Endless optical polarization control and PMD compensation

R. Noé, B. Koch, V. Mirvoda, D. Sandel
Univ. Paderborn, EIM-E, Warburger Str. 100, D-33098 Paderborn, Germany
noe@upb.de; koch/mirvoda/sandel@ont.upb.de

Abstract: We demonstrate fast endless optical polarization control for instrumentation, polarization demultiplexing and PMD compensation. Mean/max polarization error is 0.077/0.197 rad during 30 minutes at up to 56-krad/s tracking speed. A 50-Grad trajectory is also tracked.

OCIS codes: (130.3730) Lithium niobate (260.5430) Polarization

1. Introduction

Polarization-multiplexed (PDM) transmission systems with direct detection avoid the high-speed, high-power electronics required for coherent polarization-diversity detection at high bitrates. An automatic polarization control system stabilizes the polarization before the polarization demultiplexer in the receiver [1–5]. In the same way, polarization can be transformed into a principal state of a differential group delay (DGD) section to compensate for polarization mode dispersion (PMD) [5–7]. Polarization control must be be fast and endless, i.e. uninterrupted even when tracking multiple rotations of the polarization state. Starting at ~0.1 rad/s [8] the past two decades have brought the maximum endless polarization tracking speed to 38 krad/s on the Poincaré sphere, with a tracked trajectory length of 3.8 Grad, a wavelength tolerance from 1505 to 1570 nm [9], and 0 to 70°C temperature tolerance [10]. Here we increase tracking length and speed [11]. Other contenders have reported a 4.9 krad/s speed with 10 repetitive turns of one particular endless trajectory tracked in 20 ms [12], or 12.6 krad/s [13] while tracking seemingly finite polarization changes. Commercial devices reveal far slower responses [14].

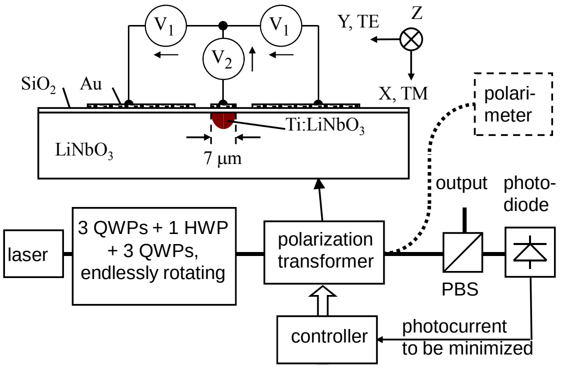


Fig. 1: Setup for high-speed polarization control experiments using an integrated-optical $LiNbO_3$ component

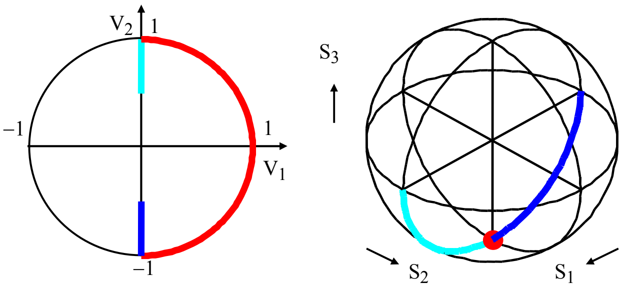


Fig. 2: Trajectory in normalized voltage plane (left) capable of passing through circular polarization (right)

2. Operation principle

For polarization transformation we use a commercial X-cut, Z-propagation $LiNbO_3$ component (EOSPACE). It contains a cascade of 8 integrated-optical Soleil-Babinet compensators (SBCs), i.e. rotary waveplates with adjustable retardation (Fig. 1). Their response time is well below 10 ns. Orientation and retardation of each SBC section can be modified with two voltages V_1 and V_2, which generate horizontal and vertical electrostatic fields, respectively, inside the waveguide. If V_1, V_2 are suitably normalized, the orientation of the fast SBC eigenmode, 2ϑ, is determined by $\tan 2\vartheta = V_2/V_1$ and can be rotated endlessly in the S_1-S_2-plane. The retardation of the SBC is thereby given by $\varphi = \pi\sqrt{V_1^2 + V_2^2}$ [7,8]. With a single SBC having a retardation $\leq\pi$, circular polarization can be transformed into any other polarization or vice versa, provided the retardation is limited when it reaches the value π. This becomes necessary whenever the input polarization reaches or passes the other circular polarization state, orthogonal to the required output one (Fig. 2). Thus, polarization tracking is uninterrupted. Voltages $V_1 \sim \cos 2\vartheta$, $V_2 \sim \sin 2\vartheta$ are needed for a rotating waveplate. The physical azimuth angle of an equivalent mechanical SBC is ϑ. We control several waveplates simultaneously. This greatly increases tolerance against device-inherent nonideal

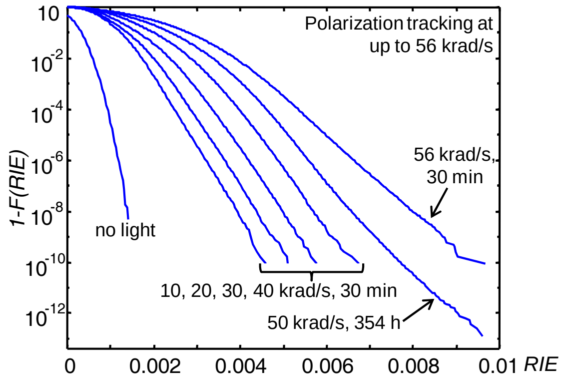


Fig. 3: Complementary distribution function 1-F(*RIE*) of relative intensity error (*RIE*) for various polarization scrambling speeds

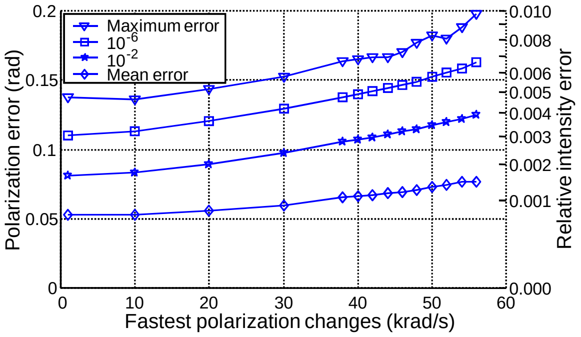


Fig. 4: Relative intensity error (*RIE*) and derived polarization error which are surpassed only with the given probabilities, as function of maximum scrambling speed in a series of 30-minute measurements

behavior and variations of the fixed output polarization, improves tracking speed and reduces required electrode voltages.

3. High-speed polarization control

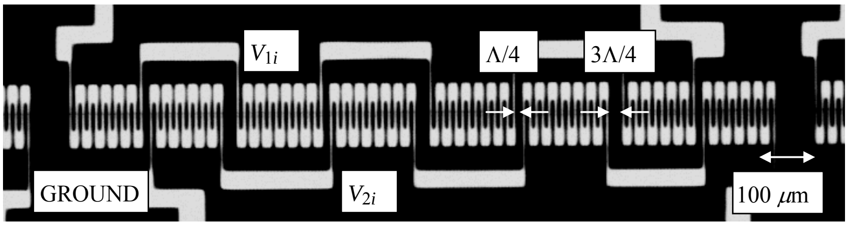
In Fig. 1, the polarization state of a laser is first scrambled, then re-stabilized. For scrambling, an auxiliary $LiNbO_3$ polarization transformer is configured as one fast rotary halfwave plate (HWP) between two rotary quarterwave plates (QWP). With linear input polarization, one HWP voltage period generates 4π of output polarization rotation. At 4.46 kHz drive frequency, polarization changes of 56 krad/s are thus generated. Mean scrambling speed is 44 krad/s ($\pi/4 \cdot 56$ krad/s). The QWP drive frequencies are 80.4 and 70.7 Hz. To increase randomness, the $LiNbO_3$ waveplates are placed between two pairs of fiberoptic QWPs which rotate endlessly at incommensurate rates between -6 and 6 Hz. The output polarization describes mostly circles with different sizes and orientations. Behind this scrambler, there is a polarization controller card with another $LiNbO_3$ polarization transformer, an FPGA and other electronics. Its output signal is passed through a polarization beam splitter (PBS), with full intensity. A feedback signal is detected at the other PBS output and minimized by a gradient search on electrode voltages. Compared to [9], the clock speed at which the electrode voltages are generated is doubled to 10 MHz. This allows to broaden the polarization dither spectrum and improve control quality or tracking speed. The electrode voltage drivers consume ~5 W. This power can be reduced, especially if needed speed is not extreme.

To assess control accuracy, the feedback signal is recorded in the FPGA every 150 ns on average, including all dithering steps, and put into a histogram. Fig. 3 shows the complementary distribution function 1-F(*RIE*) of the relative intensity error (*RIE*), i.e., the probability that the *RIE* becomes worse than the value given on the abscissa. Results are shown for maximum scrambling speeds from 10 to 56 krad/s (30 minutes each). The leftmost trace shows a no-light measurement to indicate noise and determine the point of zero intensity error (*RIE* = 0). At 50 krad/s speed we extended the measurement to 354 h. In this time of >14 days, total polarization changes of 50 Grad were tracked. No-light measurements before and after the longterm measurement revealed a *RIE* drift of 0.0003. The 50 krad/s trace is referenced to the average of these two, and therefore carries a *RIE* uncertainty on the order of 0.00015. Fig. 4 shows *RIE* and derived polarization error for various thresholds of the complementary distribution function. Results are shown for different scrambling speeds, each measured over 30 minutes. Mean/maximum polarization errors are 0.065/0.164 rad at up to 38 krad/s, and 0.077/0.197 rad at 56 krad/s.

Regarding the prime application PDM transmission, we have tracked 0.8 krad/s endless polarization changes in a 112-Gb/s PDM-DQPSK field trial [1]. With a faster polarization scrambler a tracking speed of 3.5 krad/s was obtained [11]. Both experiments were conducted with an earlier polarization controller [10], not the 56 krad/s one. A further substantial increase of endless tracking speed for PDM-DQPSK is feasible in our opinion.

4. PMD compensation

The compensation of polarization mode dispersion (PMD) is closely related to polarization control [5]. A PMD compensator is realized from several differential group delay (DGD) sections preceded by endless polarization controllers, which must be able to transform endlessly any incoming polarization into a principal state-of-polarization (PSP) of the following DGD section [6]. For polarization demultiplex purposes the last DGD section may be followed by another endless polarization transformer. It is effective to integrate all this on a birefringent X-cut, Y-propagation $LiNbO_3$ chip [15], as a distributed PMD compensator [6]. Our control principle of can be applied



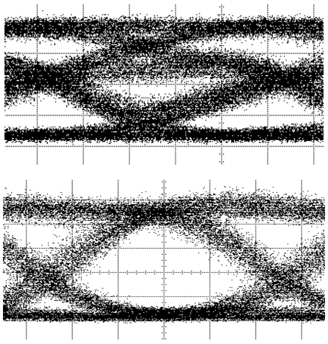


Fig. 5: *Top left:* Photograph of mode converter electrode pair (dark) for in-phase and quadrature mode conversion voltages V_{1i}, V_{2i} in X-cut, Z-propagation Ti:LiNbO$_3$ PMD compensator [15] . *Top right:* 20 Gb/s NRZ IMDD eye pattern with 10+20 ps of DGD and PMD equalizer, without control. *Bottom right:* As before, but control switched on, which compensates PMD

also here, only the circular polarizations in Fig. 2 are replaced against TE/TM PSPs. Fig. 5 (top left) shows one polarization controller or PMD compensator section with sets of comb electrodes for in-phase and quadrature mode conversion. With such devices PMD in a 20-Gb/s NRZ-IMDD transmission has been compensated (right) [15].

1st-order PMD can be determined in fairly short time (e.g., 2.4 µs) with high sensitivity (e.g., 1 ps) by arrival time detection in the clock recovery PLL [5, 16]. To this purpose, the transmitted polarization is scrambled, either optically, or, for RZ-IMDD signals, by a differential phase modulation between the polarization channels. The DGD is derived from the scrambling-induced variations in the PLL filter output signal. Optical PMD detection methods are also possible [17, 18]. Slope steepness detection indicates with good accuracy the next most important NRZ-IMDD signal distortion by PMD (beyond 1st-order PMD) [7]. High PMD orders seem to be difficult to detect [7], and their detection will generally depend on the modulation and signal format.

5. Conclusions

A 56 krad/s tracking speed and a $5{\cdot}10^{10}$ rad long tracked trajectory show that endless optical polarization control technology with LiNbO$_3$ devices has matured. Applied to PDM-DQPSK transmission it allows to develop 100GbE or even 2×100GbE transponders with available technology and moderate power consumption and cost. Close-to-ideal PMD compensation is likewise possible, preferably with an integrated distributed LiNbO$_3$ PMD equalizer.

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