Chromatic Dispersion Measurement Error Caused by Source Amplified Spontaneous Emission

T. Dennis and P. A. Williams

Abstract—**We demonstrate experimentally and theoretically the degrading effect of noise from source amplified spontaneous emission on measurements of chromatic dispersion using the modulation phase-shift method. We show that dramatic performance improvements can be realized simply by using a narrow-band tracking filter.**

Index Terms—**Calibration, chromatic dispersion, measurement errors, optical communication, optical fiber measurements.**

I. Introduction

We HAVE observed a significant source of chromatic dispersion (CD) measurement error originating from the presence of amplified spontaneous emission (ASE) in the measurement laser. The accurate measurement of CD in optical fiber is critical to the effective design of networks as data rates and link lengths increase. Dispersion causes optical data pulses to broaden through the wavelength-dependent variation in refractive index of the fiber.

We perform our measurements of CD using the highly accurate modulation phase-shift (MPS) method [1], [2]. This well-established technique offers both high wavelength and temporal resolution, which also makes it applicable to narrow-band component measurements [3], [4]. The method records as a function of wavelength the change in phase of a modulated optical carrier resulting from transmission through a length of optical fiber. Observed changes in arrival phase with wavelength represent variations in the propagation time [relative group delay (RGD)] though the device, where 360° of phase represents one period at the modulation frequency. Fitting the group delay spectrum to an equation appropriate for the type of fiber [2] allows the CD to be obtained as the slope of the curve.

A tunable laser for metrology can easily have an ASE level of a few percent or more, which is sufficient to cause a noticeable CD measurement error. The modulated monochromatic measurement laser can be modeled as a vector with a magnitude proportional to its optical power and a phase determined by the delay of the fiber. The modulated ASE noise is viewed as a superposition of monochromatic sources spread across the spectrum of the ASE, each with a magnitude and phase that add as vectors to create a constant net noise vector. In general, the diversity of the phase will cause some destructive interference and a reduction in the noise magnitude. As will be shown, the key to the reduction is avoiding the overlap of the spectrum of the broad-band noise with the zero-dispersion wavelength (ZDW) of the fiber.

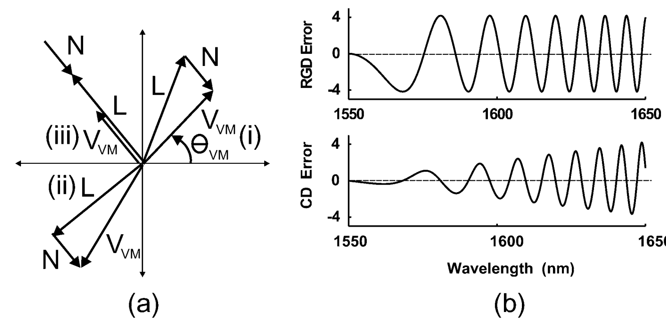

Fig. 1. (a) Vector model of the phase measurement process with constant noise, and (b) the resulting RGD and CD errors as a function of measurement wavelength. The ZDW is at 1550 nm.

Fig. 1(a) illustrates several important combinations of the variable laser vector (L) and constant net noise vector (N), each resulting in a measured radio-frequency signal on a vector voltmeter with magnitude $\mathsf{V}_{\rm VM}$ and phase $\theta_{\rm VM}$. By tuning the laser wavelength to position (i), the resultant voltmeter magnitude and phase angle are smaller than the laser's, so the measured phase lags the actual phase of the laser. In (ii), the opposite is true and the phase seen by the voltmeter leads the laser's phase. Case (iii) is special in that all vectors align and the noise does not cause a phase measurement error. Since the RGD is proportional to the phase, it too has measurement errors that oscillate about the true value with wavelength, as shown in Fig. 1(b). Also shown is the CD error, which being the derivative of the RGD also has ripples.

The vector representing the measurement laser will rotate with wavelength at a faster rate about the origin as the CD of the fiber increases, causing the RGD error ripples that occur each 360° to have increasingly shorter wavelength periods. As shown in Fig. 1(b), this causes the RGD ripples to become sharper, which in turn causes the amplitude of the CD ripples to increase. The amplitude of the RGD ripples will also increase if the optical signal-to-noise ratio (OSNR) decreases, as can happen with wavelength when the laser nears the end of its tuning range.

When the laser is tuned to wavelength λ_L, the laser and net noise vectors can be expressed as

$$\mathsf{L}(\lambda_L) = P_L(\lambda_L)\exp(i2\pi f\tau(\lambda_L)) \quad (1)$$

$$\mathsf{N}(\lambda_L) = \int \mathrm{ASE}(\lambda, \lambda_L)\exp(i2\pi f\tau(\lambda))d\lambda \quad (2)$$

respectively, where $P_L(\lambda_L)$ and $\tau(\lambda_L)$ are the laser power and group delay at λ_L, respectively, f is the modulation frequency, and $\mathrm{ASE}(\lambda, \lambda_L)$ is the ASE power spectral density when the

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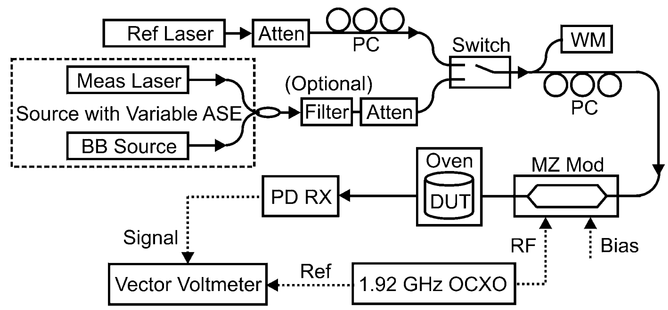

Fig. 2. Modified MPS system used to demonstrate the influence of broad-band noise. WM: Wavelength meter. MZ-Mod: Mach–Zehnder modulator. DUT: Device under test. PD-RX: Photoreceiver. OCXO: Oven-controlled crystal oscillator. PC: Polarization controller.

laser is tuned to λ_L. By definition, the measured group delay with error is given by

$$\tau'(\lambda_L) = \theta_{\mathrm{VM}}/2\pi f = \arg(\mathsf{L}(\lambda_L) + \mathsf{N}(\lambda_L))/2\pi f \quad (3)$$

where "arg" denotes the argument (phase angle) of the vector sum. We also define the OSNR as

$$\mathrm{OSNR}(\lambda_L) = 20\log_{10}(P_L(\lambda_L)/\int \mathrm{ASE}(\lambda, \lambda_L)d\lambda). \quad (4)$$

The net noise vector and OSNR depend on the laser tuning wavelength λ_L through the shape dependence of the ASE spectrum.

II. Experiment

Fig. 2 shows the MPS apparatus for this demonstration, the basic design of which has been described in previous work [4]. Because the particular measurement laser we used had low ASE ($<1\%$ of the total laser power, with an ASE peak in the C-band), we added the broad-band source to simulate a laser with higher ASE ($\sim 10\%$). The measurement laser and broad-band source were combined, and, optionally, passed through a tracking filter having a 3-dB bandwidth of 0.3 nm and a free-spectral range (FSR) of 60 nm. Programmable optical attenuators were used to maintain constant received power. Real-time variations in phase at a fixed wavelength position represented the phase drift of the system. These drifts were minimized by normalizing each value of phase to a subsequent reference phase measured at a fixed wavelength. The sources were intensity-modulated with a bias-stabilized Mach–Zehnder modulator driven by an oven-controlled crystal oscillator at 1.92 GHz and transmitted through a 12-km length of dispersion-shifted fiber (ZDW $\sim$1552 nm). The phase of the received signal relative to the electrical reference from the crystal oscillator was measured with a vector voltmeter, and from this the RGD could be calculated.

We began the demonstration with the tracking filter in place and measured the RGD of the fiber sample at nominally 50-pm intervals from 1560 to 1590 nm. Because the fiber was dispersion shifted, the RGD data was globally fit to a quadratic function spanning the entire wavelength range, giving an analytical description of the CD profile. The RGD data were analyzed a second time on a local basis by repeatedly fitting a quadratic function to 4-nm wavelength subintervals shifted by 0.2 nm. The dotted line of Fig. 3 shows the negligible CD error (the difference between the globally and locally calculated dispersions) for this filtered case. The ripples of no more than 0.05-ps/nm peak amplitude are consistent with the uncertainty of our CD measurement system. This result demonstrates that when the tracking filter is used, the expected linear CD spectrum (quadratic RGD spectrum) for dispersion-shifted fiber can be accurately measured across a broad wavelength range.

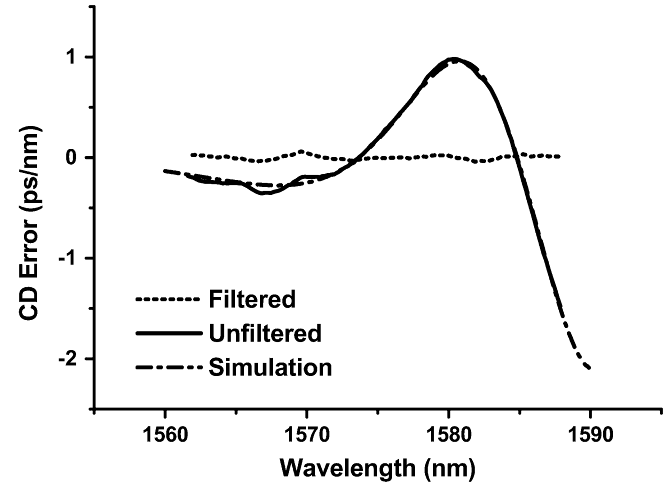

Fig. 3. Measured and simulated CD error as a function of wavelength.

This measurement procedure was repeated with the tracking filter removed. The RGD data were analyzed locally to obtain a detailed CD profile and compared to the global profile of the filtered measurement. Fig. 3 shows the oscillating CD error, with amplitude that increases dramatically with wavelength. A positive ripple of amplitude 0.95 ps/nm is located at 1580.4 nm, and a negative ripple of amplitude greater than 1.5 ps/nm appears to occur beyond 1588 nm. With dispersion values of 23.8 and 30.3 ps/nm calculated at these same positions from the filtered measurement, the ripples constitute errors of 4.2% and 5.0%.

Using measured spectra of the broad-band noise and laser ASE, the spectral variation of the laser and ASE power, and the fiber CD spectrum, a simulation of the resultant phase at the voltmeter was performed. The excellent agreement with the experiment is shown in Fig. 3, with the simulation largely obscured by the measured error. The only free parameter was the polarization-dependent modulation efficiency of the unpolarized broad-band source, which scaled the amplitude of the CD error ripples.

Fig. 4 shows the OSNR spectrum corresponding to the simulated CD error curve of Fig. 3 when a tracking filter is not used. This curve was obtained from (4) by evaluating the ASE noise integral over its entire wavelength range. The OSNR decreases significantly by 10 dB across the measurement range of 1560–1590 nm. The decrease is caused by a reduction in the output efficiency of the measurement laser as it reaches the end of its tuning range, and a corresponding increase in ASE gain. As noted by the dashed lines, the OSNR has a value of 22.8 dB at 1580.4 nm, which corresponds to the wavelength location of the CD error peak of Fig. 3.

Shown in Fig. 5 is the simulated dependence of the CD error peak at 1580.4 nm on OSNR. Noted on the plot is the experimental condition of 0.95 ps/nm of error resulting from an OSNR

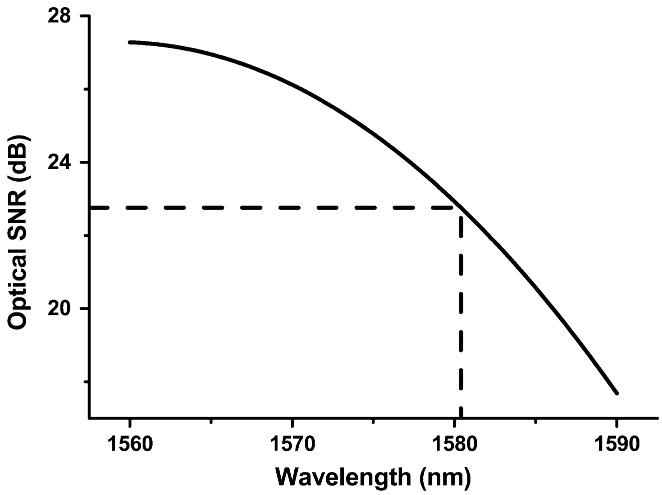

Fig. 4. OSNR as a function of wavelength corresponding to the simulated CD error curve of Fig. 3 for the unfiltered case.

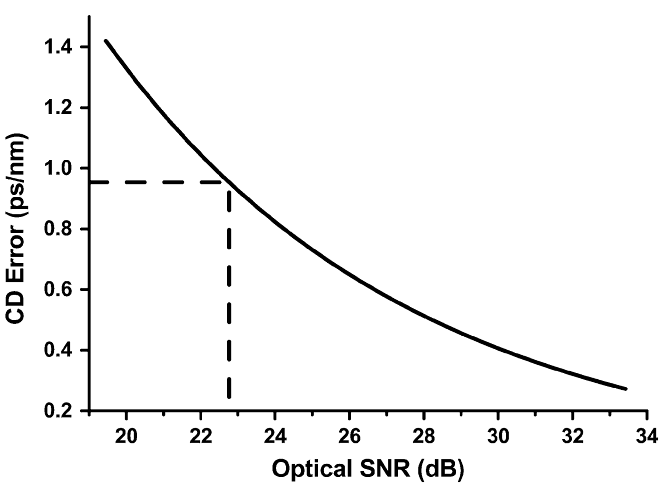

Fig. 5. Simulated OSNR dependence of the CD error ripple of Fig. 3 at a wavelength of 1580.4 nm.

of 22.8 dB. The plot shows that increasing the OSNR by 10 dB will reduce the peak CD error by only a factor of three. An increase in OSNR of 10 dB may not be achievable simply by increasing the drive current of the measurement laser, in which case a tracking filter should be used.

The CD measurement error is greatest when the broad-band noise spectrally overlaps with the ZDW of the fiber. The measurement laser with C-band ASE, but without the broad-band source, produced an error in dispersion of 0.5 % at 1580.4 nm. Replacing this laser with one having an ASE peak in the L-band resulted in a negligible error, despite having 7.5 dB more ASE optical power. The simulations showed that the net noise vector of this laser was actually more than seven times smaller than the laser having C-band ASE and should cause ten times less CD error. Equation (2) shows that when the ASE is located away from the ZDW where the CD is large, the rapid variation of the exponential argument with wavelength causes the integral to be small. However, when the ASE overlaps with the ZDW, the exponential argument varies slowly across the bandwidth of the ASE and the integral becomes larger.

III. Discussion and Conclusion

In the future, as the budget for CD becomes tighter, measurements may need to be performed on installed fiber systems containing ASE-emitting amplifiers. Using published values of CD or making sample measurements in the laboratory will not account for spool-to-spool variations and environmental factors. If narrow-band filters are not used in an amplified nonregenerative system, the accumulated amplifier ASE can actually become larger than the signal. However, it should not significantly impact the accuracy of CD measurements because the additive noise will be unmodulated and, therefore, unseen by the vector voltmeter. In addition, if the gain spectrum is uniform, the modulated ASE of the laser will experience the same gain as the laser and the phase error will be unchanged. However, if the spectrum is not uniform or gain flattened it may be possible for the ASE of the laser to experience greater gain.

The error was enhanced for the purpose of this demonstration, but we have observed it to a lesser degree ($\sim 1\%$) in other unfiltered experiments using only the laser ASE. As new metrology lasers achieve wider tuning ranges, even greater measurement error will result. In practice, a sizeable error is observed only with low OSNR and significant overlap of the ASE with the ZDW. For example, while a C-band laser will give accurate measurements for standard unshifted fiber, care must be taken when measuring shifted and nonzero-shifted fiber. A tracking filter effectively removes the measurement error, and it need not be particularly narrow, as our simulations predict that a filter with a bandwidth of 5 nm and an FSR of 60 nm will still reduce the maximum error level by a factor of 24 below that shown in Fig. 3.

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