12 krad/s Endless Polarization Stabilization with Lithium Niobate Component

B. Koch, A. Hidayat, H. Zhang, V. Mirvoda, M. Lichtinger, D. Sandel and R. Noé

Univ. Paderborn, EIM-E, Warburger Str. 100, D-33098 Paderborn, Germany, http://ont.upb.de

***Abstract*— We demonstrate an FPGA-based control system which compensates random polarization changes with a fluctuation speed of up to 12 krad/s. Endless and uninterruptible behavior is confirmed. The residual polarization mismatch remains below 0.16 rad.**

I. Introduction

Fast endless electrooptic polarization control is dearly needed for future high-performance optical transmission systems. Possible applications include demultiplexing of dual-polarization DQPSK, PMD compensation but also coherent transmission systems. Optical polarization control is bitrate- and application-independent. Dual-polarization DQPSK is readily implemented at 160 Gb/s since a couple of years [1] while coherent dual-polarization QPSK with electronic polarization control is limited to 40 Gb/s [2].

While temperature drift can cause slow but potentially large polarization changes, fiber movements and vibrations generate faster fluctuations. In a field trial, significant changes of the state-of-polarization (SOP) occurred within 100 µs [3]. Even faster polarization glitches can be provoked by slamming the door of a rack with dispersion compensating fiber (DCF) or hitting spooled DCF with a screwdriver tip [4]. Since any polarization mismatch, even during short periods of time, generally results in data loss, automatic polarization controllers must be capable to track even fastest polarization changes.

In the last two decades, a number of electrooptic endless polarization control experiments have been published [5–9]. A remarkable 4.9 krad/s tracking speed on the Poincaré sphere was reported in [7], but the mean relative intensity error (RIE) of 4% (= polarization mismatch of 0.4 rad) was too large for a practical application. Furthermore, tracking was proven only for one particular polarization trajectory during ~20 ms.

Here we demonstrate polarization control with a worst-case polarization mismatch of 0.16 rad for tracking random polarization changes at up to 12 krad/s.

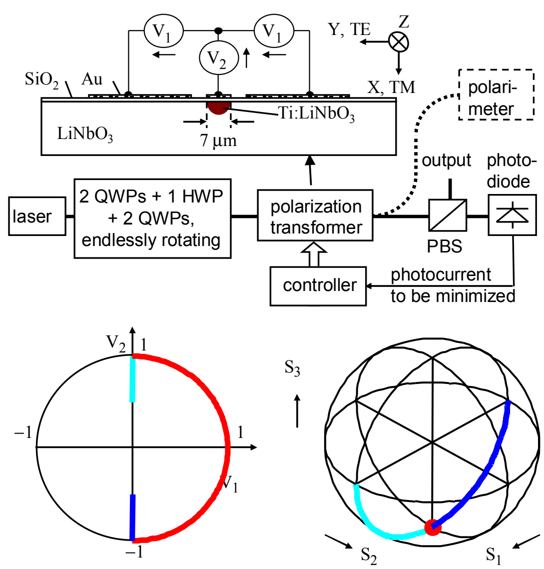

Fig. 1. Endless polarization stabilization with an integrated-optical linear retardation waveplate (electrooptic Soleil-Babinet compensator) in *X*-cut, *Z*-propagation $LiNbO_3$. Bottom: Trajectory in normalized voltage plane (left) capable of passing through circular polarization (right).

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II. Implementation

$LiNbO_3$ polarization transformers combine short response time (well below 10 ns) and sufficient stability (over temperature and time). We have developed an automatic polarization control system with an integrated-optical polarization transformer in X-cut, Z-propagation $LiNbO_3$ (EOSPACE). Its various sections can be operated as electrooptical Soleil-Babinet compensators (SBC), i.e., rotatable waveplates with adjustable retardations. Let V_1, V_2 be suitably normalized voltages which generate horizontal and vertical electrostatic fields, respectively, inside the waveguide (Fig. 1). They cause 0°/90° and 45°/–45° birefringence, respectively. When both are applied simultaneously the vector $[V_1 \quad V_2]^T$ determines by its direction one of the eigenmode orientation angles, 2ϑ, along the equator of the Poincaré sphere and by its length the retardation: $\tan 2\vartheta = V_2/V_1$, $\varphi = \pi\sqrt{V_1^2 + V_2^2}$ [5]. With such an SBC, a circular SOP can be transformed into any other SOP or vice versa. When the unknown polarization passes the other circular SOP the retardation φ reaches π. It must be limited to ≤π by keeping the voltages within the unit circle, $V_1^2 + V_2^2 \le 1$. This is possible by rotating the eigenmodes so that further SOP movement lowers retardation and voltages.

The control algorithm is digitally implemented in an field programmable gate array (FPGA). Device data are measured offline with a polarimeter and stored it in the FPGA. This allows for precise control without interruption.

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III. Experimental Results

The setup for endless polarization tracking experiments is also shown in Fig. 1. The constant SOP of a 1551 nm laser source is first scrambled by a combination of quarterwave (QWP) and halfwave plates (HWP) and then stabilized by the polarization controller. Finally, the signal passes through a polarization beam splitter (PBS). One PBS output signal is detected and provides a feedback signal for the controller. Polarization control itself is based on a gradient algorithm that dithers and subsequently optimizes the SBC voltages in the direction of the intensity gradient. A global intensity optimum is thereby reached. At the other PBS output, the maximized photointensity (–11 dBm) with a stabilized SOP is obtained. The four fiberoptic quarterwave plates rotate at incommensurate rates between –6 and +6 Hz. A bulk-optic HWP in the middle, inserted between two collimators, rotates at an adjustable rate up to 480 Hz. The resulting trajectory describes circles with different sizes and orientations on the Poincaré sphere. This makes sure that any worst cases are included. Several similar polarization rotations around the Poincaré sphere typically follow upon each other, predominantly with large radii. This stresses a polarization controller much more than limited or forth-and-back polarization changes. The maximum and calculated mean polarization fluctuation speed is 12 krad/s and 9.4 krad/s, respectively, at full HWP speed.

Performance was analyzed in a series of ≥30-minute tracking experiments, one for each of several HWP rotation rates. In order to observe even shortest tracking errors, the feedback signal, normalized and further referred to as relative intensity error (RIE), is measured every 0.5 µs and stored in a histogram in the FPGA. Fig. 2 shows the complementary distribution (cumulative density) function 1–*F(RIE)* of the RIE, i.e., the probability that the RIE becomes worse than the value given on the abscissa. Comparing to former experiments with this setup [9], we managed to reduce the execution time of one control iteration from 7 µs through 3.6 µs to presently 2 µs, which means that 500000 gradient iterations are executed per second. At 280 Hz HWP rotation rate (7 krad/s), the maximum RIE decreased from 1.81% in the slower experiment [9] to 0.46% in the current setup. Consequently, the derived tracking error decreased from 0.26 to 0.14 rad (Fig. 3). At 480 Hz HWP rotation rate (12 krad/s), the maximum RIE is 0.63% (tracking error 0.16 rad), which corresponds to a 0.03 dB loss for the maximized signal exiting at the other PBS output. Mean RIE and tracking error are <0.1% and 0.06 rad, respectively. The calculated accumulated length of all polarization trajectories tracked in Figs. 2, 3 is >40 Mrad. This validates the reliable endless operation of the control system.

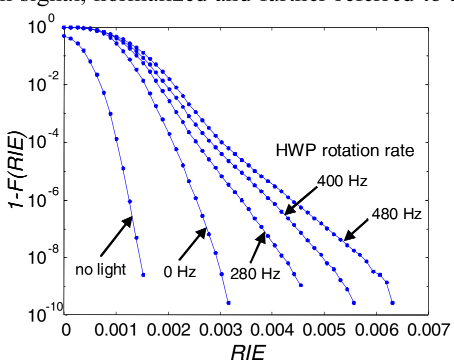

Fig. 2. Complementary distribution function 1-F(RIE) of relative intensity error (RIE) for polarization tracking at different HWP rotation rates.

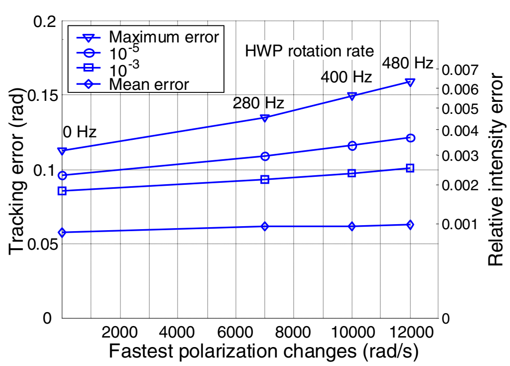

Fig. 3. Polarization tracking error at different tracking speeds, derived from the results of Fig. 2.

IV. Conclusion

We have significantly improved the performance of a fast endless polarization control system. The controller is able to stabilize worst-case 12 krad/s polarization changes with a worst-case polarization mismatch of only 0.16 rad. Performance and endless operation of the controller were verified in 30-minute period polarization tracking measurements.

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