# Optical Endless Polarization Stabilization at 9 krad/s With FPGA-Based Controller

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***Abstract*—We demonstrate endless polarization stabilization with a control speed of up to 9 krad/s, over random Poincaré sphere trajectories. These are in total >35 Mrad long, are composed in particular of difficult-to-track circles with all radii and orientations, and thereby include all possible worst cases. The maximum polarization mismatch and relative intensity errors are 0.13 rad and 0.43%, respectively. The controller runs on a field-programmable gate array and uses a commercial multistage $LiNbO_3$ polarization transformer as the control device.**

***Index Terms*—Endless polarization control, optical communication, optical polarization.**

## I. Introduction

POLARIZATION control has been initially developed to achieve polarization matching between the local oscillator and received signals in optical coherent receivers [1], [2]. Because the state of polarization (SOP) of the transmitted signal changes along the transmission fiber, an endless controller must be capable of tracking the polarization fluctuations, including any fast polarization changes due to fiber movements and vibrations. In a field trial, significant polarization changes have been observed even within 100 $\mu$s [3]. A patchcord that is dropped and spooled dispersion-compensating fiber hit by a screwdriver tip let polarization jump on time scales of 1 ms and 10 $\mu$s, respectively [4]. Any polarization mismatch, even during short periods of time, must be avoid to prevent data loss.

Advanced modulation techniques push the bitrate beyond 40 Gb/s where polarization-mode dispersion (PMD) becomes as significant as chromatic dispersion. A practical distributed PMD compensator comprises a number of differential group delay sections, each containing or preceded by a polarization transformer [5]. Since a PMD compensator must follow the birefringence evolution of the fiber as fast as possible, this implies the use of fast polarization controllers [6], [7].

Polarization-division multiplexing (PolDM) is an attractive choice to increase the spectral efficiency. Combined with differential quadrature phase-shift keying at 40 Gbaud this corresponds to a 160-Gb/s channel capacity. The big challenge in a PolDM receiver is to perform the demultiplexing of the two polarization channels. They remain fairly orthogonal during transmission and must be tracked by fast endless polarization controllers. Polarization mismatch must be minimized, ideally by interference detection [8], [9].

A number of electrooptic endless polarization control experiments have been published in the last two decades [1], [2], [5]–[7]. So far, fast polarization stabilization has been demonstrated only for a particular polarization trajectory [6], [7] with mean polarization mismatch errors of 4% (−14 dB) [7], too much for practical applications. A truly endless operation of a polarization controller can be verified only when the controller tracks a complete set of endless polarization changes, including (and most importantly) the worst-case ones. Recent publications on polarization control, with theory and with nonelectrooptic devices, include [10]–[13].

Among the various commercially available polarization transformers, only lithium niobate ($LiNbO_3$) ones combine short response time (well below 10 ns) and sufficient stability (over temperature and time). In this letter, we describe a fast endless polarization controller that uses an electrooptical Soleil–Babinet compensator (SBC) integrated in a $LiNbO_3$ waveguide. An SBC is a rotatable waveplate with adjustable retardation. The high-speed operation is achieved by implementing the control algorithm in a field-programmable gate array (FPGA).

## II. Implementation

The setup for the polarization stabilization experiment is shown in Fig. 1. An optical signal from a 1551-nm laser is passed through endlessly rotating quarter- (QWP) and halfwave (HWP) plates. Four fiber-optic QWPs rotate at unequal and incommensurate rates between −6 and +6 Hz. The bulk-optic HWP in the middle, inserted between two collimators, rotates at an adjustable rate up to 360 Hz. One HWP revolution can cause $8\pi$ rad of polarization change on the Poincaré sphere. This rotating waveplate arrangement realizes rapidly varying random SOP with a maximum speed of up to 9 krad/s, mainly circles with all possible orientations and sizes. The mean speed for equidistributed HWP input polarization is calculated to be $\pi/4$ times the maximum speed. The QWPs serve to adjust the radius and the orientation of the polarization rotations caused by the HWP. Since the HWP rotates much faster than the QWPs, 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 back-and-forth polarization changes. It is much worse than a fiber link will typically behave. Many tests confirmed the predicted demanding polarization change behavior. They were conducted at down-slowed rotation speeds which our polarimeter could fully resolve.

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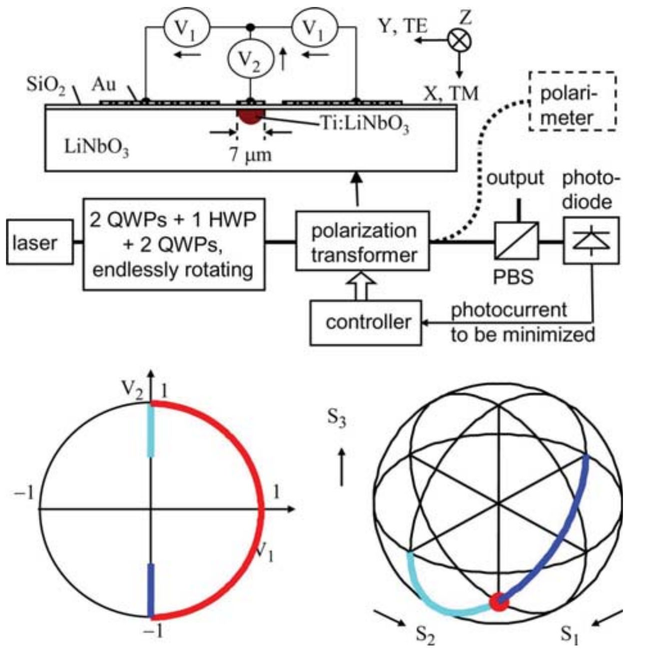


Fig. 1. Endless polarization stabilization with an integrated-optical linear retardation waveplate (equivalent to an SBC) in X-cut, Z-propagation $LiNbO_3$. TE = transverse electric; TM = transverse magnetic. Bottom: Trajectory in normalized voltage plane (left) capable of passing through circular polarization.

The polarization controller requires an electrooptic waveplate with variable retardation between a variable pair of orthogonal linear polarizations. It can be realized in X-cut, Z-propagation $LiNbO_3$, and its mechanical equivalent is an SBC. It has linear eigenmodes with physical azimuth angles $\vartheta$ and $\vartheta + \pi/2$, a retardation $\varphi$ adjustable from 0 to at least $\pi$, and the azimuth angle $\vartheta$ can be freely varied between $-\infty$ and $\infty$, like the orientation of an SBC. Let $V_1$, $V_2$ be suitably normalized voltages which generate horizontal and vertical electrostatic fields, respectively, inside the waveguide. 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 the eigenmode orientation angle $2\vartheta$ along the equator of the Poincaré sphere and by its length the retardation:$\tan 2\vartheta = V_2/V_1$, $\varphi = \phi\sqrt{V_1^2 + V_2^2}$ [1]. The actual, unnormalized $V_1$ may need an offset to tune out residual waveguide birefringence. Any SOP can be endlessly transformed by the waveplate into a circular SOP. Since any polarization can be reached by a retardation $\varphi \leq \pi$, the condition $\varphi < \pi$ holds under most circumstances. Whenever the SBC reaches the retardation limit $\pi$, its eigenmodes must be chosen so that further polarization tracking brings the retardation away from the limit [1], thereby maintaining $V_1^2 + V_2^2 \leq 1$. This is illustrated at the bottom of Fig. 1 with a trajectory in the voltage plane and corresponding polarization trajectory on the Poincaré sphere: When passing circular polarization, the voltages could increase beyond the unit circle. But instead they are changed on the periphery of the unit circle until they reach a position which allows a continuation of the Poincaré sphere trajectory by means of a voltage reduction.

The controller is implemented in an FPGA. The feedback signal for the controller is obtained from the optical signal after it is passed to a polarization beam splitter (PBS) and detected by a photodetector. The aim of the control is to minimize the feedback signal. The maximized photointensity −11 dBm with a stabilized SOP is then obtained at the other output of the PBS. 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.

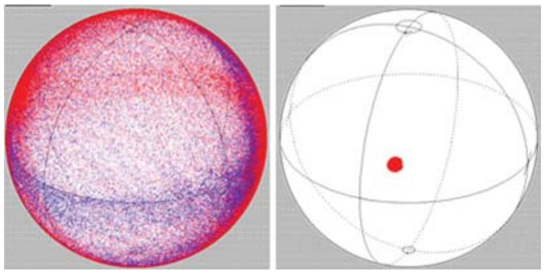

Fig. 2. Polarization changes on the Poincaré sphere without polarization stabilization (left) and with polarization stabilization (right).

The actual device is a connectorized commercial polarization transformer from EOSPACE with <3-dB insertion loss and <0.2-dB polarization-dependent loss in a 101-mm-long package. It features several variable waveplates along the same waveguide, which allowed us to maintain the required voltages at ±50 V or less. The last waveplates have fixed voltages and are used to statically transform the circular polarization generated inside the device into that linear polarization inside the PBS which is passed to the output.

The algorithm can correct a polarization mismatch of ≤1 rad essentially within one control iteration (3.6 $\mu$s), fairly in line with the discussed high practical speed demands [3], [4]. Initial searching is typically accomplished in just a few (<10) iterations but does not matter in practice because control is so fast that tracking is never interrupted. The fast digital processing in the FPGA gives the controller a control speed of almost 280 000 iterations/s. For analysis purposes, the photointensity error, i.e., the residual power falling upon the photodetector, is recorded every 0.6 $\mu$s, also during the dithering steps of the gradient algorithm.

## III. Experimental Results

Polarization tracking was first verified with a polarimeter. If the controller was switched OFF, the polarimeter showed that the Poincaré sphere instantly filled with points (Fig. 2, left) when the waveplates rotated as described before. However, after the controller was switched ON, the stabilized SOP was confined in a circle with a 0.1 rad radius (Fig. 2, right) and a degree of polarization of >0.99 was observed. The HWP rotated with a rate of 360 Hz (up to 9 krad/s polarization changes).

The performance of the controller was further analyzed in a series of ≥30-min tracking experiments, one for each of several different HWP rotation rates. Fig. 3 shows the complementary distribution (cumulative density) function 1–F(RIE) of the relative intensity error (RIE), i.e., the probability that the intensity becomes worse than the value given on the abscissa. For example, at an HWP rotation rate of 120 Hz (polarization changes up to 3 krad/s), the RIE is <0.15% during 99% of the time and

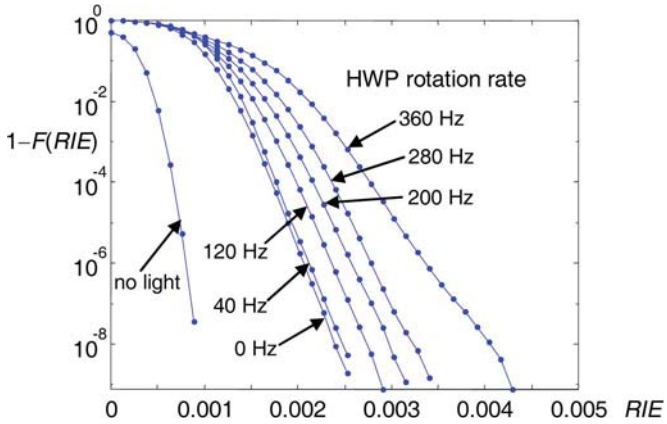


Fig. 3. Complementary distribution function 1-F(RIE) of relative intensity error (RIE) for polarization tracking of different HWP rotation rates.

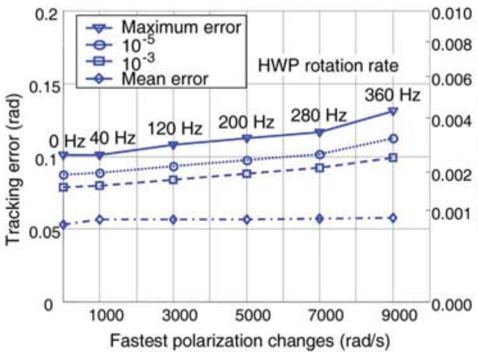


Fig. 4. Derived polarization tracking error at different tracking speeds.

it never exceeds 0.3%. The photointensity is subject to measurement errors, as shown in the reference measurement without light. Thus, the true results are likely to be better.

Fig. 4 shows the polarization mismatch (left scale) inferred from the RIE (right scale) as a function of the fastest polarization transformation changes (horizontal scale) for each HWP speed (inside diagram), for $1 - \mathrm{F(RIE)} = 0$ (i.e., $< 10^{-8}$, no worse intensity sample recorded), $< 10^{-5}$, and $< 10^{-3}$. The displayed mean polarization error, linearly averaged, at 0.06 rad is about five times better than in [7]. At 9 krad/s, a maximum RIE of 0.43% was observed at the cross polarization, corresponding to $-10\log(1 - (< 0.0043))$ dB $=< 0.02$ dB loss for the maximized signal exiting at the other PBS output. During this 30-min period, with total calculated accumulated polarization changes >12 Mrad, no polarization mismatch larger than 0.13 rad was observed. This and the lower-speed data with even smaller tracking errors validate the truly endless operation of the controller. The calculated accumulated length of all polarization trajectories tracked in Fig. 3, 4 is >35 Mrad.

## IV. Conclusion

We have presented a fast endless polarization control system with the digital processing realized in an FPGA. The controller was able to stabilize worst-case 9-krad/s polarization changes, which is the fastest endless control speed reported to date, with a maximum polarization mismatch of only 0.13 rad. Performance and endless operation of the controller were verified in long-term polarization tracking measurements. The controller is suitable for polarization demultiplexers, PMD compensators, and coherent receivers.

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