Coherent Digital Polarization Diversity Receiver for Real-Time Polarization-Multiplexed QPSK Transmission at 2.8 Gb/s

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***Abstract*—This letter presents a coherent digital polarization diversity receiver for real-time polarization-multiplexed synchronous quadrature phase-shift keying transmission with distributed feedback lasers at a data rate of 2.8 Gb/s. The tolerance against fast polarization changes and polarization-dependent loss is evaluated for different filter widths in the carrier recovery circuit. The minimum achieved bit-error rate is 3.4×10^{-7}.**

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

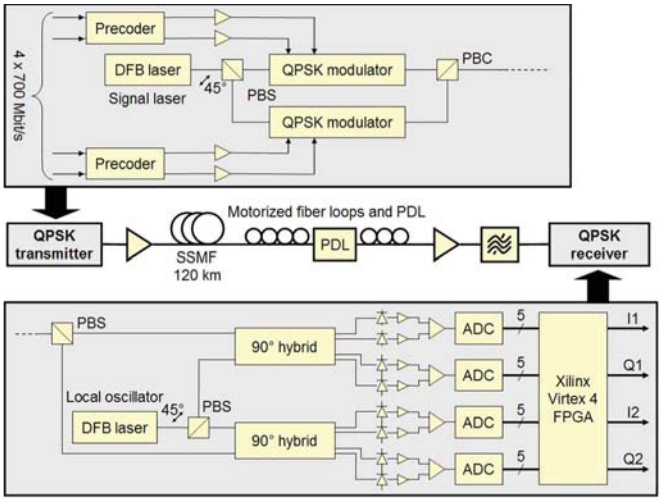

Fig. 1. Setup for 2.8-Gb/s polarization multiplexed synchronous QPSK transmission.

I. INTRODUCTION

THE interest in increasing the spectral efficiency and the tolerance to fiber nonlinearities has recently directed a lot of research towards coherent systems. In particular, synchronous quadrature phase-shift keying (QPSK) transmission promises ultimate performance and high tolerance against chromatic and polarization-mode dispersion in ultralong-haul fiber links. Feedforward carrier recovery schemes allow realizing this modulation scheme using standard distributed feedback (DFB) lasers [1]. Combined with polarization-division mulitplex QPSK can quadruple the channel capacity compared to single-polarization ON–OFF keying transmission. However, very fast polarization changes can occur at the receiver input. Therefore, the receiver must feature an adaptive compensation circuit with a response time well below 1 ms [2], which is able to follow these polarization changes. An analog compensation circuit with manual control has successfully been employed [3], but it is preferable to have an automatic polarization control integrated into the intradyne digital receiver [4], [5]. It allows recovering the carrier, controlling polarization inside a polarization diversity receiver, and compensating dispersion electronically. Many offline experiments have already shown the potential of this technology [6]–[10], and recently the first real-time implementations have been published [11], [12].

In this letter, we investigate the performance of a real-time polarization-multiplexed QPSK system at 2.8 Gb/s in different scenarios. The tolerance against fast polarization changes and polarization-dependent loss (PDL) is evaluated as well as the influence of the filter width in the feed-forward carrier recovery on achievable bit-error-rate (BER) floor and receiver sensitivity.

II. POLARIZATION-MULTIPLEXED QPSK TRANSMISSION SETUP

Four 700-Mb/s $2^{31}-1$ pseudorandom binary sequence bit streams, decorrelated for $I\&Q$ by 64 bit and for the two polarizations by 7 bit, are fed into a QPSK precoder which encodes them differentially. The output bit streams then modulate the signal of a DFB laser in two QPSK modulators [13] to generate a 2.8-Gb/s polarization-multiplexed QPSK signal (Fig. 1). After transmission over 120 km of standard single-mode fiber, the signals are received with two integrated-optical 90° hybrids [14] in a polarization diversity coherent optical receiver. Subsequent to analog-to-digital converters (ADCs) with a sampling

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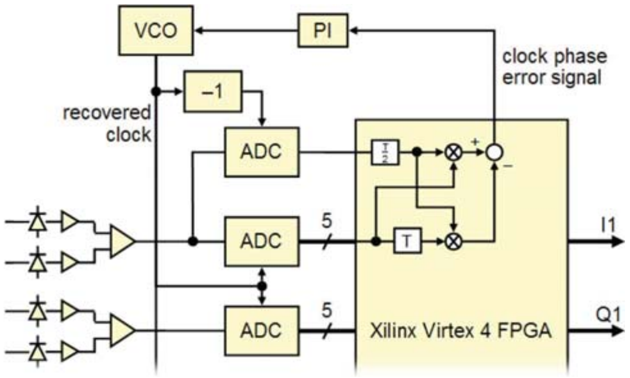

Fig. 2. Generation of clock phase error signal and clock recovery.

rate of 700 MHz, a purely electronic manipulation of an electronic equivalent of the optical field vector is undertaken in a field-programmable gate array (FPGA) to separate the two polarizations. Finally, a feedforward scheme recovers the optical carrier in spite of the 2-MHz sum laser linewidth [15]. Two different filters with a phase estimation interval $2 \cdot (2N + 1)$, $N \epsilon \{2, 4\}$ are used to demodulate the four data streams synchronously and examine the influence of the filter width on the BER. N is the number of considered samples in each polarization before and after the sample whose phase is to be estimated. Correlation of data before and behind the decision circuits is used to update the elements of the matrix which transforms the mixed-polarization electronic field vector [3]. However, a real 4×4 matrix is used, onto which a polarization-mixed real vector $[I1\ Q1\ I2\ Q2]^T$ is multiplied to obtain a polarization-separated one. This allows to automatically equalizing $I\&Q$ amplitudes and phase differences at the same time. No training sequence is needed, as the recovered data is sufficient to estimate the transmitted signal, and exhibits a unity correlation matrix. Although we use only every eighth symbol for updating the polarization control matrix, we obtain a control time constant $(1/e)$ of 12 μs, fast enough to track even fast polarization changes.

To recover the clock from the nonreturn-to-zero signal, I and Q signals of one polarization are sampled also with an inverted clock signal in additional ADCs, as shown in Fig. 2. After temporal alignment in the FPGA, these samples are correlated with the adjacent regular ones, and the results are subtracted to obtain the clock phase error signal [16]. This error signal is input into the PI controller of the clock recovery phase-locked loop. Two more error signals are also generated inside the FPGA, and used to control erbium-doped fiber amplifier gain and local oscillator (LO) frequency.

III. MEASUREMENT RESULTS

According to their specification the two DFB lasers have a sum linewidth of 2 MHz. This leads to a linewidth times symbol rate ratio of 0.0029.

Fig. 3 shows the measured BER versus optical signal-to-noise ratio (OSNR) at the receiver after transmission over a distance of 120 km for the three examined scenarios. For better readability the BERs of $I\&Q$ channels and of the two polarizations are averaged. The differences between the channels were always below 0.2 dB.

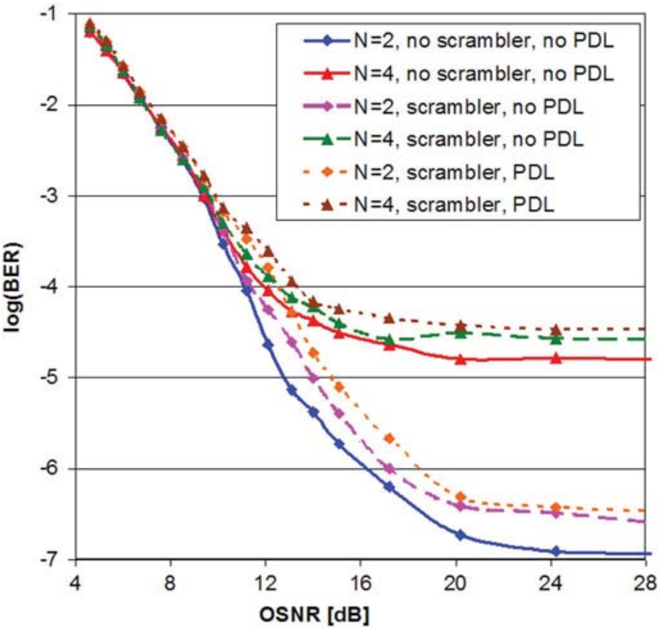

Fig. 3. Measured BER versus OSNR for constant polarization at the receiver input and for fast polarization changes with and without PDL.

The first examined scenario was static with a constant polarization at the receiver input. The best measured BER for the filter with $N = 2$ was 1.2×10^{-7}. For the filter with $N = 4$, a BER of 1.6×10^{-5} was achieved. Both recovered bit streams could be synchronized to the transmitted patterns until the preamplifier input power was set below -51 dBm, which corresponds to an OSNR of 4.5 dB.

To test the performance of the polarization control algorithm, a motorized fiber-loop polarization scrambler causing endless polarization changes at a speed of up to 50 rad/s was inserted in the transmission link. This caused the signal to be highly time-variant and degraded the minimum BER values to 2.4×10^{-7} for $N = 2$, and 2.6×10^{-5} for $N = 4$.

Finally, to additionally complicate the control task, an element with a PDL of 3 dB was inserted in the transmission link. The minimum BER again slightly degraded to 3.4×10^{-7} for $N = 2$, and 3.5×10^{-5} for $N = 4$. However, the recovered bit streams could still be synchronized until the OSNR was <4.5 dB.

Fig. 4 shows the BER variations in one polarization over a time frame of 10 min with counting intervals of 10 s for the two different filters at two OSNR levels. Only slight BER fluctuations were observed, although the polarization states changed rapidly due to the fiber loop scrambler and the 3-dB PDL element.

IV. DISCUSSION

The ~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

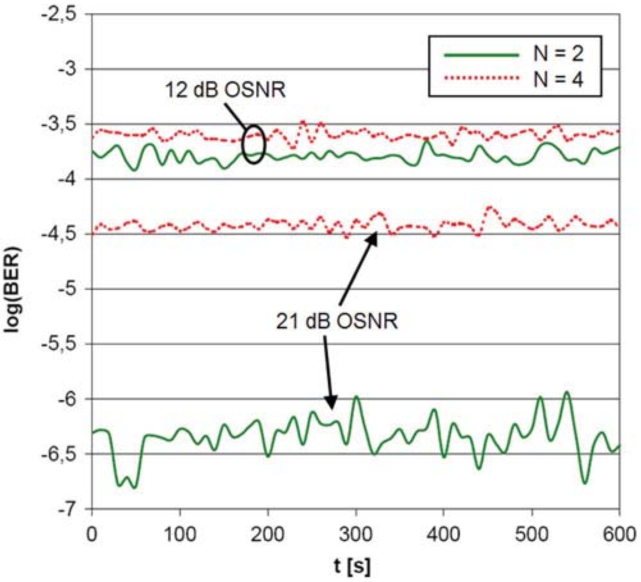

Fig. 4. Variation in time of the averaged BER for two different OSNR values.

unchanged betwen 200- and 700-Mbaud symbol rate [17]. This may also be the reason why the lower bandwidth filter $(N = 4)$ has no distinguishable performance advantage at low OSNR.

The increase of the BER floor for $N = 4$ compared to $N = 2$ is caused by its lower filter bandwidth. This theoretically increases the receiver sensitivity, but also reduces the phase noise tolerance. Therefore, the phase estimation with the lower effort $(N = 2)$ outperforms the version with $N = 4$ at low OSNRs. Although also for high OSNRs there is no distinguishable performance gain for the filter version with $N = 4$ yet, we assume that it will be advantageous for higher bit rates, where the linewidth times symbol rate product is lower.

Already at a line rate of only 0.7 Gbaud the implemented polarization tracking algorithm can follow fast polarization fluctuations. Fig. 4 clearly demonstrates the reliability and robustness of the system. The matrix was updated using the information of only one out of eight parallel processing modules in the digital receiver. Together with a potential symbol rate increase to 10 Gbaud, a substantially reduced control time constant as well as higher control accuracy seem feasible.

V. SUMMARY

We have implemented a polarization-multiplexed coherent optical synchronous QPSK transmission system at a data rate of 2.8 Gb/s. For the given linewidth times symbol rate ratio a filter width of $N = 2$ for the carrier recovery is preferable. With a PDL of 3 dB and severe endless polarization changes at a speed of up to 50 rad/s, a BER of 3.4×10^{-7} was achieved, which is well below the forward-error correction threshold. For low OSNR values, the BER performance under rapid polarization tracking does not differ from the case of constant input polarization states.

REFERENCES

[1] 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.

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

[3] S. Calabrò, T. Dullweber, E. Gottwald, N. Hecker-Denschlag, E. Müllner, B. Opitz, G. Sebald, E. D. Schmidt, B. Spinnler, C.-J. Weiske, and H. Zech, "An electrical polarization-state controller and demultiplexer for polarization multiplexed optical signals," in *Proc. ECOC 2003*, Rimini, Italy, Sep. 21–25, 2003, Paper Th2.2.2.

[4] 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.

[5] M. Tseytlin, O. Ritterbush, and A. Salamon, "Digital, endless polarization control for polarization multiplexed fiber-optic communications," in *Proc. OFC/NFOEC 2003*, Atlanta, GA, Mar. 23–28, 2003, Paper MF83.

[6] S. Tsukamoto, D.-S. Ly-Gagnon, K. Katoh, and K. Kikuchi, "Coherent demodulation of 40-Gbit/s polarization-multiplexed QPSK signals with 16-GHz spacing after 200-km transmission," in *Proc. OFC/NFOEC 2005*, Anaheim, CA, Mar. 5–10, 2005, Paper PDP29.

[7] C. Fludger, T. Duthel, T. Wuth, and C. Schulien, "Uncompensated transmission of 86 Gbit/s polarization multiplexed RZ-QPSK over 100 km of NDSF employing coherent equalisation," in *Proc. ECOC 2006*, Cannes, France, Sep. 24–28, 2006, Paper Th4.3.3.

[8] C. Laperle, B. Villeneuve, Z. Zhang, D. McGhan, H. Sun, and M. O'Sullivan, "Wavelength division multiplexing (WDM) and polarization mode dispersion (PMD) performance of a coherent 40 Gbit/s dual-polarization quadrature phase shift keying (DP-QPSK) transceiver," in *Proc. OFC/NFOEC 2007*, Anaheim, CA, Mar. 25–29, 2007, Paper PDP16.

[9] G. Charlet, J. Renaudier, M. Salsi, H. Mardoyan, P. Tran, and S. Bigo, "Efficient mitigation of fiber impairments in an ultra-long haul transmission of 40 Gbit/s polarization-multiplexed data, by digital processing in a coherent receiver," in *Proc. OFC/NFOEC 2007*, Anaheim, CA, Mar. 25–29, 2007, Paper PDP17.

[10] S. J. Savory, G. Gavioli, R. I. Killey, and P. Bayvel, "Electronic compensation of chromatic dispersion using a digital coherent receiver," *Opt. Express*, vol. 15, pp. 2120–2126, 2007.

[11] K. Roberts, "Electronic dispersion compensation beyond 10 Gb/s," in *Proc. SUM2007*, Portland, OR, Jul. 23–25, 2007, Paper Ma2.3.

[12] T. Pfau, R. Peveling, S. Hoffmann, S. Bhandare, S. Ibrahim, D. Sandel, O. Adamczyk, M. Porrmann, R. Noé, Y. Achiam, D. Schlieder, A. Koslovsky, Y. Benarush, J. Hauden, N. Grossard, and H. Porte, "PDL-tolerant real-time polarization-multiplexed QPSK transmission with digital coherent polarization diversity receiver," in *Proc. SUM 2007*, Portland, OR, Jul. 23–25, 2007, Paper Ma3.3.

[13] H. Porte, J. Hauden, N. Grossard, and R. Noé, "Modulateur QPSK intégré dans LiNbO$_3$ pour codage 2×10 Gb/s," *J. Optique et Microonde*, Mar. 24, 2006.

[14] 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," in *Proc. OAA/COTA 2006*, Whistler, Canada, Jun. 25–30, 2006, Paper CThB2.

[15] S. Hoffmann, T. Pfau, R. Peveling, R. Noé, and U. Rückert, "Hardware-efficient and phase noise tolerant digital synchronous QPSK receiver concept," in *Proc. OAA/COTA 2006*, Whistler, Canada, Jun. 28–30, 2006, Paper CThC6.

[16] C. Hogge, "A self correcting clock recovery circuit," *J. Lightw. Technol.*, vol. LT-3, no. 6, pp. 1312–1314, Dec. 1985.

[17] 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.