Full PMD Vector Measured Directly from Modulated Data Using Linear Optical Sampling

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***Abstract*—We demonstrate a new technique to monitor the polarization-mode dispersion in a fiber communication channel by analyzing the modulated data at the fiber output measured with Polarization-Sensitive Linear Optical Sampling (PS-LOS).**

I. Introduction

LINEAR Optical Sampling (LOS) is a practical means to measure the full optical field of high speed waveforms in equivalent time. Independently, measurement bandwidths have been demonstrated up to 640 Gb/s [1], phase resolutions as low as 1 mrad [2] have been achieved and the state of polarization can be resolved [3,4]. Given the ability of this powerful metrology tool to completely resolve the full time-dependent electric field (for repeated signals), it is a natural extension to use the electric field exiting a fiber channel in order to assess the distortions experienced in the fiber itself. In this paper, we use Polarization-Sensitive Linear Optical Sampling (PS-LOS) to measure the electric field of modulated light as it exits a transmission fiber and from that we determine the Polarization-Mode Dispersion (PMD) of the fiber channel.

When light propagates through a birefringent fiber, the fiber's PMD vector $\mathbf{\Omega}$ can be quantified in terms of the frequency dependence of the exiting stokes vector $\mathbf{S}$ as [5]

$$\frac{d\hat{\mathbf{S}}}{d\omega} = \mathbf{\Omega} \times \hat{\mathbf{S}}, \qquad (1)$$

Where ω is the radian frequency. The magnitude of the PMD vector is the differential group delay (DGD) or $\Delta\tau$ and can be found as

$$\Delta\tau = |\mathbf{\Omega}| = \left|\frac{d\theta}{d\omega}\right|, \qquad (2)$$

where θ is defined as the angle of rotation of the output state of polarization about the precession axis $\mathbf{\Omega}$. Therefore, frequency dependent stokes vectors can be used to determine the full PMD vector of an optical fiber.

Generally, polarimetric PMD measurements are made by sweeping the frequency (wavelength) of light into a fiber and monitoring the frequency dependence of the Stokes vector at the output. Here, we take advantage of the frequency content of a modulated (10 Gb/s) waveform to measure the frequency dependent Stokes parameters over an approximately 50 GHz bandwidth. From this, we are able to determine the PMD vector over that frequency range centered around the data laser wavelength. We use our PS-LOS system [4] to measure the polarization-dependent complex electric field out of the transmission fiber as a function of time. By applying a Fourier transform, we obtain the frequency-dependent complex electric fields $E_x(\omega)$ and $E_y(\omega)$ (x and y indicate the two orthogonal polarization states). From this, we construct the Stokes vector $\mathbf{S} = (S_1, S_2, S_3)$ as [6]:

$$\begin{aligned} S_1 &= E_x E_x^* - E_y E_y^*, \\ S_2 &= E_x E_y^* - E_y E_x^*, \\ S_3 &= i(E_x E_y^* - E_y E_x^*). \end{aligned} \qquad (3)$$

This frequency dependent Stokes vector then can be used in Equations (1) and (2) to determine the PMD of the transmission fiber.

II. Experimental Results

The experimental design consists of a distributed-feedback (DFB) data laser at approximately 1550 nm modulated with 10 Gb/s DPSK format using a zero-biased Mach-Zehnder modulator. The modulated light passes through ~ 10 m of polarization-maintaining fiber (PMF) to provide a PMD to measure (the DGD is 12.6 ps measured using a standard Jones Matrix Eigenanalysis approach [7]). The PMF was randomly aligned to the polarization state of the modulated light so that some light ended up traveling in each polarization mode of the PMF. The light is detected by our polarization-sensitive LOS system consisting of a polarizing fiber coupler connected to a pair of quadrature demodulators. We modulated the laser with a repeated 16-bit random sequence and the data was collected over 1.6 ms and averaged word-synchronously [8]. The resulting averaged electric field amplitudes in the two polarization channels are plotted in Figure 1. The Stokes vectors depend on optical phase only in terms of the difference in phase between the two orthogonal polarization states. So, no reference phase measurement was required (and no modulated phase result was obtained).

The measured Stokes vectors are plotted as a function of frequency in Figure 2. The data is only displayed out to +/- 27 GHz where noise begins to dominate due to low signal power. Of course, different data rates and modulation formats will yield different maximum frequencies. For clarity, the Stokes vectors are also plotted on the Poincaré sphere (Figure 3) where the characteristic arc is seen indicating a non-modecoupled PMD. A least-squares fit to the arc was used to find the direction of the precession axis $\hat{\mathbf{\Omega}}$, and the DGD as a function of frequency was found using

$$\Delta\theta(\omega_i) = \cos^{-1}\left(\frac{\left(\hat{\Omega}\times\hat{S}(\omega_i)\right)\bullet\left(\hat{\Omega}\times\hat{S}(\omega_{i-1})\right)}{\left|\hat{\Omega}\times\hat{S}(\omega_i)\right|\left|\hat{\Omega}\times\hat{S}(\omega_{i-1})\right|}\right), \qquad (4)$$

where i is the measurement index. The radian frequency step $\Delta\omega=\omega_i-\omega_{i-1}$ was 3.93×10^9 s^{-1}. Using Equation (2), the ratio of these values gives the magnitude of $\mathbf{\Omega}$ (the DGD) which is plotted versus frequency in Figure 4. We obtain a low-noise DGD measurement over a range of about 20 GHz with significant errors occurring at higher frequencies. We also have yet-unexplained spikes occurring near multiples of the 10 GHz modulation rate. Excluding these spikes, we obtain a mean DGD of 11.6 ps over the range of -20 GHz to 20 GHz which agrees well with the JME calculated value of 12.6 ps. We also performed this experiment using an On-Off-Keying (OOK) modulation format at 10 Gb/s and obtained similar results.

III. CONCLUSIONS

These preliminary results demonstrate the ability of PS-LOS to measure the full PMD vector in a telecommunication fiber by measuring a random (but repetitive) data pattern at the output. The measurements will improve when the frequency step size is optimized. Since the technique yields a full frequency-dependent stokes vector, it can also yield higher-orders of PMD as well.

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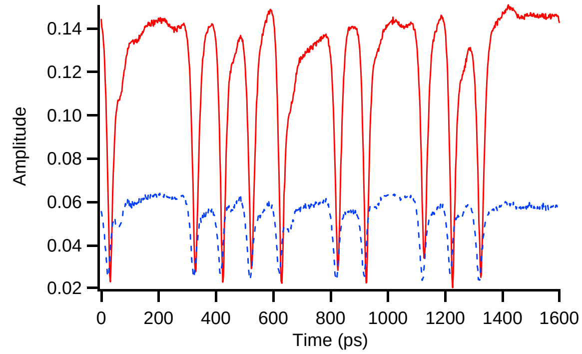

Fig. 1. Electric field amplitudes for the two orthogonal polarization states (solid and dashed) measured by the PS-LOS system for zero-biased DPSK modulation at 10 Gb/s.

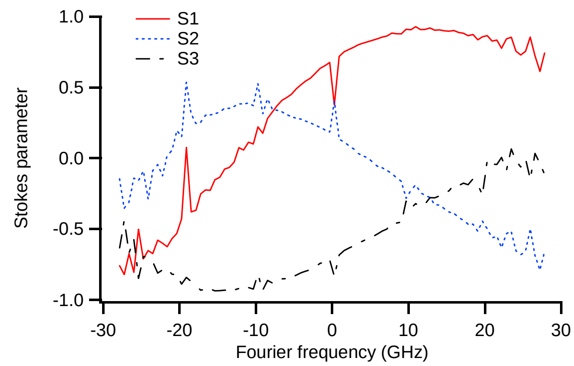

Fig. 2. Measured Stokes parameters. Noise spikes near multiples of 10 Gb/s are not yet understood.

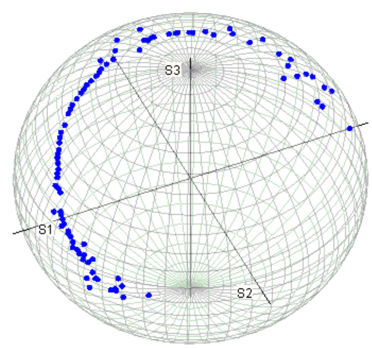

Fig. 3. Frequency-dependent Stokes vector as measured by PS-LOS.

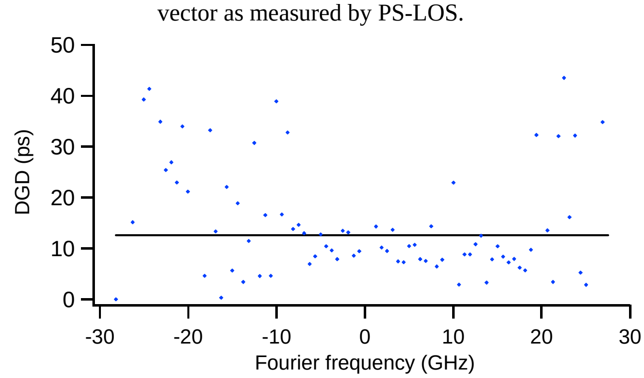

Fig. 4. DGD calculated as a function of Fourier frequency for the measured polarization-maintaining fiber. Diamonds are calculated values from the PS-LOS measurement and the solid line is the 12.6 ps JME measurement.