150fs ONLINE PMD DETECTION WITHIN 5µs

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Abstract: Light with a low-speed polarization modulation suffers arrival time variations due to PMD, detectable by integration of the VCO input signal in the clock recovery PLL. This is demonstrated in 40Gbit/s NRZ and 2×40Gbit/s RZ polarization multiplex transmission experiments.

Introduction

PMD compensators need fast and accurate PMD detection at low cost. To our knowledge, all published purely electrical methods /e.g., 1, 2/ detect quantities comparable to the eye opening. In the limit of a 1st-order DGD τ that is small compared to the bit duration the error signals are $\propto \tau^2$ and hence extremely weak. Here we generate error signals $\propto \tau$ or parts of the PMD vector $\boldsymbol{\tau}$. This allows to detect PMD at or below the eye pattern visibility limit.

Standard transmission

Theory: Consider an NRZ or RZ optical transmission system (Fig. 1) with a depolarizer at the transmitter (TX) side. This component, which can be shared by all WDM channels, modulates the signal polarization in the high kHz or low MHz region. In the receiver the depolarized light suffers variations $\Delta\hat{t}(t)$ of the arrival time, induced by PMD. The clock recovery PLL with a phase detector that often is part of the decision circuitry, a PI controller and a voltage-controlled oscillator (VCO) tracks these faithfully as long as its bandwidth is large compared to the depolarization frequency. In that case the VCO input signal is proportional to the temporal derivative $d\Delta\hat{t}(t)/dt$. $\Delta\hat{t}(t)$ itself is obtained by integration. The rms arrival time variation is $\Delta\hat{t}_{rms} = \tau/(2\sqrt{3})$.

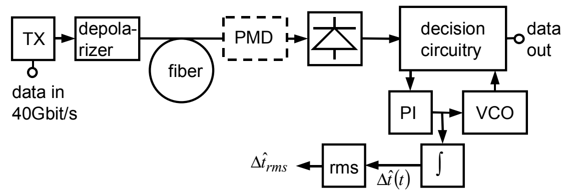

Figure 1: PMD detection based on pulse arrival time

Experiment: This technique was implemented in a 40Gbit/s NRZ transmission system. The depolarizer /3, 4/ consisted of an electroptical rotating λ/4 wave plate and a counter-rotating λ/2 plate, both driven at 250 kHz. Integration and RMS detection were implemented digitally. Measurement intervals were 4µs. EDFAs are not shown for simplicity. Fig. 2 shows exemplary signals for a test module (PMD) with 0.77 ps of DGD. These change somewhat as a function of polarization settings in front of and behind the depolarizer. Only the fast modulation of the inferred arrival time is evaluated; its slow ascent and descent is due to VCO phase noise. Fig. 3 shows eye patterns from an additional 50GHz monitor diode, triggered from the TX. At 5.5 ps of DGD essentially horizontal eye closure is visible, due to arrival time modulation. $\Delta\hat{t}_{rms}$ values measured with the least favorable depolarizer input polarization are plotted in Fig. 4. The value for 19 ps and the offset at 0 ps (back-to-back including depolarizer) allowed a theoretical curve fit. Nonoverlapping ±1-σ error intervals (also shown) between data at 0 ps and 2 ps indicated a detection limit of 2ps.

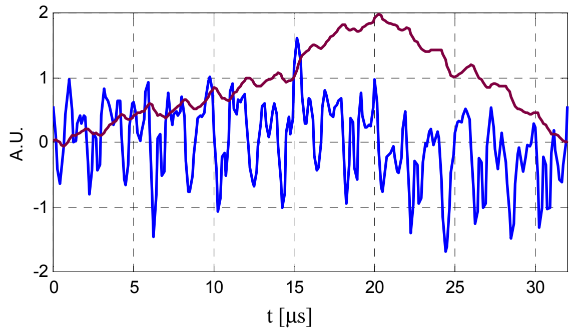

Figure 2: VCO input signal @ 0.77ps of DGD (periodic curve) and inferred arrival time (top smooth curve)

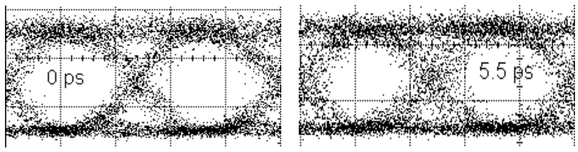

Figure 3: 40Gbit/s eye patterns @ 0 and 5.5 ps of DGD

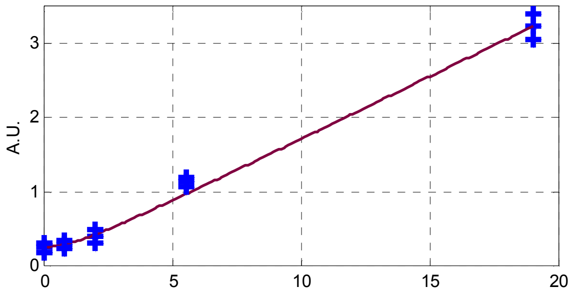

Figure 4: rms arrival time variation $\Delta\hat{t}_{rms}$ vs. DGD [ps]

RZ polarization division multiplex transmission

Theory: Polarization division multiplex transmission (PolDM) /5/ is attractive to double fiber capacity. We consider the RZ format which is generally preferred over the NRZ format because of its better nonlinearity tolerance. Assume the two bit streams are transmitted simultaneously (without interchannel time delay) with $\pm S_1$ polarizations after combination in a polarization beamsplitter (PBS; Fig. 5). A small sinusoidal FM applied to the transmitter laser in conjunction with an interchannel time delay $\tilde{\tau}$ before one of the data modulators (MOD) modulates the interchannel phase difference /6/. Another PBS demultiplexes the signals in the receiver. A signal processor (DSP) monitors detected interchannel interference terms and minimizes them by appropriate setting of a polarization controller

(PC). At the same time it assures that any PMD vector component τ_1 between the two transmitted signals just results in a static time delay between the two received bit streams. This can be taken care of by two individual clock recoveries (which possibility is not shown) or a differential clock phase shifter (DPS) that may be controlled by the integral of the measured clock phase differences in the two receiver branches. The other, detrimental PMD vector components τ_2, τ_3 can also be detected: The interchannel phase difference causes a common mode arrival time modulation $\Delta\hat{t}(t)$ of the RZ PolDM signals, which has to be absorbed by the clock recovery PLL. Integration of the VCO input signal allows to recover $\Delta\hat{t}(t)$. The rms amplitude of a suitable linear combination of at least one even and at least one odd line of the resulting Bessel spectrum /6/ is proportional to $\Delta\hat{t}_{rms} = 2^{-3/2}\sqrt{\tau_2^2 + \tau_3^2}$.

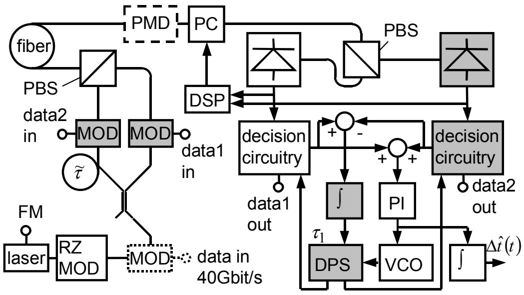

Figure 5: PMD detection in RZ PolDM system

Experiment: Clock recovery was improved. A 2×40Gbit/s RZ PolDM transmission system was set up. A 417 kHz FM was applied to the TX laser to generate interchannel phase modulation with an index $\eta = 4.2$. A Mach-Zehnder modulator (RZ MOD) driven at 20GHz generated a 40GHz RZ pulse stream. For simplicity a common data modulator (dotted MOD) was placed in front of the polarization multiplexer, and all shaded components were left out. In the receiver a $LiNbO_3$ device served as a PC. A linear combination of Bessel lines 2, 3 and 4 in the photocurrent was detected and minimized by DSP/PC. Similar processing of $\Delta\hat{t}(t)$ allowed to determine $\Delta\hat{t}_{rms}$ simultaneously. The VCO was connected directly to the decision ciruitry without DPS. For each DGD the polarizations at the PMD module input were adjusted for maximum $\Delta\hat{t}_{rms}$ ($\tau_1 = 0$, $\sqrt{\tau_2^2 + \tau_3^2} = \max.$) as the worst case (Fig. 6 left, and top traces in Figs. 7, 8), and for most DGDs also at minimum $\Delta\hat{t}_{rms}$ ($|\tau_1| = \max.$, $\sqrt{\tau_2^2 + \tau_3^2} =$ 0) as the best case (Fig. 6 right, and bottom traces in Figs. 7, 8). The sensitivity limit, again defined by nonoverlapping ±1-σ error intervals (x symbols), was 150fs (Fig. 7) and 84fs (Fig. 8) for 4.8µs and 38.4µs long measurement intervals, respectively. The latter DGD belongs to a 42mm long piece of PMF with 17 beat lengths. In order to rule out fundamental errors the received power was halved, which did not influence measured data. Next, a 185mm long, straight piece of polarizing fiber was inserted. It had a PDL of 0.08 dB, and our measurements at maximum $\Delta\hat{t}_{rms}$ indicated a DGD of ~750fs. When it was bent its PDL increased to 3.5dB and its DGD seemed to increase to ~800fs while we believe it stayed constant. This shows that PDL played only a minor role, and we have in fact measured DGDs.

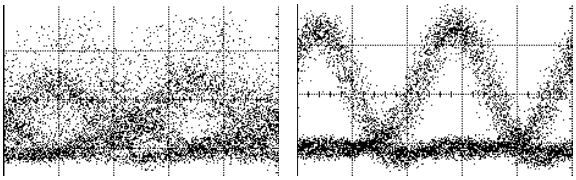

Figure 6: RZ PolDM eye patterns @ 10 ps of DGD

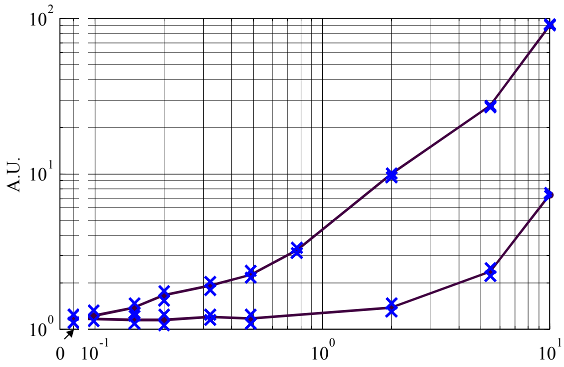

Figure 7: $\Delta\hat{t}_{rms}$ vs. DGD [ps] measured in 4.8µs

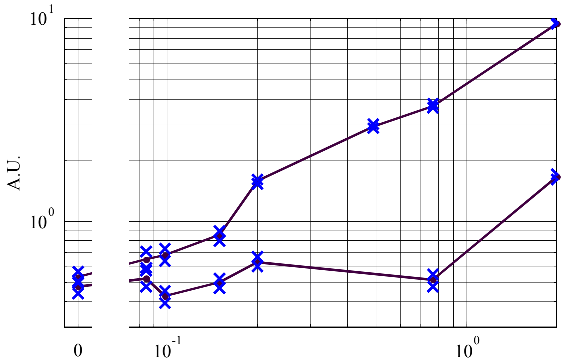

Figure 8: $\Delta\hat{t}_{rms}$ vs. DGD [ps] measured in 38.4µs

Conclusions

Arrival time detection in the clock recovery of depolarized pulses subject to PMD yields a linear measure of the DGD. Experiments have been carried out for 40Gbit/s NRZ standard transmission and 2×40Gbit/s RZ polarization division multiplex transmission, with resulting PMD detection limits of 2ps and 150fs ... 84fs, respectively.

Acknowledgement

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