Fiber Chromatic Dispersion and Polarization-Mode Dispersion Monitoring Using Coherent Detection

Biao Fu and Rongqing Hui

Abstract—**We propose and experimentally demonstrate a nondestructive method to monitor chromatic dispersion (CD) and polarization-mode dispersion (PMD) in traffic-carrying wavelength-division-multiplexing optical systems. Coherent heterodyne detection is used to down convert the spectrum of digitally modulated signal from optical domain into radio-frequency (RF) domain. By analyzing group delay difference and polarization walkoff between different frequency components through proper RF signal processing, both CD and PMD can be precisely determined. Good agreement between experimental results and theoretical values has been obtained.**

Index Terms—**Chromatic dispersion monitoring, coherent detection, heterodyne, optical communication, polarization-mode dispersion (PMD) monitoring, radio-frequency (RF) signal processing.**

FIBER chromatic dispersion (CD) and polarization-mode dispersion (PMD) are two major sources of transmission performance degradation in high-speed long-distance optical communication systems [1].

So far, several CD and PMD monitoring methods have been proposed. The measurements of eye-opening penalty, Q-factor, or BER have been proposed earlier to monitor CD [2], [3], but these electrical domain measurements are data rate dependent and are performed on per-channel basis. The phase-modulation–amplitude-modulation (AM) conversion method proposed in [4] and the AM pilot tones method proposed in [5] and [6] require nonstandard transmitters and receivers. The CD can also be determined by monitoring the power of the clock component after photodetection [7]. However, the measured clock power is influenced not only by CD but also by PMD, and these two effects cannot be separated. Sideband optical filtering technique was also proposed recently to monitor CD [8]. In this case, the measurement accuracy may depend on the optical filter's parameters such as shape, bandwidth, and detuning as well as the optical signal modulation format. In practice, the bandwidth and the shape of an optical filter is difficult to control especially when the required bandwidth is very narrow.

As far as the PMD monitoring is concerned, the effect of PMD on an optical system can be evaluated by monitoring the degree of polarization of the optical signal [9], but the results may be sensitive to the variation of signal optical spectrum and the modulation bandwidth. Vestigial sideband optical filtering has been recently proposed to evaluate PMD through measuring the strength reduction of the beating signal between the optical carrier and one of the optical clock components [10], [11]. Although this method is insensitive to effect of CD, the absolute signal strength at the beating frequency depends not only on PMD, but also on the modulation format and the spectral distribution of the optical signal. Therefore, a quantitative and reliable evaluation of PMD might not be possible.

Very recently, coherent frequency-selective polarimeter was proposed which has the ability to evaluate PMD [12]. In this method, the measurement of different frequency components within the signal bandwidth is accomplished by sweeping the LO and a polarization transformer is required to adjust the SOP of the LO at each data point to evaluate the Stokes parameter. In practical applications using this method, calibration for the PMD measurement has to take into account the LO power variation during the wavelength sweep and one has to assume the value of PMD does not change during each wavelength sweep. Most importantly, this coherent polarimeter technique, as well as the technique proposed in [13], cannot be directly used to evaluate the CD of the optical system. On the other hand, although several newly proposed CD monitoring techniques are immune to the effect of PMD [14], [15], they cannot be used to measure PMD in the system.

In this letter, we demonstrate that by combining coherent heterodyne optical detection and RF signal processing, we can accurately determine both the CD and PMD in a particular optical channel. Because RF technology is much more mature than optical technology and high-quality RF filters can be easily made with sharp frequency selectivity, extending signal processing from optical domain into RF domain will greatly enhance the system's functionality and flexibility.

With digital modulation, the optical spectrum of optical signal typically has two redundant clock frequency components and an optical carrier. Due to CD, these two clock components propagate at different speeds creating a differential delay at the receiver. In our proposed method, the coherent detection down converts the spectrum of the optical signal into RF domain in which the relative phase-delay information of the optical signal is preserved. In RF domain, the carrier and the two sidebands are selected separately by three bandpass filters. The carrier component is further split into two and used to mix with the upper and the lower sidebands independently to generate two independent clocks. After mixing, a narrow-band RF filter is used in each branch to purify the recovered clocks. The CD can be evaluated from the relative time delay Δt between these two recovered clocks by [16]

$$\Delta t = DL\lambda^2 R_b/c \tag{1}$$

where D is the fiber CD parameter, L is the fiber length, λ is the signal wavelength, c is the speed of light, and R_b is the data rate.

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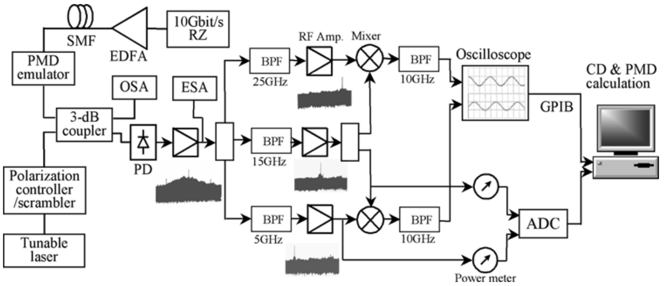

Fig. 1. Block diagram of CD and PMD monitoring using coherent detection. BPF: Bandpass filter. OSA: Optical spectrum analyzer. ESA: Electrical spectrum analyzer. ADC: Analog-to-digital converter.

Similar to the optical-domain filtering technique [8], since Δt is evaluated from the phase walkoff between the two recovered clocks, the total dispersion can be measured using this method is limited to $\pm 180^\circ$ of the relative clock phase shift, or equivalently $\pm T_b/2$ in time, where T_b is the bit length. If the sign of dispersion is known, this measurable range can be from 0° to 360°.

In PMD measurement, only the RF powers of the carrier and one of the sidebands need to be measured. The first-order DGD $(\Delta\tau)$ of the fiber system creates a differential polarization walkoff between the carrier and the sideband and their relative angular walkoff on the Poincare sphere can be expressed as [17]

$$\Delta\varphi = \pi \Delta f \cdot \Delta\tau. \tag{2}$$

Where Δf is the frequency separation between the carrier and the selected sideband. Considering that the efficiency of coherent detection depends on the SOP mismatch between the LO and the signal, the generated RF powers of the two selected frequency components are, respectively,

$$P_1 = \eta_1 P_{\text{lo}} P_{\text{sig}}(f_1) \cos^2(\varphi) \tag{3}$$

$$P_2 = \eta_2 P_{\text{lo}} P_{\text{sig}}(f_2) \cos^2(\varphi + \Delta\varphi) \tag{4}$$

where η_1 and η_2 represent the combined effects of the responsivities of the two detectors and the relative amplitudes of the selected two frequency components, P_{lo} and P_{sig} are the optical powers of the LO and the signal, φ represents the polarization mismatch between the LO and one of the selected frequency component and $\Delta\varphi$ is the SOP angle between the two selected frequency components.

Randomly scrambling the SOP of the LO makes φ a random variable while $\Delta\varphi$ is relatively stable assuming that the DGD variation in the fiber system is much slower than the polarization scrambling of the LO. After a few cycles of P_1 and P_2 passing through their maxima and minima, the RF power measured at the two branches can easily be normalized irrespective of the actual power difference between the received two frequency components, and the normalized powers of the two branches are $\cos^2 \varphi(t)$ and $\cos^2[\varphi(t) + \Delta\varphi]$, respectively. The phase difference $\Delta\varphi$ between these two power traces can easily be obtained and the first order DGD of the fiber system can then be derived by

$$\Delta\tau = \Delta\varphi / (\pi \Delta f). \tag{5}$$

The detailed experimental setup for CD measurement is shown in Fig. 1. The RZ optical transmitter consists of a laser source and two concatenated LiNbO$_3$ electrooptic modulators. The first modulator is driven by a 10-Gb/s NRZ pseudorandom binary sequence signal and the second modulator is driven by a synchronized 10-GHz clock which converts the NRZ optical signal into RZ. After transmitting through an optical fiber, the optical signal is sent to the coherent performance monitor, where it combines with the light emitted from a tunable laser (LO) through a 3-dB fiber coupler. The mixed optical signal is detected by a wide-band photodiode, which down converts the spectrum of the 10-Gb/s optical signal into RF domain. By adjusting the wavelength of the LO, the carrier frequency of the heterodyne RF signal is tuned to approximately 15 GHz. Then, this RF signal is split into three parts and each passes through a narrow-band RF filter at 5, 10, and 15 GHz, respectively, to select the carrier and the lower and the upper clock sidebands. The measured RF spectra at various stages of the circuit are shown in the inset of Fig. 1. The carrier component is further split into two and used to mix with the upper and the lower clocks independently. This generates two separate clock waveforms after narrow-band filtering at the clock frequency. An oscilloscope then displays the two clock waveforms and a computer collects the data and calculates the relative time delay between the two recovered clocks. For simplicity, the polarization scrambler in Fig. 1 was turned OFF and the SOP of the LO was kept constant to match that of the signal.

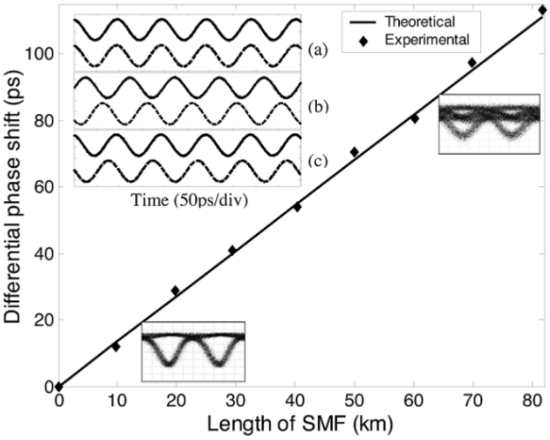

Fig. 2. Measured and actual differential delays between the two clock components versus fiber length. Solid line: Theoretical. Solid diamonds: Measured. Inset: Eye diagrams measured after 0- and 81.7-km fiber and measured lower and upper clock waveforms at 0-, 29.4-, and 60.1-km fiber length.

The results of a systematic measurement on CD versus fiber length is shown in Fig. 2, together with the results calculated with (1) using the specified fiber dispersion parameter $D = 17$ ps/nm · km. Fig. 2 shows a very good agreement between the measured and the actual differential delays between the two clock components, which verifies the accuracy of the measurement system.

In PMD measurement, a first-order PMD emulator (JDS-Fitel PE3) is added in the system to create a known value of DGD. To create a random polarization mismatch between the signal and the LO, a polarization scrambler is used. Although this polarization scrambler can be added either in the signal path or at the LO, we chose the later because for optimum operation the scrambler usually requires a fixed SOP at its input. To measure PMD, only two of the three RF frequency components are needed after the

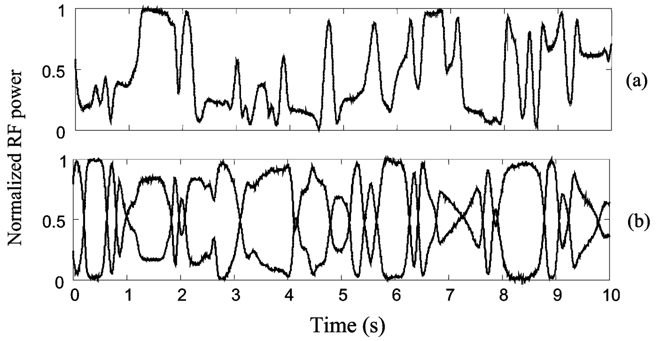

Fig. 3. Normalized carrier and clock powers versus time. Solid line: Carrier power. Dotted line: Clock sideband power. (a) $\text{DGD} = 0$ ps. (b) $\text{DGD} = 50$ ps.

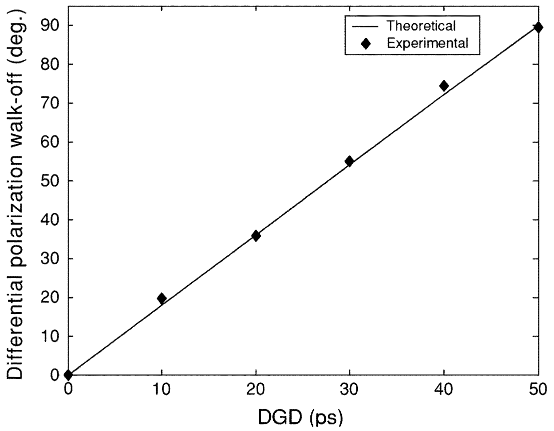

Fig. 4. Differential polarization walkoff versus the set value of DGD. Solid diamonds: Measured. Continuous line: Theoretical.

bandpass filters. The RF powers of these two frequency components are measured by two independent RF power meters which are connected to a dual-channel analog-to-digital converter. A computer system samples the two power levels, performs normalization, and calculates the DGD of the system based on (5).

The system was measured at various different DGD levels set by the PMD emulator ranging from 0 to 50 ps. Fig. 3 shows examples of the normalized RF powers versus time measured at 5 and 15 GHz by two power meters (represented by the two traces) at two different system DGD levels. Fig. 3(a) was obtained with zero DGD ($\Delta\tau = 0$) and the two traces are exactly in-phase, while for Fig. 3(b), the system DGD was set at $\Delta\tau = 50$ ps, which corresponds to $\Delta\varphi = \pi/2$ (for $\Delta f = 10$ GHz in (5). Indeed, Fig. 3(b) clearly shows that when one trace reaches the maximum the other one is at the minimum. Fig. 4 shows the measured $\Delta\varphi$ as a function of the system DGD values set by the PMD emulator. The calculated values of $\Delta\varphi$ using (5) are also plotted as the continuous line for comparison. Excellent agreement between them ensures the accuracy of this proposed method.

In conclusion, we have proposed and demonstrated a novel CD and PMD monitoring method based on coherent heterodyne detection and RF signal processing. This method is straightforward and easy to calibrate. Using a tunable laser as the LO, this setup can be used to perform instantaneous CD and DGD monitoring on each wavelength channel in a dense wavelength-division-multiplexing optical network. Unlike other conventional methods, this measurement setup is single-ended, and it does not require access to the transmitter. This monitoring system is especially useful for systems with moderate data-rate per channel where optical filters are not sharp enough to distinguish the upper and the lower sidebands [7], [8]. At very high data rate, more expensive electronics will have to be used.

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REFERENCES

[1] C. D. Pool and J. Nagel, “Polarization effects in lightwave systems,” in *Optical Fiber Communications*, I. P. Kaminow and T. L. Koch, Eds. San Diego, CA: Academic, 1997.

[2] I. Shake, H. Takara, K. Uchiyama, and Y. Yamabayashi, “Quality monitoring of optical signals influenced by chromatic dispersion in a transmission fiber using averaged Q-factor evaluation,” *IEEE Photon. Technol. Lett.*, vol. 13, no. 4, pp. 385–387, Apr. 2001.

[3] R. Wiesmann, O. Beck, and H. Heppner, “Cost effective performance monitoring in WDM systems,” in *Tech. Dig. OFC 2000*, Baltimore, MD, Mar. 2000, pp. 171–173.

[4] M. Tomizawa, Y. Yamabayashi, Y. Sato, and T. Kataoka, “Nonlinear influence on PM-AM conversion measurement of group velocity dispersion in optical fibers,” *Electron. Lett.*, vol. 30, no. 17, pp. 1434–1435, 1994.

[5] M. N. Petersen, Z. Pan, S. Lee, S. A. Havstad, and A. E. Willner, “Online chromatic dispersion monitoring and compensation using a single in-band subcarrier tone,” *IEEE Photon. Technol. Lett.*, vol. 14, no. 4, pp. 570–572, Apr. 2002.

[6] T. E. Dimmick, G. Rossi, and D. J. Blumenthal, “Optical dispersion monitoring technique using double sideband subcarriers,” in *IEEE Photon. Technol. Lett.*, Jul. 2000, vol. 12, pp. 900–902.

[7] Z. Pan, Q. Yu, Y. Xie, S. A. Havstad, A. E. Willner, D. S. Stardubov, and J. Feinberg, “Chromatic dispersion monitoring and automated compensation for NRZ and RZ data using clock regeneration and fading without adding signaling,” in *Tech. Dig. Optical Fiber Communication Conf. 2001 (OFC 2001)*, 2001, Paper WH5, pp. WH5.1–WH5.3.

[8] Q. Yu, Z. Pan, L.-S. Yan, and A. E. Willner, “Chromatic dispersion monitoring technique using sideband optical filtering and clock phase-shift detection,” *J. Lightw. Technol.*, vol. 20, no. 12, pp. 2267–2271, Dec. 2002.

[9] N. Kikuchi, “Analysis of signal degree of polarization degradation used as control signal for optical polarization mode dispersion compensation,” *J. Lightw. Technol.*, vol. 19, no. 4, pp. 480–486, Apr. 2001.

[10] T. Luo, Z. Pan, S. M. R. M. Nezam, L. Yan, A. Sahin, and A. Willner, “Chromatic dispersion-insensitive PMD monitoring using optical off-center bandpass filtering,” in *Tech. Dig. Optical Fiber Communication Conf. 2003 (OFC 2003)*, 2003, Paper ThY3, pp. 591–593.

[11] T. Luo, Z. Pan, S. M. R. M. Nezam, L. S. Yan, A. B. Sahin, and A. E. Willner, “PMD monitoring by tracking the chromatic-dispersion-insensitive RF power of the vestigial sideband,” in *IEEE Photon. Technol. Lett.*, Sep. 2004, vol. 16, pp. 2177–2179.

[12] I. Roudas, G. A. Piech, M. Mlejnek, Y. Mauro, D. Q. Chowdhury, and M. Vasilyev, “Coherent frequency-selective polarimeter for polarization-mode dispersion monitoring,” *J. Lightw. Technol.*, vol. 22, no. 4, pp. 953–967, Apr. 2004.

[13] S. M. Reza, M. Nezam, Y.-W. Song, C. Yu, J. E. McGeehan, A. B. Sahin, and A. E. Willner, “First-order PMD monitoring for NRZ data using RF clock refeneration techniques,” *J. Lightw. Technol.*, vol. 22, no. 4, pp. 1086–1093, Apr. 2004.

[14] Y. Takushima, H. Yoshimi, Y. Ozeki, K. Kikuchi, H. Yamaguchi, and H. Taga, “In-service dispersion monitoring in 32×10.7 Gbps WDM transmission system over transatlantic distance using optical modulation method,” *J. Lightw. Technol.*, vol. 22, no. 1, pp. 257–264, Jan. 2004.

[15] D. Sandel, V. Mirvoda, F. Wust, R. Noe, and C.-J. Weiske, “Signed online dispersion detection at 40 Gbit/s based on arrival time detection with 60 attosecond dynamic accuracy,” *Electron. Lett.*, vol. 38, no. 17, pp. 984–986, 2002.

[16] G. P. Agrawal, *Fiber-optic Communication Systems*, 2nd ed. New York: Wiley, 1992.

[17] D. Derickson, Ed., *Fiber Optic Test and Measurement*. Englewood Cliffs, NJ: Prentice-Hall, 1998.