20 krad/s endless optical polarisation and phase control

B. Koch, R. Noé, V. Mirvoda and D. Sandel

Presented is endless optical control not only of the state-of-polarisation of an analysed signal and its orthogonal, but also of the phase difference between the two. The normalised Stokes vector space is thereby stabilised, at the polarisation scrambling speeds of up to 20 krad/s.

Introduction: Reported optical polarisation control systems [1–5] control two degrees-of-freedom (DOF). For instance, by proper setting of a 0°- and a 45°-oriented fibre squeezer, arbitrary input polarisation can be transformed into 0° linear polarisation. In the normalised Stokes vector space this means a stabilisation of the parameter S_1, whereas parameters S_2 and S_3 are subject to an arbitrary rotation around the axis S_1. That rotation angle is the introduced change of the phase difference between the stabilised signal and its orthogonal.

In this Letter, we show that, given a third DOF, one can control this phase difference. Thereby, not only one axis but the whole normalised Stokes vector space is stabilised. This is required, for example, in quantum communication where 0°/90° and 45°/ − 45° linear polarisations must be preserved during transmission of the cryptographic keys with the BB84 protocol. We have developed a suitable polarisation control system with three DOF, capable of tracking polarisation and phase at polarisation scrambling speeds up to 20 krad/s. Moreover, this tracking is endless, i.e. uninterrupted, even for unlimited polarisation and phase changes which can occur in practice.

Control principle and setup: We assume two control polarisations C_1 and C_2, which are arbitrary but semi-orthogonal, i.e. they differ by a $\pi/2$ angle on the Poincaré sphere (Fig. 1). By a rotation on the sphere, C_1 can be transformed into 0° linear polarisation $S_1 = [1\ \ 0\ \ 0]^T$. The rotation axis must lie on a great circle of a plane that is perpendicular to the difference $S_1 - C_1$. Under conventional control, two DOF are needed for this, for example the azimuth and ellipticity of the vector $S_1 - C_1$. Marked by encircled letters *a* to *e*, different transformation trajectories of C_1 into S_1 can be seen. Trajectory *a* belongs to the rotation axis *R*, and the same rotation transforms C_2 on trajectory *a′* into 45° linear polarisation $S_2 = [0\ \ 1\ \ 0]^T$. Trajectories *b* to *e* also transform C_1 into S_1, but the same rotations transform C_2 into various other points P_b to P_e. These are semi-orthogonal to S_1 and lie on the S_2–S_3 great circle. Control of the third DOF selects the wanted rotation axis *R* and sets the phase shift between the stabilised polarisation and its orthogonal.

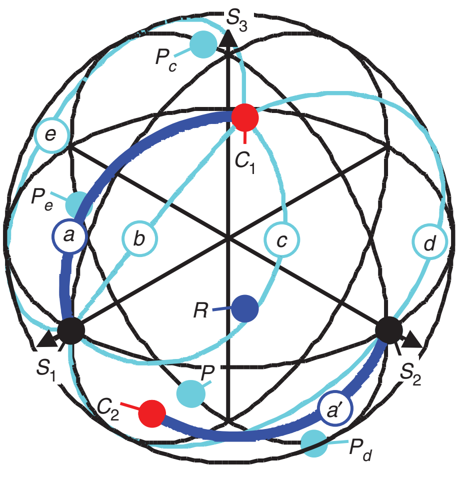

Fig. 1 *Principle of polarisation and phase control with three degrees-of-freedom*

Fig. 2 shows the setup for optical polarisation and phase control. Two unmodulated laser signals with frequencies 193.8 and 194.0 THz serve as control signals. They are combined in a coupler with 0° and 45° linear, i.e. semi-orthogonal, polarisations. A third signal with an intermediate frequency of 193.9 THz and adjustable polarisation is used for probe testing. The combined signal is passed to a fast endless polarisation scrambler. It consists of a fast rotatable halfwave plate (HWP) between two trios of quarterwave plates (QWPs), rotating at slower, incommensurate rates. For a single-polarisation signal, the scrambler generates circles with varying radii and orientations on the Poincaré sphere. This comprises many reiterating worst-case trajectories, which are difficult to track by the polarisation controller. Mean scrambling speed is $\pi/4$ times the nominal maximum value.

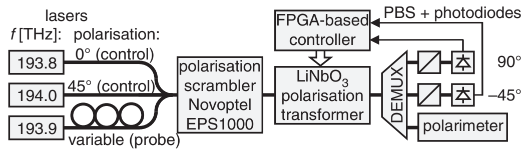

Fig. 2 *Setup for endless optical polarisation and phase control with three controlled degrees-of-freedom, using an integrated-optical LiNbO$_3$ polarisation transformer*

Top/middle/bottom laser signal exits at top/middle/bottom DEMUX output

Before the three signals are split by a DWDM DEMUX filter, all polarisation transformations of the scrambler are compensated in a subsequent $LiNbO_3$ component, which is operated by the 3DOF control system. The control signals for the first two DOF are obtained by minimising the power of the 0° (193.8 THz) signal behind a polariser, whose transmitted eigenmode is aligned to 90° polarisation. The polarisation of the 0° signal is thereby stabilised. Depending on the introduced phase difference between 0° and 90° polarisations, the 45° (194.0 THz) signal is rotated on the S_2–S_3 great circle. That signal is passed through a second polariser aligned to 135°, whose output power serves to control the third DOF. The 193.9 THz probe signal is connected to a polarimeter.

Experimental results: The two polarisers' output powers are normalised and referred to as the relative intensity errors (*RIE*s) of the 0° and 45° signals. For control error analysis, samples of the *RIE*s are put into histograms at a sampling frequency of ∼3.3 MHz during control. After 1 hour of measurement, the complementary distribution function 1 − F (*RIE*) of the *RIE*s is derived from the histograms. Fig. 3 shows these for different scrambling speeds. Maximum (mean) polarisation errors are: 0.08 (0.04) rad for 0° and 0.14 (0.06) rad for 45° at 0.1 krad/s scrambling; 0.12 (0.06) rad for 0° and 0.16 (0.06) rad for 45° at 20 krad/s scrambling. The larger error of the 45° signal is mainly caused by the PMD of the scrambler and the controller, which degrades the semi-orthogonality of the two control signals. This does not influence phase tracking performance, since the 45° *RIE* is simply minimised as far as possible by the controller. Finally, the normalised Stokes vector space stabilisation is verified using the 193.9 THz probe signal and a polarimeter. The probe signal was set to six polarisations corresponding to 0°, 90°, 45°, − 45° linear and right/left circular polarisation at the transmitter, see Fig. 4. Polarisation measurement was halted when moving the probe signal to the next polarisation.

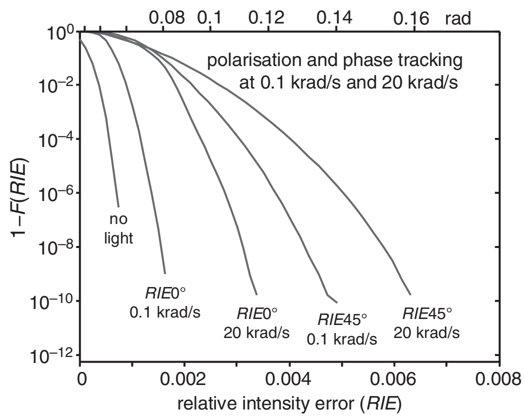

Fig. 3 *Complementary distribution functions of relative intensity errors (RIE) of 0° polarisation (193.8 THz) and 45° polarisation (194 THz), each measured at scrambling speeds of 0.1 and 20 krad/s over 1 h*

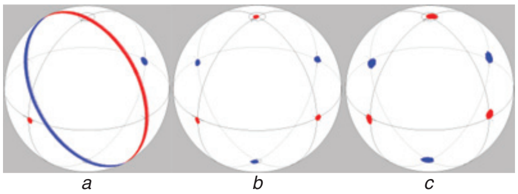

Fig. 4 *Probe signal transmitted at six fundamental polarisation states*

a Without differential phase control, only 0° and 90° signal polarisation is stable
b Differential phase control enables transportation of the whole normalised Stokes vector space, shown at 0.1 krad/s
c 20 krad/s scrambling

Without differential phase control (e.g. only the 0° *RIE* is minimised), 45°, −45° linear and right/left circular polarisations are transformed to random points on the S_2–S_3 great circle, see Fig. 4*a*. Only 0° and 90° polarisations are stabilised. With additional differential phase control, the whole normalised Stokes vector space is ported to the receiver. Polarimeter screen shots are shown for 0.1 krad/s, Fig. 4*b*, and 20 krad/s, Fig. 4*c*. Spot radii are in the order of 0.04 and 0.06 rad, respectively. The fact that spot radii are hardly increased by the 200 times faster scrambling suggests that spot size at low scrambling speed is mainly caused by PMD. The PMD of the controller and the scrambler were determined to be of the order of 25 and 30 fs, respectively. The sum of these, 55 fs, can explain a spot radius of already 0.035 rad for the given frequency difference of 100 GHz.

In a further test at 0.1 krad/s scrambling speed, the 45° control polarisation was misaligned to another linear polarisation before the multiplexer. This did not sensibly change the Poincaré sphere spot size of the probe signal set to 45° polarisation, which shows that semi-orthogonality is not critical.

Conclusion: We have demonstrated simultaneous tracking of the polarisation and the phase difference of an analysed polarisation and its orthogonal. The whole normalised Stokes vector space is thereby stabilised. Demanding tests by continuous and endless polarisation scrambling proved the reliability of the system. For the 0° signal, maximum and mean polarisation errors were 0.12 and 0.06 rad, respectively, during a measurement time of 1 hour at 20 krad/s polarisation scrambling.

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