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

Part of the lecture materials were adopted from powerpoint slides of Gerd Keiser’s book 2010, Copyright © The McGraw-Hill Companies, Inc.
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 $P_i$.

\[
\text{Loss (dB)} = -10 \log_{10} \left( \frac{P_o}{P_i} \right) = 10 \log_{10} \left( \frac{P_i}{P_o} \right)
\]

\(P_o \leq P_i\)

*In electronics, dB = 20 \log_{10} \left( \frac{V_o}{V_i} \right)*
The logarithmic unit has the advantage that the operations of multiplication (and division) reduce to addition (and subtraction).

In numerical values: \[ \frac{P_o}{P_i} = 10^{\left[-\text{Loss(dB)/10}\right]} \]

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

\[ \gamma L = -10 \log_{10} \left(\frac{P_o}{P_i}\right) \]

\( \gamma \) (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:

\[
dBm = 10 \log_{10} \left( \frac{\text{Power}}{1 \text{ mW}} \right)
\]

e.g. 1 mW = 0 dBm; 10 mW = 10 dBm; 100 \(\mu\)W = -10 dBm

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

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

\[\Rightarrow \text{loss} = -10 \log_{10} \left( \frac{100 \ \mu\text{W}}{1 \text{ mW}} \right) = 10 \text{ dB}\]

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 $P_{\text{out}}$ if 200 µW of optical power is launched into the fiber. We first express the input power in dBm units:

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

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

$$P_{\text{out}} \text{ (dBm)} = 10 \log \left( \frac{P_{\text{out}} \text{ (W)}}{1 \text{ mW}} \right) = 10 \log \left( \frac{P_{\text{in}} \text{ (W)}}{1 \text{ mW}} \right) - \alpha z$$

$$= -7.0 \text{ dBm} - (0.4 \text{ dB/km}) (30 \text{ km})$$

$$= -19.0 \text{ dBm}$$

In unit of watts, the output power is

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

$$= 12.6 \mu \text{W}$$
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 \text{ 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) \ \frac{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

- UV absorption
  - (negligible in the IR)
- IR absorption
- Absorption loss in infrared region
- Measured loss of fiber
- Absorption loss in ultraviolet region
- Scattering loss

Graphical representation of loss (dB/km) vs. Photon energy (eV) and Wavelength (µm).
Extrinsic absorption

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

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

- Since these OH\textsuperscript{-} absorption peaks are sharply peaked, narrow spectral windows exist around 1.3 μm and 1.55 μm which are essentially unaffected by OH\textsuperscript{-} 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

Prior to 2000 the fiber transmission bands were referred to as “windows.”

OFS AllWave fiber: example of a “low-water-peak” or “full spectrum” fiber.

(Lucent 1998)
Three major spectral windows where fiber attenuation is low

The 1\textsuperscript{st} window: 850 nm, attenuation 2 dB/km

The 2\textsuperscript{nd} window: 1300 nm, attenuation 0.5 dB/km

The 3\textsuperscript{rd} window: 1550 nm, attenuation 0.3 dB/km

1550 nm window is today’s standard \textbf{long-haul} communication wavelengths.
## Absorption Losses of Impurities

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

*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*
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.

\[ \theta > \theta_c \quad \text{and} \quad \theta < \theta_c \]

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

Silica glass is amorphous.
• Rayleigh scattering results from random inhomogeneities that are small in size compared with the wavelength.

\[ \text{<< } \lambda \]

• 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) \( \propto \frac{1}{\lambda^4} \)

Where else do we see Rayleigh scattering?
Rayleigh scattering is the dominant loss in today’s fibers.

Rayleigh Scattering $(1/\lambda^4)$

0.2 dB/km
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.

\[ M_{\text{eff}} = M_\infty \left\{ 1 - \frac{\alpha + 2}{2\alpha\Delta} \left[ \frac{2a}{R} + \left( \frac{3}{2n_2kR} \right)^{2/3} \right] \right\} \]

**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 \( a = 25 \mu m \). 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

\[ \frac{M_{\text{eff}}}{M_\infty} = 1 - \frac{\alpha + 2}{2\alpha\Delta} \left[ \frac{2a}{R} + \left( \frac{3}{2n_2kR} \right)^{2/3} \right] \]

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

\[ = 0.42 \]

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

\( n_{\text{eff}} = n_1 \)

\( n_{\text{eff}} = n_2 \)

\( V \propto 1/\lambda \)

- Phase velocity for mode \( m = \omega/\beta_m = \omega/(n_{\text{eff}}(m) k_0) \)
  (note that \( m = 0 \) mode is the \textit{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 = \( \frac{\omega}{\beta_{lm}} = \frac{\omega}{(n_{\text{eff}}(lm) k_0)} \)
(note that LP\(_{01}\) mode is the \textit{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:
  \[ t_0 = \frac{L}{v_{m=0}} \approx \frac{Ln_1}{c} \quad (v_{m=0} \approx \frac{c}{n_1}) \]

- The highest-order mode traveling near the critical angle needs time:
  \[ t_m = \frac{L}{v_m} \approx \frac{Ln_2}{c} \quad (v_m \approx \frac{c}{n_2}) \]

=> the pulse broadening due to modal dispersion:

\[ \Delta T \approx t_0 - t_m \approx \left(\frac{L}{c}\right) (n_1 - n_2) \]

\[ \approx \left(\frac{L}{2cn_1}\right) \text{NA}^2 \quad (n_1 \sim n_2) \]
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

$\Rightarrow$ Pulse duration $= 1 / 10^7 \text{ s} = 100 \text{ ns}$

Using the above e.g., each pulse will spread up to $\approx 100 \text{ ns}$ (i.e. $\approx$ pulse duration !) every km

$\Rightarrow$ The broadened pulses overlap! (Intersymbol interference (ISI))

*Modal dispersion limits the bit rate of a fiber-optic link to $\sim 10 \text{ Mb/s}$. (a coaxial cable supports this bit rate easily!)

30
Bit-rate distance product

- We can relate the pulse broadening $\Delta T$ to the *information-carrying capacity* of the fiber measured through the bit rate $B$.

- Although a precise relation between $B$ and $\Delta T$ depends on many details, such as the pulse shape, it is intuitively clear that $\Delta T$ 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)

$$BL < 2c \frac{n_{\text{core}}}{NA^2}$$

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 $\lambda_o$. For LEDs, $\Delta \lambda$ is likely to be a significant percentage of $\lambda_o$. 
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*.

<table>
<thead>
<tr>
<th>Light sources</th>
<th>Linewidth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-emitting diodes</td>
<td>20 nm – 100 nm</td>
</tr>
<tr>
<td>Semiconductor laser diodes</td>
<td>1 nm – 5 nm</td>
</tr>
<tr>
<td>Nd:YAG solid-state lasers</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>HeNe gas lasers</td>
<td>0.002 nm</td>
</tr>
</tbody>
</table>
• 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

\[ E = E \exp i(kz - \omega t) \]

where \( E \) 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, \( \phi = \text{constant} \) and thus \( kdz - \omega dt = 0 \). If we track this point of constant phase, we find that it is moving with a velocity of

\[ v_p = dz/dt = \omega/k \] \hspace{1cm} \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:

$$\omega_1 = \omega_0 + \delta \omega, \quad \mathbf{k}_1 = \mathbf{k}_0 + \delta \mathbf{k}$$

$$\omega_2 = \omega_0 - \delta \omega, \quad \mathbf{k}_2 = \mathbf{k}_0 - \delta \mathbf{k}$$
The space- and time-dependent total real field of the wave packet is given by

\[ E_{\text{packet}} = E \exp \left( i(k_1 z - \omega_1 t) \right) + \text{c.c.} + E \exp \left( i(k_2 z - \omega_2 t) \right) + \text{c.c.} \]

\[ = 2E \left\{ \cos \left[ (k_0 + dk)z - (\omega_0 + d\omega)t \right] + \cos \left[ (k_0 - dk)z - (\omega_0 - d\omega)t \right] \right\} \]

\[ = 4E \cos (zdk - td\omega) \cos (k_0 z - \omega_0 t) \]

The resultant wave packet has a carrier, which has a frequency \( \omega_0 \) and a propagation constant \( k_0 \), and an envelope \( \cos (zdk - td\omega) \).

Therefore, a fixed point on the envelope is defined by \( zdk - td\omega = \text{constant} \), and it travels with a velocity

\[ v_g = \frac{dz}{dt} = \frac{d\omega}{dk} \quad \text{group velocity} \]
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*. 
When a light pulse with a spread in frequency $\delta \omega$ and a spread in propagation constant $\delta k$ propagates in a dispersive medium $n(\lambda)$, the group velocity:

$$v_g = \frac{d\omega}{dk} = \frac{d\lambda}{dk} \frac{d\omega}{d\lambda}$$

$$k = n(\lambda) \frac{2\pi}{\lambda} \implies \frac{dk}{d\lambda} = \left(\frac{2\pi}{\lambda}\right) \left[(\frac{dn}{d\lambda}) - \left(\frac{n}{\lambda}\right)\right]$$

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

Hence

$$v_g = \frac{c}{n - \lambda(\frac{dn}{d\lambda})} = \frac{c}{n_g}$$

Define the group refractive index $n_g = n - \lambda(\frac{dn}{d\lambda})$
Group refractive index $n_g$ vs. $\lambda$ for fused silica
Phase velocity $c/n$ and group velocity $c/n_g$ vs. $\lambda$ for fused silica

Phase velocity dispersion $v = c/n$

Group velocity dispersion (GVD) $v_g = c/n_g$
Group-Velocity Dispersion (GVD)

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

• A specific spectral component at the frequency $\omega$ (or wavelength $\lambda$) would arrive at the output end of length L after a time delay:

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

• 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

$$\Delta T = \frac{dT}{d\lambda} \Delta \lambda = \left[ \frac{d(L/v_g)}{d\lambda} \right] \Delta \lambda$$

$$= L \left[ \frac{d(1/v_g)}{d\lambda} \right] \Delta \lambda$$
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 \( \text{ps}/(\text{km-nm}) \).

\[
D = d(1/v_g)/d\lambda = c^{-1} \frac{dn_g}{d\lambda} = c^{-1} \frac{d[n - \lambda(dn/d\lambda)]}{d\lambda} \\
= -c^{-1} \lambda \frac{d^2n}{d\lambda^2}
\]
Dispersion parameter $D = - \left( \frac{\lambda}{c} \right) \frac{d^2n}{d\lambda^2}$

- Fused silica

- 1276 nm

- "Anomalous" ($D > 0$)

- "Normal" ($D < 0$)
Variation of $v_g$ with wavelength for fused silica

- "Normal" ($D < 0$)
- "Anomalous" ($D > 0$)

Red goes faster

$D_{mat} = 0$
@ 1276 nm

C band
Material dispersion \( D_{\text{mat}} = 0 \) at \( \lambda \sim 1276 \text{ nm} \) for fused silica.

This \( \lambda \) is referred to as the zero-dispersion wavelength \( \lambda_{ZD} \).

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 two 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 **material dispersion**.

(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 $\lambda$. (Recall the mode field diameter)

This is known as **waveguide dispersion**.

$$\Rightarrow D(\lambda) = D_{\text{mat}}(\lambda) + D_{\text{wg}}(\lambda)$$
Waveguide dispersion in a single-mode fiber

Waveguide dispersion depends on the \textit{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 $\lambda$ of the LP$_{01}$ mode see different effective indices $n_{\text{eff}}$
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

$$v_{g,\text{eff}} = \frac{d\omega}{d\beta}$$

Waveguide propagation constant

or

$$v_{g,\text{eff}}^{-1} = \frac{d\beta}{d\omega}$$

Waveguide effective index

$$= \frac{d}{d\omega} (c^{-1} \omega n_{\text{eff}})$$

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

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

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

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

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

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

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

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

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

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

• In the absence of material dispersion (i.e. when $\text{NA}$ is independent of $\omega$), $V$ is directly proportional to $\omega$, so that

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

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

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

$\Rightarrow$The dependence of $D_{wg}$ on $\lambda$ may be controlled by altering the core radius, the $\text{NA}$, or the $V$ number.
• $D_{\text{wg}}(\lambda)$ compensate some of the $D_{\text{mat}}(\lambda)$ and shifts the $\lambda_{\text{ZD}}$ from about 1276 nm to a longer wavelength of about 1310 nm.

Typical values of D are about 15 - 18 ps/(km-nm) near 1.55 µm.
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 \textit{dispersion-limited distance}:

$$L_D = \frac{1}{(D B \Delta \lambda)}$$

e.g. For $D = 17 \text{ ps/(km}\cdot\text{nm})$, $B = 2.5 \text{ Gb/s}$ and $\Delta \lambda = 0.03 \text{ nm}$

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

(It is known that dispersion limits a 2.5 Gbit/s channel to roughly 900 km! Therefore, chromatic dispersion is \textit{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:

\[ L_D = \frac{1}{(D B \Delta \lambda)} \]

*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 \( \Rightarrow \Delta \lambda \propto B \)

\[ \Rightarrow L_D \propto \frac{1}{B^2} \]
Chromatic dispersion in high-bit-rate systems

e.g. In standard single-mode fibers for which $D = 17 \text{ ps/(nm km)}$ 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:

$$L_D \approx \frac{784 \text{ km}}{16} \approx 50 \text{ km}!$$

(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

$$\frac{dD(\lambda)}{d\lambda} = S_0$$

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

$S_0$ is known as the zero-dispersion slope measured in $\text{ps}/(\text{km-nm}^2)$.
For Corning SMF-28 fiber, $\lambda_{ZD} = 1313$ nm, $S_o = 0.086$ ps/nm$^2$-km.

The chromatic pulse broadening near $\lambda_{ZD}$:

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

empirical $D(\lambda) = \left(\frac{S_o}{4}\right) (\lambda - \lambda_{ZD}^4/\lambda^3)$
• 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

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

*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 $\lambda = 1.55$ $\mu$m, 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/(nm² · km). Compare the dispersions for this fiber at wavelengths of 1280 nm and 1550 nm.

Solution: Using Eq. (3.47) we find that

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

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

\[ = 17.5 \text{ ps/(nm · km)} \]

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

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

\[ = -2.86 \text{ ps/(nm · km)} \]
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 $\Delta$, it is possible to design the fiber such that $\lambda_{zd}$ is shifted into the neighborhood of 1.55 $\mu$m. 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 $\mu$m. Such fibers are called dispersion-flattened fibers.
The design of dispersion-modified fibers often involves the use of multiple cladding layers and a tailoring of the refractive index profile.
• Since dispersion slope $S > 0$ for singlemode fibers $\Rightarrow$ different wavelength-division multiplexed (WDM) channels have different dispersion values.

*SM fiber or non-zero dispersion-shifted fiber (NZDSF) with $D \sim$ 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 ⇒ 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**

![Graph showing dispersion compensation](image)

- **SM fiber**: +ve dispersion
- **DCF**: -ve (due to large -ve \( D_{wg} \))

<table>
<thead>
<tr>
<th>SM</th>
<th>DCF</th>
<th>SM</th>
<th>DCF</th>
<th>SM</th>
<th>DCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ve</td>
<td>-ve</td>
<td>+ve</td>
<td>-ve</td>
<td>+ve</td>
<td>-ve</td>
</tr>
</tbody>
</table>

*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.

Pulse broadening with chirping

Pulse compression with dechirping

Initial chirp and broadening by a transmission link

Compress the pulse to initial width

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 $D(1550 \text{ nm}) \sim 17 \text{ ps/(km-nm)}$.

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

assume the semiconductor (diode) laser linewidth $\Delta \lambda \sim 1 \text{ nm}$.
⇒ The DCF needed to compensate for 1700 ps with a large negative-dispersion parameter

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

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

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

$\Rightarrow D_{\text{DCF}}(\lambda) \sim -113$ 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:

\[ L_2 \frac{dD_2}{d\lambda} = - L_1 \frac{dD_1}{d\lambda} \]

\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.

\[ D_2 L_2 = - D_1 L_1 \]

\[ L_2 \frac{dD_2}{d\lambda} = - L_1 \frac{dD_1}{d\lambda} \]

\Rightarrow Dispersion and slope compensation: \( \frac{D_2}{(dD_2/d\lambda)} = \frac{D_1}{(dD_1/d\lambda)} \)

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

Within the spectral window \((\lambda_1, \lambda_2)\), \(D_{DCF}/D_{SM} = -6\)

\[ S_{DCF} = -12/(\lambda_2 - \lambda_1); \quad S_{SM} = 2/(\lambda_2 - \lambda_1) \Rightarrow S_{DCF}/S_{SM} = -6 \]

\[ \Rightarrow \text{Dispersion slope compensation: } (D_{SM}/S_{SM}) / (D_{DCF}/S_{DCF}) = 1 \]
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*.

- 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*. 

![Diagram showing horizontal and vertical modes](image)
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 $\text{birefringence}$.  

\[ B = n_x - n_y \]  

assuming $n_x > n_y \Rightarrow y$ 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

Elliptical polarization
• 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).

\[
\text{PMD pulse broadening} \quad \Delta T_{\text{PMD}} = D_{\text{PMD}} \sqrt{L}
\]

\(D_{\text{PMD}}\) is the PMD parameter (coefficient) measured in \(\text{ps}/\sqrt{\text{km}}\).

\(\sqrt{L}\) models the “random” nature (like “random walk”)

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

*Today’s fiber (since 90’s) PMD parameter is 0.1 - 0.5 ps/\(\sqrt{\text{km}}\).

*(Legacy fibers deployed in the 80’s have \(D_{\text{PMD}} > 0.8 \text{ ps}/\sqrt{\text{km}}\).)*
e.g. Calculate the pulse broadening caused by PMD for a singlemode fiber with a PMD parameter $D_{\text{PMD}} \sim 0.5 \text{ ps/} \sqrt{\text{km}}$ and a fiber length of 100 km. (i.e. $\Delta T_{\text{PMD}} = 5 \text{ ps}$)

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

$\Rightarrow$ 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

conventional

Unpol. input

Pol. input

Pol. input

polarization-preserving

Unpol. input

Unknown output (random coupling between all the polarizations present)

Unknown output

Unknown output

Unknown output

Pol. output
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.
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>
<thead>
<tr>
<th>Application</th>
<th>Data rate (Gb/s)</th>
<th>50-μm core 500 MHz.km</th>
<th>50-μm core 2000 MHz.km</th>
<th>62.5-μm core 160 MHz.km</th>
<th>62.5-μm core 200 MHz.km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethernet</td>
<td>1</td>
<td>550</td>
<td>860</td>
<td>220</td>
<td>275</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>82</td>
<td>300</td>
<td>26</td>
<td>33</td>
</tr>
<tr>
<td>Fibre Channel</td>
<td>1</td>
<td>500</td>
<td>860</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>300</td>
<td>500</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>82</td>
<td>300</td>
<td>26</td>
<td>33</td>
</tr>
<tr>
<td>SONET/SDH</td>
<td>10</td>
<td>85</td>
<td>300</td>
<td>25</td>
<td>33</td>
</tr>
</tbody>
</table>
## Examples of Specialty Fibers

<table>
<thead>
<tr>
<th>Specialty fiber type</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erbium-doped fiber</td>
<td>Gain medium for optical fiber amplifiers</td>
</tr>
<tr>
<td>Photosensitive fibers</td>
<td>Fabrication of fiber Bragg gratings</td>
</tr>
<tr>
<td>Bend-insensitive fibers</td>
<td>Tightly looped connections in device packages</td>
</tr>
<tr>
<td>Termination fiber</td>
<td>Termination of open optical fiber ends</td>
</tr>
<tr>
<td>Polarization-preserving fibers</td>
<td>Pump lasers, polarization-sensitive devices, sensors</td>
</tr>
<tr>
<td>High-index fibers</td>
<td>Fused couplers, short-λ sources, DWDM devices</td>
</tr>
<tr>
<td>Photonic crystal fibers</td>
<td>Switches; dispersion compensation</td>
</tr>
</tbody>
</table>
## ITU-T Recommendations for Fibers (2)

<table>
<thead>
<tr>
<th>ITU-T rec. no.</th>
<th>Title and description</th>
</tr>
</thead>
</table>
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 |
### Table 3.2  Recommendations for fibers used in telecom, access, and enterprise networks

<table>
<thead>
<tr>
<th>ITU-T rec. no.</th>
<th>Title and description</th>
</tr>
</thead>
</table>
| 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 |
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 |