Record 59-krad/s Polarization Tracking in 112-Gb/s 640-km PDM-RZ-DQPSK Transmission

Benjamin Koch, Reinhold Noé, *Senior Member, IEEE*, Vitali Mirvoda, Helmut Griesser, *Member, IEEE*,
Steffen Bayer, and Horst Wernz

***Abstract*—We present results obtained with a fast optical polarization controller. Tracking errors were <0.208 rad on the Poincaré sphere during 282 hours of endless polarization scrambling at up to 60 krad/s speed. Fifty-kilorad/second polarization changes were tracked at wavelengths between 1513 nm and 1600 nm. With this subsystem we optically demultiplexed the two polarizations of a 112-Gb/s PDM-RZ-DQPSK signal transmitted over 640 km of fiber at 59 krad/s. This is the fastest polarization control reported for this or higher bitrate and direct detection.**

***Index Terms*—Lithium niobate, optical fiber communication, optical fiber polarization, quadrature phase shift keying.**

I. INTRODUCTION

POLARIZATION-MULTIPLEXED (differential) quadrature phase shift keying (PDM-(D)QPSK) is the key modulation format in coming high-performance transmission networks.

Polarization demultiplexing is possible in an electronic polarization-diversity receiver. If this is a coherent one [1], [2], then power consumption is quite high and/or symbol rate is limited. If it is interferometric with direct detection [3], then symbol rate seems likewise to be limited.

In contrast, optical polarization control is broadband. When used with an error signal that indicates residual polarization interference [4] it permits optical demultiplexing of the two PDM channels. Standard interferometric receivers can be used, with minimum power consumption and maximum symbol rate [4]–[11]. Polarization tracking speed can be up to 40 krad/s on the Poincaré sphere [11]. Control must be "endless", capable of tracking without any interruption polarization states that wander many times around the Poincaré sphere. Speed must be maintained on all possible trajectories, including the ones which are hardest to track. We generate a sufficient, complete set of trajectories with an endless polarization scrambler.

Single-polarization tracking speed has risen from ~0.1 rad/s [12] to 56 krad/s (over 30 min) and 50 krad/s (over 354 h) [10].

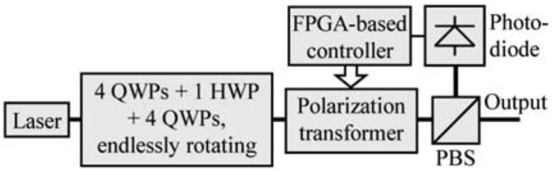

Fig. 1. Setup for single-polarization control experiments.

A wavelength range 1505–1570 nm was permissible [13]. Here, we increase wavelength range, demultiplexing performance, and tracking speed (1.475 × as high as in [11]).

II. SINGLE-POLARIZATION TRACKING

In single-polarization tracking, the polarization controller restabilizes a polarization-scrambled, unmodulated laser signal. This requires at least one Soleil-Babinet compensator (SBC), i.e., a rotatable waveplate with adjustable retardation. A retardation $\leq \pi$ suffices to transform any input into fixed circular output polarization [12]. We use a commercial $LiNbO_3$ polarization transformer containing a cascade of eight integrated-optical SBCs. The stabilized signal is fed into a polarization beam splitter (PBS); see Fig. 1. The optical power at one PBS output is detected and used as an error signal. A gradient descent algorithm, implemented in a field-programmable gate array (FPGA), acts on the control voltages to minimize the error signal. At the same time, the other PBS output provides full intensity. Polarization is scrambled by a fast rotating $LiNbO_3$ halfwave plate (HWP, up to 4.8 kHz electrical) between two quartets of asynchronously rotating fiberoptic quarterwave plates (QWPs, several Hertz mechanical). This generates circles on the Poincaré sphere with variable sizes and orientations. Mean is $\pi/4 \times$ maximum scrambling speed.

The controller was tested in a long-term measurement with mean and maximum polarization change speeds of 47 and 60 krad/s, respectively. The normalized feedback signal is a measure of the relative intensity error (RIE). It is recorded in the FPGA and put into a histogram at a sampling frequency >6 MHz for analysis purposes. Observed RIE errors depend on the combined rms electrode voltage (rms summation from all electrodes), which determines the dithering depth. The corresponding mean and maximum calculated polarization errors are plotted in Fig. 2 for 10 and 50 krad/s maximum scrambling rate, measured at eight different dithering depths over 10 min each. Errors increase if dither is large. Small dither improves mean errors while maximum errors get worse due to a decreased measurement signal-to-noise ratio. We found that a combined rms voltage of ~0.45 V minimized the maximum RIE errors and adopted this value, to increase tracking speed compared to [10], [11]. To the same purpose, we flattened

Manuscript received June 11, 2010; revised July 16, 2010; accepted July 17, 2010. Date of publication July 26, 2010; date of current version September 06, 2010. This work was supported in part by Deutsche Forschungsgemeinschaft, Bundesministerium für Wirtschaft und Technologie and Bundesministerium für Bildung und Forschung.

B. Koch, R. Noé, and V. Mirvoda are with the University of Paderborn, 33098 Paderborn, Germany (e-mail: koch@ont.upb.de; mirvoda@ont.upb.de; noe@upb.de).

H. Griesser, S. Bayer, and H. Wernz are with Ericsson GmbH, 71522 Backnang, Germany (e-mail: helmut.griesser@ericsson.com; steffen.bayer@ericsson.com; horst.wernz@ericsson.com).

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Digital Object Identifier 10.1109/LPT.2010.2060719

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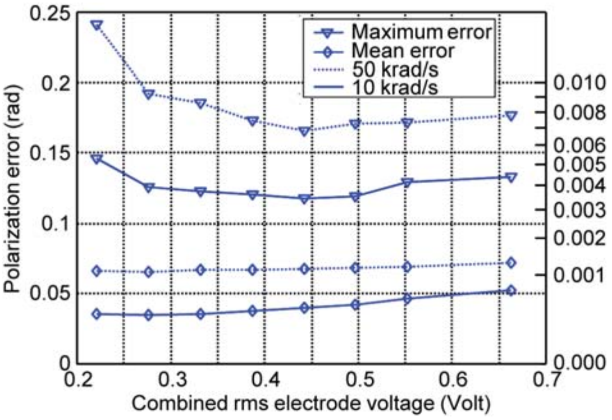

Fig. 2. Mean and maximum polarization errors at 10 and 50 krad/s scrambling versus combined rms electrode voltage (dithering depth).

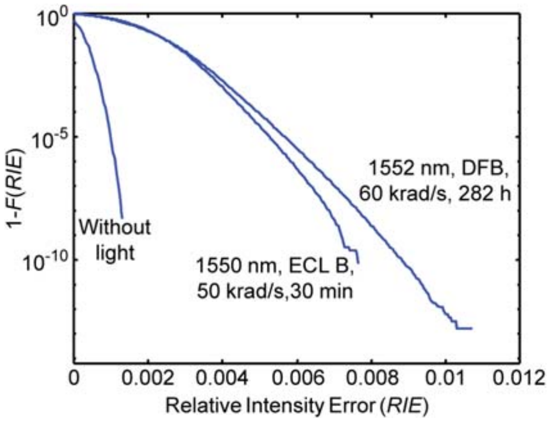

Fig. 3. Complementary distribution function $1 - F(\mathrm{RIE})$ of relative intensity error (RIE) for 30 min at 50 krad/s and 282 hours at 60 krad/s scrambling speed. Zero point $(\mathrm{RIE} = 0)$ is determined without light.

the dither frequency spectrum of the gradient algorithm, by improving the hardware driving conditions.

Fig. 3 shows the complementary distribution function $1 - F(\mathrm{RIE})$ of the RIE, i.e., the probability that the RIE becomes worse than the value given on the abscissa. The long trace represents a measurement over 282 hours at a wavelength of 1552 nm. During this time, a 47.8 Gigaradian long polarization trajectory was tracked. The RIE never exceeded 1.075%, the mean RIE was 0.118%. Corresponding maximum (mean) polarization errors are 0.208 (0.069) rad.

Next, the system was tested with a maximum scrambling speed of 50 krad/s at ten different wavelengths, over 30 min for each of them. The result obtained at 1550 nm is also plotted in Fig. 3 (short trace). Fig. 4 shows RIEs and associated polarization errors for various thresholds of the complementary distribution function between 1513 and 1600 nm wavelengths. Two different external cavity lasers (ECLs) were used for short and long wavelengths. The standard deviation of the optical power, measured without polarizer at a sampling rate of 780 kHz, was 0.33% with ECL B and 0.20% with ECL A. The lower noise of ECL A is due to an optical filter, which improved spectral purity and could be tuned no lower than 1513 nm. Therefore, mean RIE under polarization control is slightly worse with ECL B.

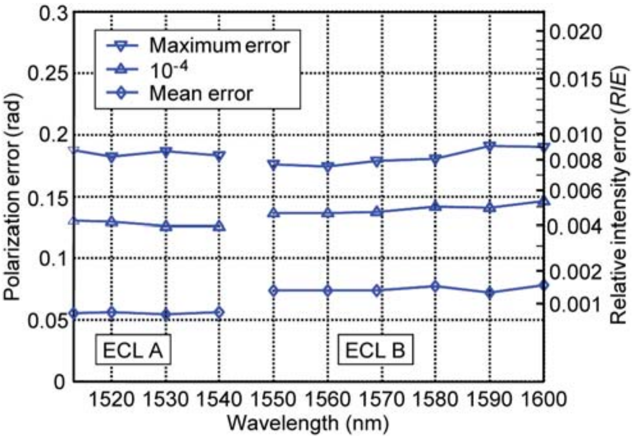

Fig. 4. Relative intensity error (RIE) and polarization errors which are surpassed only with given probability, as function of wavelength for 30-min measurements at 50 krad/s scrambling speed.

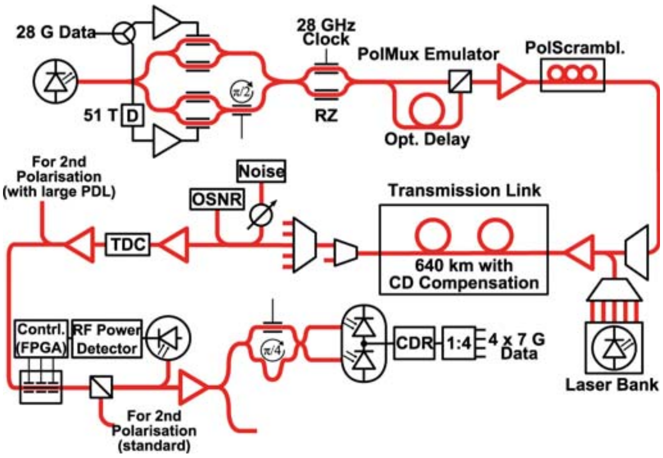

Fig. 5. PDM-RZ-DQPSK setup including fast polarization scrambler at transmit side and polarization tracking based on interference control at receiver.

III. DUAL-POLARIZATION TRACKING AT 112-Gb/s

The polarization control system was used to optically demultiplex the polarizations of a 112-Gb/s PDM-RZ-DQPSK signal. The transmitter was based on a nested Mach-Zehnder configuration followed by an RZ modulator (Fig. 5). I and Q signals at 28 Gbaud were generated from one $2^{11}-1$ pattern with a mutual delay of 51 bit, to obtain an even distribution of symbol transitions and a smooth optical spectrum. Polarization was multiplexed by combining two copies of the 56 Gb/s RZ-DQPSK signals with a mutual delay of 10.7 ns, precisely bit aligned. The DWDM spectrum was completed by 13 unmodulated laser signals distributed over the whole C-band.

The hardware of Section II was duplicated, but in a version apt for dual polarization demultiplex: At the receive side, the polarization controller transformed the signal polarizations so that the two channel signals were demultiplexed to the outputs of a subsequent polarization beam splitter. A 10-GHz photoreceiver with an attached diode detector measured the radio frequency (RF) power carried by the intensity of the optical DQPSK signal [4], thereby indicating residual interference. The RF power is minimized by the controller. Error signal quality

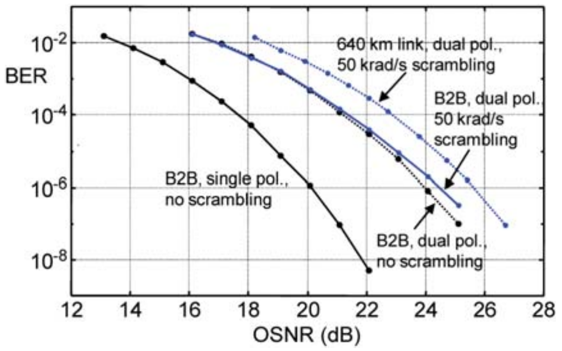

Fig. 6. Back-to-back (B2B) performance with one or two polarizations and with additional polarization scrambling; comparison of B2B performance with transmission over 640-km link at span launch power of 0 dBm and 50 krad/s maximum scrambling.

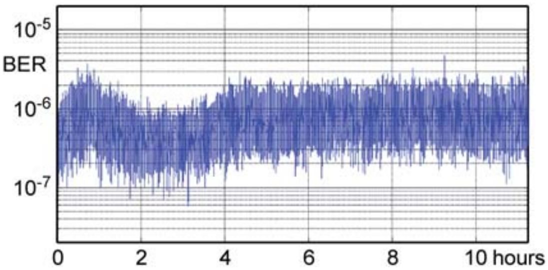

Fig. 7. BER records in 640-km link with approximately one sample per second, showing long-term stability for maximum polarization changes of 59 krad/s. Total trajectory is 1.83 Grad long.

turned out to be sufficiently good for high-speed polarization demultiplex, in spite of the random nature of the DQPSK interference. Alternatively, an accumulated interference signal can be obtained by measurements in both channels, so as to minimize the mean influence of polarization-dependent loss (PDL). As a superior variant, two independent polarization controllers, polarizers and interference detectors can individually remove interference from each channel signal even if PDL is large. After polarization demultiplex we demodulated DQPSK the standard way in a delay interferometer (FSR 33 GHz) and balanced photodiodes.

The straight link consisted of 100 GHz (de)multiplexers, a 50-GHz deinterleaver and seven spans of G.652 fiber spools with lengths between 80 and 97 km. Fiber-based dispersion compensators were inserted as interstage devices in approximately every second line EDFA. No Raman amplification was used. A tunable dispersion compensator (TDC) removed residual dispersion. At the receiver input the OSNR was ~26.7 dB for our chosen channel launch power (sum in both polarizations) of 0 dBm.

The OSNR performance of the transmitter and receiver without link, TDC, and system filtering but with additional noise loading is shown in Fig. 6 for different configurations (all results measured on a 7-Gb/s tributary). A single polarization channel required an OSNR of 16 dB for a bit-error ratio (BER) of 10^{-3}. For two polarization channels the OSNR requirement was 3.5 dB higher; like in [9] there was an excess penalty of 0.5 dB. The gap increased to ~4 dB for a BER of 10^{-9}, maybe due to a slight residual polarization crosstalk. When polarizations were scrambled at 50 krad/s we found only a small penalty at low BER compared to the case without scrambling. Note that this scrambling speed is about two orders of magnitude higher than the maximum scan speed of the typically reported Agilent polarization scrambler (e.g., [8]). The transmission of the signal over the link of 640 km results in an extra penalty of 1 dB at BER 10^{-6}.

To examine the long-term stability the polarization scrambler in front of the link was set to a maximum speed of 59 krad/s (46 krad/s mean speed). The BER of one tributary was recorded over >11 hours (1.83 Gigaradian trajectory length), showing a variation of about 1.5 decades (Fig. 7).

IV. CONCLUSION

We have demonstrated endless optical polarization control at a record speed of 60 krad/s over 282 hours. The trajectory was 47.8 Gigaradian long in total. Control quality was uniform within the tested wavelength range 1513–1600 nm.

Endless optical polarization demultiplexing has been shown in a PDM-RZ-DQPSK transmission with direct detection, over a DWDM-link with 640 km of SSMF. The bitrate of 112 Gb/s was higher than in [1]–[3]. The tracking speed of 59 krad/s, higher than in [4]–[11], sets a record. Tracking and transmission performance was stable over 11 h, longer than in [11] and with improved distance and BER.

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