Lasers that transmit data on optical fibers do not produce monochromatic light. Instead, they provide a narrow spectrum that includes many wavelengths. The physical characteristics of optical fibers cause some of these wavelengths to travel faster or slower than others (Figure 1). This effect, called chromatic dispersion, can cause serious problems at data rates of 10 Gbps and above for two reasons. First, higher bandwidths mean broader spectra and thus, more pulse spreading. Second, as data rates increase, pulses become narrower and occur closer together. As a result, a pulse can more readily overlap with its neighbors, so a receiver cannot distinguish between them. (See, "What causes chromatic dispersion? ".)

Chromatic dispersion can prevent successful transmission of laser radiation in high-speed, long-haul optical systems operating in the C band (1530–1563 nm). In this band, the relatively high chromatic dispersion of a fiber accumulates linearly with distance. Systems that use the C band often need to include some dynamic compensation techniques to overcome the effects of chromatic dispersion. To decide how much compensation is required, you need to measure chromatic dispersion in the system's fibers.
Figure 2. The graph plots relative group delay vs. wavelength for an optical fiber. The slope at a point provides the chromatic dispersion for a specific wavelength. At the zero-dispersion wavelength (\(l_0\)), two closely spaced frequency components travel at approximately the same speed. Plotting the delays for the various wavelengths shown in Figure 1 produces a curve such as the one shown in Figure 2. This curve lets you relate the wavelengths in a laser pulse to the relative delays they experience in reaching a receiver. The laser's center wavelength, at which most energy occurs, coincides with \(l_0\) on the graph. This wavelength provides the benchmark against which an instrument measures other delays. The graph plots relative group delay, which represents the delays for all the wavelengths in the laser's output over a set length, typically 1 km.

The slope of the group-delay curve at any point provides the chromatic-dispersion coefficient, \(D\), in units of ps/nm-km. Thus, the chromatic dispersion equals the rate of change of the group delay with respect to wavelength. The sign of the slope indicates whether energy at a specific wavelength reaches the end of the fiber before (positive) or after (negative) energy at the center wavelength, \(l_0\). The information in Table 1 shows the maximum dispersion that a fiber-optic system can tolerate at three standard bit rates.

Measure dispersion two ways

Engineers use two main methods to measure chromatic dispersion: the modulation phase-shift method (MPS) and the differential phase-shift method (DPS). (Other methods, such as swept-laser interferometry, exist, but they're not as common.) Both methods let you calculate chromatic dispersion in lengths of optical fibers from less than 0.2 m to thousands of kilometers, and you can use these methods to analyze the chromatic dispersion in components such as interleavers, filters, and fiber Bragg gratings.

These two methods measure the phase shift of a modulated optical signal as it passes through a device under test (DUT). The resulting test data relates the measured phase change to specific wavelengths.

The majority of test systems used to measure chromatic dispersion in installed fiber employ the DPS method, which provides faster measurements than the MPS method. In most cases, though, the MPS method provides superior accuracy. If you need to measure the characteristics of installed fiber, use the DPS method. When you must make high-accuracy measurements on narrowband components, use the MPS method.
Test systems that use the MPS method directly measure changes in the phase of a modulated pulse and compute group-delay values. The MPS method uses a high-frequency sine wave, typically between 10 MHz and a few GHz, from an RF network analyzer to modulate the intensity of light produced by a tunable laser source (TLS) (Figure 3). Chromatic-dispersion test systems based on the MPS method can resolve a delay as short as 0.001 ps, or 1 fs.

The modulated signal passes through a DUT—assume it’s a length of optical fiber—and reaches an optical receiver that demodulates it. The RF network analyzer measures the phase difference between the modulated signal that passes through the fiber and the original modulation signal. While the PC changes the wavelength of the TLS in small steps, a fiber with chromatic-dispersion characteristics causes a slight change in modulation phase. You can calculate the relative group delay, \( dt \):

\[
dt = \left( \frac{Df}{360} \right) \times \left( \frac{1}{f_m} \right)
\]

where:
- \( Df = \) the phase change in degrees induced by the wavelength shift
- \( f_m = \) the modulation frequency in Hz

Then, you can calculate the dispersion, \( D \):

\[
D = \left( \frac{dt}{dl} \right) \times \left( \frac{1}{L} \right)
\]

where:
- \( dl = \) the wavelength change in meters
- \( L = \) the length of the optical fiber in meters

Once you set up an MPS test system, it requires no manual adjustments. The laser source determines the wavelength accuracy, and the crystal timebase in the network analyzer determines the timing accuracy. Temperature changes can cause instruments to drift, though, so you should make chromatic-dispersion measurements quickly. A typical MPS measurement can take from a few seconds to a few minutes.

A test system can perform MPS measurements by using a TLS in either stepped mode or swept mode. In the stepped mode, after the TLS "steps" to a new wavelength, the instrument acquires the phase data. Optical-fiber measurements require steps of 0.5–1 nm, and narrowband components require steps of 1–100 pm.

DPS dithers wavelengths
Unlike the MPS method that measures group delay, the DPS method directly measures chromatic dispersion. Both methods modulate the amplitude of a laser signal. But test systems based on the DPS method (Figure 4) also "dither" the laser's wavelength around the central wavelength. Dithering modulates the wavelength within a frequency range of about 100 MHz to 3 GHz. Thus, the signal from the DUT exhibits both phase and wavelength changes.

A DPS test system directly determines the value of chromatic dispersion at a selected wavelength by measuring the change in group delay across a small (dithered) wavelength interval. The resulting chromatic dispersion represents the average dispersion over the wavelength interval. The DPS method can provide rapid measurements, but because the dithering produces an average value, that value may differ slightly from the actual dispersion. In most cases, that's an acceptable tradeoff for the measurement speed gained.

The group delay in narrowband components may vary rapidly across the component's bandwidth. Thus, resolving the group delay variation exhibited by such components requires lower modulation frequencies and small wavelength steps.

A DPS test system made up of the blocks shown in Figure 4 will calculate the dispersion, \( D \), in units of ps/nm-km using the following equation:

\[
D = \frac{df}{360 \times (dl) \times L \times f_m}
\]

where:
- \( df \) = the phase change in degrees induced by the wavelength shift
- \( f_m \) = the RF modulation frequency in Hz
- \( L \) = the length of the optical fiber in meters

**Optimize measurement accuracy**

Until recently, chromatic-dispersion testing focused solely on optical fiber. The optical characteristics of fiber change smoothly with respect to wavelength, and the fiber covers a relatively wide bandwidth. Thus, tests could use relatively large wavelength steps, usually 0.5–1 nm.

But newer dense wavelength-division multiplex (DWDM) systems include narrowband devices such as filters and multiplexes that operate over a narrow band of wavelengths. These devices require testing over small wavelength intervals of 1–100 pm.
Some of these narrowband devices produce a high-frequency ripple in the group delay. This characteristic can cause problems for system designers, because even a small change in wavelength may cause a large change in the magnitude and sign of the chromatic dispersion. Figure 5 shows the ripple in the group delay for an optical component measured with an MPS test system using 0.1-pm wavelength steps and a 100-MHz modulation frequency.

Reducing the modulation frequency and wavelength step provides better measurement resolution for narrowband components. But these smaller and smaller steps eventually run into a noise limit. To reduce noise, an instrument can take more samples and average them, but the additional measurements increase the overall test time. Lowering the modulation frequency and using smaller wavelength steps can produce a phase change that exceeds the range of the phase detector, thus producing an aliasing error. (Some commercial test systems automatically avoid such conditions for fiber test.)

Typically, for optical-fiber measurements, you can choose a high-modulation frequency (2 GHz) and a large wavelength step (1 nm). For narrowband measurements, though, you should choose a modulation frequency below 500 MHz and a wavelength step of less than 100 pm.

The inherent wavelength accuracy (0.1 nm) of a tunable laser may suffice for testing narrowband components. But if you need higher wavelength accuracy, such as when you’re testing a high-speed, long-haul fiber link, you’ll need to substitute a tunable external-cavity laser for the TLS and add a wavelength meter to your test system. A cavity laser provides finer wavelength control, and a wavelength meter provides a precise wavelength reference. Routing some of the laser’s output to the wavelength meter and monitoring the wavelength meter with the test system’s PC provides a control loop that keeps the tunable laser on a set wavelength.

Control dispersion

Control of chromatic dispersion in optical transmission systems proves critical to the design and construction of long-haul, high-speed telecommunication systems. Designers must reduce the dispersion so error rates in such systems reach an acceptable level. A range of components such as dispersion-compensating fiber and fiber Bragg gratings and techniques such as using the soliton-like behavior of optical pulses now mitigate the effects of dispersion. Many of these techniques were used first in submarine cable systems, in which multiplexed-wavelength signals at high bit rates travel over long distances.

Table 1. The relation between dispersion, bit rates, and link length.
<table>
<thead>
<tr>
<th>Bit rate (Gbps)</th>
<th>2.5</th>
<th>10</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum dispersion (ps/nm)</td>
<td>16,000</td>
<td>1000</td>
<td>63</td>
</tr>
<tr>
<td>Maximum link length (km)</td>
<td>941</td>
<td>59</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: Data assume 1 dB dispersion penalty; standard single-mode fiber with dispersion = 17 ps/nm-km, and external modulation.

**References**