# Fast Adaptive Polarization and PDL Tracking in a Real-Time FPGA-Based Coherent PolDM-QPSK Receiver

Mohamed El-Darawy, Timo Pfau, *Student Member, IEEE*, Sebastian Hoffmann, Ralf Peveling,
Christian Wördehoff, Benjamin Koch, *Student Member, IEEE*, Mario Porrmann, *Member, IEEE*,
Olaf Adamczyk, *Member, IEEE*, and Reinhold Noé, *Member, IEEE*

***Abstract*—Fast polarization changes of 40 krad/s and 6-dB polarization-dependent loss (PDL) are tracked in a 2.8-Gb/s real-time coherent quadrature phase-shift keying receiver. The tolerance against fast polarization changes and PDL is measured for different polarization control time constants. The sensitivity penalty of the receiver at a polarization change speed of 40 krad/s is 0.7 dB at bit-error rate (BER) of $1 \times 10^{-3}$, with a BER floor of $6.1 \times 10^{-7}$. With an additional PDL of 6 dB, these figures become 1.7 dB and $9.6 \times 10^{-6}$, respectively.**

***Index Terms*—Heterodyning, optical polarization, quadrature phase-shift keying (QPSK), synchronous detection.**

## I. INTRODUCTION

IN ORDER to improve the spectral efficiency and hence increase the transmission capacity and the transmission distance, a combination of complex modulation formats such as quadrature phase-shift keying (QPSK) and polarization-division multiplexing (PolDM) is used to quadruple the capacity of optical transmission systems. However, the fast polarization changes and polarization-dependent loss (PDL) that occur in the fiber link, e.g., by mechanical vibrations, can cause a severe degradation of the sensitivity in coherent receivers, where the coherent detection process is polarization-sensitive [1]. Implementations of coherent detection employing high-speed digital signal processing (DSP) have been recently proposed [2], [3] and demonstrated [4]–[6], where the carrier phase and polarization drifts of the optical signal are estimated and tracked by real-time DSP without phase-locked loop. The coherent receiver must be able to recover the carrier phase and to line up with the state of polarization (SOP) at the receiver input. The polarization tracking process has to be capable of following the fastest polarization changes in order to guarantee error-free transmission.

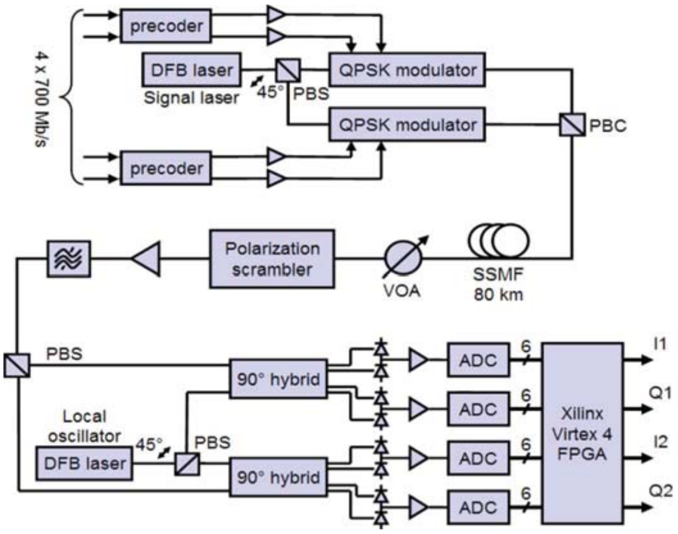

Fig. 1. Setup for 2.8-Gb/s polarization-multiplexed synchronous QPSK transmission.

In this letter, we examine the capabilities of the adaptive algorithm for tracking fast polarization changes in a real-time field-programmable gate array (FPGA)-based PolDM-QPSK receiver running at a data rate of 2.8 Gb/s. The tolerance against polarization changes is examined up to 40-krad/s gradients on the Poincaré sphere and the effect of PDL is analyzed.

## II. EXPERIMENTAL SETUP

### A. Polarization-Multiplexed QPSK Transmitter and Synchronous Receiver

The transmitter uses a distributed feedback (DFB) signal laser ($\Delta f_S = 1$ MHz) and two QPSK modulators driven by four precoded 700-Mb/s bit streams [7]. The precoder performs Gray as well as differential encoding of the $2^{31} - 1$ pseudo-random binary sequence input data (Fig. 1). After transmission through 80 km of standard single-mode fiber, the received signal power is controlled by a variable optical attenuator and then fed into a polarization scrambler and amplified before

Manuscript received June 11, 2008; revised July 22, 2008. First published August 22, 2008; current version published October 15, 2008. This work was supported in part by the European Union under Contract FP6-004631.

M. El-Darawy, T. Pfau, S. Hoffmann, B. Koch, O. Adamczyk, and R. Noé are with the Department of Optical Communication and High-Frequency Engineering, University of Paderborn, 33098 Paderborn, Germany (e-mail: eldarawy@ont.uni-paderborn.de; pfau@ont.uni-paderborn.de; hoffmann@ont.uni-paderborn.de; koch@ont.uni-paderborn.de; adamczyk@ont.uni-paderborn.de; noe@ont.uni-paderborn.de).

R. Peveling, C. Wördehoff, and M. Porrmann are with the Department of System and Circuit Technology, Heinz Nixdorf Institute, University of Paderborn, 33102 Paderborn, Germany (e-mail: ralf.peveling@hni.uni-paderborn.de; cwoerdeh@hni.uni-paderborn.de; mario.porrmann@hni.uni-paderborn.de).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2008.2004685

1041-1135/$25.00 © 2008 IEEE

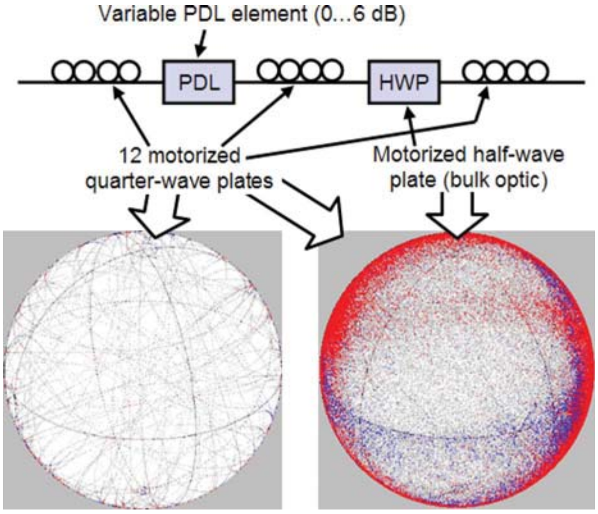

Fig. 2. Polarization scrambler and the corresponding fast polarization changes displayed on the Poincaré sphere.

detection. The amplified and filtered optical signal is superimposed with a second DFB laser ($\Delta f_{\mathrm{LO}} = 1$ MHz) acting as the local oscillator in two $\mathrm{LiNbO_3}$ optical 90° hybrids and detected with four photodiode pairs [8]. After analog-to-digital conversion with 1 sample/symbol, the data is demultiplexed into eight parallel modules to allow processing inside an FPGA at a lower clock speed. The digital samples are multiplied with an estimate of the inverse Jones matrix to separate the two polarizations. Then a feedforward scheme recovers the optical carrier despite the 2-MHz sum laser linewidth [9]. A filter with a phase estimation interval of five symbols is used to demodulate the four data streams synchronously. The correlation of data before and behind the decision circuit is used to track the SOP [10]. A switch allows us to change the polarization control time constant between $c = 3.0\ \mu$s and $c = 0.75\ \mu$s, for either a better accuracy or a faster control speed.

### *B. Fast Polarization Scrambler*

The polarization scrambler consists of four motorized fiber-optic quarter-wave plates (QWPs) followed by a variable fiber-optic PDL element, another four QWPs followed by a bulk-optic half-wave plate (HWP), and finally again four QWPs (Fig. 2). The 12 QWPs rotate at different speeds ensuring that the polarization state covers all points on the Poincaré sphere and that the PDL $\approx 2$ dB of the HWP is uncorrelated with the variable PDL element. The rotation frequency of the motor that drives the HWP can be adjusted between 0 and 612 Hz. With a gearbox tooth ratio of 39 : 15 from the motor to the HWP (0–1592 Hz) and up to $8\pi$ rad rotation on the Poincaré sphere per HWP rotation, the maximum speed of polarization changes is 40 krad/s.

The polarization scrambler was tested by applying an unmodulated laser signal at its input and measuring the SOP at its output with a polarimeter. Fig. 2 (left) shows the SOP covering the full Poincaré sphere with only the motors driving the 12 QWPs. After additionally turning on the motor driving the HWP, the Poincaré sphere fills with points [Fig. 2 (right)] because the polarimeter sampling rate of 1 kHz is too slow to follow the fast polarization changes.

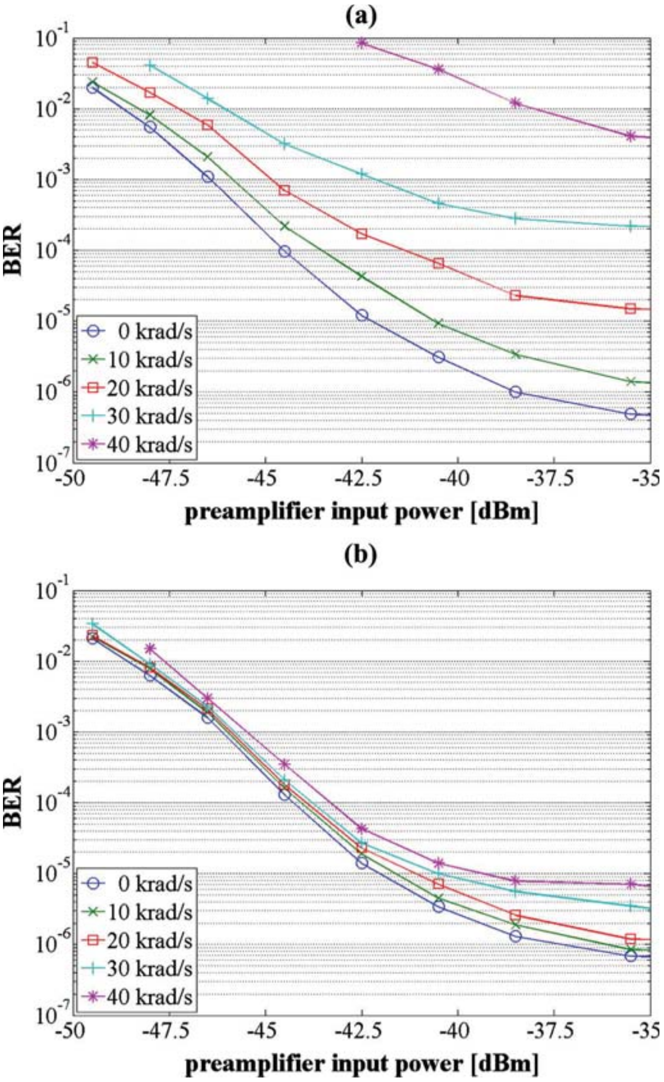

Fig 3. BER (I&Q averaged) versus optical power at the preamplifier input for different speeds of polarization change. (a) For $c = 3.0\ \mu$s (slow control) and (b) for $c = 0.75\ \mu$s (fast control).

## III. MEASUREMENT RESULTS

The polarization controller occasionally could not lock during start-up, when the polarization scrambler (HWP and QWPs) was halted. This occurs when the SOP differs strongly from the initial controller matrix and can be solved by resetting the controller with a different starting matrix. With an operating scrambler, the controller always locked at start-up and no further loss of lock was observed throughout the measurement time.

First the PDL element was set to 0 dB and the bit-error rate (BER) for different optical preamplifier input powers at polarization fluctuation speeds of 0, 10, 20, 30, and 40 krad/s for slow [Fig. 3(a)] and fast [Fig. 3(b)] polarization control was measured. The $\sim$13.4-dB penalty with respect to theory is believed to be mainly due to thermal noise, excess electrical receiver bandwidth (1.2 GHz), and individual photoreceiver overload by broadband (15 GHz) amplified spontaneous emission and LO power. So far, the sensitivity has remained essentially unchanged betwen 200- and 700-Mbaud symbol rate [11].

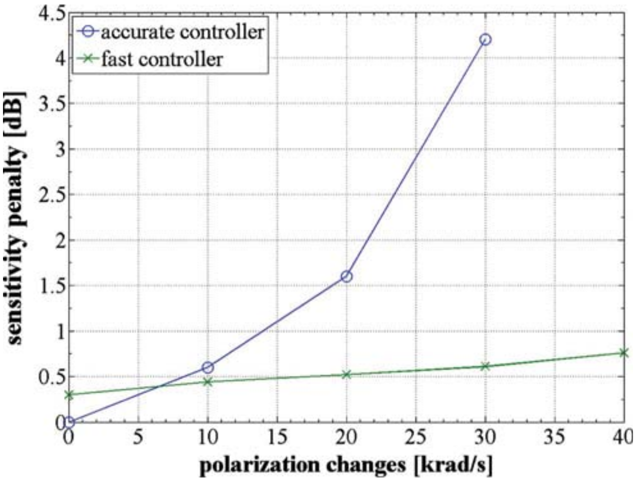

Fig. 4. Receiver sensitivity penalty at BER of $1 \times 10^{-3}$ versus speed of polarization changes on the Poincaré sphere.

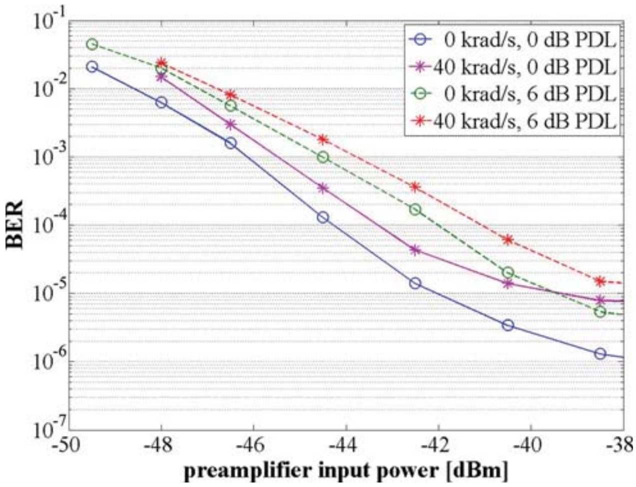

Fig. 5. BER versus optical preamplifier input power for 0 and 6 dB of PDL.

The slower polarization control with $c = 3.0$ $\mu$s achieves at BER of $1 \times 10^{-3}$ a 0.3-dB better sensitivity at 0 krad/s than the faster with $c = 0.75$ $\mu$s due to its higher accuracy. This is because the average deviation caused by fluctuations in the controller is higher for the fast control speed than for the slower one. It is clear from Fig. 3 that for fast polarization changes the fast polarization controller outperforms the slower one. The observed BER floor is a consequence of the large laser linewidth (2 MHz total) relative to the symbol rate of 700 MHz. At lower polarization change speeds it is nearly identical for both control speeds ($3.8 \times 10^{-7}$ for slow and $6.1 \times 10^{-7}$ for fast control at 0 krad/s) in contrast to those at 40 krad/s ($3.1 \times 10^{-3}$ for slow and $4.3 \times 10^{-6}$ for fast control). Also from that point of view fast polarization control is preferable for large polarization change speeds.

In terms of receiver sensitivity, the slow controller outperforms the fast one as long as the polarization change speed is below ~7 krad/s (Fig. 4). For a sensitivity penalty of 1 dB, the receiver with fast polarization control can tolerate polarization changes with a speed higher than 40 krad/s on the Poincaré sphere, while the slow one tolerates polarization changes with a speed up to 14 krad/s.

In a second step, the receiver tolerance against PDL was investigated with the PDL set to 6 dB and the BER versus optical preamplifier input power measured at 0 and 40 krad/s. The results were similar for both control time constants. Therefore, only the results for fast polarization control with time constant $c = 0.75$ $\mu$s are shown in Fig. 5. For 6 dB of PDL rather than 0 dB, the extra sensitivity penalty (at a BER of $10^{-3}$) is 1.5 dB at 0 krad/s and 1.7 dB at 40 krad/s.

## IV. SUMMARY

We have investigated real-time polarization and PDL tracking in a coherent PolDM QPSK receiver with polarization change speeds up to 40 krad/s. The receiver sensitivity penalty introduced by polarization scrambling at 40 krad/s is only 0.7 dB at BER of $1 \times 10^{-3}$ for a polarization control time constant $c = 0.75$ $\mu$s, compared to the best achievable with 0 krad/s and $c = 3.0$ $\mu$s. When 6 dB of PDL is added, the sensitivity is reduced additionally by up to 1.7 dB. PDL is, therefore, the dominant factor for sensitivity degradation.

## REFERENCES

[1] P. Krummrich, E. Schmidt, W. Weiershausen, and A. Mattheus, "Field trial results on statistics of fast polarization changes in long haul WDM transmission systems," presented at the Proc. OFC/NFOEC 2005, Anaheim, CA, Mar. 6–11, 2005, Paper OThT6.

[2] R. Noé, "Phase noise-tolerant synchronous QPSK/BPSK baseband-type intradyne receiver concept with feedforward carrier recovery," *J. Lightw. Technol.*, vol. 23, no. 2, pp. 802–808, Feb. 2005.

[3] E. Ip and J. Kahn, "Feedforward carrier recovery for coherent optical communications," *J. Lightw. Technol.*, vol. 25, no. 9, pp. 2675–2692, Sep. 2007.

[4] A. Leven, N. Kaneda, and Y. Chen, "A real-time CMA-based 10 Gb/s polarization demultiplexing coherent receiver implemented in an FPGA," presented at the Proc. OFC/NFOEC 2008, San Diego, CA, Feb. 24–28, 2008, Paper OTuO2.

[5] L. Nelson, S. Woodward, M. Feuer, X. Zhou, P. Magill, S. Foo, D. Hanson, D. McGhan, H. Sun, M. Moyer, and M. O'Sullivan, "Perfomrance of a 46-Gbps dual-polarization QPSK transceiver in a high-PMD fiber transmission experiment," presented at the Proc. OFC/NFOEC 2008, San Diego, CA, Feb. 24–28, 2008, Paper PDP9.

[6] T. Pfau, M. El-Darawy, C. Wördehoff, R. Peveling, S. Hoffmann, B. Koch, O. Adamczyk, M. Porrmann, and R. Noé, "32-krad/s polarization and 3-dB PDL tracking in a realtime digital coherent polarization-multiplexed QPSK receiver," presented at the Proc. IEEE/LEOS Summer Topical Meetings, Acapulco, Mexico, Jul. 21–23, 2008, Paper MC2.4.

[7] N. Grossard, J. Hauden, H. Porte, P. Mollier, S. Ibrahim, and R. Noé, "Low chirp QPSK modulator integrated in poled Z-cut $LiNbO_3$ substrate for 2 × multiGb/s transmission," presented at the Proc. ECOC 2007, Berlin, Germany, Sep. 16–20, 2007, Paper 10.3.5.

[8] P. Cho, G. Harston, A. Greenblatt, A. Kaplan, Y. Achiam, R. Bertenburg, A. Brennemann, B. Adoram, P. Goldgeier, and A. Hershkovits, "Integrated optical coherent balanced receiver," presented at the Proc. OAA/COTA 2006, Whistler, Canada, Jun. 28–30, 2006, Paper CThB2.

[9] S. Hoffmann, T. Pfau, O. Adamczyk, R. Peveling, M. Porrmann, and R. Noé, "Hardware-efficient and phase noise tolerant digital synchronous QPSK receiver concept," presented at the Proc. OAA/COTA 2006, Whistler, Canada, Jun. 28–30, 2006, Paper CThC6.

[10] R. Noé, "PLL-free synchronous QPSK polarization multiplex/diversity receiver concept with digital I&Q baseband processing," *IEEE Photon. Technol. Lett.*, vol. 17, no. 4, pp. 887–889, Apr. 2005.

[11] T. Pfau, S. Hoffmann, R. Peveling, S. Bhandare, S. K. Ibrahim, O. Adamczyk, M. Porrmann, R. Noé, and Y. Achiam, "First real-time data recovery for synchronous QPSK transmission with standard DFB lasers," *IEEE Photon. Technol. Lett.*, vol. 18, no. 18, pp. 1907–1909, Sep. 15, 2006.