100 krad/s endless polarisation tracking with miniaturised module card

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For the first time, an endless optical polarisation tracking speed of 100 krad/s is demonstrated. During a 64-hour measurement, a polarisation trajectory of 18 gigaradian length was tracked with mean and maximum polarisation errors of 0.096 and 0.220 rad, respectively.

Introduction: Optical polarisation control is required to stabilise the unknown and fluctuating state of polarisation of an optical signal. This is useful for optical PMD compensation, coherent detection and notably for optical polarisation demultiplexing.

The polarisation controller must be endless, i.e. it has to track the fastest expected polarisation changes without interruption even if the polarisation trajectory wanders many times around the Poincaré sphere [1].

Optical polarisation demultiplexing is very valuable because it avoids costly high-speed signal processors in electronic demultiplex receivers. Even more importantly, the optical solution consumes less power and can easily be applied to data rates of 200 Gbit/s [2] or higher. For a direct-detection optical polarisation diversity arrangement [3] the latter is not evident.

In [4] and [5], a 112 Gbit/s signal has been tracked at polarisation change speeds of 380 and 800 rad/s, respectively. Other publications show slower or manual polarisation control. In 2010, we tracked 40 krad/s at 200 Gbit/s [2] and 59 krad/s at 112 Gbit/s [6].

Endless polarisation control setup: The signal of an unmodulated laser source is passed through an endless polarisation scrambler (Novoptel EPS1000). The scrambler consists of another $LiNbO_3$ polarisation transformer, which is controlled to act as a fast-rotating halfwave plate between two pairs of more slowly-rotating quarterwave plates. The polarisation trajectory at its output describes endless circles with changing sizes and orientations on the Poincaré sphere. Polarisation changes and their directions are thereby equally distributed over the Poincaré sphere. The rotation speed of the halfwave plate determines the maximum polarisation change speed, while the mean speed is $\pi/4$ times the maximum one.

To increase tracking speed beyond 60 krad/s [6] we rebuilt the controller hardware completely. The compact board has a size of 78 × 150 mm and a total height of 15 mm (component height: 10 mm above board). The latter is determined by the $LiNbO_3$ polarisation transformer, which is soldered into the board. The whole control module can be integrated as a daughterboard into the receiver hardware. All required voltages are generated on-board from a single +5 V supply. Power consumption is only 5 W.

Fig. 1 shows the polarisation control module in a configuration for polarisation demultiplexing [2, 6]. A polarisation beam splitter, two couplers and interference detectors for both polarisation channels are mounted on top of the board (other than in Fig. 2).

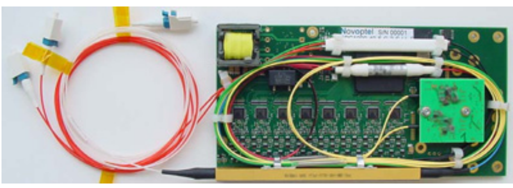

Fig. 1 *Polarisation controller card in configuration for polarisation demultiplexing of polarisation-multiplexed DQPSK signals*

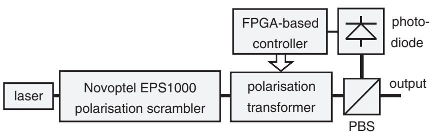

Fig. 2 *Test setup for endless polarisation control experiments*

After scrambling, the polarisation controller stabilises polarisation again, see Fig. 2. The signal passes through the $LiNbO_3$ polarisation transformer of the controller and a polarisation beam splitter (PBS). Nearly all of the light exits at one of the two PBS outputs. Residual light of the orthogonal polarised PBS output is detected at the other PBS output and serves as a feedback signal for the polarisation controller. It is known that if a polarisation controller passes this strict test (60 krad/s in [6]) then it also performs well in the slightly less demanding task of polarisation demultiplexing (59 krad/s in [6]). A Spartan-3A DSP FPGA (Xilinx) acts as a controller and sets digital-to-analogue converters every 120 ns in order to modulate electro-optic waveplate voltages and track polarisation.

Experimental results: The feedback signal is minimised by the polarisation controller. For control analysis purposes, feedback signal samples are accumulated into a histogram during control. The samples are normalised to a relative intensity error (RIE). Fig. 3 shows the complementary distribution function 1-F(RIE) of the RIE, e.g. the probability that the RIE becomes worse than the value on the abscissa.

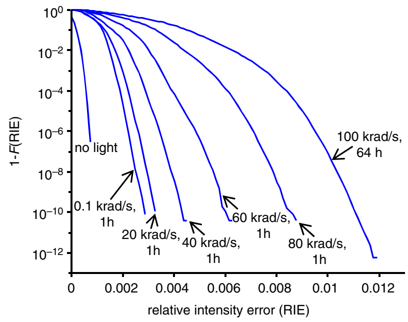

Fig. 3 *Complementary distribution functions 1-F(RIE) of relative intensity errors (RIE), each measured over 1 or 64 hours at different maximum polarisation scrambling speeds*

Every curve shows a measurement over at least one hour at a defined maximum polarisation scrambling speed. The leftmost curve shows a reference measurement without light to determine the zero point RIE = 0. The next five curves show one-hour measurements at up to 0.1, 20, 40, 60 and 80 krad/s. The rightmost curve shows a long-term measurement over 64 hours at a top scrambling speed of 100 krad/s.

The polarisation error E in radians can be derived from the RIE by $E = 2 \cdot \operatorname{asin}(\sqrt{RIE})$. Fig. 4 shows the polarisation errors, which are surpassed with probabilities of 0.5 (mean error), 10^{-3}, 10^{-6} and 0 (maximum error). At 0.1 krad/s, mean and maximum polarisation errors are 0.052 and 0.11 rad, respectively. At slow scrambling speeds, polarisation errors are mainly caused by polarisation dithering and measurement noise. Therefore, the mean polarisation error changes hardly up to a scrambling speed of 20 krad/s. At higher scrambling speeds, mean polarisation errors rise linearly to the polarisation scrambling speed. They can be understood as the slope error of an integral controller. At up to 60 krad/s, the maximum error after one hour is 0.160 rad. With the older setup, an error as large as 0.190 rad was reached or surpassed with the same probability at the same scrambling speed [6]. At 100 krad/s polarisation scrambling (78 krad/s mean polarisation change speed), mean polarisation error is 0.096 rad. The control time constant, as estimated from mean polarisation error divided by mean polarisation change speed, is 1.2 µs. During this long-term measurement a maximum polarisation error of 0.220 rad on a polarisation trajectory of about 18 gigaradian length was measured.

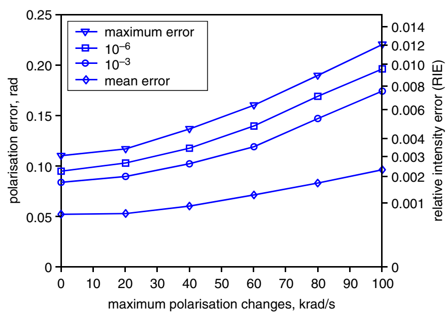

Fig. 4 *Relative intensity error and corresponding polarisation errors, which were surpassed with given probability*

Conclusion: Our polarisation controller in the form of a compact module card tracks endless polarisation changes with up to 100 krad/s speed. Tracking speed is improved 1.67-fold over the previous value 60 krad/s. Control accuracy at a given tracking speed is likewise significantly improved.

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One or more of the Figures in this Letter are available in colour online.

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