CHROMATIC DISPERSION ANALYSIS METHODS

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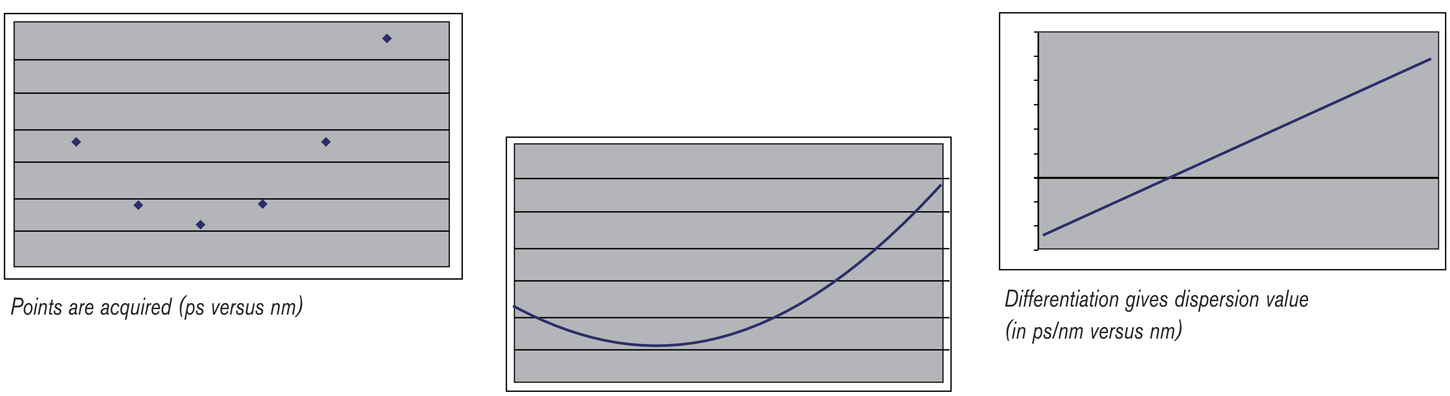
Fiber networks consist of both old and new fibers, all of which must be used to maximum efficiency. Initially, fiber-optic networks operated at a wavelength of 1310 nm and many of the fibers installed at this time were never characterized in the 1550 nm window. One additional problem that should not be overlooked is that shifted and unshifted fibers may have been accidentally combined, along with compensation modules and amplifiers, which can generate unusual dispersion characteristics.

Chromatic dispersion is a variation in the velocity of light (group velocity) according to wavelength. This variation in velocity causes the pulses of a modulated laser source to broaden when traveling through the fiber; up to a point where pulses overlap and bit error rate increases. As this increase in bit error rate interferes with both the quality and speed of the signal, chromatic dispersion (CD) is a major limiting factor in high-speed transmission. Therefore, to ensure adequate quality of service, it is extremely important that carriers compensate for this type of signal distorsion. The widespread use of DWDM systems covering the C and L bands (1530 nm to 1625 nm) will certainly create a need for accurate wideband CD compensators. However, ensuring proper CD compensation starts with proper testing.

For fiber, there are two main methods of measuring chromatic dispersion. The first is by measuring the variation in the arrival times of different pulses that have been sent simultaneously, at various wavelengths, through the fiber (pulse-delay method, as described in FOTP-168); and the second is by using a modulated variable-wavelength source and measuring the change in modulation phases according to wavelength (phase-shift and differential phase-shift methods, as described in FOTP-169 and FOTP-175, respectively).

In most methods, the instrument starts by measuring the pulse delay (in ps), as a function of wavelength. Chromatic dispersion is actually the rate of change in this delay. Therefore, in order to obtain the CD value, a delay curve must be differentiated. However, because only a limited amount of points can be acquired and because one cannot differentiate an exact curve from merely a few points, an approximate curve is plotted from the points (called a fit) and then differentiated. Of course, the more points acquired, the better this approximation and the more accurate the results will be.



Points are acquired (ps versus nm)

A curve is fitted (ps versus nm)

Differentiation gives dispersion value (in ps/nm versus nm)

Figure 1: Typical steps in the calculation of chromatic dispersion.

Pulse-Delay Method

The pulse-delay method measures differential delay between optical pulses of various wavelengths, using a multiple-wavelength transmitter at one end of the fiber and a receiver at the other end (or at the same end when using an OTDR). Figure 2 shows a typical CD test setup.

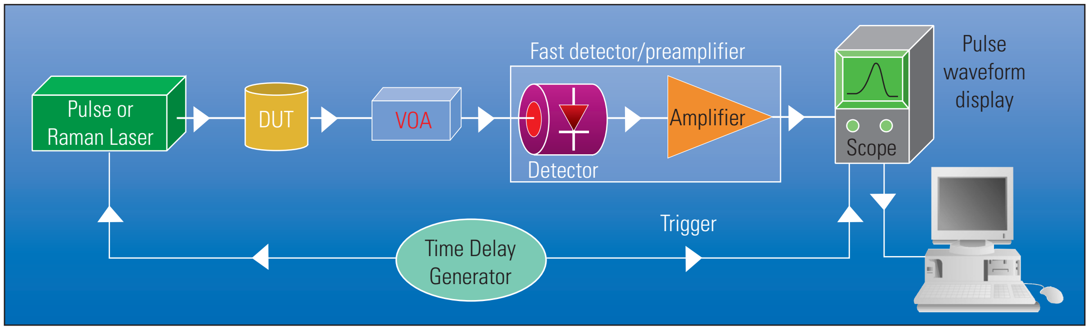


Figure 2: Schematic of the pulse-delay method, where the source and receiver are at different ends of the fiber. OTDR-based methods use same schematic but include source and receiver in the same unit.

A simple way to implement this method is to have a bank of four to eight lasers that can be activated from a single pulse generator. The first laser wavelength is used as the reference time delay (given a relative group delay of zero) and the other wavelengths' transmission times are compared against this reference time. The acquired time-delay points are plotted on a graph, and a curve is then fitted to these points and used to differentiate the final chromatic dispersion curve.

Disadvantages of OTDR-Based Pulse-Delay Methods

Several vendors use an OTDR to do this. The obvious advantage of doing so is the capacity to perform one-end testing, as well as the simplicity and low cost of the method. On the other hand, there are several reasons for not choosing this method.

One of the main disadvantages of using an OTDR for this type of testing is that errors can be introduced when positioning the arrival time of the pulses on the graph, particularly as pulses widen due to the effects of chromatic dispersion. In addition, OTDRs do not exhibit high wavelength accuracy (typically ± 3 nm). So both the delay and the wavelength accuracy are affected. Furthermore, OTDRs usually give a maximum of four points on the delay graph, and this limited number of points also affects accuracy. Therefore, although these vendors readily specify a repeatability measurement, they do not mention accuracy.

As described in the FOTP-224 standard (see Appendix below), each fiber type corresponds to a specific type of curve. Having more than one fiber type in the tested link will lead to odd curve-fitting behavior that will be impossible to interpret with only four data points. So this method is limited to links composed of a single fiber type. As per the FOTP-224 standard, most fibers, when tested over a wide wavelength range (which is the case with this method), have to be modeled by a 5-term equation, which cannot be solved when only four points are acquired. Systematically, even if a link contains only one type of fiber, a bad fiber fit is used, violating the standard, and further decreasing accuracy.

Dynamic range is often an issue when selecting a test set. Because one of the four points is generally set at around 1310 nm, the signal at this point attenuates much faster, so total testing distance must be evaluated according to the specified dynamic range at 1310 nm. Also, this dynamic range is usually specified with the longest possible OTDR pulse (typically 20 µs), but as per the FOTP-168 standard, which describes the pulse-delay method, "*...multiple laser diodes at several l shall be considered sufficient if they are of less than 400 ps.*" Using 20-µs pulses thereby violates the standard by a significant factor.

Phase-Shift Methods

Favored methods for CD measurement are the phase-shift and the differential phase-shift methods.

In addition to being more accurate, one of the main advantages of these methods is that a simple tunable filter/monochromator can be used as a wavelength selector. And since this device can be placed at several different positions, a multitude of test points can be acquired, thus increasing the accuracy of the dispersion measurement and optimizing tests in the wavelength region of interest.

Differential Phase-Shift Method

In this method, a sinusoidally modulated light source (of type $x = A\sin(\omega t+\phi)$, where ϕ is the phase and ω is the modulation frequency) is coupled to the fiber under test, and the phase of the modulated signal exiting the fiber at a first wavelength is compared with the phase at a second wavelength. Average chromatic dispersion over the interval between the two wavelengths is determined from the phase-shift and wavelength interval.

The receiver unit records the differential output from the phase meter (produced by a pair of test wavelengths) and provides an output representing the phase difference between the two wavelengths. Phase difference translates into delay when divided by the frequency of modulation of the source ($\Delta t = \Delta\phi / 2\pi f$, where f is the modulation frequency). Then, a second pair of wavelengths is selected and another local measurement is taken, and so on.

This implies that the user must set up, in the software, a step between local measurements, as well as a range (interval) over which each local measurement will be taken, rendering the setup a bit complex.

In this method, the phase meter (the receiver unit) has to be provided a reference signal with the same frequency component as the modulated signal (source unit) against which to measure the differential phases of the signal sources. This implies that the reference signal be synchronized, and this can be achieved by connecting a fiber to both source and receiver so as to establish communication between the two.

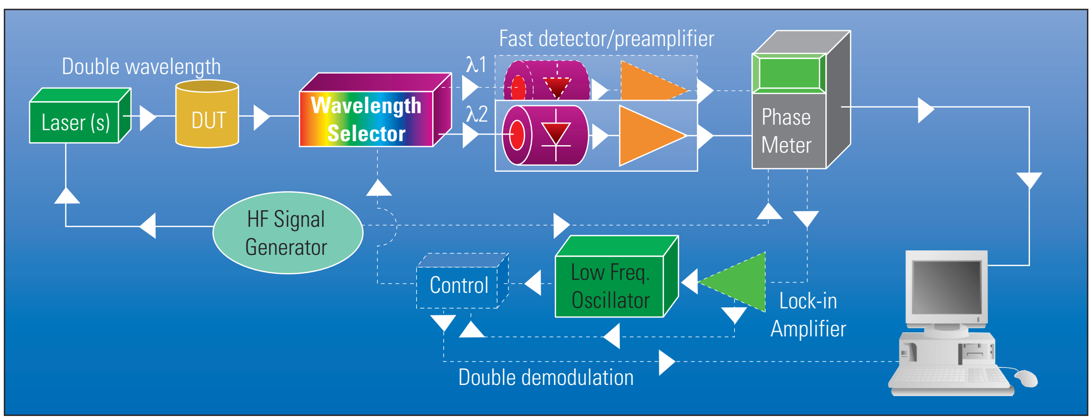


Figure 3: In the differential phase-shift method, a communication mechanism must exist between the source and the receiver for synchronization.

Disadvantages of the Differential Phase-Shift Method

Because for each acquired point the reference is a neighboring point, setting a large step between the two points will reduce relative error, increasing the accuracy of individual acquisition points. However, the large interval between points also means fewer points, thus requiring more approximation to extrapolate a fit. Therefore, when using optimized parameters with the differential phase-shift method, each individual point is highly accurate, but the fit is done with very little information (dangerous in multifiber-type systems).

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Another key point in CD measurement is the broadness of the wavelength source. When using a laser, this is not an issue, but when using a broadband source, filtering is required. Some of the products based on this technique tend to have very wide filter bandwidth, which not only adds uncertainty, but may violate applicable standards (The FOTP-175 defines *"...Filter the optical spectrum to give a spectral line of FWHM in the 1 to 5 nm range. A monochromator may be used for filtering"*). It is therefore important to check bandwidth specifications with the vendor.

Phase-Shift Method

The main idea of the phase-shift method is to measure the relative phase changes (relative to a fixed reference) in the detected signal as the wavelength is altered. This can be done either by using an electrical local phase reference, which requires communication between the source and the receiver; or by using one of the transmitted wavelengths as the reference, thus avoiding the need for communication, but inducing other limits (discussed below). By varying the wavelength, various phase information is gathered and compared to the phase of the reference (as opposed to the differential phase-shift, where a selectable wavelength is compared to a second selectable wavelength).

Since all values are compared to a fixed reference, the step between points can be much smaller than in the case of the differential phase-shift method, thus allowing the acquisition of a lot more points. This is critically important, as more points imply better curve fitting and, therefore, higher potential accuracy. If a transmitted wavelength is used as reference, measurements in the vicinity of this wavelength will suffer from a lack of power transmitted to the monochromator, creating a 1 to 2 nm blind spot around the reference wavelength. Intelligence implemented in the FTB-5800 CD Analyzer allows the user to ignore points in this area to avoid misinterpreting results.

In this method also, relative group delay is obtained by measuring the relative phase-shift incurred by sinusoidally modulated light propagating through the test fiber (relative because compared to a reference, not an absolute value). To select a number of wavelengths within the range of interest, one can either use a modulated LED, with a monochromator or a bank of modulated continuous wave lasers, as described above. The monochromator-based method is the most flexible, as it allows a varied number of measurement points and/or wavelength range.

Disadvantages of the Phase-Shift Method

As in the pulse-delay method, the acquired points are fitted to a curve, which is then differentiated to produce chromatic dispersion data. The big danger in this method is that since the selected wavelength can be far away from the reference, phase difference can be high and can create ambiguities in phase shift of 360*n degrees (where n is an integer). The system must therefore track 360° phase changes by choosing wavelength steps that are sufficiently small for high dispersion, when required.

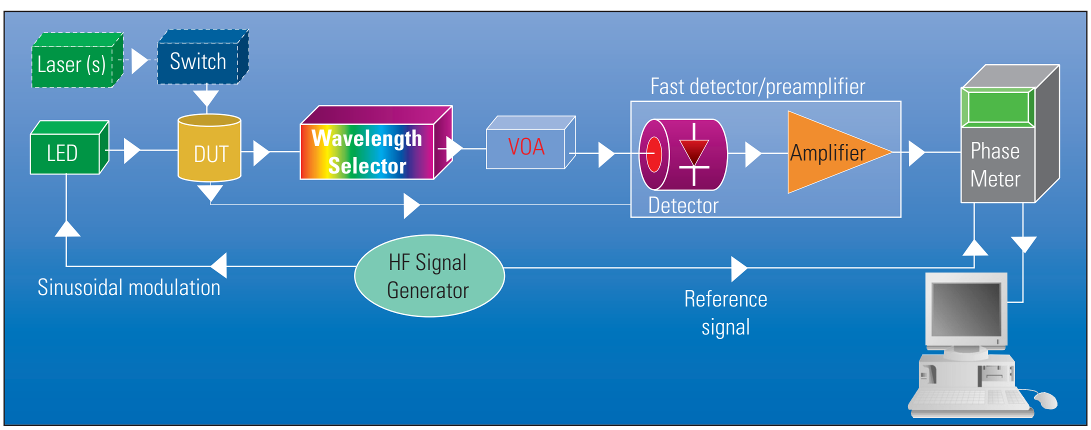

Figure 4: Typical test setup using the phase-shift method, with electrical reference.

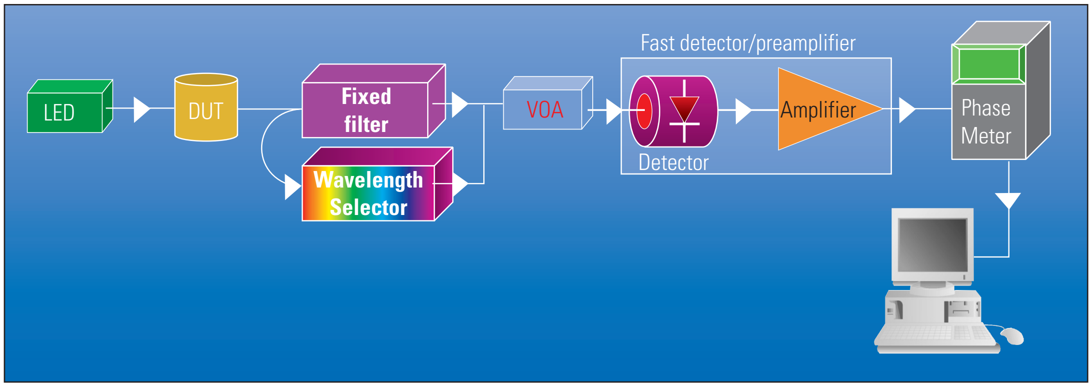

Figure 5: Typical test setup using the phase-shift method, with optical reference.

Conclusion

Once the installed fiber has been characterized, the next task is to install compensation systems to bring the overall chromatic dispersion within the operating limits of the transmission system. This being said, if the external fiber network is accurately characterized, then there are ways to compensate for the effects of chromatic dispersion in order to maximize the bandwidth capabilities of the system. But proper compensation requires proper testing, namely because the cost of compensation techniques is quite high. It is therefore important to ensure accurate CD testing so as to avoid making costly decisions based on test results that are not entirely accurate. Hence, knowing the limits of each method will surely help determine the most suitable test solution.

APPENDIX

Extract of Chromatic Dispersion Specifications for Fiber (FOTP-224)

a) Dispersion-Unshifted Fibers

These exhibit a zero dispersion wavelength in the 1310 nm region. The dispersion characteristics may accurately be modeled by a 3-term Sellmeier equation within the 1310 nm region, or by a 5-term Sellmeier equation over a wider wavelength range.

b) Dispersion-Shifted Fibers

These exhibit zero dispersion at a wavelength which is significantly higher than 1310 nm, typically around 1550 nm, the dispersion of which is accurately modeled using a quadratic delay data fit (or equivalently by a linear dispersion fit) within a specific wavelength range around lambda zero, or by a 5-term Sellmeier equation over a wider wavelength range.

c) Non-Zero Dispersion Fibers

These exhibit small but finite chromatic dispersion in the 1550 nm waveband. No approved data fit exists at present (although a 5-term Sellmeier equation is possibly acceptable as a useful fit in the main wavelength regions of interest).

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