OPTIMIZED POLARIZATION SCRAMBLERS FOR PMD DETECTION

Vitali Mirvoda, David Sandel, Frank Wüst, Reinhold Noé
Univ. Paderborn, FB 14/850, Warburger Str. 100, 33098 Paderborn, Germany, http://ont.upb.de
mirvoda@ont.upb.de; sandel@ont.upb.de; wuest@ont.upb.de; noe@upb.de

Abstract *A polarization scrambler with a single electrooptic waveplate is presented. A preliminary version allowed to detect 680fs of PMD at 40Gbit/s within 9.6us. With a 2nd waveplate a scrambler independent of input polarization was realized.*

Introduction

Regarding PMD detection, spectral analysis has been a workhorse for a while but is being challenged by methods with scrambled polarization /1-5/. In the context of polarization holeburning in EDFAs, scrambling has previously been associated with mere depolarization where just the degree of polarization (DOP) vanishes /6/. While rotating linear polarization is a depolarized signal it is not suitable to indicate PMD with circular principal states-of-polarization. Rather, true scrambling requires that also the covariance matrix of normalized Stokes vectors of the generated polarizations equal 1/3 times the identity matrix.

Other design goals consist in a minimized hardware effort, shortest possible scrambling period, low harmonic content and independence of input polarization. Convincing solutions to these problems have not been published, to our knowledge.

Single-waveplate scrambler

__Theory:__ A polarization scrambler needs just one X-cut, Y-prop. $LiNbO_3$ electrooptic Soleil-Babinet compensator (SBC) /7/ or waveplate with circular input polarization. Required TE-TM phase shift alone and and TE-TM mode conversion alone (in rad) would be $\varphi_{PS} = 0.98\sin\omega t + 1.35\sin 2\omega t$, $\varphi_{MC} = 0.98\cos\omega t - 1.35\cos 2\omega t$, respectively, but applied together they produce a time-variable retardation of $\varphi = \sqrt{\varphi_{PS}^2 + \varphi_{MC}^2}$ between a pair of linearly polarized eigenmodes, one of which is characterized by the normalized Stokes vector $[\varphi_{PS}/\varphi \quad \varphi_{MC}/\varphi \quad 0]^T$. Their combination results in an output polarization pattern with a 120° rotation symmetry about the circular axis of the Poincaré sphere. Its covariance matrix equals 1/3 times the unity matrix, and its gravity center is in the origin.

This scrambler is particularly useful if all WDM channels have equal polarizations, or if channels with like and orthogonal polarizations are interleaved in the frequency domain. A quarterwave plate on the same chip can be used to convert horizontal/vertical linear into the right/left circular polarizations needed for scrambling.

__Experiment:__ An SBC was used to generate circular input polarization of a subsequent scrambler SBC (Fig. 1). Both were part of a commercially available integrated polarization transformer. A polarimeter was conncted to the device output. The resulting Poincaré sphere trace was recorded with a period of ~1s for demonstration purposes (Fig. 2). Axes are arbitrary since there was an unspecified polarization transformation between scrambler and polarimeter. Eigenvalues of the covariance matrix were ~1/3 with relative differences of just ±1.35%. This is the ultimately achievable relative PMD detection accuracy. Residual DOP was 1.7%.

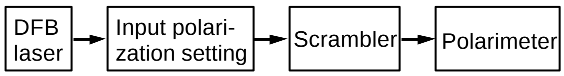

Fig 1: Experimental setup

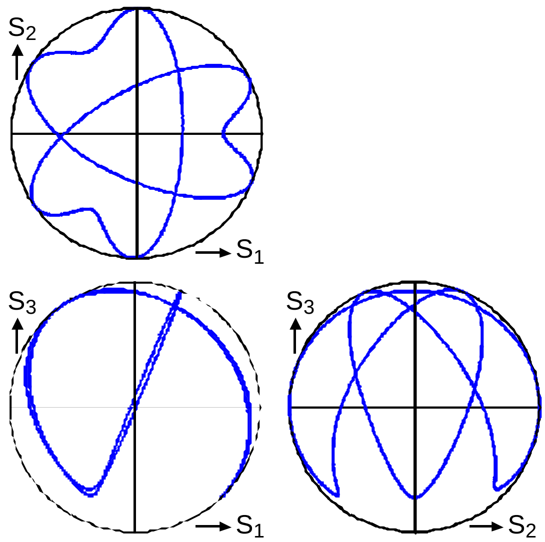

Fig 2: Projections of measured output polarization trace of single-waveplate polarization scrambler.

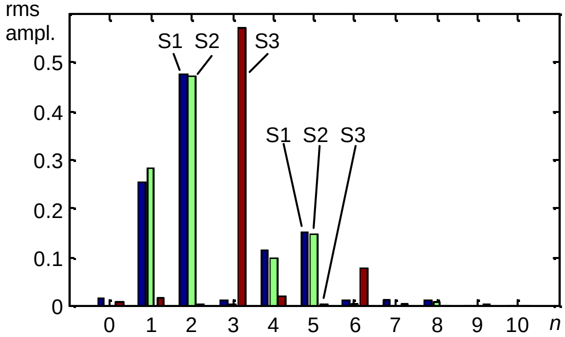

Fig 3: Harmonics spectra of Stokes parameters.

The rms amplitudes of Stokes parameters measured at different multiples nw of w are given in Fig. 3. Most of the power is contained in harmonics n = 1, 2 (both for S_1, S_2) and n = 3 (for S_3), respectively.

The scrambling period was then shortened to 4.8us. Limited polarimeter speed did not allow covariance matrix analysis any longer. However, in spite of a limited driver amplifier bandwidth the degree-of-polarization worsened only to 4% which indicates that scrambling was still nearly perfect at this speed.

Using a preliminary, less optimized version of this scrambler, with a 4fold rotation symmetry and a non-zero DOP, arrival time detection of PMD (conducted as described in /3/) at 40Gbit/s NRZ has already been tested with a 680fs worst case sensitivity in a 9.6us measurement interval.

Polarization-independent scrambler

Theory: We now seek a covariance matrix of the scrambler output polarization equal to 1/3 times the identity matrix not just for one but for all input polarizations. A particular solution to this problem is a retarder with a retardation of $5\pi/6$ and eigenmodes which are equidistributed on the Poincaré sphere. If arbitrary constant retarders are added before and/or behind this particular retarder the general solution is obtained.

Here is a possible implementation: Two concatenated SBCs are operated with equal retardations having a sine-like probability distribution in the interval [0; π], statistically independent from the orientation angles. Both SBCs are rotated in the same direction at the same speed but their orientation angles differ by $\pi/6$ on the Poincaré sphere. In order to obtain a finite scrambling period we use the approximation

$$j_{PS1} = A - B \qquad j_{PS2} = A + B$$

$$A = 0.28 \cdot \sin wt - 1.15 \cdot \sin 3wt + 0.82 \cdot \sin 4wt$$

$$B = 0.26 \cdot \cos wt + 0.37 \cdot \cos 3wt + 0.14 \cdot \cos 4wt$$

$$j_{MC1} = C - D \qquad j_{MC2} = C + D$$

$$C = -0.99 \cdot \cos wt - 1.40 \cdot \cos 3wt - 0.52 \cdot \cos 4wt$$

$$D = 0.07 \cdot \sin wt - 0.31 \cdot \sin 3wt + 0.22 \cdot \sin 4wt$$

where the indexes 1, 2 denote the two SBCs.

Experiment: Two subsequent SBCs on the same chip were used for scrambling. Another SBC with circular input polarization generated a grid of 51 scrambler input polarizations, fairly equidistributed on the whole Poincaré sphere. The covariance matrix of the output polarizations was measured and its eigenvalues were determined, separately for each input polarization. A histogram of eigenvalues is shown in Fig. 4. The minimum of the smallest eigenvalue was 0.25. The maximum of the largest eigenvalue was 0.37. So the achievable relative accuracy of an arrival time-based PMD detector will vary by ±18% depending on scrambler input polarization and principal states-of-polarization of the fiber. Stokes parameter spectra depend on scrambler input polarization. The squared magnitude of the output Stokes parameter has been averaged over all (normalized) Stokes parameters and all input polarizations. In Fig. 5 the amplitudes of that spectrum are plotted. Although there is no direct physical significance it is clear that there are more harmonics as a price to pay for the enormous advantage of being (fairly) polarization-insensitive.

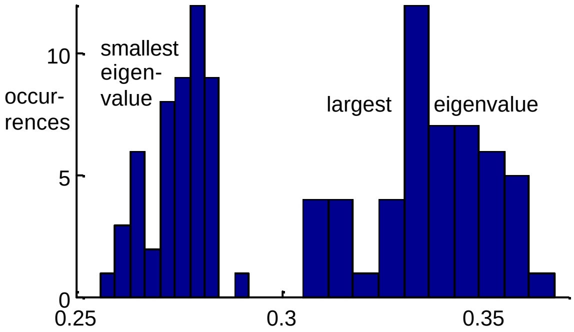

Fig 4: Histograms of largest and smallest eigenvalue of 51 covariance matrices.

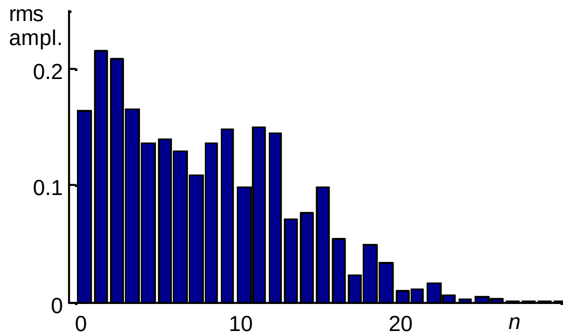

Fig 5: Harmonics spectra of output Stokes parameter averaged over all input polarizations.

Conclusions

A polarization scrambler with a single electrooptic waveplate for circular input polarization and a polarization-independent polarization scrambler with two electrooptic waveplates have been presented. They can be used for arrival time detection of PMD, and PMD detection schemes which require a polarimeter.

Acknowledgement

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