

set $\omega = (\omega_1 + \omega_2)/2, \ \beta = (\beta_1 + \beta_2)/2$

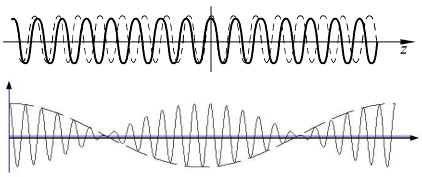
$$\omega_1 = \omega + \Delta\omega, \ \beta_1 = \beta + \Delta\beta$$
$$\omega_2 = \omega - \Delta\omega, \ \beta_2 = \beta - \Delta\beta \qquad \Delta\omega \ll \omega, \ \Delta\beta \ll \beta$$

$$E = E_1 + E_2 = 2E_0 \cos(t\cdot\Delta\omega - z\Delta\beta)\cos(\omega\cdot t - \beta\cdot z)$$

Slowly varied "simple harmonic wave"

$$E = E_1 + E_2 = 2E_0 \cos(t\cdot\Delta\omega - z\Delta\beta)\cos(\omega\cdot t - \beta\cdot z)$$

- Two-color wave is a simple harmonic wave with slow amplitude variation.

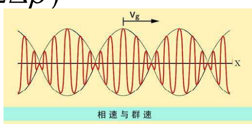


$$E = E_1 + E_2 = 2E_0 \cos(t\cdot\Delta\omega - z\Delta\beta)\cos(\omega\cdot t - \beta\cdot z)$$

Amplitude: $2E_0 \cos(t\cdot\Delta\omega - z\Delta\beta)$

Group velocity:

The transmission velocity of constant-amplitude surface

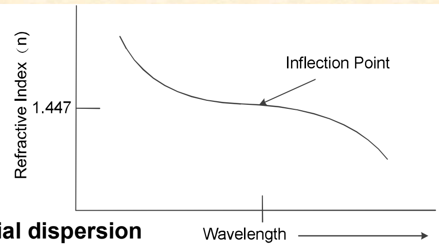


Constant amplitude $\longrightarrow t\cdot\Delta\omega - z\cdot\Delta\beta = \text{const}$

$$\mathrm{d}t\cdot\Delta\omega - \mathrm{d}z\cdot\Delta\beta = 0$$

The amplitudes at（*z*, *t*）and（*z*+d*z*, *t*+d*t*）are the same

$$\Rightarrow \upsilon_g = \frac{\mathrm{d}z}{\mathrm{d}t} = \frac{\Delta\omega}{\Delta\beta} \quad \rightarrow \frac{d\omega}{d\beta}$$



In this case i.e., material dispersion

$$Group\ \ delay = \frac{\mathrm{d}\beta}{\mathrm{d}\omega} = \frac{\mathrm{d}(nk)}{\mathrm{d}\omega} = \frac{\mathrm{d}(nk)}{\mathrm{d}(ck)} = \frac{1}{c}\frac{\mathrm{d}(nk)}{\mathrm{d}k}$$

$$= \frac{1}{c}\frac{\mathrm{d}(n\frac{2\pi}{\lambda})}{\mathrm{d}\frac{2\pi}{\lambda}} = \frac{1}{c}(n + \frac{2\pi}{\lambda}\frac{\mathrm{d}n}{\mathrm{d}\frac{2\pi}{\lambda}}) = \boxed{\frac{1}{c}(n - \lambda\frac{\mathrm{d}n}{\mathrm{d}\lambda})}$$

The group delay is related to the slope of the curve that plots refractive index as a function of wavelength.

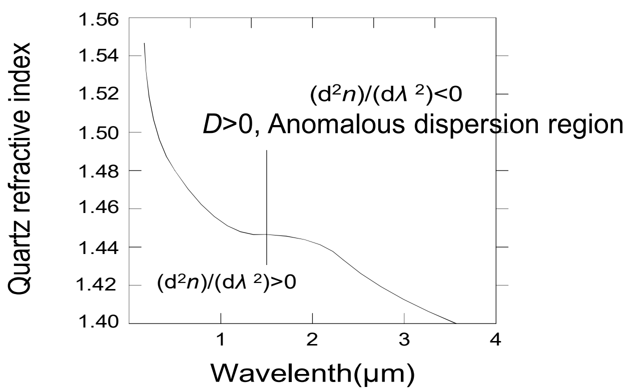
The characteristic dispersion can be calculated as the rate of change of the group delay with wavelength.

$$D_{\text{material}} = \frac{\mathrm{d(group\ delay)}}{\mathrm{d}\lambda} = \frac{-\lambda}{c}\cdot\frac{\mathrm{d}^2 n}{\mathrm{d}\lambda^2}$$

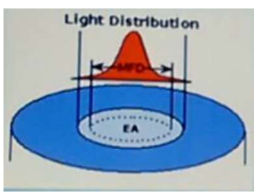
Characteristic dispersion is relative to the second order derivative of refractive index to wavelength. Therefore, we can not think the variable index with wavelength must lead to the material dispersion.

The total pulse spreading over the length of fiber can be calculated

$$\Delta t_{\text{material}} = D_{\text{material}} L\Delta\lambda = \frac{-L\lambda\Delta\lambda}{c}\cdot\frac{\mathrm{d}^2 n}{\mathrm{d}\lambda^2}$$



•Waveguide dispersion



It is a separate effect, arising from the distribution of light between core and cladding, which is wavelength dependent.

Light travels faster in the cladding and slower in the core, because higher refractive index in the core.

The distribution of long wavelength light stretches far in the cladding. Thus the efficient refractive index of longer wavelength light is smaller, and the group velocity of longer wavelength light is faster.

We can change the fiber's refractive index profile to achieve different waveguide dispersion.

波导色散

In this case i.e., waveguide dispersion

$$\text{Group delay (caused by waveguide dispersion)} = \frac{1}{c}\cdot\frac{\mathrm{d}(nkb\Delta)}{\mathrm{d}k} \approx \frac{n\Delta}{c}\cdot\frac{\mathrm{d}(Vb)}{\mathrm{d}V}$$

$$D_{\text{waveguide}} = \frac{\mathrm{d}\,(\text{Group delay})}{\mathrm{d}\lambda} \approx -\frac{V}{\lambda}\cdot\frac{\mathrm{d}\,(\text{Group delay})}{\mathrm{d}V}$$

$$\approx -\frac{n\Delta}{c\lambda}\cdot V\frac{\mathrm{d}^2(Vb)}{\mathrm{d}V^2}$$

$$\Delta t_{\text{waveguide}} = LD_{\text{waveguide}}\delta\lambda$$

$$= -\frac{Ln\Delta}{c\lambda}\cdot \boxed{V\frac{\mathrm{d}^2(Vb)}{\mathrm{d}V^2}}\delta\lambda$$

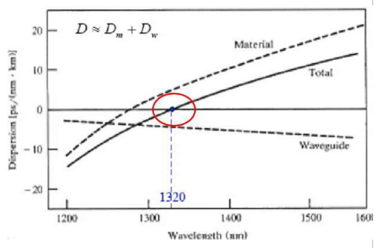
Waveguide dispersion factor

b is the normalized propagation constant

色度色散

The chromatic dispersion

$$\text{Disp}_{\text{chromatic}} = \text{Disp}_{\text{material}} + \text{Disp}_{\text{waveguide}}$$



$$|\text{Disp}_{\text{material}}| > |\text{Disp}_{\text{waveguide}}|$$

- Material dispersion is usually larger than waveguide dispersion;
- Waveguide dispersion is usually negative [负]
- Waveguide dispersion decreases with wavelength to offset the material dispersion

波导色散随波长减小，以抵消材料色散

光纤的发展

The development of optical fibers

(1) G.651 fiber: operation wavelength 850nm, multimode, loss 3 dB/km

(2) G.652 fiber: NDSF, zero dispersion wavelength 1310 nm, low loss wavelength 1550 nm

(3) G.653 fiber: DSF，zero dispersion wavelength 1550 nm；low loss wavelength 1550 nm

(4) G.655 fiber: NZDSF，Lucent: zero dispersion wavelength 1530 nm; Corning: >1570 nm

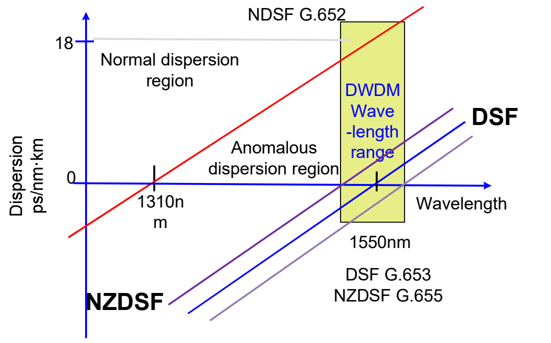
(5)G.656 fiber: DFF, almost unchanged dispersion at a comparatively large wavelength range.

(6) Large effective area fiber：LEAF，to decrease the nonlinear effects

(7) Dispersion compensation fiber：DCF，opposite dispersion to that of the transmission fiber

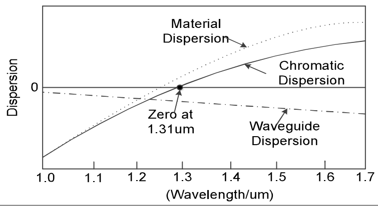
(8) All wave fiber： remove the absorption loss from OH^-

The dispersion comparison of three types of fibers



G.652 standard single mode fiber

- **Its near zero dispersion wavelength is 1.3 μm at which the transmission distance of the optical transmission is limited by the fiber loss.**
- **However, the loss of this type of fiber at 1.3 μm is comparatively large, about 0.3 dB/km~0.4 dB/km, at 1.5 μm is comparatively small, about 0.2 dB/km~0.25 dB/km.**
- **The chromatic dispersion is 3.5 ps/(nm·km) at 1.3 μm and 20 ps/(nm·km) at 1.55 μm. At 1.55 μm, this type of fiber can support 2.5 Gb/s transmission system, but is not suitable for 10 Gb/s signals with a transmission distance beyond 50 km as a result of large chromatic dispersion.**



Application of G.652 single mode fiber

It has been widely used in most of the optical communication system.

The transmission distance of 2.5 Gb/s system is limited to 600 km by dispersion.

The transmission distance of 10 Gb/s system is limited to 34 km by dispersion.

The cost of the scheme G.652+DCF is quite high.

Conclusion:

This type of fiber is not suitable for high speed transmission beyond 10 Gb/s, but can be used in the DWDM below 2.5 Gb/s.

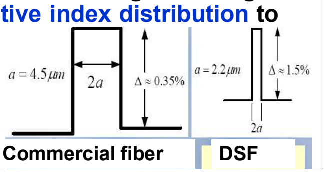
Dispersion shifting fiber

Mechanism：

At the wavelength range of 1.3 μm~1.7 μm, the zero dispersion can be always obtained by changing the fiber structure parameters （a, △ and g）. The zero dispersion wavelength can be identical to the wavelength with lowest loss by shifting the zero dispersion wavelength from 1.3 μm to 1.55 μm.

Method：

The material dispersion is unchanged, the zero dispersion wavelength can be shifted to long wavelength direction by changing the refractive index distribution to increase waveguide dispersion.



G.653 single mode fiber（DSF）

- **The DSF whose zero dispersion wavelength is shifted from 1.3 μm to 1.55 μm is defined as G.653 single mode fiber by ITU.**
- **However, the DSF with zero dispersion wavelength at 1.55 μm is not beneficial for multi-channel WDM transmission. Specifically, multi channels lead to a reduced gap between channels. Therefore, the FWM will cause the channel crosstalk. 四波混频-比较大的非线性会造成信号串扰，发生混叠**
- **If the total dispersion is equal to zero, the negative effects of FWM are large. In contrast, a slight dispersion will lead to a weakened FWM. Accordingly, a type of new fiber was fabricated, i.e., non zero dispersion shifting fiber G.655.**

Application of G.653 single mode fiber

Low loss, small effective area

Long distance and single channel high speed EDFA system.

The is the main problem, not beneficial for DWDM technology.

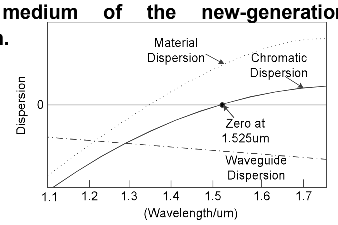
Conclusion:

This type of fiber is suitable for high speed single channel transmission beyond 10 Gb/s, but not for DWDM thus almost eliminated by the market

G.655 single mode fiber (NZ-DSF)

Non zero dispersion shifting fiber is one type of specific dispersion shifting fibers. Its zero dispersion wavelength is not at 1.55 μm but at 1.525 μm or 1.585 μm.

Non-zero dispersion shifting fiber can weakens the negative effects from both dispersion and FWM, but standard single fiber and DSF can only remove one of them. Therefore, NZ-DSF is an improved fiber and very suitable for high density WDM system, thus it is an ideal transmission medium of the new-generation optical communication system.



Application of G.655 single mode fiber

Low loss at the wavelength range of 1530~1565 nm.

The dispersion within the operation window is low.

The slight dispersion significantly weakens the FWM.

Submarine transmission systems. 海底光缆

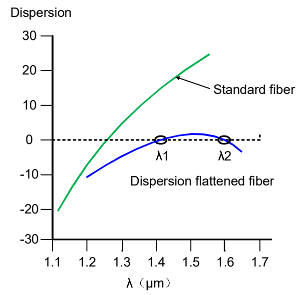
It is suitable for DWDM system.

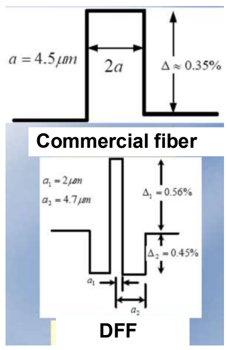
Conclusion:

This type of fiber is suitable for high speed DWDM system beyond 10 Gb/s and also the ideal choice of the large capacity DWDM in the future.

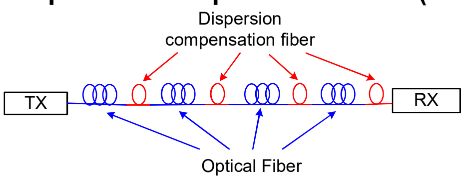
色散平坦光纤
Dispersion flattened fiber（G.656)

G.656 fiber：DFF，the dispersion values are almost similar at a large wavelength range. It is suitable for WDM systems

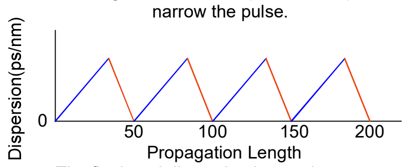




Dispersion compensation fiber (DCF)



Though both normal and anomalous dispersions will lead to pulse broadening, the suitable dispersion compensation can narrow the pulse.



The final total dispersion is equal to zero

Dispersion compensation fiber (DCF)

损耗对光纤的影响：输出功率降低
色散对光纤的影响：产生了啁啾（线性）
为什么不能先使用正向色散光纤，到终点再使用负向色散光纤来补偿色散呢？

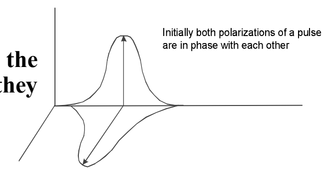
如果整个过程只有色散和损耗，那还好，可以完全补偿；
在中继站和中继站(Repeater station)之间的EDFA，会同时对受激辐射(Stimulated radiation)和自发辐射(Spontaneous radiation)进行增益，而自发辐射部分相当于噪声；
但结果往往不尽如人意，由于介质具有非线性系数，这个过程会积累(accumulate)非线性效应，因此最终无法完全补偿色散，存在残留的色散(There is residual dispersion)。

(3) Polarization-mode dispersion

Definition: it caused by the distinct transmission velocities of two orthogonal polarization modes which are resulted from the stress, temperature, bending, etc. induced asymmetric characteristic of the fiber.

In a single mode fiber, light transmits in two distinct polarization modes whose electric fields are perpendicular to each other.

Normally the two behave just the same in the fiber, it means they can't be distinguished.



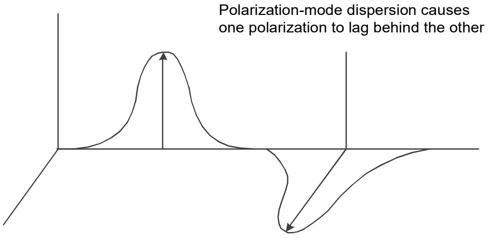
The existence of two polarization modes would not matter if optical fibers and all the forces applied to it are perfectly symmetrical.

However, nothing is perfect.

Within the fiber, the forces applied to it from outside would cause slight differences in the refractive index experienced by light in two polarization modes. This effect is called as birefringence.

Manufacturing stresses produce only a tiny difference-around one part in 10 million (10^{-7}) in optical fibers, but that tiny effect can become significant when very fast pulses go through long lengths of fiber.

If that birefringence was uniform along the length of the fiber, light in the faster polarization mode would travel about one wavelength faster ahead of the slower mode every 10 meters.



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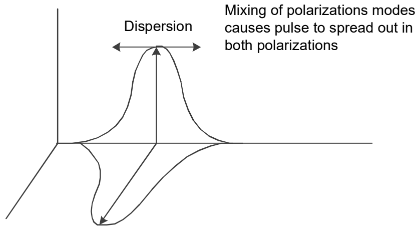
However, the effect is not simple because the difference called as differential group delay (DGD) fluctuates in a seemingly random manner, producing polarization-mode dispersion.

The DGD varies with time all along the length of the fiber, like a low-level background noise. It dose not accumulate consistently along the fiber, but grows larger with distance on average.



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The increase in the average value is proportional to the square root of fiber length times a characteristic polarization-mode dispersion.

$$\Delta t_{\mathrm{DGD}} = D_{\mathrm{PMD}} \times \sqrt{\text{fiber length}}$$

For the current optical fiber, the characteristic PMD value is below 0.1ps/km$^{-1/2}$

Polarization-mode dispersion is less of a problem than chromatic dispersion. [比色度色散问题要小]

In practice, PMD is not significant at data rates of 2.5 Gbit/s or less. But careful control is required for long-distance transmission at higher speeds.

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