Self-Coherent Receiver for PolMUX Coherent Signals

J. Li[1], C. Schmidt-Langhorst[2], R. Schmogrow[1], D. Hillerkuss[1], M. Lauermann[1]
M. Winter[1], K. Worms[1], C. Schubert[2], C. Koos[1], W. Freude[1], J. Leuthold[1]
1: Institute of Photonics and Quantum Electronics, Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany,
2: Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut, Einsteinufer 37, 10587 Berlin, Germany
Email: jingshi.li@kit.edu

Abstract: A compact polarization-diversity self-coherent receiver with reduced complexity is proposed. Requirements on input polarization tracking is relaxed by a variant CMA equalizer. Experiments are performed for 50 and 100 Gb/s PolMUX-NRZ-QPSK signals.

OCIS codes: (060.4510) Optical communication; (060.5060) Phase modulation

1. Introduction

Coherent detectors are key to next generation multi-level polarization multiplexed coherent modulation formats such as quadrature phase-shift keying (PolMUX-QPSK) [1]. However, coherent detection schemes require a high-quality local oscillator (LO) laser which is costly and introduces a limited wavelength operation range of the receiver.

Recently, self-coherent detection using delay interferometers (DI) has been suggested for the detection of coherent signals [2] [3]. Here the LO is avoided and a broad wavelength acceptance range is obtained. The typical setup requires 4 DIs for the in-phase (I) and quadrature (Q) component of each polarization. Each DI needs to be controlled separately in order to match the signal's baud rate ($1 / T$) and to guarantee orthogonality between the I- and Q-DIs. Therefore, efforts to reduce the number of DIs are needed to make this technology practical. One method is to use two polarization insensitive DIs and only then separate the polarizations at the outputs [2]. However, polarization-insensitive DIs are intricate to fabricate. A second method consists in combining the I- and Q-DIs. This technique works well with planar lightwave circuit (PLC) technology, e.g. with 2x4 MMIs [4]. While the PLC technology is well suited for the mass market it is inflexible in that the time delay in integrated optics cannot be continuously tuned. Conversely, solutions based on free-space optics offer good thermal stability, a large operation wavelength range and a true delay tunability. Yet, combining I and Q demodulation in one DI is not straight forward and the authors are not aware of any report on such an endeavor.

In this paper, we present a polarization diversity self-coherent receiver based on free-space optics, where we reduce the number of DIs in two steps from 4 to 1. We combine the I- and Q-DIs for each polarization into a single DI. Furthermore, we propose a polarization diversity self-coherent receiver scheme in which the optical components of a single DI are re-used for both polarizations. As our DI comprises of a tunable delay in one arm (up to 30 mm delay in free-space) it is possible to continuously adapt the delay to the respective baud-rate of the signal [5]. Moreover, we introduce a simple modified CMA equalizer with reference phase feedback to separate the polarizations in the digital field recovery algorithm. We experimentally validate the concept of the the proposed pol-diversity self-coherent receiver scheme with 12.5 GBd (50 Gb/s) and 25 GBd (100 Gb/s) PDM-NRZ-QPSK signals.

2. Detector design and DSP outline

A conventional approach for a self-coherent detector is shown in Fig. 1(a). Its optical front-end includes 4 DIs which have a time delay τ that is optimized with respect to the symbol rate of the detected signal. The signal is first split into the two polarization components E_x and E_y (which in general do not correspond to the transmitter's polarization components) by a polarization beam splitter (PBS). Then each polarization is fed into 2 orthogonal DIs (90° phase offset) (I- and Q-DIs) and four balanced detectors are used to detect the signal components.

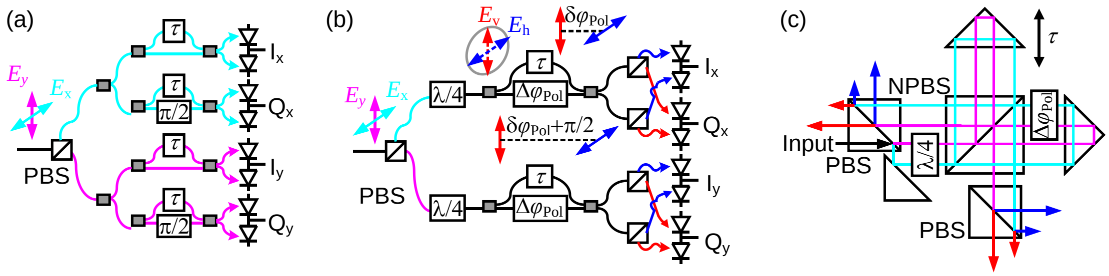

Fig. 1: Schematics of polarization diversity self-coherent receivers (a) Conventional configuration with 4 DIs, (b) Self-coherent receiver with 2 DIs, (c) free-space micro-optical implementation where all elements are folded into 1 DI only.

To combine the I- and Q-DIs into a single DI (Fig. 1(b)), we propose to first use quarter wave plates (QWP) to convert the E_x and E_y components into circular polarizations (sum of horizontal and vertical fields E_h and E_v with equal powers). Each circular polarization is fed into a separate DI [6] where it is split and recombined in a 50/50 non-polarizing beam splitter (NPBS). In one DI branch we introduce the time delay τ and in the other path we place a birefringent element $\Delta\varphi_\mathrm{Pol}$, both acting differently on the h- and v- components of the circular light. Assuming there is a residual phase difference $\delta\varphi_\mathrm{pol}$ between E_h and E_v in the delay branch, we use the birefringent element to set the phase difference in the short branch to $\delta\varphi_\mathrm{pol} + \pi/2$ resulting in a 90° phase offset between the h- and v-components. Using PBSs at the DI outputs the E_h and E_v fields are separated and combined on the balanced detectors. Specifically, the I-component of each polarization component is formed by the h-polarized signals while the Q-component is formed by the v-polarized signals. Thus we have reduced the number of required DIs to only 2 DIs in this newly proposed configuration.

In Fig. 1(c), we propose a further reduction of required components in a free space optics implementation. Using a mirror, the two orthogonal polarizations are mapped into the same DI configuration with two beams propagating in parallel sharing the same optical elements. The signals are split and combined with one single NPBS and reflected back with two corner reflectors. One reflector is mounted on a movable actuator that introduces a time delay τ. In the other branch, the birefringent element is set to align the orthogonal phase offset between the I and Q components. Two PBSs (including the one at the input) are used to separate the signals into h and v polarizations. The signals can be coupled to fibers or directly on photodiodes providing electrical signals for further processing. With this novel setup, 4 logic DIs in a polarization diversity self-coherent detection scheme are folded into one single and compact Michelson delay interferometer structure with one single actuator tuning the time delay.

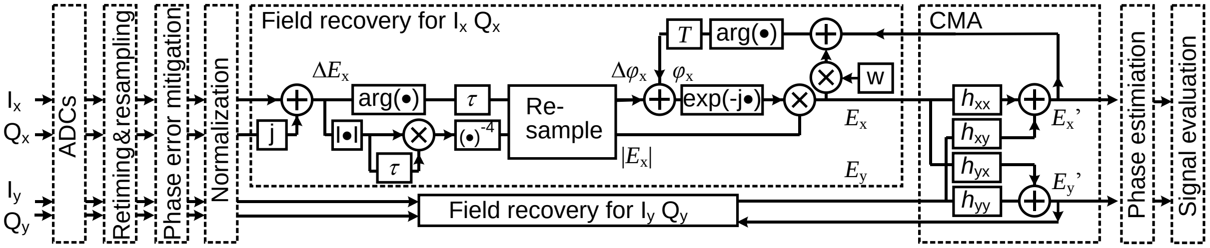

Fig. 2: Digital signal processing flow chart. Details of a field and polarization recovery algorithms is presented.

The digital signal processing flow chart for our setup is shown in Fig. 2. After digitization of the electrical signals I_x, Q_x, I_y, Q_y the clock is extracted and the four waveforms are synchronized and re-sampled with a time delay τ between adjacent samples. Then, two sources of phase errors in the DIs are numerically mitigated. One is the IQ-phase imbalance within each detected polarization, the other is the differential phase offset between the two detected polarizations. Both are static errors that can be measured in advance or estimated with the measured waveforms. After normalization the differential phasor $\Delta E_{x,y} = I_{x,y} + \mathrm{j}Q_{x,y}$. is constructed to start field recovery. Next its amplitude is estimated by $\left|E_{x,y}(t)\right| \approx \sqrt[4]{\left|\Delta E_{x,y}(t)\right|\left|\Delta E_{x,y}(t+\tau)\right|}$ [2]. In Ref. [5] we have shown that a partial time delay, e.g. $\tau = ½\,T$ or $¼\,T$ improves the estimation of the signal amplitude. However, the smallest τ is limited by the bandwidth of the photo detectors and ADCs. The estimated amplitude and the differential phase are then re-sampled to 1 sample per symbol. Next, the differential phase $\Delta\varphi_{\mathrm{x,\,y}}$ is added to a phase reference and combined with $|E_{x,\,y}|$ resulting in the complex field phasor $E_{x,\,y}$. A butterfly CMA equalizer [7] is subsequently applied for polarization separation. As the CMA is very sensitive to residual differential phase errors within the DIs (which leads to increasing phase errors of $E_{x,y}$ in the field recovery), we use the filtered field $E_{x,\,y}$' as a corrector for the phase reference by combining it with the recovered phase. The smaller the DI phase error, the larger the weighting factor 'w' we can use. As a last step, phase estimation [8] and signal evaluation is applied.

3. Experimental setup and results

In the experiment (Fig. 3(a)) a PolMUX-NRZ-QPSK signal is generated by modulation of an external cavity laser (1547.6nm) with two uncorrelated PRBS of length 2^{15}-1 in a dual-MZM and a bit-aligned polarization multiplex stage with a delay of several bits. The signal is amplified and filtered before sent into the self-coherent detector applying the scheme depicted in Fig. 1(b) with two DIs only. The input signal polarization needs only approximate adjustment to the receiver polarizations states (here e.g. by a polarization controller (PC)) due to the CMA polarization separation algorithm. A real time scope (50 GS/s, 20GHz bandwidth) is used to digitalize the waveforms for off-line processing.

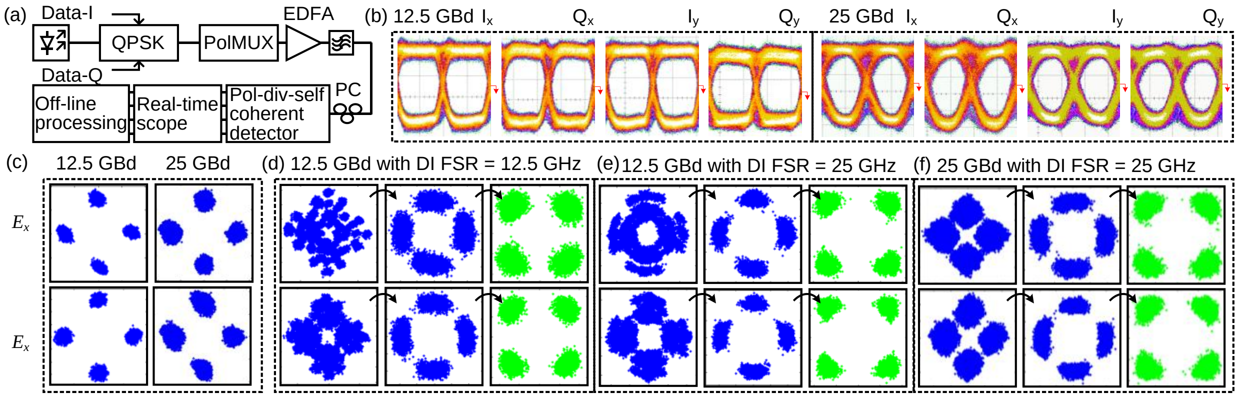

Fig. 3: (a) Experimental setup (b)+(c) Polarization-resolved I/Q eye diagrams and received constellations with receiver polarization aligned to the signal polarization; (d) - (f) Polarization-unaligned signal constellations (blue, differential phasors), constellations after polarization recovery (blue, differential phasors) and constellations after phase estimation (green, recovered field phasors), from left to right at (d) 12.5 GBd with DI FSR = 12.5 GHz, (e) FSR = 25 GHz and (f) 25 GBd with FSR = 25 GHz

We used two signal baud rates, namely 12.5 GBd (50 Gb/s) and 25 GBd (100 Gb/s). As a reference we aligned the receiver polarization to the data signal, and time delay τ to the symbol duration T. The obtained eye diagrams (Fig. 3(b), measured with Agilent DCA sampling oscilloscope) have Q^2 factor ≈ 20 dB which verifies a good quality signal generation and self-coherent reception. Constellation diagrams of the differential phasors (Fig. 3(c), measured with real time scope) also verify a good quality reception. We attribute the stronger noise in the 25 GBd constellation to the bandwidth limitation of the real time scope. Next we tested the self-coherent receiver with non-aligned polarizations. Since only polarization mixing is considered in this measurement, we set the FIR butterfly filter length to 1 tap only although larger filter lengths could also be used to receive e.g. signals with PMD. Exemplary results are shown in Fig. 3(d)-(f), where we plot the received constellation, the constellation after polarization recovery and the recovered field constellation after phase estimation (window size of $3T$) for a 1µs time duration. For the 12.5 GBd signal, a DI FSR of 25GHz ($\tau = 40$ ps $= T/2$, Fig. 3(e)) yields a clearer recovered constellation (error vector magnitude (EVM) = 13.0%, 12.4%) compared to a DI FSR of 12.5 GHz ($\tau = 80$ ps $= T$, Fig. 3(d), EVM = 19.0%, 17.5%) as predicted [5]. For reception of the 25 GBd signal (Fig. 3(f)) we only used a DI FSR = 25 GHz ($\tau = T$) due to the bandwidth limitation of the real time scope. In our experiments we found that the algorithm for polarization separation and field recovery converges well when the signal polarization is rotated against the PBS exes at the receiver input by < 35°. Simulations show that for angle rotations >35° (up to 45°), the recovered signal's EVM increases above 30%. We attribute this to the rapidly varying amplitude which occurs in such cases on the detectors and which cannot be estimated with high enough accuracy in the differential field reconstruction algorithm. The use of a simple polarization tracker with relaxed requirements is thus recommended to operate the self-coherent receiver at arbitrary polarizations.

4. Conclusion and acknowledgement

We have proposed a polarization diversity self-coherent receiver which requires only two separate DIs to receive a PolMUX QPSK signal. Our implementation of this new DI scheme comprises a continuously tunable FSR to adapt to various symbol rates. A compact free-space optics implementation can further reduce the number of required components to a single DI which is shared by the two polarization components. By introducing a simple modified CMA equalizer with reference phase feedback in the digital field recovery algorithm, we experimentally verify the proposed self-coherent receiver scheme with PolMUX-NRZ-QPSK signals at symbol rates of 12.5 GBd (50 Gb/s) and 25 GBd (100 Gb/s).

This work has been supported by the European Commission's Network of Excellence *EuroFOS* and the Karlsruhe School of Optics and Photonics (KSOP).

4. References

[1] D. van den Borne, et. al., J. Lightwave Technol. vol. 25, pp. 222-232, (2007)
[2] X. Liu, S. Chandrasekhar, and A. Leven, Opt. Express 16, 792-803 (2008)
[3] M. Nazarathy, et. al., J. Lightwave Technol. 26, 1921-1934 (2008)
[4] C. R. Doerr and L. Chen, ECOC' 10, Post-deadline Paper PD3.6, (2010)
[5] J. Li, et. al., Proc. 2009 IEEE LEOS Annual Meeting, pp. 135-136, paper TuA4 (2009)
[6] J. Li, et. al., Proc. OFC' 10, paper JWA24 (2010)
[7] Seb J. Savory, Opt. Express 16, 804-817 (2008)
[8] R. Noe, IEEE Photon. Tech. Lett., vol. 1, pp. 887-889 (2005)