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
1.0.2	07.11.2012	QAM, DPSK, duobinary and ASK added, minor corrections	R. Noé
1.0.3	18.01.2014	ASK and Bessel line detection described in detail	R. Noé
1.0.4	30.10.2016	PS-QPSK added	R. Noé

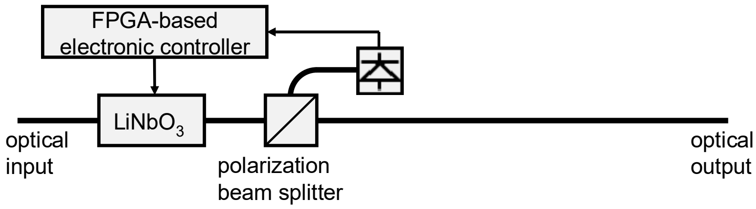
Contents

Summary

Error signal generation is described in many application scenarios of the EPC1000 family of endless polarization controllers: direct and coherent detection, single and dual polarization signals, modulation formats PDM-DQPSK, PDM-QAM, PDM-DPSK, PDM-duobinary, PDM-ASK, PS-QPSK.

Novoptel GmbH
EIM-E
Warburger Str. 100
33098 Paderborn
Germany
www.novoptel.com

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

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

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

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

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

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

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

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

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

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

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

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

$$\delta = 2\arcsin\sqrt{RIE} \approx 2\sqrt{RIE} . \quad (7)$$

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

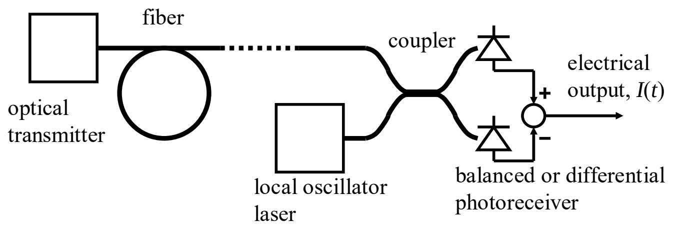
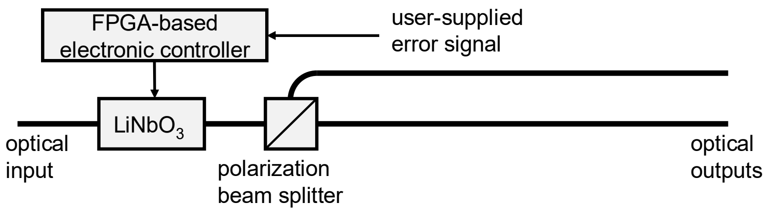


Fig. 2: Coherent optical transmission setup



EPC1000-??-?-?-**2**-?-??-**N**

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

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

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 and QAM signals

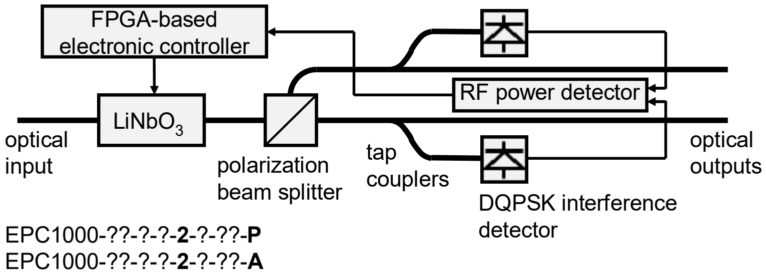


Fig. 4: Simplified block diagram of EPC1000 endless polarization controller with interference detection of polarization-multiplexed DQPSK signals

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

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

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

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

For simplicity we again assume orthonormal $\mathbf{E}_{pol,1}$, $\mathbf{E}_{pol,2}$. Terms $\frac{1}{2}\left|\mathbf{E}_{S,i}\right|^2 = P_{S,i}$ ($i = 1,2$) are constant, identical channel powers $P_{S,1} = P_{S,2} = P_S/2$, each equal to half the total signal power P_S. The expectation value of P_1 is $\langle P_1 \rangle = \frac{1}{2}\left(\left|\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,1}\right|^2 + \left|\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,2}\right|^2\right) = P_S/2$. We substitute $\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,i} = \sqrt{2P_{S,i}}\, e^{j\arg\left(\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,i}\right)} \cos(\delta_i/2)$. 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

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

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

$$P_{2,AC} = -P_{1,AC} \,. \tag{14}$$

This is evident because the total power is constant, $P_1 + P_2 = P_{S,1} + P_{S,2} = P_S = \frac{1}{2}|\mathbf{E}_S|^2$. 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. RZ signals hence yield a better interference extinction ratio than NRZ signals.

QAM signals with independent zero-mean modulation in both quadratures, such as 16-QAM signals, can also be polarization-demultiplexed the same way. The difference to DQPSK signals is that there are more amplitude levels. The interference extinction ratio is therefore decreased compared to DQPSK signals.

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

Interference detection of polarization-multiplexed DPSK and duobinary signals

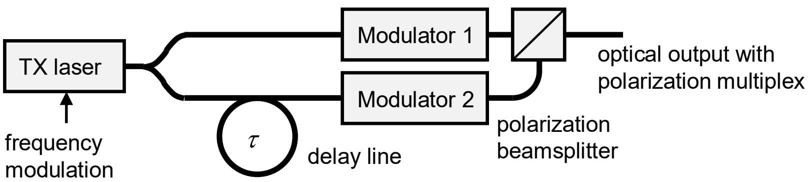


Fig. 5: Randomization of polarization channel interference by frequency modulation of the transmitter laser combined with a differential delay τ between the two polarization branches in the transmitter

DPSK and **duobinary** signals are modulated in only one quadrature, like standard ASK signals. So the polarization channels interfere only when the phase difference ψ between the polarization channels is sufficiently close to 0 or π. Interference must therefore be adequately randomized. The electrical interference amplitude is proportional to $|\cos\psi|$, the interference power proportional to $|\cos\psi|^2 = (1/2)(1+\cos(2\psi))$. A phase jump by π does not change the term $\cos(2\psi)$. Hence we neglect from now on the DPSK or duobinary modulation and look upon ψ as if it contained only much slower phase variations due to effects in optical waveguides.

Although the actual function is more complicated one may define something that could be called an equivalent averaging time in the EPC1000 endless polarization controller. Currently it is on the order of T = 80 ns * 2^{ATE} where ATE is the averaging time exponent (SPI register 020h). Since the mean value $\overline{\psi}$ of the interference phase ψ is not controlled one must obviously modulate $\psi(t)$ so that $\overline{\cos(2\psi(t))} = 0$ holds, where the overbar means averaging over T.

A straightforward way to achieve this is a frequency shift by 1/T of one polarization channel signal at the transmitter.

In order to avoid a lossy and expensive frequency shifter one may instead simply utilize the combination of a differential delay τ between the two polarization channels and a transmitter (TX) laser frequency modulation, see Fig. 5. Laser FM is often permissible and possible, in particular for SBS suppression. Let the modulation frequency be f = 1/T and the peak-to-peak frequency deviation ΔF_{pp}. This results in

$$F(t)=\frac{\Delta F_{pp}}{2}\sin(2\pi f(t+\tau/2))$$ momentary frequency excursion, (16)

$$\Psi(t)=-\frac{\Delta F_{pp}}{2f}\cos(2\pi f(t+\tau/2))$$ momentary angle excursion, (17)

$$\psi(t)=\Psi(t)-\Psi(t-\tau)+\overline{\psi}=\eta\sin(2\pi ft)+\overline{\psi}$$ phase difference, (18)

$$\eta=\pi\,\Delta F_{pp}\,\tau\,\mathrm{sinc}(\pi f\tau)$$ angular modulation index of ψ. (19)

Note that the polarization multiplexer not only introduces the time delay τ but, together with transmission fiber and polarization tracker, also a mean phase delay $\overline{\psi}$. Usually, $\overline{\psi}$ can not be predicted and may vary over time. While the phase difference ψ has the angular modulation index η we must work with the relevant doubled phase difference 2ψ and associated angular modulation index 2η ! We obtain

$$\overline{\cos(2\psi(t))}=\overline{\cos\left(2\eta\sin(2\pi ft)+2\overline{\psi}\right)}=J_0(2\eta)\cos\left(2\overline{\psi}\right). \qquad (20)$$

To fulfill $\overline{\cos(2\psi(t))}=0$ we need to set $J_0(2\eta)=0$. For $2\eta\approx 2.405$ the lowest possible frequency deviation results,

$$\Delta F_{pp}=\frac{1.202}{\pi\,\tau\,\mathrm{sinc}(\pi f\tau)}. \qquad (21)$$

To give an example: We work with EPC1000 at ATE = 1, T = 160 ns and with a delay time τ = 10 ns (~2 m of fiber). The calculated TX modulation frequency is f = 1/T = 6.25 MHz. Initial tuning of f for optimum control performance is highly recommended, especially at low ATE values. At that high frequency f there is almost no thermally, only carrier-induced laser FM. The modulation steepness may for instance be 100 MHz/mA. The peak-to-peak frequency deviation is calculated as ΔF_{pp} = 39 MHz. Only a small laser modulation current of 0.39 mApp is needed to achieve it. The parasitic intensity modulation is negligible, and the frequency modulation itself is negligible for interferometric DPSK demodulation.
The TX laser frequency modulation need not be sinusoidal. Other shapes likewise allow suppressing the mean of $\cos(2\psi(t))$, for instance a sawtooth.

The described differential phase modulation with $J_0(2\eta)=0$ need not necessarily be brought about by the combination of TX laser frequency modulation and differential time delay τ. Instead, it may be directly applied by a phase modulator which is placed before or behind one of the data modulators in Fig. 5.

Interference detection of polarization-multiplexed ASK signals

Like DPSK and duobinary signals, **ASK** signals of **NRZ**, **RZ** and **CSRZ** type are modulated in only one quadrature. But the phase relation between the two polarization channels does not depend on modulation. The interference phase must again be randomized.

(i) A first interference detection approach is identical to the above-described for DPSK and duobinary, including sinusoidal differential phase modulation with $2\eta\approx 2.405$. Only capacitive coupling is required to remove the DC component from the photodetected polarization channel signals and to assure that the electrical power is an RF power. The EPC1000 supports this approach with error signal generation type P (= PIN photoreceiver(s) and RF power detector).

(ii) A second interference detection approach is supported by the EPC1000 with error signal generation type O (= optical) combined with a detection of Bessel lines (consult Novoptel). This is explained in the following:

The broadband RF power measurement is an asynchronous detection with heavy subsequent lowpass filtering. The baseband width is more than 3 orders lower than the pre-detection (RF) bandwidth. Sensitivity can be improved if the (quasi-)DC components of the ASK signal interference are evaluated with a low pre-detection bandwidth. The procedure was first reported in [2].

With respect to (11), (12) we may set $c_{1,2} = e^{j\varphi_{1,2}} \begin{cases} \sqrt{2} \\ 0 \end{cases}$, which leads to $\langle c_{1,2} \rangle = e^{j\varphi_{1,2}} / \sqrt{2}$, $\langle c_2^* c_1 \rangle = e^{j(\varphi_1 - \varphi_2)} / 2$. From (12), (13) the mean detected power is

$$\begin{aligned} \langle P_1 \rangle &= P_{S,1} \cos^2(\delta_1/2) + 2\sqrt{P_{S,1} P_{S,2}} \cos\psi \cos(\delta_1/2)\cos(\delta_2/2) \\ &+ P_{S,2} \cos^2(\delta_2/2) = (P_S/2)(1 + \sin(\delta_1)\cos(\psi)) \end{aligned} \quad (22)$$

with $\psi = \varphi_1 - \varphi_2 + \xi$ where ξ is polarization-dependent. Other than in (13), ψ does not vary with modulation. Furthermore it holds

$$\langle P_1 \rangle - \langle P_2 \rangle = P_S \sin(\delta_1)\cos(\psi) \equiv S_1 . \quad (23)$$

This is the non-normalized horizontal/vertical Stokes parameter .
To estimate the interference we need a differential phase modulation between the polarization channels, for example of sinusoidal type and as sketched in Fig. 5. We expand the interference term

$$\begin{aligned} &\cos(\psi(t)) = \cos(\eta \sin(2\pi f t) + \overline{\psi}) \\ &= \cos(\eta \sin(2\pi f t))\cos(\overline{\psi}) - \sin(\eta \sin(2\pi f t))\sin(\overline{\psi}). \\ &= \begin{pmatrix} \left(J_0(\eta) + 2\sum_{k=1}^{\infty} J_{2k}(\eta)\cos(2k2\pi f t) \right)\cos\overline{\psi} \\ -\left(2\sum_{k=1}^{\infty} J_{2k-1}(\eta)\sin((2k-1)2\pi f t) \right)\sin\overline{\psi} \end{pmatrix} \end{aligned} \quad (24)$$

The even and odd Bessel lines appear and vanish as a function of the unpredictable mean phase difference $\overline{\psi}$. So, at least one even and one odd Bessel line must be detected, and their electrical powers $P_{e,0} \sim J_0^2(\eta)\cos^2\overline{\psi}$, $P_{e,2k} \sim 2J_{2k}^2(\eta)\cos^2\overline{\psi}$ and $P_{e,2k-1} \sim 2J_{2k-1}^2(\eta)\sin^2\overline{\psi}$, respectively, must be added with suitable weighting.
Assume that the powers of both demultiplexed polarization channels are measured and subtracted to form (23) S_1. Even though, the DC term $P_{e,0}$ is not usable in practice because the channel powers can not be balanced reliably to such a degree as is needed for measuring small interferences.
If a small laser pump current modulation, say 1%, is applied like in Fig. 5 then the 1st harmonic is likewise corrupted by the resulting parasitic amplitude modulation. However, even a non-perfect balancing of the polarization channel powers suffices to suppress it to a negligible value, <0.1% or so. So we consider using 1st harmonic $P_{e,1}$ and 2nd harmonic $P_{e,2}$. Going from $\overline{\psi} = 0$ to $\overline{\psi} = \pi/2$ should not change the interference signal, even if η deviates in the course of time. Hence, a good choice is the point $\frac{1}{J_2^2(\eta)} \frac{dJ_2^2(\eta)}{d\eta} = -\frac{1}{J_1^2(\eta)} \frac{dJ_1^2(\eta)}{d\eta}$ where relative changes of η, with opposite effects on $J_1(\eta)$ and $J_2(\eta)$, have the least relative influence on the error signal for all $\overline{\psi}$. This requires $\eta \approx 2.37$. Total interference can be calculated by $P_{tot} = \frac{J_2^2(\eta)}{J_1^2(\eta)} P_{e,1} + P_{e,2} = 0.66 \cdot P_{e,1} + P_{e,2}$. The relative sensitivity on η for all $\overline{\psi}$ is bounded by $\frac{\eta}{P_{tot}} \frac{dP_{tot}}{d\eta} = \pm 1.85$.

If this sensitivity is considered too high one can work with $\eta \approx 3.05$ at the maximum of $J_2^2(\eta)$ where it holds $dP_{e,2}/d\eta = 0$ and $P_{e,1} = P_{e,3}$ (due to $2\,dJ_n(\eta)/d\eta = J_{n-1}(\eta) - J_{n+1}(\eta)$). We set

$P_{tot} = a_1 P_{e,1} + P_{e,2} + a_3 P_{e,3}$ with $a_3 = a_1 b$. We choose $b = -\frac{d\eta}{dJ_3^2(\eta)} \frac{dJ_1^2(\eta)}{d\eta}$ to achieve $d\left(a_1 P_{e,1} + a_3 P_{e,3}\right)/d\eta = 0$ and $a_1 = \frac{J_2^2(\eta)}{J_1^2(\eta) + bJ_3^2(\eta)}$ to make P_{tot} independent of $\overline{\psi}$. Consequently it holds $dP_{tot}/d\eta = 0$ for all $\overline{\psi}$. The calculated weighting is $P_{tot} = 0.73 \cdot P_{e,1} + P_{e,2} + 1.6 \cdot P_{e,3}$. Choosing slighly lower a_1 and associated $a_3 = a_1 b$ can be beneficial if η varies, due to opposite curvatures $dJ_2^2(\eta)/d\eta < 0$, $d\left(a_1 J_1^2(\eta) + a_3 J_3^2(\eta)\right)/d\eta > 0$.

If only one channel power (22) is measured then the unknown and fluctuating mean power $P_S/2$ must but practically cannot be subtracted and even the 1st harmonic is too much disturbed by parasitic amplitude modulation. So the 2nd harmonic is the lowest usable. Analog to the above we obtain either $P_{tot} = 0.76 \cdot P_{e,2} + P_{e,3}$ at $\eta \approx 3.55$, with relative sensitivity bounded by ±2.17, or $P_{tot} = 0.64 \cdot P_{e,2} + P_{e,3} + 1.32 \cdot P_{e,4}$ at $\eta \approx 4.2$.

Fig. 6 illustrates the various spectral powers and their weighting for the four discussed operation modes. Usage of low harmonics with associated small η maximizes the tolerance of relative changes of η.

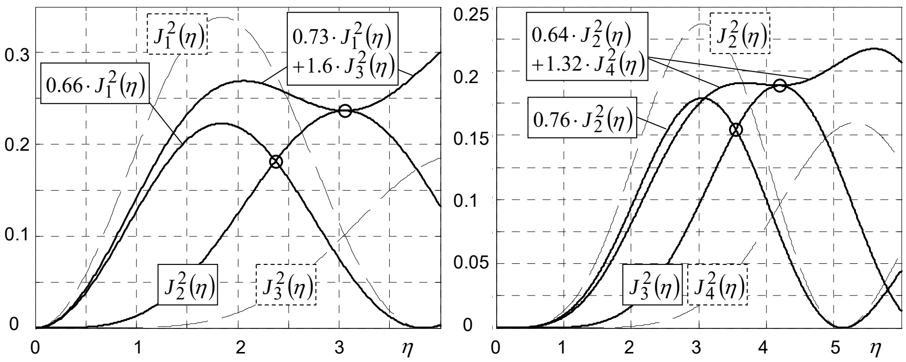


Fig. 6. Interference powers as a function of differential phase modulation index η. Suggested operation points are marked by circles. Left: Usage of 1st and 2nd harmonic at $\eta \approx 2.37$, or 1st 2nd and 3rd harmonic at $\eta \approx 3.05$. Right: Usage of 2nd and 3rd harmonic at $\eta \approx 3.55$, or 2nd, 3rd and 4th harmonic at $\eta \approx 4.2$.

The optional Bessel line detection of the EPC1000 supports all these four operation modes. Generally speaking, total interference power is calculated according to $P_{tot} = \sum_i a_i P_{e,i}$. The weights a_i can be set for either $i = 1,2,3$ or $i = 2,3,4$. If only two spectral lines are to be detected then one of the weights is set to zero.

We define the individual normalized averaged powers $P_{ave,i}$ to be the respective averaged $P_{e,i}$ divided by the averaged sum $\sum_i P_{e,i}$ of the three powers. The EPC1000 makes the $P_{ave,i}$ available via SPI, USB and GUI. It also outputs a PWM signal (CMOS 3.3V) with the mean voltage $\frac{P_{ave,1}}{P_{ave,1} + P_{ave,3}} \cdot 3.3\,\mathrm{V}$ or $\frac{P_{ave,2}}{P_{ave,2} + P_{ave,4}} \cdot 3.3\,\mathrm{V}$, depending on chosen spectral lines. There is one logic low and one logic high interval per PWM period. The period is $(P_{ave,1} + P_{ave,3}) \cdot 2^{16} \cdot 20\,\mathrm{ns}$ or $(P_{ave,2} + P_{ave,4}) \cdot 2^{16} \cdot 20\,\mathrm{ns}$ long, i.e. not longer than ≈1.3 ms. The PWM signal represents the average power distribution between the two outer harmonics and can serve for an automatic control of the modulation index η.

Intensity modulation detection of polarization-switched QPSK signals

PS-QPSK transmits two orthogonal polarization states alternately. Hence there is no interference. The intensity modulations of the two polarization states are complementary, $P_{S,1} + P_{S,2} = P_S = \text{const.}$, $P_{S,1} \in \{0, P_S\}$. For the demultiplexed channel powers P_1, P_2 and their difference $P_1 - P_2$ one may write

$$\begin{aligned}
P_1 &= \frac{1}{2}\left|\mathbf{E}_{pol,1}^{+}\mathbf{E}_S\right|^2 = \frac{1}{2}\left(\left|\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,1}\right|^2 + \left|\mathbf{E}_{pol,1}^{+}\mathbf{E}_{S,2}\right|^2\right) \\
&= P_{S,1}\cos^2(\delta_1/2) + P_{S,2}\sin^2(\delta_1/2) = P_{S,1}\cos^2(\delta_1/2) + (P_S - P_{S,1})\sin^2(\delta_1/2) \\
P_2 &= P_{S,2}\cos^2(\delta_1/2) + P_{S,1}\sin^2(\delta_1/2) = (P_S - P_{S,1})\cos^2(\delta_1/2) + P_{S,1}\sin^2(\delta_1/2) \\
P_1 - P_2 &= P_{S,1}\cos^2(\delta_1/2) + (P_S - P_{S,1})\sin^2(\delta_1/2) - (P_S - P_{S,1})\cos^2(\delta_1/2) - P_{S,1}\sin^2(\delta_1/2) \\
&= (2P_{S,1} - P_S)\left(\cos^2(\delta_1/2) - \sin^2(\delta_1/2)\right) = \pm P_S\cos\delta_1
\end{aligned} \quad . (25)$$

If the EPC1000 demultiplexes the two polarization states correctly, each channel intensity modulation is maximum. So it suffices to maximize the AC component of $P_1 - P_2$. Thereby $\delta_1 \in \{0, \pi\}$ is achieved (normal or swapped channel demultiplex). This works like the interference detection for polarization-multiplexed (D)QPSK, but the detected RF component must be maximized rather than minimized. That can be set in the EPC1000.

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

1. R. Noé, Essentials of Modern Optical Fiber Communication, Springer Berlin Heidelberg, March 2010, ISBN 978-3-642-04871-5 (Print) 978-3-642-04872-2 (Online), DOI 10.1007/978-3-642-04872-2

2. Noé, R. et al., Crosstalk detection schemes for polarization division multiplex transmission. IEEE J. Lightwave Techn. 19(2001)10, pp. 1469-1475, http://www.novoptel.de/Control/Literature/569105A0d01_annot.pdf

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, http://www.novoptel.de/Control/Literature/05523896_annot.pdf

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