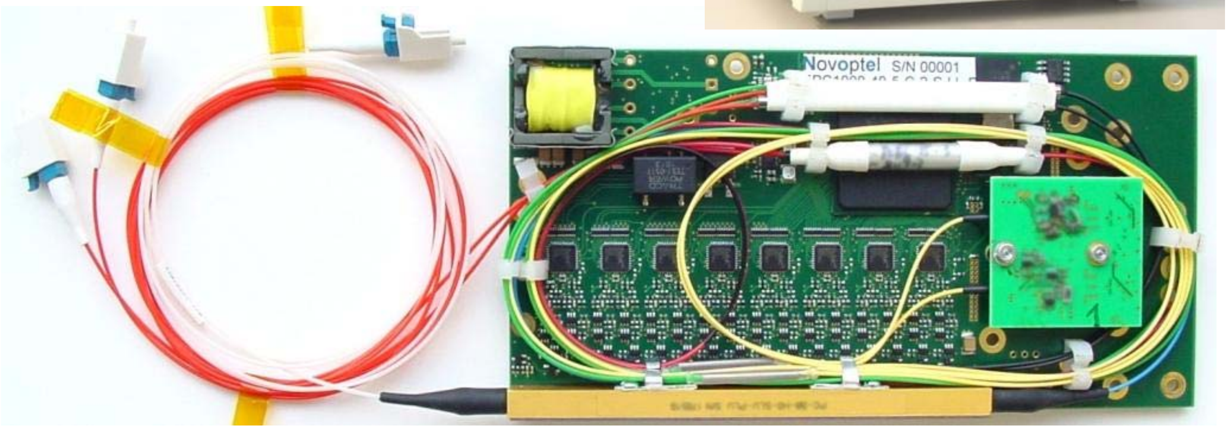
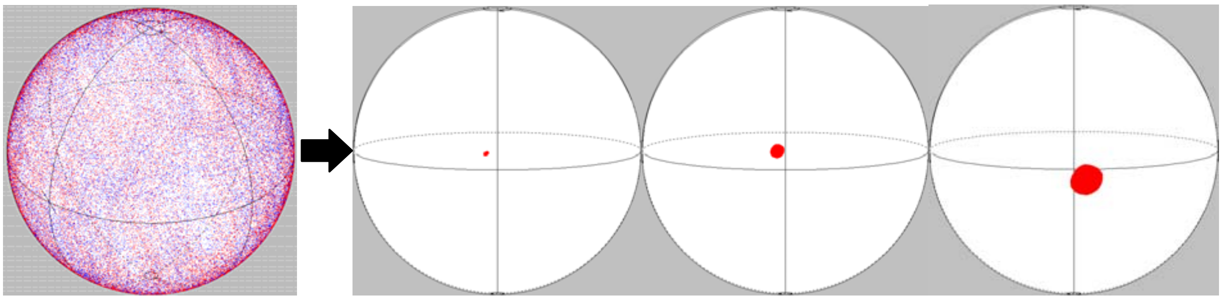


EPC1000 series

Polarization controllers
Polarization demultiplexers

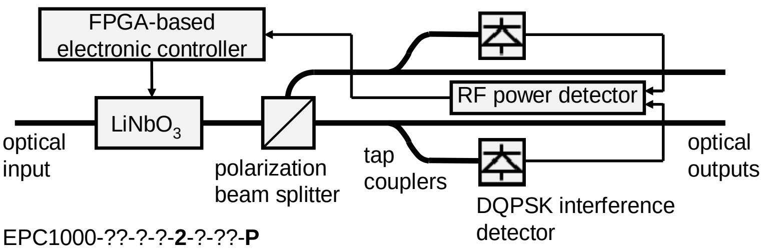


- **Guaranteed endless tracking (control) speed: 40 krad/s** on Poincaré sphere
- Can be made faster: **60 krad/s** are unproblematic. **100 krad/s** available since 2011.
- To our knowledge, **Novoptel's endless polarization tracking speed is at least 100 times as high as that of competitor products.** If you are aware of something better then please inform us so that we can correct this statement.
- Extremly reliable: More than **350 Gigarad** were tracked in several extended tests.



Scrambled (example) Controlled @ 10 krad/s 40 krad/s 100 krad/s

- Wavelength range: **C band**, optionally **extended to L band** and S band.
- Temperature range: **-10°C to +70°C**; extension is possible.
- Power consumption: About **5 W** from single **+5 V** source. Compatible with the needs of 40 Gb/s, 100 GbE, 2x100 GbE, 4x100 GbE and other transponders. Can be further reduced.
- Interfaces for external controller or computer: **Software commands (SPI)**, **digital hardware lines**.
- Functionality: **Channel swapping** (to exchange demultiplexed polarization channels, may for example be activated by a framer/mapper), **reset**, **control** (on/off), modification of important parameters (**control gain** and **speed**, **dither amplitude**, **delay time** of supplied error signal)
- **In-field upgradable firmware** and **remote access** possibility for diagnosis and troubleshooting
- **Various configurations** are available, **desktop units**, **plug-in module cards**, **IP cores**.
- Options: User-supplied error signal, **arbitrary and endlessly variable output polarization**, ...
- **EPX1000 = cost-saving desktop unit with combined functionalities of EPC1000 and 10 Mrad/s polarization scrambler EPS1000**
- Contact us for data sheet and further information. We are eager to accomodate special needs.



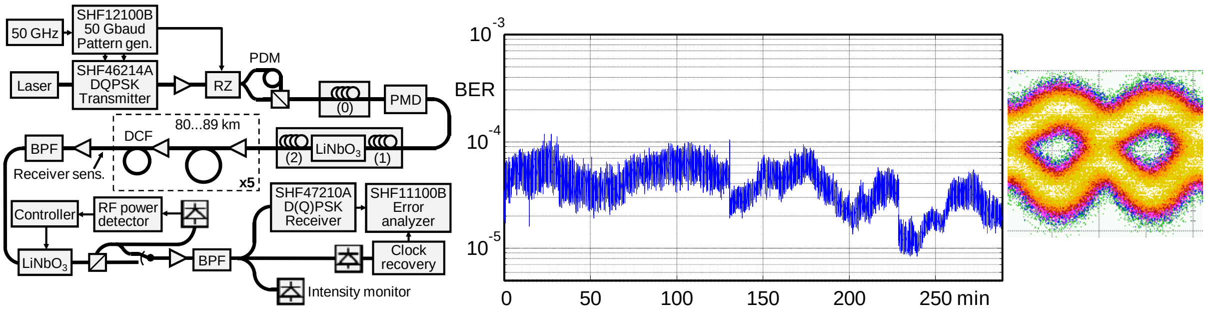
EPC1000-??-?-?-**2**-?-??-**P**

Configuration example:

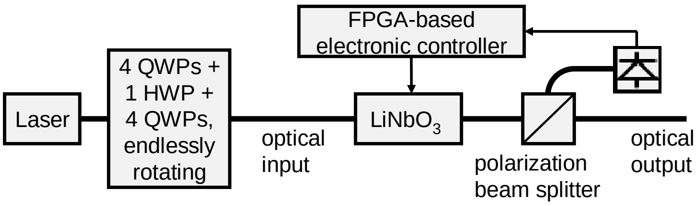
EPC1000 with interference detection for **demultiplexing of polarization-multiplexed DQPSK or QAM signals**. Everything is mounted on controller card (see picture above).

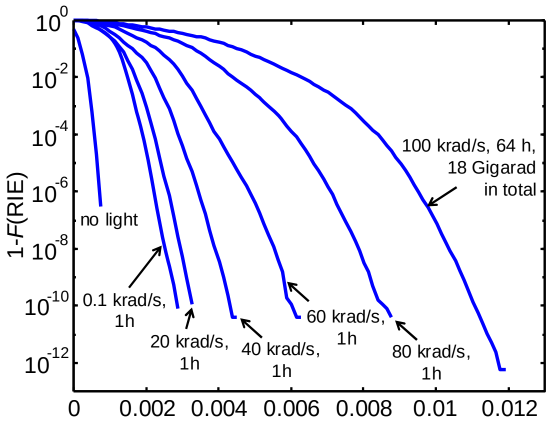
Results obtained with Novoptel EPC1000

World's highest data rate in polarization-agile realtime transmission with 4 bit/symbol: 200 Gb/s, 430 km polarization-multiplexed DQPSK transmission with 40 krad/s polarization tracking speed (IEEE PTL 22(2010)9, pp. 613-615)

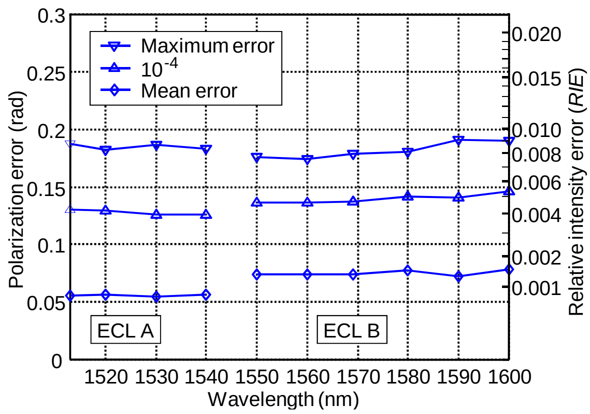


World's fastest endless optical polarization control: 100 krad/s on Poincaré sphere tracked over 64 h (B. Koch et al, Electronics Letters, Vol. 47, No. 14, 2011, pp. 813-814)





Complementary distribution function 1–*F*(*RIE*) of relative intensity error (*RIE*) for 1 hour at 0.1, 20, 40, 60, 80 krad/s, and for 64 hours at 100 krad/s scrambling speed (18 Gigarad in total). The zero point (*RIE* = 0) is determined without light.



Relative intensity error (*RIE*) and polarization errors which are surpassed only with the given probability, as a function of wavelength for 30-minute measurements at 50 krad/s scrambling speed.

About Novoptel GmbH (www.novoptel.com)

Novoptel GmbH in Paderborn, Germany, was incorporated by Prof. Dr.-Ing. Reinhold Noé and Dipl.-Ing. Benjamin Koch in 2010 as a spin-off of the University of Paderborn, with the aim of developing and delivering **nov**el **opt**ics and **el**ectronics for **tel**ecommunication. Leveraging 2+ decades of pioneer experience in optical polarization control as well as knowledge about the needs of the telecom industry, the two founders and the team have brought this technology to an unprecedented maturity and have developed standalone units, modules and intellectual property cores for ultrafast optical endless polarization control. All these have the same technical basis and control a $LiNbO_3$ integrated electrooptic polarization transformer.

- Novoptel has developed products, manufactures and ships them, counts on growth from own resources and will not promise anything it can not hold.
- We have preferred to step onto the marketplace only after the technical challenges and problems were solved. This has taken years; it is even correct to say 20+ years. But we believe that it is verifiable technical performance, proven reliabilty, and experience, combined with a competitive cost structure, which will succeed, not claims, publicity or headcount.
- Enthusiastic customer feedback shows that we are on the right track. Yet we are always willing to learn.

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Novoptel

Application note 1
Error signals for polarization control

Revision history

Version	Date	Remarks	Author
0.9.1	06.01.2011	Draft version	R. Noé
1.0.0	27.09.2011	Final version	R. Noé
1.0.1	18.11.2011	Typo corrected	R. Noé

Summary

Error signal generation in various application scenarios of the EPC1000 family of endless polarization control modules is described.

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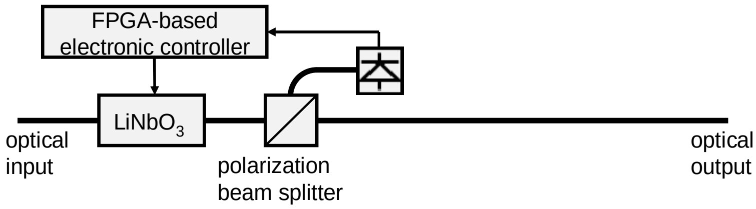
Optical power of cross-polarized signal



EPC1000-??-?-?-**1**-?-??-**O**

Fig. 1: Simplified block diagram of EPC1000 endless polarization controller with optical power measurement in cross polarization

The simplest way of determining polarization mismatch errors is it to measure the optical power behind a polarization beam splitter or polarizer. Let $\mathbf{E}_S$ be the normalized optical field vector of the optical wave behind the $LiNbO_3$ polarization transformer, before an ideal polarization beam splitter or polarizer with normalized transmitted eigenmode $\mathbf{E}_{pol,1}$. The output field behind the polarization beam splitter or polarizer is

$$\mathbf{E}_{out} = \mathbf{E}_{pol,1}\mathbf{E}^{+}_{pol,1}\mathbf{E}_S = \mathbf{J}_{pol}\mathbf{E}_S \,. \tag{1}$$

Here $\mathbf{J}_{pol} = \mathbf{E}_{pol,1}\mathbf{E}^{+}_{pol,1}$ is the Jones matrix of the polarizer. The + sign means Hermitian conjugate. The output signal has the Jones vector $\mathbf{E}_{pol,1}$, multiplied by the scalar quantity $\mathbf{E}^{+}_{pol,1}\mathbf{E}_S$. The relative intensity RI or normalized output power equals

$$RI = \left|\mathbf{E}^{+}_{pol,1}\mathbf{E}_S\right|^2 . \tag{2}$$

The relative intensity error RIE, i.e. the normalized power of the cross-polarized output signal, is the complement of the RI,

$$RIE = 1 - RI = \left|\mathbf{E}^{+}_{pol,2}\mathbf{E}_S\right|^2 , \tag{3}$$

where $\mathbf{E}_{pol,2}$ is the second polarizer eigenmode, orthogonal to $\mathbf{E}_{pol,1}$. Orthogonality means it holds

$$\mathbf{E}^{+}_{pol,2}\mathbf{E}_{pol,1} = 0 \,. \tag{4}$$

Using normalized Stokes vectors ($\mathbf{S}$ instead of $\mathbf{E}$, with unchanged indices), we can write

$$RI = (1/2)\left(1 + \mathbf{S}^{T}_{pol,1}\mathbf{S}_S\right) = (1/2)(1+\cos\delta) = \cos^2(\delta/2) = (1/2)\left(1 - \mathbf{S}^{T}_{pol,2}\mathbf{S}_S\right), \tag{5}$$

$$RIE = (1/2)\left(1 - \mathbf{S}^{T}_{pol,1}\mathbf{S}_S\right) = (1/2)(1-\cos\delta) = \sin^2(\delta/2) = (1/2)\left(1 + \mathbf{S}^{T}_{pol,2}\mathbf{S}_S\right), \tag{6}$$

where T means the transpose and δ, the polarization error, is the angle between $\mathbf{S}_S$ and $\mathbf{S}_{pol,1}$ on the Poincaré sphere. RI measurements are directly influenced by intensity fluctuations. It is therefore better to measure the RIE. This is sketched in Fig. 1. From the RIE we can calculate the polarization error

$$\delta = 2\arcsin\sqrt{RIE} \approx 2\sqrt{RIE} \,. \tag{7}$$

The approximation holds for small δ.
A standard, highly accurate characterization procedure of EPC1000 endless polarization controllers is it to record RIE over time and to display the complementary distribution function $1 - F(RIE)$ of the relative intensity error.

Electrical power in coherent receiver

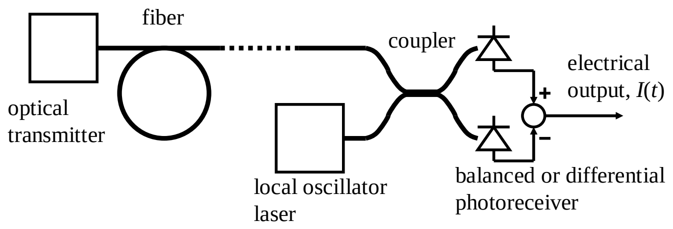


Fig. 2: Coherent optical transmission setup

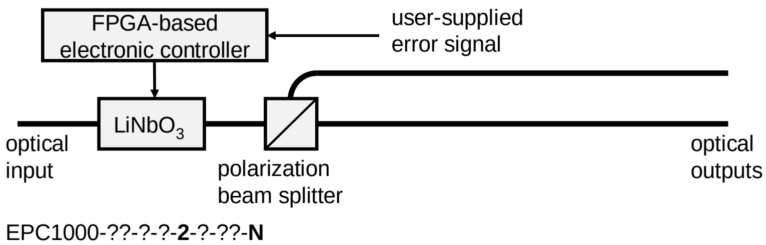


Fig. 3: Simplified block diagram of EPC1000 endless polarization controller, suitable for electrical power measurement in coherent receiver

A very similar scenario occurs in coherent receivers (Fig. 2). With signal and local oscillator fields

$$\mathbf{E}_S = \mathbf{E}_{S,0} e^{j\omega_S t} \qquad \mathbf{E}_{LO} = j\mathbf{E}_{LO,0} e^{j\omega_{LO} t} \tag{8}$$

and a coupler transfer matrix $\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix}$ the photocurrent difference is obtained as

$$\begin{aligned} I &= R(P_1 - P_2) = R\,\mathrm{Re}\left(j\mathbf{E}_{LO}^+\mathbf{E}_S\right) = R\,\mathrm{Re}\left(\mathbf{E}_{LO,0}^+\mathbf{E}_{S,0} e^{j\omega_{IF} t}\right) \\ &= 2R\sqrt{P_S P_{LO}}\,\frac{\left|\mathbf{E}_{LO,0}^+\mathbf{E}_{S,0}\right|}{\left|\mathbf{E}_{S,0}\right|\left|\mathbf{E}_{LO,0}\right|}\cos\left(\omega_{IF} t + \varphi_{IF}\right) \\ \omega_{IF} &= \omega_S - \omega_{LO} \qquad \varphi_{IF} = \arg\left(\mathbf{E}_{LO,0}^+\mathbf{E}_{S,0}\right) \\ P_S &= \frac{1}{2}\left|\mathbf{E}_S\right|^2 \qquad P_{LO} = \frac{1}{2}\left|\mathbf{E}_{LO}\right|^2 \end{aligned} \tag{9}$$

Here ω_{IF} is the (angular) intermediate frequency (IF) and φ_{IF} a phase angle. The electrical AC signal power in the coherent receiver is proportional to the relative intensity

$$RI = \frac{\left|\mathbf{E}_{LO,0}^+\mathbf{E}_{S,0}\right|^2}{\left|\mathbf{E}_{S,0}\right|^2\left|\mathbf{E}_{LO,0}\right|^2} = (1/2)\left(1 + \mathbf{S}_{LO}^T\mathbf{S}_S\right) = (1/2)(1+\cos\delta) = \cos^2(\delta/2) \tag{10}$$

where δ is the angle between signal polarization $\mathbf{S}_S$ and local oscillator polarization $\mathbf{S}_{LO}$ on the Poincaré sphere. Note that the field vectors $\mathbf{E}$ are not normalized here whereas the Stokes vectors $\mathbf{S}$ are normalized. We see that the electrical power in a coherent receiver behaves like the optical power behind a polarizer. As a consequence, the error signal in the configuration of Fig. 3 can be the electrical power measured in a coherent receiver of Fig. 2.

Interference detection of polarization-multiplexed DQPSK signals

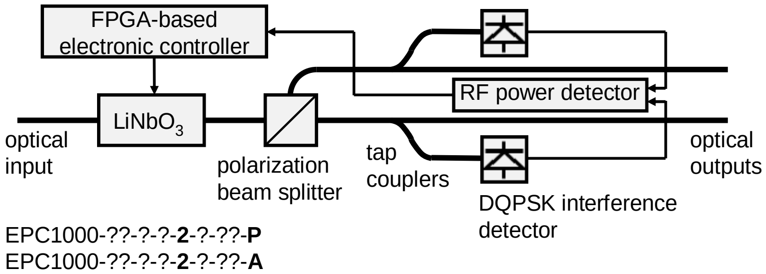


Fig. 4: Simplified block diagram of EPC1000 endless polarization controller with interference detection of polarization-multiplexed DQPSK signals

The foregoing possibilities are applicable for single-polarization signals. In contrast, the present scenario is for polarization-multiplexed (= dual-polarization) DQPSK signals which form an unpolarized sum signal

$$\mathbf{E}_S = \mathbf{E}_{S,1} + \mathbf{E}_{S,2} = c_1\mathbf{E}_{S,1,0} + c_2\mathbf{E}_{S,2,0} \,. \qquad (11)$$

All the same the polarization channel signals $\mathbf{E}_{S,1} = c_1\mathbf{E}_{S,1,0}$, $\mathbf{E}_{S,2} = c_2\mathbf{E}_{S,2,0}$ can be separated. The polarization channels should be orthogonal to each other, $\mathbf{E}_{S,2}^{+}\mathbf{E}_{S,1} = 0$. $\mathbf{E}_{S,1,0}$, $\mathbf{E}_{S,2,0}$ are unmodulated optical carriers, usually from the same optical source. The modulated polarization channel signals have no carriers because the complex modulation symbols $c_1 = e^{j\varphi_1}(\pm 1 \pm j)/\sqrt{2}$, $c_2 = e^{j\varphi_2}(\pm 1 \pm j)/\sqrt{2}$ have zero means $\langle c_1 \rangle = 0$, $\langle c_2 \rangle = 0$. They also are uncorrelated, $\langle c_2^{*} c_1 \rangle = 0$. The brackets mean expectation value, the star denotes the complex conjugate, and φ_1, φ_2 are individual phases of the polarization channels.

Behind the polarization beam splitter or polarizer the optical signal is fully polarized with an amplitude proportional to $\mathbf{E}_{pol,1}^{+}\mathbf{E}_S$. Its power equals

$$P_1 = \frac{1}{2}\left|\mathbf{E}_{pol,1}^{+}\mathbf{E}_S\right|^2 = \frac{1}{2}\left(\left|\mathbf{E}_{S,1}\right|^2 + 2\,\mathrm{Re}\left(\left(\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,1}\right)\left(\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,2}\right)^{*}\right) + \left|\mathbf{E}_{S,2}\right|^2\right). \qquad (12)$$

For simplicity we again assume orthonormal $\mathbf{E}_{pol,1}$, $\mathbf{E}_{pol,2}$. Terms $\frac{1}{2}\left|\mathbf{E}_{S,1}\right|^2 = P_{S,1}$ and $\frac{1}{2}\left|\mathbf{E}_{S,2}\right|^2 = P_{S,2}$ are constant channel powers, usually identical $P_{S,1} = P_{S,2} = P_{S,12}$. We can substitute $\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,i} = 2\sqrt{P_{S,i}}\,e^{j\arg\left(\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,i}\right)}\cos(\delta_i/2)$ ($i = 1,2$). The angles δ_i on the Poincaré sphere between the transmitted polarizer eigenstate and the polarization channel signals obey $\delta_1 + \delta_2 = \pi$. The AC part of the power is now

$$P_{1,AC} = 2\sqrt{P_{S,1}P_{S,2}}\,\cos(\delta_1/2)\cos(\delta_2/2)\cos(\psi) = P_{S,12}\sin(\delta_1)\cos(\psi) \qquad (13)$$

with $\psi = \arg\left(\left(\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,1}\right)\left(\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,2}\right)^{*}\right)$. At the other polarization beam splitter output the signal amplitude is proportional to $\mathbf{E}_{pol,2}^{+}\mathbf{E}_S$, and the AC part of the respective power equals

$$P_{2,AC} = -P_{1,AC} \,. \qquad (14)$$

This is evident because the sum $P_1 + P_2$ equals the constant power $P_S = \frac{1}{2}\left|\mathbf{E}_S\right|^2$. It is possible to detect P_1, P_2 or their difference $P_1 - P_2$ in two photoreceivers. The AC part of the measured photocurrent or photocurrent difference is always proportional to $\sin\delta_1$. The expectation value of the electrical power is proportional to $\left\langle (\sin(\delta_1)\cos(\psi))^2 \right\rangle = (1/2)\sin^2(\delta_1)$. This is due to the uncorrelated DQPSK modulation symbols. We can therefore define the relative intensity error as

$$RIE = \sin^2(\delta_1). \qquad (15)$$

This is similar to (6) but a certain level of RIE requires only half as large a polarization mismatch angle ($\delta_1 = \delta/2$)!

While we have tacitly assumed NRZ signal format the same holds also for time-aligned RZ signals. The only difference is that there is a strong clock signal component in the photocurrents. It is usually outside the bandwidth of the photoreceivers used for this interference detection.

For time-interleaved RZ signal the interference becomes much weaker. Fortunately, the receiver is also much less subject to interference.

Relation between relative intensity error and feedback signal

Ideally there should be a linear relation between the above-defined relative intensity error RIE and the feedback signal of EPC1000 endless polarization controllers. This is fairly much the case.

The relation is particularly linear for error signal generation type O, i.e., optical power measurement of the cross-polarized signal in configuration EPC1000-??-?-?-1-?-?-O, where a PIN diode measures optical power. The feedback signal minimum (= zero RIE) varies minimally with temperature and due to finite polarizer extinction. The feedback signal maximum depends on optical input power. EPC1000 endless polarization controller performance is always tested with error signal generation type O before possibly changing to another type.

The relation may be assumed to be less linear for error signal generation types P and A, i.e., interference detection of polarization-multiplexed DQPSK signals in configurations EPC1000-??-?-?-2-?-?-P and EPC1000-??-?-?-2-?-?-A. This is due to optical noise and due to the fact that the RF power detector presumably exhibits a not exactly quadratic behavior. Experimentally, the possible deviations from a linear mapping between RIE and feedback signal are unproblematic, as extended dual-polarization DQPSK transmission tests have shown. The feedback signal minimum (= zero RIE) may lie at about 30% of the full range. Like the feedback signal maximum it depends on the applied optical power, symbol rate and signal format (RZ or NRZ).

Literature

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2. Noé, R. et al., Crosstalk detection schemes for polarization division multiplex transmission. IEEE J. Lightwave Techn. 19(2001)10, pp. 1469-1475.

3. B. Koch et al., Record 59-krad/s Polarization Tracking in 112-Gb/s 640-km PDM-RZ-DQPSK Transmission, IEEE Photonics Technology Letters, Vol. 22, No. 19, pp. 1407-1409, 1. Oct. 2010

4. Publications listed in http://www.novoptel.de/Control/Control_publications_en.php