Chromatic dispersion measurement error caused by source amplified spontaneous emission

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Abstract: We demonstrate the degrading effect of noise from amplified spontaneous emission on measurements of chromatic dispersion using the modulation phase-shift method. Dramatic performance improvement is achieved with a narrow-band tracking filter.

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1. 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 refractive index variation of the fiber.

We perform our measurements of chromatic dispersion using the highly accurate modulation phase-shift (MPS) method [1-4]. 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 or 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 chromatic dispersion 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, each with a magnitude and phase, that add as vectors to create a net noise vector. In general the diversity of the phase will cause some destructive interference and reduce the noise magnitude. As will be shown, the key to the reduction is the overlap of the spectrum of the broadband noise with the zero-dispersion wavelength (ZDW) of the fiber. The stationary spectrum of the noise creates a vector with constant phase and amplitude that adds vectorially with the variable vector of the tunable laser.

Figure 1 (a) illustrates several important combinations of the laser (L) and net noise vector (N), each resulting in a measured RF signal on a vector voltmeter with magnitude V_{VM} and phase θ_{VM}. By tuning the laser wavelength

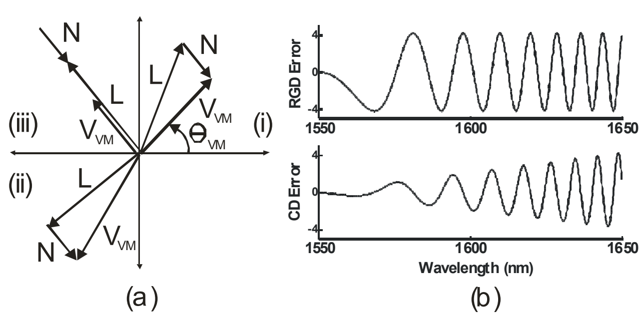

Fig. 1. (a) The vector model of the phase measurement process with constant noise, and (b) the resulting RGD and CD errors as a function of measurement wavelength. The zero-dispersion wavelength is at 1550 nm.

to position (i), the resultant voltmeter magnitude and phase angle are smaller than the laser, 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. 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 chromatic dispersion 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 increase if the optical signal-to-noise ratio (SNR) decreases, as can happen with wavelength when the laser nears the end of its tuning range. This can be seen in Fig. 1 (a), where a magnitude reduction of the laser vector and/or an increase in the net noise vector will increase the phase measurement error. The CD ripples will increase even more dramatically than shown in Fig. 1 (b).

2. Experiment

Figure 2 shows the MPS apparatus for this demonstration, the basic design of which has been described in previous work [4]. Because the particular C-band measurement laser used had low ASE (<1 % of the total laser power) we added the broadband source to simulate a laser with high ASE (~10%). The measurement laser and broadband

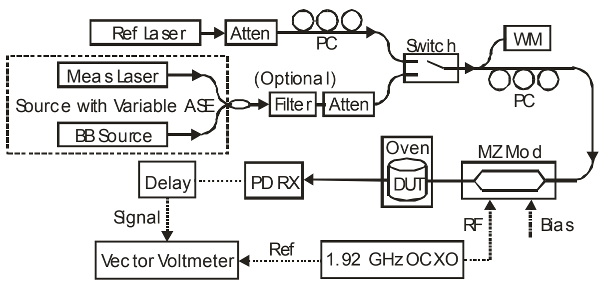

Fig. 2. The modified MPS system used to demonstrate the influence of broadband noise, showing the wavelength meter (WM), Mach-Zehnder modulator (MZ-Mod), device under test (DUT), photo receiver (PD-RX), oven-controlled crystal oscillator (OCXO) and polarization controllers (PC).

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. A mechanical optical switch was used to alternate between the reference and measurement sources. 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 ~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. Being shifted fiber, 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 sub-intervals shifted by 0.2 nm. Figure 3 shows the negligible CD error (the difference between the globally and locally calculated dispersion) for this filtered case, with ripples of no more than 0.05 ps/nm peak amplitude. This result demonstrates that when the tracking filter is used, the expected linear CD spectrum (quadratic RGD spectrum) for

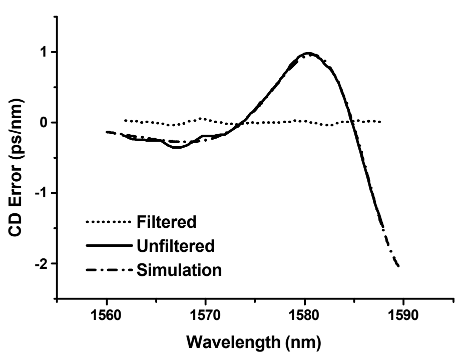

Fig. 3. The measured and simulated chromatic dispersion error as a function of wavelength.

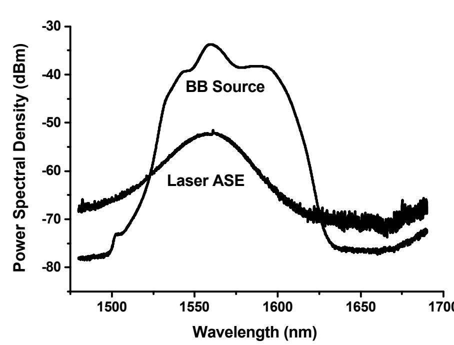

Fig. 4. The spectra of the broadband (BB) source (solid line) and the laser ASE (dashed line) when tuned to 1560 nm.

dispersion-shifted fiber can be accurately measured across a broad wavelength range.

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. Figure 3 shows the oscillating CD error, with an amplitude that increases dramatically with wavelength. A positive ripple of amplitude 1.0 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 noise (Fig. 4), the optical SNR, 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 broadband source, which scaled the amplitude of the CD error. The ASE had the same polarization state and therefore the same modulation efficiency as the laser. The measured electrical SNR after the modulator was 5 dB *higher* than expected by the input optical SNR. Therefore, the required reduction of the broadband noise by 4.0 dB to achieve the agreement in Fig. 3 seems reasonable.

The CD measurement error is greatest when the broadband noise spectrally overlaps with the ZDW of the fiber. In this situation the noise experiences less phase diversity and less destructive interference, resulting in a larger net noise vector. The C-band measurement laser without the broadband source produced at least a 0.5 % error in measured CD. Replacing the C-band laser with an extended L-band laser (1545 to 1645 nm) resulted in a negligible error, despite having 7.5 dB more ASE optical power. This was predicted by the simulations, which showed that the net noise vector of the L-band laser was actually more than 7 times smaller than the C-band laser, and should cause 10 times less CD error.

3. Discussion

In the future, as the budget for chromatic dispersion 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. The amplifier ASE accumulated through a nonregenerative system can actually become larger than the signal. However, it should not have a significant impact on the accuracy of CD measurements because the additive noise will not be modulated and will not appear as a vector component on the 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 gain spectrum is not uniform, or mechanisms such as spectral hole burning apply, it may be possible for the ASE of the laser to experience greater gain. Such preferential amplification is more significant when the laser is at the edge of the gain spectrum. Additionally, if the amplifier ASE power is very large, the detector could saturate and indirectly influence the measured phase.

The error was enhanced for the purpose of this demonstration, but we have observed it to a lesser degree (~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 significant error is observed only with low SNR and good 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 non-zero 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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