Pulsewidth Distortion Monitoring in a 40-Gb/s Optical System Affected by PMD

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***Abstract*—A novel technique for monitoring the pulse broadening due to polarization-mode dispersion (PMD) in optical systems is described. The technique is based on the measurement of the Stokes vectors at different frequencies over the spectrum of the received optical pulse and does not require *a priori* knowledge of the fiber PMD statistics or details of the optical path. The validity of our technique has been demonstrated by both simulation and experimental results.**

***Index Terms*—Optical communication, optical performance monitoring, polarization-mode dispersion.**

I. Introduction

THE REAL time measurement of pulse distortion due to polarization-mode dispersion (PMD) in an optical link without knowledge of the transport history is a critical milestone toward optical performance monitoring for optical networks [1]. This type of measurement can be used for channel and path "health" assessment and to provide feedback to dynamic PMD compensation elements. Direct measurement of the PMD-induced pulse distortion is a more appropriate measurement for this class of applications than the standard approaches to the PMD analysis based on a statistical description [2]. Recently, a 10-Gb/s field experiment was performed that utilized a tunable bandpass filter to analyze the state-of-polarization for PMD-compensation [3]. However, the effects of limited filter bandwidths and resulting PMD estimation errors were not considered. In this letter, we present a new technique that allows direct monitoring of pulse broadening due to PMD without using statistics. This technique is based on an estimated differential group delay (DGD) obtained through the measurement of the Stokes vectors at different frequencies over the received pulse spectrum. The validity of the technique is demonstrated by both simulation and experimental results.

Manuscript received August 10, 2001; revised October 31, 2001.

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Publisher Item Identifier S 1041-1135(02)00881-9.

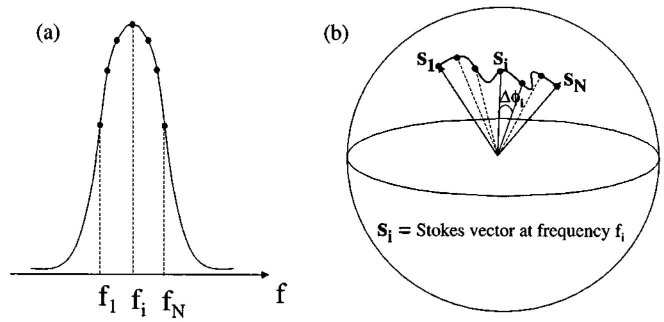

Fig. 1. (a) Frequency sweep over the pulse spectrum. (b) Corresponding motion of the Stokes vector on the Poincaré sphere.

II. Output Pulsewidth Estimation Using the Poincaré Sphere Method

In this section, a novel method is described which allows one to estimate the rms width τ_{out}^2 of a pulse at the output of a PMD fiber. Poole *et al.* showed in [4] that $\tau_{\text{out}}^2 = \tau_{\text{in}}^2 + \gamma(1-\gamma)\Delta\tau^2$, where τ_{in} is the input rms width, γ reflects the relative power launched in the two principal states and $\Delta\tau$ is the differential delay time. The maximum pulse broadening $\Delta\tau^2/4$ is obtained when the power is equally distributed between the two PSPs ($\gamma = 1/2$).

The Poincaré sphere method [5] is based on the estimation of the effective DGD using

$$\Delta\tau_{\text{eff}} = \frac{\Delta\Phi}{2\pi\Delta f} \tag{1}$$

where $\Delta\Phi$ is the angular width of the arc described by the Stokes vector on the Poincaré sphere in the frequency window Δf. Our technique consists in measuring the Stokes vector at several frequencies over the pulse spectrum (see Fig. 1), and estimating the effective DGD using (1) with

$$\Delta\Phi = \sum_{i=1}^{N-1} \Delta\phi_i \qquad \Delta f = f_N - f_1. \tag{2}$$

$\Delta\Phi$ is the total angular motion of the Stokes vector on the Poincaré sphere from frequency f_1 to frequency f_N. The effective DGD depends both on the real DGD $\Delta\tau$ and on the relative power in the principal states of polarization (PSPs) γ

$$\Delta\tau_{\text{eff}} = 2\sqrt{\gamma(1-\gamma)}\,\Delta\tau \tag{3}$$

that yields

$$\tau_{\text{out-est}}^2 = \tau_{\text{in}}^2 + \frac{\Delta\tau_{\text{eff}}^2}{4}. \tag{4}$$

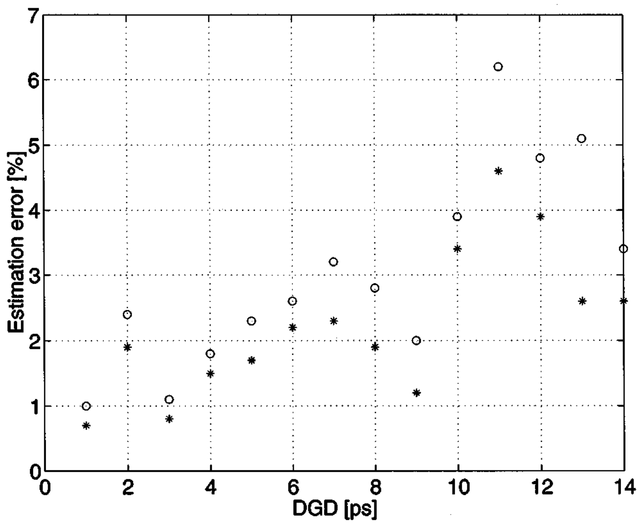

Fig. 2. Error in the estimation of the pulsewidth for different values of DGD. Stars: New Poincaré sphere method. Circles: Standard method.

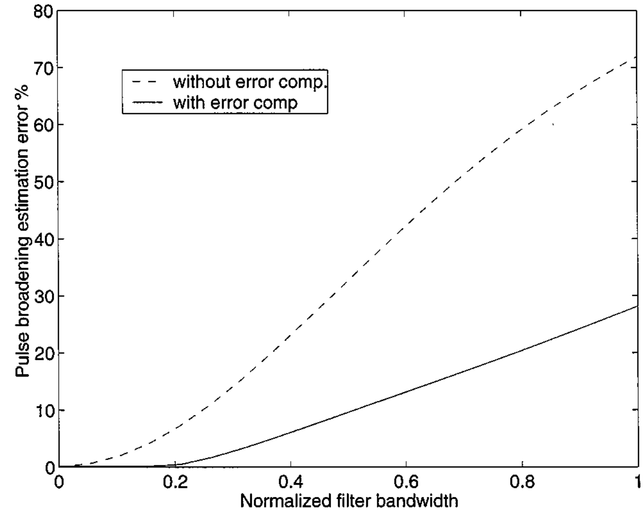

Fig. 3. Error in the estimation of the pulse broadening versus the normalized filter bandwidth with and without error compensation. Parameters: DGD $\simeq$ 8.5 ps (the pulse broadening is around 40%), $\Delta f = 50$ GHz and N_f is equal to 10.

Equations (3) and (4) are exact for first-order PMD only. When higher order PMD is present, a residual estimation error rises, which is negligible in most practical cases, as shown in Fig. 2 and in the following experimental results. A set of simulations has been run, where the PMD fiber consists of 15 segments of polarization-maintaining fiber with a DGD equal to 1.8 ps each. The effective DGD has been estimated using both (1) with $\Delta f = 50$ GHz and $N = 5$[1] (stars) and the relation $\Delta\tau_{\text{eff}} = d\Phi/d\Omega$ evaluated at the pulse center frequency (circles). The error in the estimation of the output pulsewidth has been obtained averaging the results over all the possible input polarization states of the pulse. The input pulse shape is Gaussian, with rms width $\tau_{\text{in}} = 4.2$ ps, which corresponds to a full-width at half-maximum of 45 GHz. The first technique gives better results that the second one for all values of DGD, and it consents to keep the estimation error always under 5%.

A. Realistic Measurement

In this section, the issue of the nonzero bandwidth of the optical filters in front of the polarimeter used to measure the Stokes parameters at different frequencies is investigated. Fig. 3 (dashed line) shows the error, with respect to the case of infinite resolution, in the estimation of the output pulse broadening when a Gaussian filter is used to sweep the frequencies over the pulse spectrum (dashed line), versus the bandwidth of the filter. The bandwidth values have been normalized over the FWHM width of the pulse spectrum. It is evident that the estimation of the pulse broadening is much more accurate when a filter with a steep transfer function is used.

B. Error Compensation

The error in the pulse broadening estimation due to the finite resolution of the filters used to measure the Stokes vectors occurs for two principal reasons.

1) The measured Stokes vectors are different from the real ones, yielding an error in the evaluation of $\Delta\Phi$ in (1).
2) When we evaluate the Stokes vector at a given frequency f_i, we are actually measuring the average of the Stokes vector over the filter bandwidth, weighted by the power spectrum of the pulse, which is not symmetric around f_i. This approach corresponds to measuring the Stokes vector at the shifted frequency

$$f_i' = f_i + \int (f|H(f - f_i)|^2 P(f)\, df) \tag{5}$$

where $H(f)$ is the transfer function of the filter and $P(f)$ is the pulse power spectrum. One way of compensating for the second cause of error is to evaluate the real frequencies at which the Stokes vectors are measured at the two extreme points of the frequency interval (f_1' and f_N') using (5) and then replacing Δf with $\Delta f' = f_N' - f_1'$.

The pulse broadening estimation error after compensation is shown in Fig. 3 (solid line). The residual error is due to the uncertainty in the measurement of the Stokes vector, which is larger for higher filter bandwidths. It can be shown, running a large number of simulations, that the error in the estimation of the pulse broadening, either with or without error compensation, depends very little on the amount of DGD present in the fiber, and consequently on the magnitude of pulse broadening.

After error compensation, the experimental error in the polarimeter and the instability of the input polarization state will probably be the dominant error factors.

III. Experimental Results

The experimental setup is reported in Fig. 4. A fiber ring laser generates optical pulses with FWHM of 8 and 5 ps, which propagate through the PMD emulator. The PMD emulator is composed by sixteen segments in the first measurement and eight segments in the second measurement of polarization-maintaining fiber with a DGD equal to 1.8 ps each. The

[1]Several simulations have been run in order to optimize the values of Δf and N. It turns out that Δf can be chosen between the full-width at half-maximum (FWHM) and twice the FWHM of the pulse spectrum and that reasonable values for N are between five and ten.

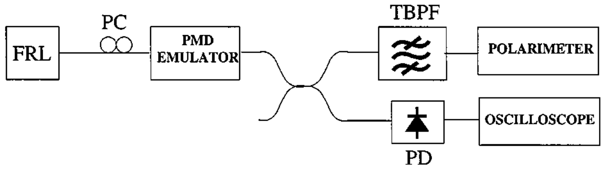

Fig. 4. Experimental setup. FRL: Fiber ring-laser. TBPF: Tunable bandpass filter. PC: Polarization controller. PD: Photodetector.

polarization controller is used to change the input polarization state of the pulses in order to obtain the desired pulse broadening. The tunable bandpass filter is used to select the different frequencies at which the Stokes vectors are measured by the polarimeter. The transfer function of the filter can be approximated by a Gaussian filter with a FWHM bandwidth equal to 30 GHz. An oscilloscope is used to store the pulse shape at the output of the fiber, and from that the rms width of the pulse can be measured.

A. Measurement 1

In the first set of measurements, the fiber ring laser generated 8-ps pulses, which corresponds to a FWHM of the pulse spectrum of 56 GHz and a normalized filter bandwidth (see Section II-A) of 0.53. The average DGD in the PMD emulator was 8.5 ps. First, the polarization controller was adjusted to maximize the output pulsewidth, yielding a pulse broadening of about 70%. We measured the Stokes vectors and the power at the output of the PMD emulator and used the Poincaré sphere method to estimate the pulse broadening with $\Delta f = 75$ GHz and $N = 7$. We finally used (5) to compensate for the error due to the finite resolution of the optical filter. Without error compensation, we obtain an error of 33% in the estimation of the pulse broadening, while after the compensation the error is reduced to only 10%. This results are in excellent agreement with those of Fig. 3, with a normalized filter bandwidth equal to 0.53. We obtain very similar results if we adjust the polarization controller in order to reduce the pulse broadening to 33%. The error before the compensation is 31%, while after the compensation it is reduced to 9%.

B. Measurement 2

In the second set of measurements, 5-ps pulses are generated, which corresponds to a FWHM of the pulse spectrum of 90 GHz and a normalized filter bandwidth of 0.33. In this case, we expect a lower estimation error, since the normalized bandwidth is smaller. The average DGD in the PMD emulator was 4.6 ps. We proceeded in a similar way as in the first set of measurement, adjusting the polarization controller to obtain a pulse broadening of 62% and of 33%, respectively. We used $\Delta f = 90$ GHz and $N = 8$. Before compensation, we obtained an error of 19% and 15%, respectively, while after compensation the estimation errors were reduced to 5% and 6%. The results are again in perfect agreement with those of Fig. 3, with the normalized filter bandwidth equal to 0.33.

IV. Conclusion

In this letter, we have presented a novel technique of estimating the pulse broadening due to PMD in optical systems. The technique is based on the measurement of the Stokes vectors at different frequencies over the spectrum of the received optical pulse and does not require *a priori* knowledge of the fiber PMD statistics. We have demonstrated the validity of our technique with both simulations and experiments.

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