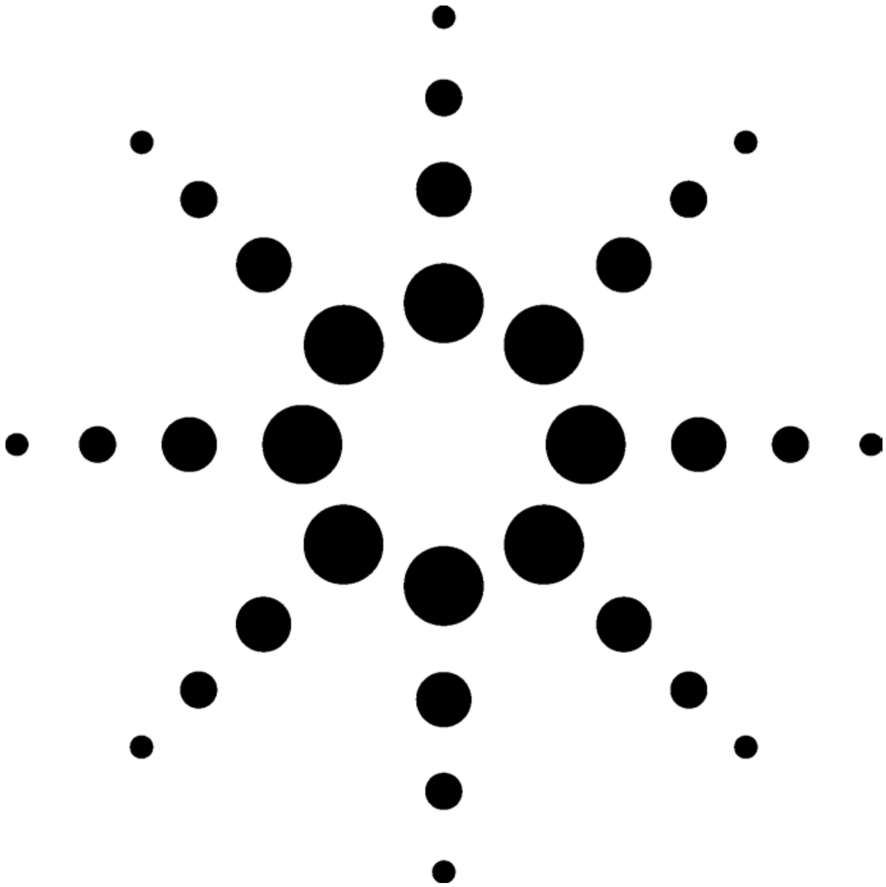
Improving Chromatic Dispersion and PMD Measurement Accuracy

White Paper



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Signal transmission over optical fibers relies on preserving the waveform from transmitter to receiver. But when light goes through optical fibers, the timing of the pulses can be smeared by fiber dispersion. Chromatic dispersion (CD) delays the signal depending on the wavelength of the light and polarization mode dispersion (PMD) makes the delay dependent on the polarization of the light. Because a signal is distributed over a range of wavelength and polarization, the pulses become dispersed. Although this group delay (GD) actually varies by small amounts, the short duration of the pulses, or bits, at today's high data rates makes this significant. For example, the bit duration of a 10 Gb/s signal is only 100 ps.

Dispersion must be considered and sometimes even compensated in the design of optical networks. The attainable transmission distances are limited by the amount of total dispersion. Calculations for the accumulation of CD and PMD along a link are detailed in IEC 61282-7 and IEC 61282-3, respectively, from the International Electrotechnical Commission. The tolerable dispersion depends primarily on the data rate. The amount of tolerable dispersion, related to the dispersion penalty parameter, also depends on the width of the wavelength range (linewidth) used by the signal. This linewidth increases with data rate, but also increases if the transmitter wavelength shifts with modulation, called chirp. Time-resolved chirp measurement is described in IEC 61280-2-10.

Methods have been developed and standardized for measuring CD and PMD in fibers, and recently also for other optical components, which bring other requirements like higher wavelength resolution. The IEC standard 60793-1-42 describes measurements for CD in fibers while IEC 60793-1-48 details methods for fiber PMD. Recently, to reduce test costs and enhance accuracy, instrumentation has been developed to obtain CD and PMD from the same measurement. This is done by measuring GD dependence on both wavelength and polarization. One of the methods, used in the Agilent 86038B Photonic Dispersion and Loss Analyzer, is well known as modulation phase shift (MPS), and is already included for CD in IEC 60793-1-42, as well as a draft document for PMD test in links, to be IEC 61280-4-4. The other newer method, swept-wavelength interferometry, is used in the Agilent 81910A All-Parameter Analyzer and is especially powerful for high-resolution analysis of optical components.

Accuracy of CD Measurements Depends on Resolution

Methods like MPS measure relative GD, the difference in delay from one GD measurement to the next, expressed in ps. Varying the wavelength between each measurement results in a spectrum of relative GD vs. wavelength. So the parameters whose uncertainty can be directly specified are GD and wavelength. For fibers, and devices used to compensate fiber dispersion, the rate of GD change over wavelength, the CD, is needed and expressed as ps/nm. For fiber the CD per length, ps/nm-km, is useful since CD scales with length. So how can CD measurement uncertainty be derived from the instrument specifications?

The CD uncertainty has a contribution due to GD uncertainty and another due to relative wavelength uncertainty. As illustrated in Fig. 1, the CD uncertainty also depends upon the wavelength step over which the GD slope is determined; the CD uncertainty can be reduced by using wider wavelength resolution. As a formula:

$$D = \frac{\Delta\tau}{\Delta\lambda} \text{ and } \varepsilon_D = \frac{1}{\Delta\lambda}\varepsilon_{\Delta\tau} + D\frac{\varepsilon_{\Delta\lambda}}{\Delta\lambda},$$

where the dispersion is *D*, the change in GD and wavelength are Δτ and Δλ and the uncertainty for each parameter is given by ε. The dispersion uncertainty depends on the wavelength step, Δλ, and the relative wavelength uncertainty contributes proportional to the dispersion, *D*. So for measuring fibers or dispersion compensators with high CD, very high relative wavelength accuracy is important. For example, if relative GD uncertainty is ±50 fs and relative wavelength uncertainty is ±1 pm, then the CD uncertainty is ±0.05 ps/nm + 0.1% for 1-nm resolution but ±0.005 ps/nm + 0.01%, averaged over 10 nm resolution. For a fiber with 1000 ps/nm CD, about 60 km standard single-mode fiber, this would be ±1.05 ps/nm or ±0.105 ps/nm, respective of the resolution. The GD uncertainty itself can also be significantly reduced by smoothing over points taken within the chosen resolution window.

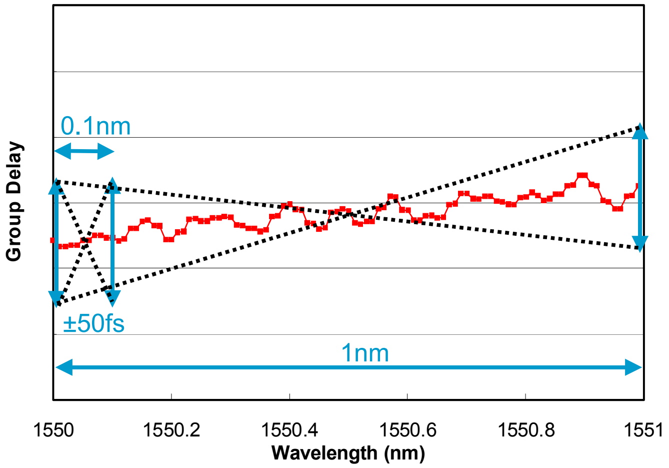

Figure 1. Group delay spectrum showing how the uncertainty in the CD, the slope, depends on the chosen wavelength resolution.

Fiber PMD Accuracy Depends on Wavelength Range

Polarization-resolved GD can be used to obtain the differential group delay, DGD. The DGD value gives the delay time difference between the fast and slow polarization states in the fiber and is also expressed in units of ps. The DGD of fiber usually varies with wavelength, and the DGD at the wavelength of a signal determines the amount of its degradation. However, as explained below, for fiber it is also important to determine the average DGD over a wide wavelength range. This average is called PMD.

The wavelength dependence occurs because the signal polarization changes along the fiber differently depending on the wavelength, so the fast and slow axes of the fiber segments are aligned differently for different wavelengths. When the alignment is higher, the segments tend to add together, while anti-aligned segments cancel each other, reducing the total DGD.

The DGD of a fiber also changes with time, because environmental effects like temperature and stress change the optical properties of the fiber along its length, and also the way the polarization of the light changes along the fiber. The DGD spectrum measured one day may not be the same as that measured at a later time. Any measured DGD value could occur at any other wavelength at another time.

Because of this variability with time, an “average” value, PMD, is used to calculate the probability of the DGD exceeding the tolerance level of the network. The PMD parameter represents the DGD spectrum and its time dependence with a single value. The statistical behavior of PMD also means that doubling the fiber length does not double the PMD. Instead it increases with the square root of length and the fiber PMD coefficient is given in units of ps/km$^{-1/2}$. A typical PMD limit for 10 Gb/s signals is 10 ps or 10% of the bit duration.

DGD can be averaged over time or wavelength to determine PMD. But time averaging is impractical because the DGD may only change on a time-scale of days or slower. This means that a tolerable measurement duration usually doesn’t give a sufficient sample of the possible DGD behavior. Instead, PMD measurement methods average DGD over wavelength, requiring a wavelength range giving adequate sampling. The necessary range is found to depend on the PMD value itself [1]. In Fig. 2 are shown DGD spectra for two fibers with different PMD levels, although from the same loose-tube buffer with 2.5 km length. The DGD varies more rapidly over wavelength when the average value is higher. Obviously the measured average value depends on the actual wavelength range chosen and for lower PMD, a wider wavelength range must be sampled. While a measurement gives an “accurate” measure of the fiber PMD for a certain wavelength range at a given time, the validity of this PMD value at a later time depends on sufficient sampling.

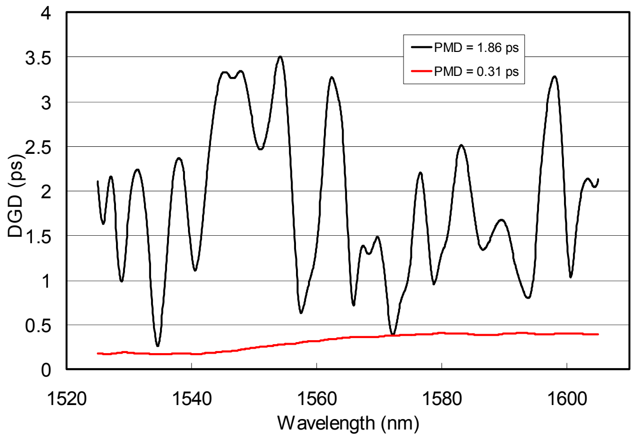

Figure 2. Differential group delay spectra for two 2.5-km fibers, showing how the variation over wavelength depends on the average level.

This corresponds to analyses indicating an uncertainty contribution for PMD measurement, ΔPMD, with limited wavelength range according to:

$$\frac{\Delta PMD}{PMD} = \pm \frac{\alpha}{\sqrt{PMD * 2\pi * \Delta f}} ,$$

where Δf is the measurement range (expressed as frequency) and α is a constant (0.9 in Ref. [1] and 1.12 in Ref. [2]). For some sample PMD values and measurement ranges, the resulting uncertainty is given in Table 1, using α=1.12.

Relative PMD Uncertainty	PMD=0.1ps	PMD=1.0ps	PMD=10ps
BW=10nm, Δf=1.25THz	±130%	±40%	±13%
BW=50nm, Δf=6.25THz	±56%	±18%	±5.6%
BW=100nm, Δf=12.5THz	±40%	±13%	±4.0%
BW=200nm, Δf=25THz	±28%	±8.9%	±2.8%

Table 1. Relative PMD uncertainty due to finite wavelength range, BW, of measurement. Results calculated for measurements centered at 1550 nm using α=1.12.

Interaction of CD and PMD in Measurement Accuracy

CD and PMD together in a device add addition sources of uncertainty to dispersion measurements, which can be reduced by simultaneous CD and PMD measurement. First, the DGD contributes directly to the GD uncertainty ε_T, if the polarization of the test signal is not controlled or averaged. The contribution to CD uncertainty is given by

$$\varepsilon_D = \pm \frac{DGD}{\Delta\lambda} ,$$

which would be an average contribution of ±1 ps/nm, at 1-nm resolution, for a fiber with 1 ps PMD; a major contribution. But measuring the polarization dependence of the GD and using the polarization-averaged GD values can eliminate this error.

However, since signals are polarized, using polarization-averaged GD to determine CD is only valid if the GD slope is the same for any given polarization. But the GD curve for fixed input polarization can be tilted with respect to the average. This polarization-dependent CD can be determined if the instrumentation also measures the way PMD depends on wavelength, known as 2nd-order PMD. This is an advantage over measurements that only determine average PMD. CD primarily affects DGD or PMD uncertainty by converting wavelength uncertainty or instability into delay uncertainty. For a 1000 ps/nm CD fiber, a 1 pm wavelength uncertainty makes 1 ps DGD uncertainty. Especially in swept-wavelength DGD measurements, which are very desirable for speed purposes, high wavelength accuracy and repeatability are important.

The Role of Speed and Stability

Optimizing measurement speed can reduce uncertainty. Fast measurements help stability and reduce costs, but increasing the averaging with more measurement time reduces the uncertainty. In many GD measurements, the uncertainty is statistical noise, so that doubling the time reduces uncertainty by a factor of $\sqrt{2}$. The benefit of averaging depends on the stability of both instrumentation and fiber. Consider particularly the effect of temperature on the fiber GD, which changes by about .001% with 1° C temperature change. Then a 20 km fiber, which has about 100 µs GD, will change by about 1ps/s when the temperature changes 4°C/hour. Thus temperature stability is very important, both in the instrument and tested device. Measuring shorter lengths of fiber reduces this problem, to the extent allowed by fiber homogeneity. But using measurements of short fibers to calculate for longer spans requires a higher accuracy in the measurement, and wider wavelength range for PMD measurement. Which loops us back to the importance of these measurement specifications!

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References:

[1] N. Gisin, et al., “How Accurately Can One Measure a Statistical Quantity Like Polarization-Mode Dispersion”, IEEE Photon. Technol. Lett. **8**, 1671 (1996).

[2] M. Shtaif and A. Mecozzi, “Study of the frequency autocorrelation of the differential group delay in fibers with polarization mode dispersion”, Opt. Lett. **25**, 707 (2000).