# Crosstalk Detection Schemes for Polarization Division Multiplex Transmission

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***Abstract*—Polarization division multiplex (PolDM) is a bandwidth-efficient and sensitive modulation format suitable for upgrading bandwidth-limited trunk lines. We show how control signals for polarization demultiplex can be obtained efficiently. For interleaved return-to-zero (RZ) signals, incoherent crosstalk has to be detected and minimized. In other cases, in particular for nonreturn-to-zero (NRZ) signals, coherent crosstalk senses penalties much better and should be detected instead. NRZ transmission experiments with either scheme are presented at a data rate of 2 $\times$ 10 Gb/s, with endless polarization tracking. Polarization mode dispersion (PMD) tolerance is also assessed.**

***Index Terms*—Interference, optical crosstalk, optical fiber communication, optical polarization.**

## I. INTRODUCTION

RAPID increase in wavelength-division multiplexing (WDM) systems capacity is ultimately limited by available fiber bandwidth or amplification bandwidth. Present trunk lines contain C-band erbium-doped fiber amplifiers (EDFAs) and would require costly upgrading to L-band for a capacity increase. It is, therefore, desirable to improve the bandwidth efficiency (bits per second per hertz). Polarization division multiplex (PolDM) means that there are two orthogonally polarized signals to double the data throughput. Bandwidth efficiency is doubled if both polarization channels have equal carrier frequencies, to which case we restrict ourselves. Polarization control and a polarization beamsplitter or polarizers are needed at the receiver side for polarization demultiplexing [1]. For nonreturn-to-zero (NRZ) and maybe also return-to-zero (RZ) signal formats, the polarization channels are normally clocked bit-synchronously, and nonperfect polarization demultiplexing results in coherent crosstalk. However, a variant with bit-interleaved alternate-polarization RZ pulses is possible that does not exhibit coherent crosstalk [1]. If bandwidth is not limited, the bit-interleaved alternate-polarization RZ scheme needs just a single receiver without polarization control, but this is outside the scope of this paper. PolDM [1]–[5] doubles bandwidth efficiency and is also attractive because this advantage comes together with high receiver sensitivity and acceptable polarization mode dispersion (PMD) tolerance [6]. It performs better than multilevel intensity modulation or polarization shift keying (PolSK) [7], [8]. Angle-modulated multilevel modulation schemes tolerate only little phase noise (QPSK) or are not bandwidth-efficient (4-FSK).

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The only significant drawback of PolDM is the need for polarization control at the receiver side. However, if PMD compensation is required anyway, the extra effort is minimum because a small output section of an $x$-cut, $y$-prop $LiNbO_3$ PMD equalizer [9] can be reserved for polarization control. In Section II, we concentrate on the generation of error signals for polarization control. Previously, monitoring of the received clock signal has been proposed [1], but this is restricted to bit-interleaved alternate-polarization RZ signals and requires signal processing at this high frequency. In [2], pilot tones were employed. This scheme is attractive because of its simplicity, but slightly reduces the eye opening. More important, the relative small amplitudes of pilot tones give a low control signal signal-to-noise ratio (SNR) or require long averaging times. In [3], different channel clock frequencies were employed to generate an error signal, but this is not allowed in practice. We propose switching or correlation techniques, which allow detection of incoherent interchannel crosstalk. This is most useful in systems with bit-interleaved alternate polarization RZ pulses. In other cases, namely, NRZ and bit-synchronous RZ, coherent interchannel crosstalk dominates, but an interference-detection scheme can exploit it for significantly improved polarization control. Channel identification is also discussed (Section III). Correlation and interference detection techniques are implemented in 2 $\times$ 10 Gb/s PolDM NRZ transmission experiments (Section IV). Endless polarization tracking is demonstrated and PMD [10] tolerance is assessed.

## II. GENERATION OF CONTROL SIGNALS

### A. Signals in the Presence of Polarization-Dependent Loss (PDL)

PDL [11] influences polarization orthogonality and is, therefore, a major potential crosstalk source for PolDM. Let us investigate the detection of one PolDM channel in the presence of PDL. Its Jones vector can be written as

$$\underline{\mathbf{E}}_1 = b_1 e^{(j\varphi+\zeta)} \begin{bmatrix} e^{j\delta}\cos(\gamma/2) \\ \sin(\gamma/2) \end{bmatrix} \tag{1}$$

while the undesired channel has the Jones vector

$$\underline{\mathbf{E}}_2 = b_2 \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \tag{2}$$

The transmitted bits are $b_1, b_2 \in \{0, 1\}$. The effects of PDL are expressed by a variable $\zeta$, which indicates unequal channel amplitudes, and an azimuth angle $\gamma$ of the polarization ellipse, which can indicate a loss of polarization orthogonality. These

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are $\zeta = 0$ and $\gamma = 2n\pi$ with integer $n$, respectively, in the absence of PDL. Angle $\delta$ is a phase difference between the two components of $\underline{\mathbf{E}}_1$. There may be an additional phase modulation or offset $\varphi$ between the two channels. If a common phase is dropped for simplicity, other polarization transformations can be fully expressed by two more phase angles, which will be taken into account by polarization control at the receiver.

At the receiver side, there is an ideal polarizer, which lets the polarization state with normalized Jones vector

$$\underline{\mathbf{E}}_{\rm pol} = \begin{bmatrix} e^{j\sigma}\cos(\rho/2) \\ \sin(\rho/2) \end{bmatrix} \tag{3}$$

pass. Here, $\rho$ is the azimuth angle and $\sigma$ is the phase difference between the two components of $\underline{\mathbf{E}}_{\rm pol}$. The electric field behind the polarizer has the Jones vector $\underline{\mathbf{E}}_{\rm pol}$, multiplied by the amplitude

$$\underline{e} = \underline{\mathbf{E}}_{\rm pol}^{+}(\underline{\mathbf{E}}_1 + \underline{\mathbf{E}}_2) = b_1 e^{(j\varphi+\zeta)}\underline{D} + b_2\sin(\rho/2) \tag{4}$$

with an abbreviation

$$\underline{D} = e^{j(\delta-\sigma)}\cos(\rho/2)\cos(\gamma/2) + \sin(\rho/2)\sin(\gamma/2). \tag{5}$$

The resulting photocurrent is

$$I = |\underline{e}|^2 = b_1 A + b_2 B + 2b_1 b_2 C \tag{6}$$

where

$$A = e^{2\zeta}|\underline{D}|^2 \qquad B = \sin^2(\rho/2) \qquad C = \mathrm{Re}\,\underline{C}$$
$$\underline{C} = e^{(j\varphi+\zeta)}\underline{D}\sin(\rho/2). \tag{7}$$

The *desired signal* amplitude is $A$. *Incoherent crosstalk* is caused by $B \neq 0$. *Coherent crosstalk*, which depends on the interchannel phase difference $\varphi$, is indicated by $C \neq 0$. Perfect polarization matching for $\underline{\mathbf{E}}_1$ with $\underline{D} = \pm 1$ and maximized signal amplitude $A = e^{2\zeta}$ requires $\sigma = \delta + n\pi$, $\rho = (-1)^n\gamma$ with integer $n$. However, crosstalk from $\underline{\mathbf{E}}_2$ is more harmful than a finite signal loss [1]. Therefore, we desire $\rho = 2n\pi$, instead, which results in $B = C = 0$

$$I = b_1 e^{2\zeta}\cos^2(\gamma/2). \tag{8}$$

In the absence of PDL ($\gamma = \delta = \zeta = 0$), the general case results in

$$\underline{C} = (1/2)e^{j(\varphi-\sigma)}\sin\rho. \tag{9}$$

### B. Incoherent Crosstalk

Let us denote by $\langle\cdot\rangle$ the average with respect to statistically independent $b_1$, $b_2$. The number of averaged bits may be on the order of 10 000 or beyond. These information bits, as well as their complements $1-b_1$ and $1-b_2$, are available at the decision circuit outputs. A straightforward way to achieve $\rho = 0$ consists of minimizing a signal

$$\langle(1-b_1)I\rangle = B/4 = (1/4)\sin^2(\rho/2) \tag{10}$$

which is obtained by what may be called the *switching scheme*. Its implementation requires an analog switch driven by the recovered inverted data signal $1-b_1$, which should have NRZ format. Its input signal is the photocurrent $I$. No restrictions (i.e., NRZ, RZ, interleaved) apply for the unrecovered bits in (6). The switched signal is $(1-b_1)I$. Averaging of the switched signal results in a useful control signal (10). Switch input and output signals must be direct current (dc)-coupled, or the control signal would be spoiled.

More easily implemented in a laboratory environment is correlation in a four-quadrant multiplier, as later shown in Fig. 2, with at least one input being alternating current (ac)-coupled. $b_i$ and $b_i-1/2$ with $i = 1, 2$ are dc- and ac-coupled NRZ recovered data signals, respectively, and $I - \langle I\rangle$ is the ac-coupled photocurrent with NRZ or RZ signals. Correlation results can be written as

$$\begin{aligned} &\langle(b_1-1/2)(I-\langle I\rangle)\rangle \\ &\quad = \langle(b_1-1/2)I\rangle = \langle b_1(I-\langle I\rangle)\rangle = (A+C)/4 \\ &\langle(b_2-1/2)(I-\langle I\rangle)\rangle \\ &\quad = \langle(b_2-1/2)I\rangle = \langle b_2(I-\langle I\rangle)\rangle = (B+C)/4. \end{aligned} \tag{11}$$

The three equivalent correlation expressions in each equation show that at least one correlator input must be ac-coupled.

Term $C$ fluctuates strongly as a function of the interchannel phase difference $\varphi$. At this point, it is useful to guarantee by some means a time-variable $\varphi(t)$ with $\overline{\cos\varphi} = \overline{\sin\varphi} = 0$. The overbar signifies averaging with respect to $\varphi$. Averaging should take place over an integer number of periods. Some microseconds are usually sufficient. For simplicity, changes of $\varphi$ are assumed not to be correlated with the bit patterns. The equidistributed $\varphi$ results in $\overline{C} = 0$. Such differential phase modulation will be generated if two independent laser sources with (almost) identical frequencies are used for the two polarizations, or as explained in the next section.

Polarization control is possible if we minimize

$$\overline{\langle(b_2-1/2)(I-\langle I\rangle)\rangle} = B/4 = (1/4)\sin^2(\rho/2) \tag{12}$$

hereafter called the *cross-correlation scheme* because the photocurrent in receiver 1 is correlated with the digital output of receiver 2. Otherwise, we may choose to maximize

$$\overline{\langle(b_1-1/2)(I-\langle I\rangle)\rangle} = A/4 \tag{13}$$

in an *autocorrelation scheme*. Note that this is not a true autocorrelation, rather the cross correlation of the signals before and behind the decision circuit of receiver 1.

Without PDL, all schemes achieve perfect polarization matching $A = 1$, $B = C = 0$. With PDL, the autocorrelation scheme yields suboptimum results $A = e^{2\zeta}$, $B = \sin^2(\gamma/2)$, $C = e^{\zeta}\cos\varphi\sin(\gamma/2)$. The other schemes work fine also in the presence of PDL and yield $A = \cos^2(\gamma/2)$, $B = C = 0$. Both correlation schemes require $\overline{\cos\varphi} = \overline{\sin\varphi} = 0$ in order to work properly, which is not needed for the switching scheme.

Note that the described schemes can also be used if the decision takes place only after demultiplexing 1 : 2, as described in [12]. Of course, a ~3-dB control speed penalty is suffered, which can be alleviated by increased detection hardware effort. The switch in the switching scheme must be closed only when two neighbor bits are equal to zero. The correlation schemes

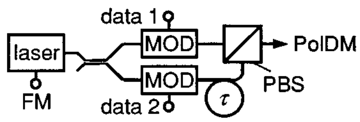



Fig. 1. Sinusoidal transmitter FM causes sinusoidal interchannel differential phase modulation.

can be implemented directly with a multiplier having a reduced bandwidth, with a demultiplexed decision bit at one and the detected photocurrent at the other input.

### C. Coherent Crosstalk

For simplicity, neglect PDL. In the limit of small $|\rho| \ll 1$ expressions $A = 1 - \rho^2/4, B = \rho^2/4, C = (\rho/2)\cos(\varphi - \sigma)$ are found. Coherent crosstalk $C$ manifests itself if $\cos(\varphi - \sigma) \neq 0$ holds. If, like in [3], unequal optical frequencies were chosen for the two channels, $\overline{C}$ would vanish even within one bit period, but the bandwidth advantage of PolDM would be diminished. Coherent crosstalk will, therefore, occur in almost all practical PolDM systems, with the exception of PolDM RZ systems in which the orthogonally polarized channel signals are interleaved in the time domain.

Even a fairly small $\rho \neq 0$ spoils the signal by coherent crosstalk, whereas incoherent crosstalk and signal loss are much smaller because they are proportional to $\rho^2$. However, the disadvantage of PolDMs being very sensitive to coherent crosstalk can be substantially reduced or even eliminated if coherent crosstalk is also used to generate a polarization control signal.

In Fig. 1, where we momentarily ignore frequency modulation (FM) and $\tau$, the signal from a single transmitter laser is split 1 : 1 into two arms. Each branch signal is intensity modulated by one information bit. Signals are recombined with orthogonal polarizations in a polarization beamsplitter (PBS). It is useful to generate a quasicontinuous differential phase shift $\varphi = 2\pi F t$ by placing a serrodyne phase modulator or a frequency shifter in one of the arms. The resulting rms amplitude of the spectral line at frequency $F$ in the photocurrent is

$$\left\langle 2b_1b_2|\underline{C}| \Big/ \sqrt{2} \right\rangle = 2^{-3/2} e^{\zeta} |\underline{D} \sin(\rho/2)|. \qquad (14)$$

As desired according to the PDL discussion in [1], it vanishes if the polarizer is set orthogonal to signal 2 ($\rho = 2n\pi$), which is needed for crosstalk-free reception of signal 1 or orthogonal to signal 1 [$\underline{D} = 0, \sigma = \delta + n\pi, \rho = (-1)^n\gamma + \pi$] for crosstalk-free reception of signal 2.

As shown in Fig. 1, it is possible to avoid the extra phase modulator or frequency shifter. A sinusoidal FM with frequency $F$ and a peak-to-peak optical frequency deviation $\Delta f_{pp}$ is applied to the transmitter laser and results in a differential (interchannel) phase modulation. It has a Bessel spectrum with modulation index

$$\eta = \pi \Delta f_{pp} \tau \operatorname{sinc}(\pi F \tau). \qquad (15)$$

With

$$\varphi = \overline{\varphi} + \eta \sin 2\pi F t \qquad (16)$$

where the mean value $\overline{\varphi} = 2\pi f_o \tau + \mathrm{const}$ depends on the optical frequency $f_o$, we obtain

$$\begin{aligned} C &= \operatorname{Re} e^{(j(\varphi + \operatorname{arc} D) + \zeta)} |\underline{D}| \sin(\rho/2) \\ &= \left( \begin{aligned} &\left( J_0(\eta) + 2\sum_{k=1}^{\infty} J_{2k}(\eta)\cos(2k2\pi F t)\right)\cos(\overline{\varphi} + \operatorname{arc}\underline{D}) \\ &- \left( 2\sum_{k=1}^{\infty} J_{2k-1}(\eta)\sin((2k-1)2\pi F t)\right)\sin(\overline{\varphi} + \operatorname{arc}\underline{D}) \end{aligned} \right) \\ &\quad \cdot e^{\zeta}|\underline{D}|\sin(\rho/2). \end{aligned} \qquad (17)$$

If the powers of at least one even and one odd Bessel line are detected with suitable weighting, the total power becomes independent of $\overline{\varphi}$. The Bessel line $J_0$ is corrupted by other dc terms anyway, and $J_1$ could be corrupted by several effects explained below, especially for large $\Delta f_{pp}$, which are needed to achieve a given $\eta$ if $\tau$ is low. A simple choice would be to detect $J_2$, $J_3$. However, the result would be quite sensitive to changes of $\eta$. It is better to detect the powers of $J_2$, $J_3$, and $J_4$ with such a weighting that the control signal, i.e., the total power $P_{\mathrm{tot}}$, is not only independent of $\overline{\varphi}$ but also, to first order, of changes of $\eta$. This makes it possible to tolerate a certain laser FM efficiency drift due to reflections or aging. The required settings are

$$P_{\mathrm{tot}} = 0.64P_2 + P_3 + 1.32P_4 \qquad \eta = 4.2 \qquad (18)$$

where $P_k$ are the powers measured at frequencies $kF$. The aggregate coherent crosstalk power $P_{\mathrm{tot}} \propto e^{2\zeta}|\underline{D}|^2 \sin^2(\rho/2)$ behaves similarly as the incoherent crosstalk amplitude $B$ but contains less noise. If desired, its amplitude $\sqrt{P_{\mathrm{tot}}} \propto e^{\zeta}|\underline{D}\sin(\rho/2)|$ can be used instead as a control signal. For $\rho \to 0$, it is $\propto|\rho|$, while all schemes exploiting incoherent crosstalk yield signals $\propto\rho^2$, where $\rho^2 \ll |\rho|$. The interference detection scheme, therefore, outperforms the incoherent schemes, by far, in all configurations that may exhibit coherent crosstalk.

The delay time $\tau$ decorrelates the two orthogonally polarized optical signals due to phase noise of the transmitter laser. For a Lorentz line having a width $\Delta f_l$(full-width at half maximum), the term $e^{j\overline{\varphi}}$ has the autocorrelation function

$$l(\hat{t}) = \begin{cases} e^{-2\pi|\hat{t}|\Delta f_l}, & |\hat{t}| \leq \tau \\ e^{-2\pi\tau\Delta f_l}, & |\hat{t}| > \tau \end{cases} \qquad (19)$$

and the power spectral density

$$\begin{aligned} &\frac{dP(f)}{df} \\ &= e^{-2\pi\tau\Delta f_l}(\delta(f) - 2\tau \operatorname{sinc}(2\pi f \tau)) \\ &\quad + \frac{\Delta f\left(1 - e^{-2\pi\tau\Delta f_l}\cos(2\pi f\tau)\right) + f e^{-2\pi\tau\Delta f_l}\sin(2\pi f \tau)}{\pi\left(\Delta f_l^2 + f^2\right)}. \end{aligned} \qquad (20)$$

The normalized power in each Bessel (Dirac) line is $e^{-2\pi\Delta f_l \tau}$ and, therefore, suffers a 3-dB penalty only for $\Delta f_l \tau = 0.11$. Clearly, the spectral powers are augmented by parasitic laser amplitude modulation. This can be taken care of by subtracting constants from the measured Fourier coefficients, especially at the fundamental frequency $F$. Of course, the timing of the modulation at the transmitter has to be communicated to the receiver; otherwise the phase angles of the Fourier coefficients would be unclear. This is possible if the frame clock of a forward-error correction scheme or a similar signal is synchronized with the transmitter modulation and recovered at the receiver to provide the needed timing information.

Furthermore, a nonsinusoidal frequency modulation may influence the Fourier coefficients, thereby spoiling the Bessel spectrum. However, a weighted sum of three harmonic powers, say, those for $F$, $2F$, and $3F$, can still yield a control signal independent of $\overline{\varphi}$.

Another effect of the frequency modulation is that PMD with a differential group delay (DGD) will result in a polarization modulation of up to $2\pi \cdot \Delta f_{pp} \cdot$ DGD radians on the Poincaré sphere surface. This depolarization must be tolerated by the system.

## III. Channel Identification

Doubts have been raised as to whether the two data channels can be identified properly. To answer this question, let us consider a similar, well-known, and well-solved problem: In any time-division multiplexed data transmission system, the initial status of the clock frequency divider in the receiver is unknown, and the data streams of lower multiplex hierarchies may be cyclically permuted. The problem is solved by sending frame information together with the payload. It is easy to send not just frame but also polarization channel information. If the undesired channel is received, the polarization control system is interrupted and directed to acquire the other channel instead. Success is indicated by correct channel information and can, if necessary, be enforced by repeated attempts. This operation occurs only once at startup and is therefore tolerable; if polarization could not be tracked reliably PolDM transmission would not be accepted anyway.

## IV. 2 × 10 G/s PolDM NRZ Transmission Experiments

### A. Cross-Correlation Scheme

The cross-correlation scheme was chosen because the switching scheme could not be implemented due to lack of suitable hardware. For generation of a 2 × 10 Gb/s PolDM signal, one modulated optical 10-Gb/s signal from transmitter TX was split 1 : 1 and recombined in a PBS with orthogonal polarizations, after delaying one branch signal by ~50 ns (Fig. 2). This setup was chosen because there was only one intensity modulator available. The signal passed a motorized polarization transformer (MPT) with four endlessly rotating fiber-optic $\lambda/4$ plates. It was transmitted through attenuators (not shown), EDFAs, and a bandpass filter. At the receiver, the signal was split 1 : 1. Each branch contained a commercial electrooptic polarization transformer (EPT), a fiber-optic polarizer (POL), and a 10-Gb/s photoreceiver. Clock recovery was also implemented. Cross correlation was realized by two EXOR gates operating as multipliers (solid, not dotted lines in Fig. 2). Each

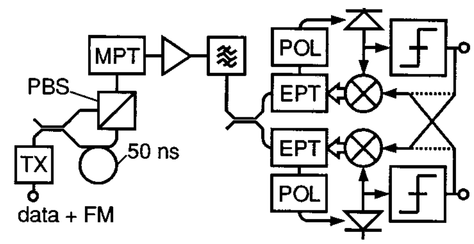



Fig. 2. Transmission setup for cross- (——) and autocorrelation (· · · · ·) schemes.

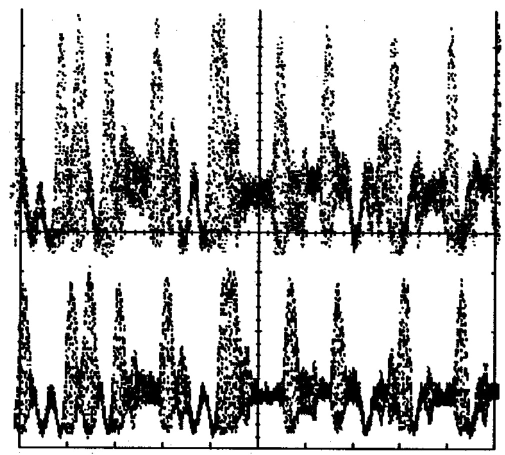


Fig. 3. Detected 10-Gb/s signals, polarization control off.

EPT was adjusted to minimize one cross-correlation product. Averaging time was on the order of 20 $\mu$s.

Fig. 3 shows sections of the pseudorandom bit-stream sequence at the two decision circuit inputs without polarization control. Since polarizations are misaligned, massive interchannel interference occurs during $b_1 = b_2 = 1$. The TX laser frequency was modulated at ~100 kHz with a frequency deviation of a few hundred megahertz. This FM caused a differential phase modulation of angle $\varphi$ due to the 50-ns delay line. Measured degree-of-polarization was 0.02, which means the two orthogonal channel signals had almost equal amplitudes and $\overline{C}$ was very small. Choice of the modulation frequency was not critical.

Signal acquisition was straightforward. Polarizations were correctly set even before the clock phase-locked loop was locked because decisions at random times contained enough useful information at the multiplier inputs. Polarization lock was always acquired in fractions of a second. The $\lambda/4$ plates of MPT were rotated with different speeds and directions, resulting in ~1 rad/s polarization change speeds on the Poincaré sphere. Clear signals were obtained (Fig. 4) because each electrooptical polarization transformer tracked the minimum of a cross-correlation product. Eye diagrams are shown in Fig. 5. Increased noise in the upper traces is due to a sampling head with wider bandwidth. MPT-induced "breathing" of one channel at the expense of the other allowed estimation of a PDL of ~1.8 dB, mostly due to the EDFAs. Bit error rate (BER) was measured in the resistance-reactance at 2.5 Gb/s by demultiplexing a regenerated 10-Gb/s signal. Transmission

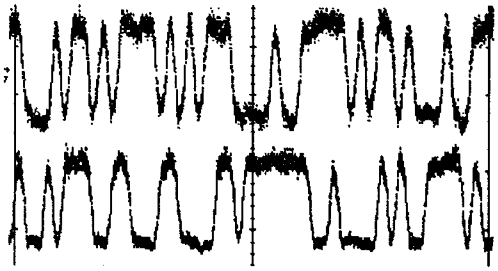
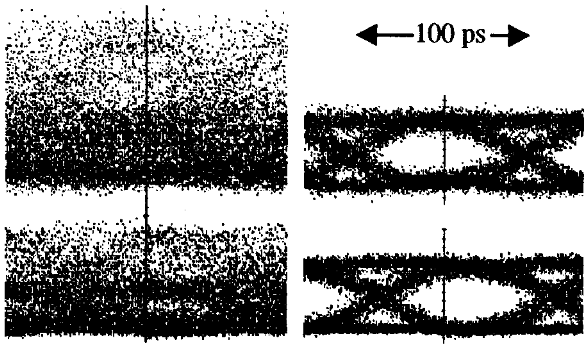


Fig. 4. Detected 10-Gb/s signals, polarization control on, while tracking endless polarization changes.




(a) (b)

Fig. 5. Eye diagrams corresponding to (a) Fig. 3 and (b) Fig. 4.

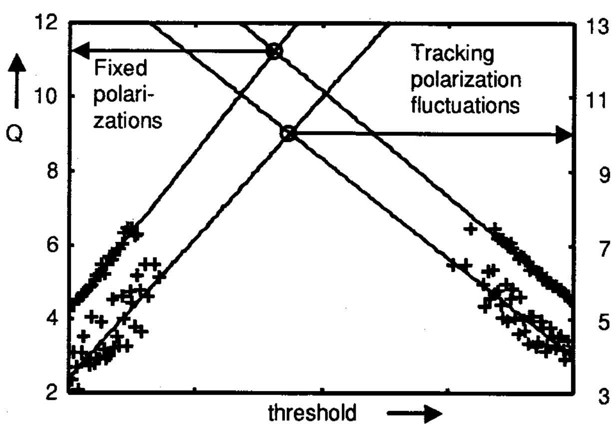



Fig. 6. $Q$ factors (top) back-to-back and (bottom; vertically offset) with rotating MPT.

was nearly error-free (one error in 45 min at 2.5 Gb/s, i.e., BER $= 1.5 \cdot 10^{-13}$). It was verified that control was not possible without laser FM.

A decision-circuit threshold was scanned. Extrapolation of measured $Q$ values $\geq$3 yielded $Q$ factors of 11.2 back-to-back and 10 with slowly rotating MPT, respectively (Fig. 6).

### B. Autocorrelation Scheme

The autocorrelation scheme was implemented by laying the straight dotted rather than the crossed solid lines in Fig. 2. The autocorrelation signals were maximized by appropriate settings of the EPTs. Corresponding signal traces and eye diagrams are shown in Fig. 7 and are virtually identical to the left half of Figs. 4 and 5(b), respectively. No unusual signals were observed for other MPT settings either, except for breathing due to PDL.

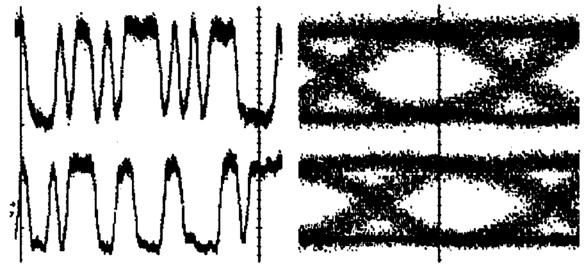


Fig. 7. 10-Gb/s signals with maximized autocorrelation rather than minimized cross-correlation products.

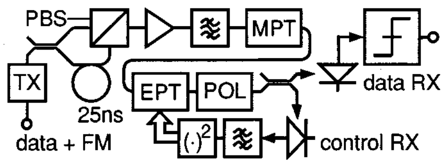



Fig. 8. Transmission setup for interference detection scheme.

BER performance was also checked with rotating MPT and turned out to be fine. However, little time was available for testing.

Because PDL was present in the setup and was experienced through MPT operation, this performance surprises. It has been predicted that the autocorrelation scheme should be inferior in the presence of PDL. The reasons are not fully understood, and the setup had to be taken apart shortly after. Note, however, that

$$\begin{aligned} \langle b_1 I \rangle &= (A + B/2)/2, \\ \langle b_2 I \rangle &= (A/2 + B)/2, \end{aligned} \quad \text{for } \overline{C} = 0. \tag{21}$$

Such or similar correlation products can be generated if the multipliers are plagued by internal offsets. This may, indeed, have been the case because only one offset voltage common to both inputs could be adjusted on each EXOR gate. Maximizing $\langle b_1 I \rangle$ and minimizing $\langle b_2 I \rangle$ both yield polarization settings in between the extreme cases outlined by (12) and (13), and this could be a reason why differences between cross- and autocorrelation schemes were not observable.

### C. Interference Detection Scheme

For implementation of the interference detection scheme, the setup of Fig. 8 was chosen. The delay in the transmitter was reduced to 25 ns. A transmitter laser with a linewidth of 1 MHz was chosen. Here, $\Delta f_l \tau = 0.025$ was very small, probably smaller than required.

An attenuator was placed before the MPT, which now contained eight endlessly rotating fiber-optic $\lambda/4$ plates. For simplicity, only one channel was recovered at the receiver side. A portion of the received signal was tapped off into a slow photoreceiver for control purposes. Normally, one would tap the detected electrical data signal instead. A sinusoidal frequency modulation at $F = 500$ kHz was applied to the TX laser, with a peak-to-peak optical frequency deviation $\Delta f_{pp} = 54$ MHz for a differential phase modulation index $\eta = 4.2$. The mean phase difference $\overline{\varphi}$ fluctuated with laser frequency and temperature. This could be seen from fading of even versus odd Bessel lines, or from changes in the eye pattern if FM was switched

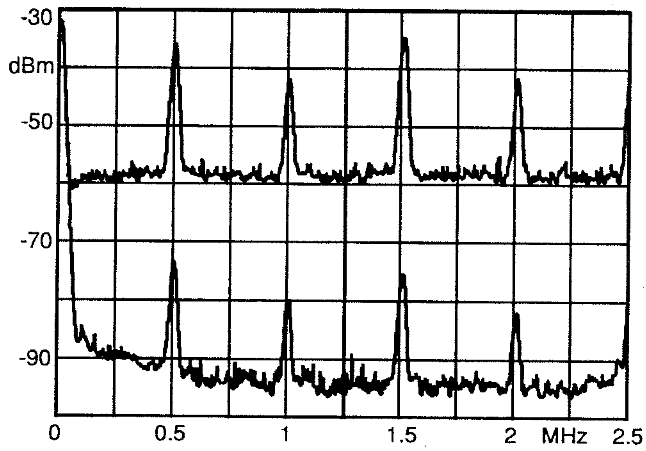



Fig. 9. Electrical Bessel spectra in control receiver with control switched off: (top) maximum interference and (bottom) minimum interference, both measured in maximum-hold mode.


Fig. 10. Received eye diagrams of (a) one 10-Gb/s channel, back-to-back and (b) worst case with 25 ps of differential group delay.

off. A bandpass filter selected Bessel lines $J_2$, $J_3$, and $J_4$ (at 1, 1.5, and 2 MHz) as parts of the spectrum (17) with suitable weighting. A subsequent squarer returned the weighted power sum (18). Averaging time was again on the order of 20 $\mu$s.

Fig. 9 shows Bessel spectra in the control receiver. Maximum hold mode was taken because even and odd Bessel lines faded in antiphase. The top trace is valid for maximum interchannel interference with polarization control off. Either channel could be acquired, depending on polarization setting before control was switched on. After signal acquisition, polarization control was again stopped and the bottom trace was recorded. It is ~40 dB down, which indicates that the residual polarization mismatch error at the operation point is $|\rho| \sim 0.01$ according to (9). The levels measured at $F = 500$ kHz are higher than expected, presumably due to nonsinusoidal frequency modulation.

Fig. 10(a) shows a received 10-Gb/s eye diagram while polarization control is running. The zero level is a bit broadened because the intensity modulator bias was chosen suboptimally. Because modulator drive voltage was insufficient, the one level should be broader than in the previous experiments if polarization control were as good or bad as before. Nonetheless, the interference-sensitive ones are very clear, which indicates good polarization control. BER was again measured on one demultiplexed 2.5-Gb/s data stream. A $Q$ factor of 18 was found (Fig. 11, top). The motorized polarization transformer was then operated to produce polarization fluctuations of ~1 rad/s on the Poincaré sphere surface. No error was recorded during 3 h. Later, the polarization control speed was increased, which allowed us to compensate for endless polarization fluctuations of ~10 rad/s. Vigorous fiber shaking without bit errors became possible. Another speed increase by at least a factor of three could be obtained without shortening the measurement intervals if data transfer times from an external PC were eliminated.

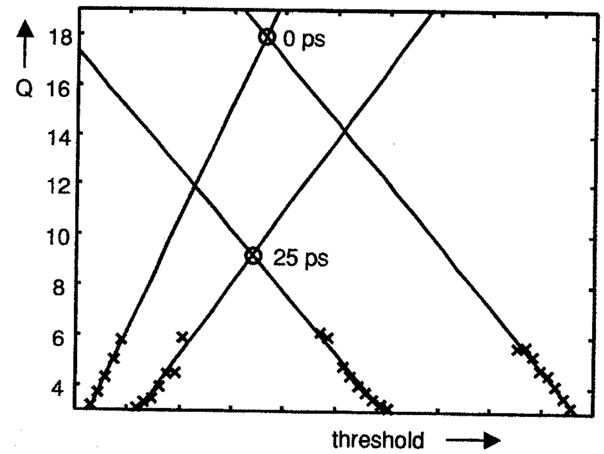



Fig. 11. (Top) $Q$ factor measurements back-to-back and (bottom) worst case with 25 ps of differential group delay.

The MPT was stopped to assess PMD tolerance: a piece of polarization-maintaining fiber having a differential group delay of 25 ps was inserted before the EPT, and its input polarization was adjusted manually via the MPT for maximum penalty. Fig. 10(b) shows the corresponding eye diagram, again with running polarization control. The $Q$ factor was nine in that case (Fig. 11 bottom). The extrapolated measurements are slightly bent upwards, which suggests that the true $Q$ factor could be even better, as expected for a limited non-Gaussian amount of eye closure due to PMD.

All these data show a significant superiority of the interference detection scheme over the correlation schemes for polarization alignment in an NRZ PolDM receiver. It is also simpler to implement. However, if interleaved RZ pulses are transmitted, interchannel interference may disappear, and the switching or the cross-correlation scheme becomes necessary and sufficient.

The same experimental complexity as here was employed in a recently published experiment [13] where a polarization controller improved the separation of adjacent, densely packed WDM channels with orthogonal polarizations. The permissible DGD $\times$ symbol-rate product was 0.06. The present scheme needs just half as many lasers in a WDM environment and supports a DGD $\times$ symbol-rate product of ~0.25. More details on PMD tolerance will be published in [14].

## V. Conclusion

Signal acquisition in polarization division multiplex receivers has been proposed, based on measurement of incoherent (switching, cross-correlation, and autocorrelation schemes) or coherent (interference detection scheme) interchannel crosstalk. PolDM transmission of $2 \times 10$ Gb/s has been demonstrated with equal optical and clock frequencies in the two channels. The correlation schemes and the interference detection scheme have been implemented, the latter yielding better results. Endless polarization changes in the transmission fiber are supported, and an experimental 25-ps PMD tolerance has been found.

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