Direct Measurement of Vector Polarization-Mode Dispersion From Repeated Random Data by Use of Linear Optical Sampling

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***Abstract*—Polarization-dependent optical sampling techniques measure the complex electric field, allowing one to monitor the degrading effects of a communication channel. Here we show the ability to extract the polarization-mode dispersion of the transmission channel from a remote measurement of transmitted repeated 10-Gb/s differential phase-shift keying modulated data. This approach is independent of modulation format and data rate. We demonstrate results both with and without referencing to the laser phase. We achieve a differential group delay resolution of 0.2 ps for an unreferenced measurement.**

***Index Terms*—Coherent detection, linear optical sampling, optical performance monitoring, polarization-mode dispersion (PMD).**

I. INTRODUCTION

ADVANCES in coherent communication techniques based on phase modulation and polarization multiplexing schemes necessitate high-speed tools able to measure the amplitude, phase, and polarization state of these optical signals. Polarization-sensitive linear optical sampling (PS-LOS) provides such capability [1], [2]. This coherent detection, equivalent-time technique is essentially a complex polarimetric optical oscilloscope (bandwidth capability exceeding 1 THz) providing a full time-domain description of the transmitted optical signal. This rich information allows unprecedented analysis of the transmitted signal and the impairments it has experienced. Here we demonstrate the ability of PS-LOS to directly measure the polarization-mode dispersion (PMD) experienced by a repeated random data stream without additional demodulators or detectors.

Optical performance monitoring techniques for estimating PMD in installed fiber networks have been pursued extensively. Some techniques estimate PMD indirectly by measuring aspects of PMD-induced signal distortion (such as RF spectral power [3], degree of polarization [4], eye opening, or asynchronous delay-tap "eye" pattern recognition [5]). More direct techniques measure the spectral dependence of the transmitted state of polarization (SOP) by which PMD is defined. Differential techniques measure this change between two fixed frequencies [6], but the most direct approach is to measure the full spectral dependence of the SOP by use of a fast polarimeter [7], an optical Fourier transformer [8], or frequency-tuned coherent detection [9]. Our work here follows the approach of [9], but instead of a dedicated frequency-swept polarimeter, we demonstrate that these measurements can be made with an un-modified PS-LOS system which is more universally applicable to a suite of high-speed measurement needs (including time-domain waveform reconstruction). PMD measurements using PS-LOS have previously been demonstrated ([1] and [10]) but with the additional requirement of a third demodulation/detection arm or a switchable delay. Our approach eliminates the need to measure a reference phase altogether, allowing more rapid sampling, and data-rate independence.

This approach relies on the fundamental definition of PMD. For light transmitted through an optical fiber, the fiber's PMD vector Ω is defined in terms of the frequency dependence of the exiting Stokes vector $\mathbf{S}$ as [11]

$$\frac{d\hat{\mathbf{S}}}{d\omega} = \mathbf{\Omega} \times \hat{\mathbf{S}} \tag{1}$$

where ω is the radian frequency. The magnitude of the PMD vector [differential group delay (DGD)], denoted $\Delta\tau$, is

$$\Delta\tau = |\mathbf{\Omega}| = \left|\frac{d\theta}{d\omega}\right| \tag{2}$$

where θ is the rotation angle of the SOP about the precession axis $\mathbf{\Omega}$. Since PS-LOS measures the full time-dependent electric field (including polarization), the frequency-dependent Stokes vectors can be found and used to determine the full PMD vector ($\mathbf{\Omega}$, not just $\Delta\tau$) of an optical fiber path.

Our PS-LOS system measures the time-dependent polarization-dependent complex electric fields out of the transmission fiber $E_k(t) = A_k(t)\exp(\Delta\omega t + \varphi_{\rm laser}(t) + \varphi_{\rm mod}(t) + \varphi_k(t))$, where the subscript k indicates the x or y orthogonal polarization states, A is the electric field amplitude, $\Delta\omega$ is the optical frequency, t is time, $\varphi_{\rm laser}$ is the laser phase noise, $\varphi_{\rm mod}$ is the phase modulation, and φ_x and φ_y are the polarization-dependent phases due to fiber PMD. Without further measurements, we cannot distinguish these various phase components. Fortunately, we do not need to. Independent complex Fourier transforms of E_x and E_y give the frequency-dependent electric fields $\tilde{E}_k(\omega) = \tilde{A}_k(\omega)\exp(\tilde{\varphi}_k(\omega))$, where $\tilde{\varphi}_k$ includes both polarization-dependent and independent contributions to the spectral phase. The frequency-dependent Stokes vector is given

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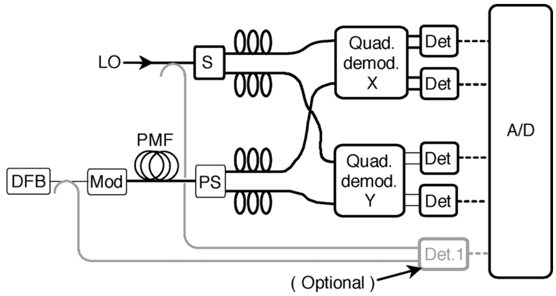

Fig. 1. Polarization-sensitive LOS setup. LO: mode-locked fiber laser local oscillator; DFB: data laser; Mod: Mach–Zehnder modulator; PMF: polarization-maintaining fiber; S: nonpolarizing splitter; PS: polarization splitter; Det: 200-MHz balanced detectors; Det.1: 800-MHz balanced detector; A/D: analog-to-digital oscilloscope. Solid lines are optical fiber paths; dashed lines are electrical.

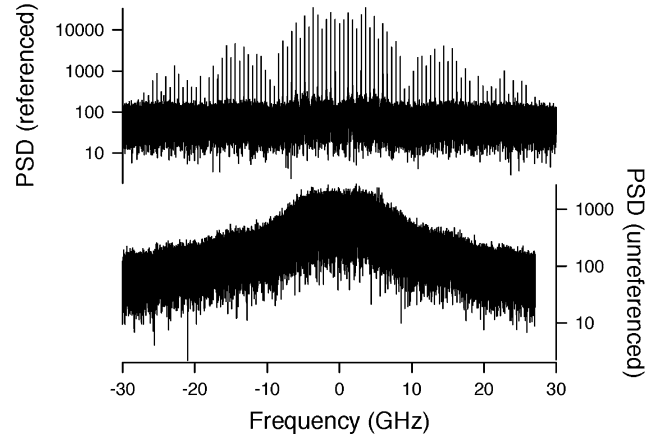

Fig. 2. Power spectral density of electric fields measured with LOS. Spectrums are from a Fourier transform of time-domain measurements. Upper: spectrum from phase-referenced time-domain; Lower: spectrum from unreferenced time-domain (frequency-shifted to remove the ~20-MHz beat frequency lock offset).

as $\tilde{\mathbf{S}}(\omega) = (\tilde{S}_1, \tilde{S}_2, \tilde{S}_3)$ [12]

$$\begin{aligned}\tilde{S}_1(\omega) &= |\tilde{E}_x(\omega)|^2 - |\tilde{E}_y(\omega)|^2\\ \tilde{S}_2(\omega) &= 2|\tilde{E}_x||\tilde{E}_y|\cos(\tilde{\varphi}_y - \tilde{\varphi}_x)\\ \tilde{S}_3(\omega) &= 2|\tilde{E}_x||\tilde{E}_y|\sin(\tilde{\varphi}_y - \tilde{\varphi}_x)\end{aligned} \tag{3}$$

which then can be used with (1) and (2) to determine the PMD of the transmission fiber. Note that the phases of the x and y electric fields only occur as the difference $\tilde{\varphi}_y - \tilde{\varphi}_x$, so polarization-independent phases cancel. This is a key simplification since equivalent-time sampled measurements cannot distinguish between laser phase and modulation phase by temporal behavior alone. Of course, it is still necessary to measure the optical phases of $E_x(t)$ and $E_y(t)$. But, once the fields are Fourier transformed, taking the difference of their frequency-dependent phases eliminates any phase terms not due to PMD. The bandwidth extent of the modulation format determines the spectral range which can be used to characterize the PMD.

II. Experimental Setup

Our measurements were carried out with the polarization-sensitive LOS setup shown in Fig. 1. The LOS technique uses a short-pulsed laser as a local oscillator (LO) to interferometrically down-sample modulated light from a data laser by use of a quadrature demodulator. The demodulator interferes the LO with the data laser and has four optical outputs (one pair 180° apart in phase, and a second pair 90° away from the first). Each optical output pair is incident on a balanced photodetector. This approach allows measurement of amplitude and phase of the signal's optical electric field.

The signal to be measured is produced by a distributed-feedback (DFB) diode laser (data laser) modulated by a Mach–Zehnder modulator at minimum-bias [producing differential phase-shift keying (DPSK)] at 9.601 GHz with a repeated random 16-bit word. The LO is a temperature-stabilized mode-locked fiber laser (1560-nm center frequency; 100-MHz repetition rate; filtered to 0.5-nm bandpass). The DFB laser is weakly offset-locked to one frequency tooth of the LO in order to generate a nominally 20-MHz beat note between the two lasers. Two identical optical quadrature demodulators (designated X and Y) are used to measure the optical field in two orthogonal polarization states. The LO is split between these demodulators by a nonpolarizing splitter, whereas the output of the data laser is split with a polarizing splitter to resolve the SOP of the modulated light. Lengths of polarization-maintaining (PM) fiber can be inserted into the fiber path to produce the PMD impairment. The resulting mixing products are detected with four 200-MHz bandwidth balanced detectors and over-sampled at 2 GSa/s by an oscilloscope-based analog-to-digital (A/D) converter.

As mentioned, we use a passive phase referencing approach that eliminates the need to identify the premodulated laser phase at all. However, in order to compare our unreferenced results with those achievable using direct phase-referencing, we performed our measurements with an optional extra detector ("Det.1" in Fig. 1) to directly measure the unmodulated laser phase for comparison purposes only. Our data show results for both approaches, which we distinguish as "unreferenced" and "referenced."

III. Results

With a section of PM fiber in the fiber path (DGD is 12.5 ps measured by Jones matrix eigenanalysis), we measured the full transmitted electric field for a duration of 100 μs. In principle, both the unreferenced and the phase-referenced approaches should be independent of phase noise on the data laser. However, we found a residual noise penalty for the unreferenced case. We attribute this to phase jumps between samples which exceeded π, causing ambiguities in the Fourier transform process. To minimize phase noise effects due to the fairly large linewidth of our data laser (~10 MHz in a 7.5-ms sweep time), we increased the effective temporal sampling period from 1 to 10 ps (reducing the overall measurement time). For equivalent time sampling, this allows the measurement to complete in 10 μs (10 times faster), effectively narrowing the laser linewidth. This made the difference between usable and unusable results. A plot of the measured power spectral density PSD $=|\tilde{E}_x(\omega)|^2 + |\tilde{E}_y(\omega)|^2$ for the referenced and unreferenced cases is shown in Fig. 2. Of particular interest are the discrete spectral lines (due to the short word-length) visible

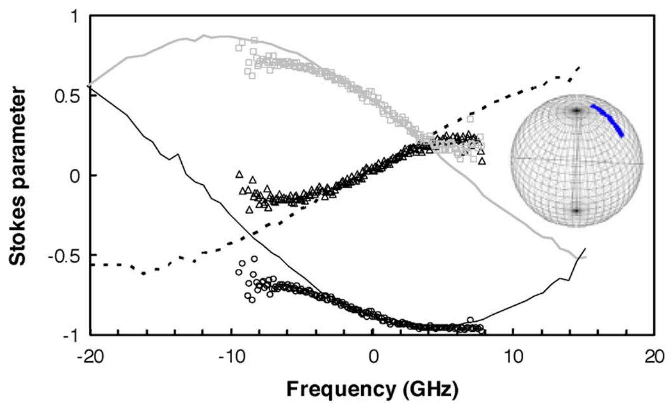

Fig. 3. Stokes parameters versus optical frequency: measured without phase referencing (symbols), and with phase referencing (lines). Inset: unreferenced data plotted on Poincaré sphere (8-GHz range).

in the referenced data but washed out in the unreferenced case. This is the effect of the phase noise penalty.

Applying (3) to the measured frequency-domain electric fields yields the Stokes parameter spectrum (shown for both the unreferenced and phase-referenced cases in Fig. 3). As expected, phase referencing gives a lower noise result valid over a wider spectrum. The unreferenced Stokes parameters (shifted in frequency to account for the lock-frequency offset) are noisier and have distortions at high Fourier frequencies where the noise floor begins to dominate. To reduce noise on the Stokes result, a threshold is used (in both cases) calculating Stokes parameters only at frequencies with sufficient PSD. Interestingly, the unreferenced case allows a finer achievable spectral resolution due to blurring of the peaks in the power spectrum. This illustrates that this measurement technique does not require a particular modulation format, only that the format produce a sufficiently populated power spectrum.

The measured spectral Stokes parameters (unreferenced) yield the characteristic arc when plotted on the Poincaré sphere (Fig. 3 inset). As mentioned, the DGD is determined from the rate of change of the Stokes vector as a function of frequency. We performed a nonlinear curve fit to the arc to determine its precession axis $\hat{\mathbf{\Omega}}$ representing the principal SOP. From this and the measured Stokes spectrum $\hat{\mathbf{S}}(\omega)$, we determine the precession rate as

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

where the index i indicates point number. Linearly fitting $\Delta\theta(\omega)$ allows us to estimate [by (2)] the DGD $\Delta\tau$ of the PM fiber. We find a value of 11.2 ps, in good agreement with the known value of 12.5 ps. We suspect that some disagreement between the two is attributable to stray PMD in an erbium-doped fiber amplifier used to boost the signal and possible distortion from the remaining noise floor.

IV. Discussion and Conclusion

We have measured the full polarization dispersion vector (PDV) $\mathbf{\Omega} = \Delta\tau\hat{\mathbf{\Omega}}$ using an unmodified PS-LOS setup with no requirement to reference to the laser phase. For the non-mode-coupled PMD measured, $\mathbf{\Omega}$ has no frequency dependence. However, for mode-coupled fibers $\mathbf{\Omega}(\omega)$ would be measurable as well.

Since DGD is measured as an angular change rather than an arc length on the Poincare sphere, the accuracy is independent of the launched SOP (except when light is launched exactly along one PSP). However, DGD uncertainty due to noise σ_φ on the measured Stokes vector will depend on the launched SOP, limiting the minimum measurable DGD as $\Delta\tau_{\min} = \sigma_\varphi/2\pi F\sin(\alpha)$ where F is the data modulation frequency, and α is the angle between the launched SOP and the PSP of the fiber link (in Poincare sphere coordinates). This means for our system, with $\sigma_\varphi \sim$10 mrad (maximum) and $F = 10\times10^9$ Hz our minimum measureable DGD will be about 0.2 ps (when $\alpha = \pi/2$). The bandwidth of LOS is fundamentally limited only by the pulsewidth of the sampling laser, and data rates above 1 THz should be achievable with the minimum measurable DGD scaling proportionally to the modulation rate (40 Gb/s should have an approximate 0.05-ps resolution). Our 100-MHz sample rate sets the maximum DGD limit (due to aliasing) at about $\Delta\tau_{\max} = \pi/(2\pi\cdot 100\text{ MHz})$ or 5 ns.

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