Polarization-Sensitive Linear Optical Sampling for Characterization of NRZ Polarization-Multiplexed QPSK

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Abstract: We describe polarization-sensitive phase-referenced linear optical sampling for measuring polarization, amplitude, and phase of a high speed optical waveform. With a single measurement, we simultaneously measure both orthogonal polarization channels of 2×10 GB/s polarization-multiplexed QPSK.

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1. Introduction

The combination of higher modulation bandwidths, phase shift keying (PSK) formats and polarization multiplexing create a significant challenge for characterizing the phase and amplitude of modulated optical waveforms. Modulation frequencies greater than 40-100 GHz become too fast for sampling by purely electronic means, and the PSK formats require characterizations to include sensitivity to optical phase. Optical sampling (both linear and nonlinear) approaches have been demonstrated that allow high-speed sampling of electric-field amplitude and phase in equivalent time. [1,2] However, in order to fully characterize the electric field, the state of polarization must also be measured. This is particularly important for polarization multiplexed (POLMUX) formats. Here, we describe a modification to a phase-referenced linear optical sampling (LOS) apparatus [3] that simultaneously measures the amplitude and phase in two orthogonal polarization states, resulting in a full-polarization characterization of the optical amplitude and phase waveform produced by a modulator or component. Our work differs from [4] in that we do not require adjacent-channel time delay nor phase integration, and we use a single measurement, rather than two.

LOS interferes ultrafast sampling-laser pulses with the optical waveform, yielding an equivalent-time measurement of the complex waveform with a bandwidth limited only by the pulsewidth of the sampling laser. The phase and amplitude are recovered by using a quadrature demodulator (a pair of differential detectors with a 90° optical shift between them). With respect to polarization, there are currently two types of LOS implementations. One achieves a stable 90° shift polarimetrically [5] and requires an input polarizer on the demodulator, yielding a "polarization-dependent" result. This means that the reported amplitude and phase are only for the particular polarization state transmitted by the polarizer, and the polarization state must be physically reoriented in order to characterize the light in another polarization state. For a POLMUX signal, this approach yields a mixture of the two orthogonally polarized channels. Physically reorienting the input polarizer will yield one or the other state (but not both). The second implementation uses an integrated optic waveguide geometry yielding a "polarization-independent" result– the net amplitude and phase of the waveform's electric field, independent of its polarization state.[6] However, this approach is ineffective when trying to measure POLMUX modulation, where one wishes to know simultaneously the complex electric field in each of the two orthogonally polarized states (not merely their quadrature sum). To fully characterize a POLMUX format, a "polarization-sensitive" measurement is needed for describing the electric-field amplitude and phase as a function of their polarization state. We demonstrate such a system here.

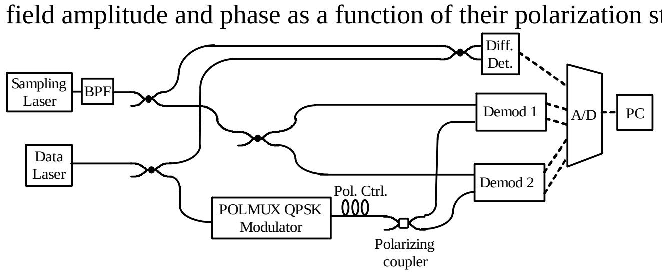

Fig. 1(a). Polarization-sensitive LOS measurement setup. BPF is 0.5 nm FWHM bandpass filter; Pol. Ctrl. is polarization controller; A/D is 2 GS/s oscilloscope; PC is a computer; Demod is a quadrature demodulator, solid lines are optical fiber; dashed lines are electrical.

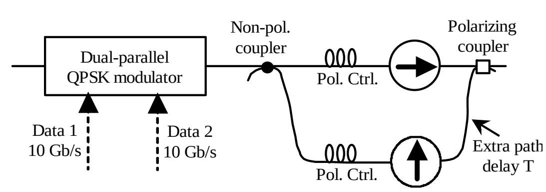

Fig. 1(b). POLMUX QPSK modulator. Pol. Ctrl. is polarization controller, encircled arrows indicate polarization orientation travelling in fiber; solid lines are optical fiber and dashed lines are electrical.

2. Experimental approach

We achieved this full-polarization characterization using the setup of Figure 1(a). The modulated optical waveform is split by a polarizing coupler and incident on two identical quadrature demodulators; each mixes with the sampling laser (a 1550 nm cavity-stabilized mode-locked fiber laser, 100 MHz repetition rate[7]). This allows the demodulator pair to simultaneously measure the amplitude and phase of the light in two orthogonal polarization states. This constitutes a full characterization of the polarization-dependent electric field. In order to remove the data laser phase noise from the measurement [3] , a separate differential detector (bandwidth 800 MHz) with no polarization sensitivity measures the beat between the sampling laser and the unmodulated data laser. The phase of the beat is extracted by use of a Hilbert transform. For a phase-stable sampling laser, the noise on this beat phase is dominated by the phase noise of the data laser. Since the light in the two POLMUX channels comes from the same data laser, this measured reference phase can be subtracted from the phase reported by each demodulator to yield the modulated phase alone. The residual phase noise due to incomplete path-matching between the reference path and the demodulated paths is $\sigma_\varphi = (2\pi\Delta\nu t_d)^{1/2}$, where $\Delta\nu$ is the FWHM linewidth of the data laser (500×10^3 Hz for our distributed feedback (DFB) laser) and t_d is the path mismatch (about 2 ns in this case), predicting a σ_φ of around 80 mrad. In fact, we measured a residual unaveraged phase noise of ~390 mrad, indicating we are not limited by reference path matching. The path match between the data laser and the two demodulators must be much more precise to allow accurate registration between bits in the two polarization channels. These two paths are matched to within 5 ps. Each individual demodulator is as described in [3] and uses the polarimetric approach to yield stable quadrature detection (350 MHz detector bandwidth). The phase-referenced output of the two demodulators yields the complex modulation on the data laser in two orthogonal polarization states of the data laser.

In order to demonstrate this polarization-sensitive measurement, we generate a polarization-multiplexed QPSK test signal at 10 GB/s. This is done as shown in Figure 1(b). A 2×10 GB/s NRZ QPSK signal (Pseudo-random bit sequence (PRBS), 127 bit word length) is generated using a dual parallel modulator. The modulated signal is split by a nonpolarizing coupler into two paths of unequal length (optical delay difference T), which are recombined by a polarizing coupler. In general, the resulting polarization-dependent modulated signal has two orthogonally polarized components E_1 and E_2 such that $E_q = R_q e^{i\varphi_q} E_D e^{i\varphi_D}$, where the index $q=\{1,2\}$, E_D and φ_D are respectively the electric field amplitude and intrinsic phase of the data laser, R_1 and R_2 are the modulation amplitudes, and φ_1 and φ_2 are the modulation phases in the two orthogonally propagating polarization states. If $R(t)$ denotes the QPSK residual amplitude modulation and $\varphi_m(t)$ the phase modulation, then we have $R_1(t)=R(t)$, $R_2(t)=R(t-T)$, $\varphi_1(t)=\varphi_m(t)$, and $\varphi_2(t)=\varphi_m(t-T)$. This signal travels through optical fiber to the input of our polarization sensitive LOS (figure 1(a)). This transport fiber imparts a random unitary transformation (rotation through angle θ) of the polarization state. Thus the orthogonal fields E_{par} and E_{perp} measured by the polarization-sensitive LOS can be related (Jones notation[8]) to E_1 and E_2 as

$$\begin{pmatrix} |E_{par}| e^{i\varphi_{par}} \\ |E_{perp}| e^{i\varphi_{perp}} \end{pmatrix} E_D e^{i\varphi_D} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \end{pmatrix} E_D e^{i\varphi_D}. \quad (2)$$

For a stable sampling laser amplitude, the normalized field modulation amplitude and phase modulation of the two polarization-multiplexed channels can be recovered from E_{par} and E_{perp} by inverting the rotation and subtracting the laser phase,

$$\begin{gathered} R_1 = \sqrt{\left(|E_{par}|\cos\theta\cos\varphi_{par} - |E_{perp}|\sin\theta\cos\varphi_{perp}\right)^2 + \left(|E_{par}|\cos\theta\sin\varphi_{par} - |E_{perp}|\sin\theta\sin\varphi_{perp}\right)^2}, \\ R_2 = \sqrt{\left(|E_{par}|\sin\theta\cos\varphi_{par} + |E_{perp}|\cos\theta\cos\varphi_{perp}\right)^2 + \left(|E_{par}|\sin\theta\sin\varphi_{par} + |E_{perp}|\cos\theta\sin\varphi_{perp}\right)^2}, \\ \varphi_1 = \arctan\left\{\frac{|E_{par}|\cos\theta\sin\varphi_{par} - |E_{perp}|\sin\theta\sin\varphi_{perp}}{|E_{par}|\cos\theta\cos\varphi_{par} - |E_{perp}|\sin\theta\cos\varphi_{perp}}\right\}, \quad \varphi_2 = \arctan\left\{\frac{|E_{par}|\sin\theta\sin\varphi_{par} + |E_{perp}|\cos\theta\sin\varphi_{perp}}{|E_{par}|\sin\theta\cos\varphi_{par} + |E_{perp}|\cos\theta\cos\varphi_{perp}}\right\}. \end{gathered} \quad (3)$$

3. Experimental results

A data modulation rate of 10.001 GHz (referenced to the 100 MHz sampling laser repetition rate) yielded an equivalent sampling period of 1 ps. The 1550 nm DFB data laser provided 50 μW onto each demodulator. The data is averaged word-synchronously over 10^5 points (7.9 words) with a 2 ps bin width. Figure 2(a) shows the measured phase modulation eye diagrams for φ_{par} and φ_{perp}. As expected, E_{par} and E_{perp} are misaligned with the two POLMUX channels, resulting in distorted eye patterns without the four distinct phase levels characteristic of QPSK modulation. However, by applying equations (3) in software, we recover the amplitude and phase modulation functions on each of the POLMUX channels. This recovered phase modulation eye diagram is shown in Figure 2(b). The rotation angle θ=150.503° was chosen (through simple trial and error) as that which yielded the most open phase eye diagrams and the greatest correlation between recovered amplitude waveforms between the two channels (estimated by eye). Figure 3 shows the measured amplitude modulation recovered from Equation (3) for each channel. Note the T=5.9 ns time shift between the two channels due to the differential delay in the POLMUX stage.

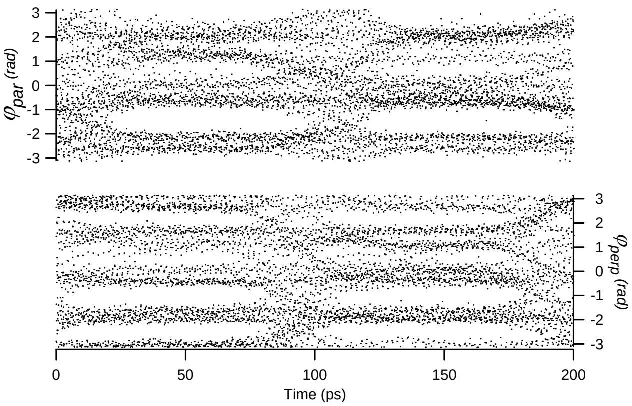

Figure 2(a). Phase eye patterns (2 bit length) as measured by the two orthogonal demodulators.channels (clearly not polarization-aligned with the POLMUX channels).

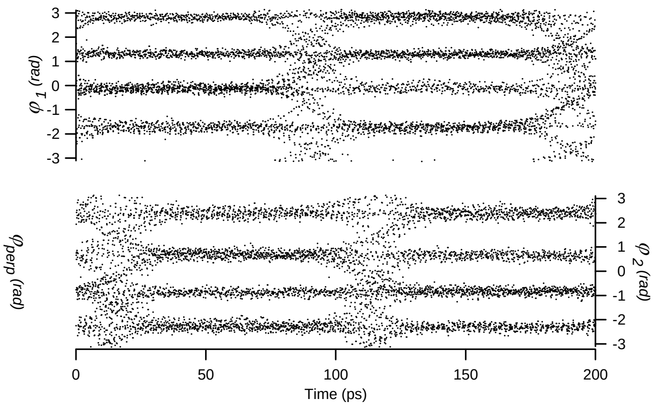

Figure 2(b). Phase eye patterns of the two orthogonal polarization states aligned with the POLMUX axes. Recovered with a software rotation of θ=150.305°. The time shift between φ_{par} and φ_{perp} is real and a consequence of the delay difference in the POLMUX arms.

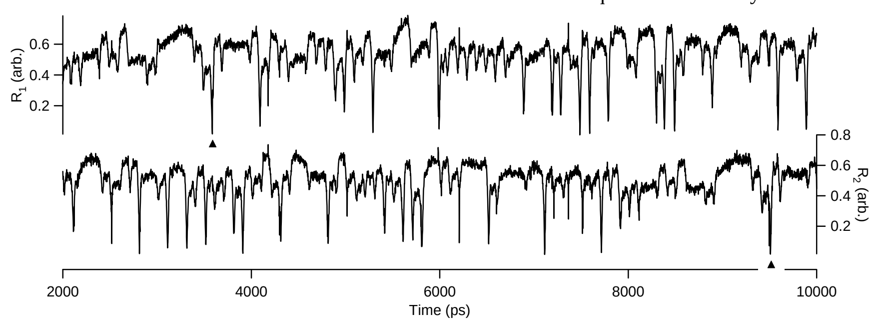

Figure 3. Word-synchronous amplitude modulation for each arm of the POLMUX. The two ▲ symbols indicate an equivalent point in each pattern. The delay between these points (5.9 ns) is the delay between the POLMUX arms.

4. Conclusion

This polarization sensitive approach allows characterization of the full Jones vector of a modulated electric field while removing the phase noise of the data laser. We demonstrated the usefulness of this approach by measuring a polarization-multiplexed signal and extracting the two orthogonally polarized components. Since, this polarization-sensitive measurement fully measures the electric field in orthogonal polarization states, it can also yield the normalized “polarization-independent” electric field $E_{PI} = \sqrt{E_{par}^2 + E_{perp}^2}\, e^{i(\varphi_{par} + \varphi_{perp})/2}$ that would be expected from a polarization-independent LOS geometry. For simplicity, our demonstration was done at 2×10 Gb/s, but as with all LOS measurements, the ultimate bandwidth is limited only by the pulse width of the sampling laser.

5. References

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