and RZ signals at a DGD of 100 ps and electrical bandwidths of 8 GHz and 1.87 GHz. We have observed that the power in isolated spaces rises more quickly for NRZ signal format than RZ signal format as receiver electrical bandwidth is decreased, which, in turn, give a higher penalty for NRZ signal than RZ signal at a narrow electrical bandwidth.

3. Summary

We measured the dependence of PMD-induced penalty on receiver characteristics in an optically preamplified receiver. The penalty is strongly dependent on the location of the decision point and on the electrical filter bandwidth of the receiver. We also confirmed that, for an optically preamplified receiver, RZ signals are more tolerant of first-order PMD than NRZ signals for typical receiver electrical bandwidths.

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TuI5 **3:00 pm**

Experimental Verification of Reduced Sensitivity of Optical Duobinary Modulation to Higher Order PMD

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1. Introduction

Polarization mode dispersion (PMD) has been identified as a major system degrading effect putting a limit to highspeed optical transmission systems. Therefore much research work has been carried out on numerical and experimental analysis of its impact on system performance[1,2] and consequently on possible compensation strategies. Mitigation of PMD-induced distortions can be done either in the optical or electrical domain.[3,4] Most of today's PMD compensation strategies only take care of the impact of first order PMD, however (residual) higher order PMD effects are also relevant for system performance.[5]

In this contribution, we isolate the effect of higher order PMD and show that using a bandwidth reduced modulation format—such as duobinary coding—is an effective way to decrease signal distortions caused by higher order PMD. Our experimental results provide a quantification of higher order PMD linked to the observed system penalty.

2. PMD theory and already performed work

First order PMD is well understood and can be described with the parameters (i) differential group delay (DGD, $\Delta\tau$) and (ii) principle states of polarization (PSP). In contrast, for a mathematical description of higher order PMD the combined frequency dependency of DGD and PSP has to be computed.[6] For analyzing PMD distortion it is useful to consider the PMD vector $\vec{\Omega}$ as a Taylor series expansion at the optical carrier frequency ω_0

$$\vec{\Omega}(\omega) = \underbrace{\vec{\Omega}(\omega_0)}_{\textit{first order}} + \underbrace{\dot{\vec{\Omega}}(\omega_0)\,(\omega-\omega_0) + \ldots}_{\textit{second order and higher order}} \qquad (1)$$

with the PMD vector $\vec{\Omega}(\omega) = \tau(\omega)\cdot\vec{s}(\omega)$, $\tau = \Delta\tau/2$ and the stokes vector $\vec{s}$. First order PMD is characterized by $\vec{\Omega}(\omega_0)$ where the length of $\vec{\Omega}$ defines the DGD value $\Delta\tau$

$$|\vec{\Omega}| = \Delta\tau/2 \qquad (2)$$

and the direction of $\vec{\Omega}$ stets the PSP. Second order PMD is specified by

$$|\dot{\vec{\Omega}}| = \left|\frac{\partial\vec{\Omega}}{\partial\omega}\right| = \left|\frac{\partial\tau}{\partial\omega}\cdot\vec{s} + \tau\cdot\frac{\partial\vec{s}}{\partial\omega}\right|$$

$$= \tau_\omega = \sqrt{\dot{\tau}^2 + \tau^2\,|\dot{\vec{s}}|^2} \qquad (3)$$

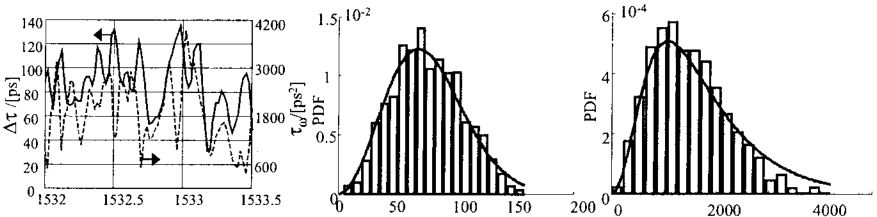
where $\dot{\tau}$ characterizes the wavelength dependency of the DGD and $\dot{\vec{s}}$ describes the depolarization effect caused by the rotation of the PSP.[5,6] For a system performance analysis it is indispensable to know the impact of τ_ω to the system penalty. Eq. 1 points out that signal distortion caused by 2nd and higher order PMD is strongly dependent on the frequency difference $\omega - \omega_0$ or the bandwidth of the used modulation format. Hence, bandwidth reduced modulation formats will exhibit reduced sensitivities to higher order PMD effects.

Duobinary coding as a bandwidth reduced modulation format has been investigated in detail showing essential advantages for dense WDM systems like increased dispersion tolerance and improved spectral efficiency.[7] The behavior of duobinary modulation in combination with first order PMD has been presented experimentally in[8] showing similar performance as conventional binary (NRZ) transmission, which is according to Eq. 1 perspicuously since 1st order PMD is wavelength independent. The actual advantage of duobinary coding with respect to higher order PMD (due to its reduced bandwidth as indicated in Eq. 1) has been investigated in[9] and[10] where these first experimental comparisons indicate reduced signal distortion (reduced power penalty, PP) for duobinary modulation. However, the actual PMD situations were not characterized and therefore no direct quantification of 2nd order PMD to system penalty can be established. In addition, only a special PMD situation is analyzed since the used PMD emulator is build of only two pieces of polarization maintaining fiber. Hence, the frequency dependency of the DGD is not taken into account and only higher order effects with respect to the variation of the PSP with frequency can be established.

In our work in contrast, we consider a higher order PMD condition equivalent to an installed fiber where both DGD and PSP are dependent on frequency. Moreover, we link the 2nd order coefficient to the measured system penalty which is essential for system design. This enables us to carry out a complete and in-depth analysis of the impact of higher order PMD effects on the system performance of conventional binary and duobinary transmission.

3. Experimental results and discussion

Our used PMD-emulator is build of a concatenation of 15 pieces of polarization maintaining fibers. A precise electronically temperature controlled fiber storage box is provided to establish a stable DGD situation. This is necessary to compare different modulation formats within the same DGD situation. Otherwise, only statistical results can be drawn from measurements. Fig. 1 shows samples of the measured wavelength dependency of the DGD ($\Delta\tau$) and the 2nd order parameter (τ_ω) as well as the statistics of both parameters (measured in the wavelength range of 1530 to 1560 nm with a $\Delta\lambda$ = 0.02 nm). The Maxwell probability density function (PFD) for



TuI5 **Fig. 1.** Measurement results of the used PMD emulator: sample DGD and second order PMD (left) and corresponding statistics (middle and right); solid lines show theoretical expected value.

the DGD and the theoretical PDF of τ_ω given in[6] are plotted as solid lines. A good match of experimental and theoretical data can be stated proofing the accuracy of the PMD emulation. Note, that the PMD emulator exhibits a PMD value of ≈80 ps since it is intended to be used for PMD compensator performance testing where high values are required.

The experimental setup is displayed in Fig. 2. Using an optical switch the output of the tunable laser source can be directed to the transmitters (Tx) for both transmission formats and the PMD measurement equipment. This allows precise measurements at exactly the same wavelength in a short time. In order to show signal distortions caused by higher order PMD only, we eliminate 1st order PMD by aligning the input state of polarization to the PSP. This is done by manually changing the input polarization with a polarization controller while monitoring the received eye diagram. This adjustment to receive the "best possible eye opening" can be regarded as a first order PMD compensator. A standard preamplified direct detecting receiver (Rx) is used in both cases and sensitivity penalties (BER of 10^{-9} with PRBS of $2^{11}-1$) are measured.

For both modulation formats the penalties (compared to each back-to-back case) versus 2nd order PMD parameter τ_ω are shown in Fig. 3. The penalties correspond to the same PMD situation; in some cases for the same 2nd order parameter value multiple measurements are performed at different wavelengths.

It can be observed in Fig. 3 (left) that the penalties for duobinary transmission are always lower than for binary. Even for very high 2nd order PMD values, e.g. 3500 ps² the penalty in the duobinary case does not exceed 3 dB whereas for binary a penalty of ≈12dB is measured. 2nd order PMD adds to or subtracts to residual chromatic dispersion.[5] Since no fiber based dispersion is considered in this experiment PMD induced chromatic dispersion can create negative penalty values (see Fig 3 (left)) for duobinary modulation (which is due to the typical duobinary property that the eye is widened for some increasing dispersion values!). In addition, the spectral energy of the duobinary signal is more concentrated at the center frequency (carrier frequency) or at the center PSP to which the signal is aligned to. Thus the depolarization effect caused by the frequency dependent rotation of the PSP is less affective than for standard on-off keying. In order to illustrate signal distortion caused by higher order PMD only, The eye diagrams depicted in Fig. 3 (right) were measured for a high PMD value of 3200 ps². Besides, the back-to-back eye diagrams of both modulation formats are also shown.

4. Conclusion

We study the effect of higher order PMD and show that using a bandwidth reduced modulation format—such as duobinary coding—is an effective way to decrease signal distortions caused by (residual) higher order PMD. Our experimental results link the actual higher order PMD to the observed system penalty and therefore a quantitative evaluation is possible.

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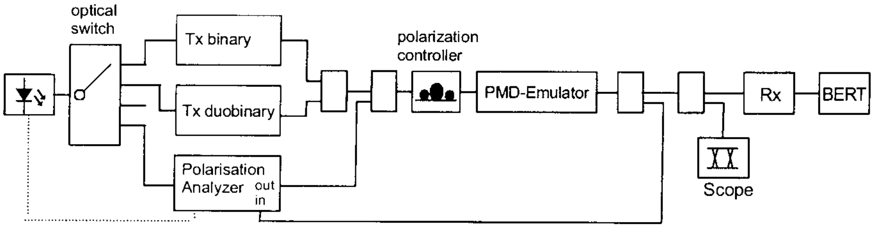
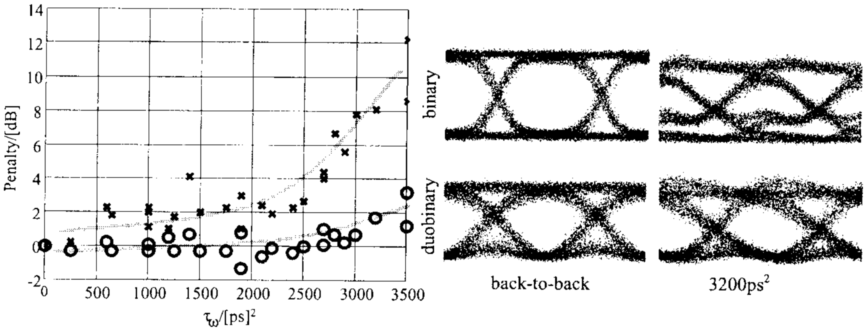


TuI5 Fig. 2. Test setup with conventional binary (NRZ) and duobinary transmitter (Tx), PMD emulator and standard preamplified receiver (Rx). The input polarization is adjusted to best case while monitoring the output eye.



TuI5 Fig. 3. Measured Power Penalty vs. 2nd order PMD parameter τ_ω for binary (x) and duobinary (o) transmission (left); input polarization was aligned to the PSP in order to eliminate 1st order PMD effects. Eye diagrams of binary (top) and duobinary (bottom) at 10 Gb/s in the back-to-back case (left) and with signal distortion caused by higher order PMD only (right) with a 2nd order PMD value of 3200 ps².

TuI6 **3:15 pm**

Sensitivity Penalty distribution in fibers with PMD: a novel semi-analytical technique

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Determining the Outage Probability (OP) of fiber communication systems in the presence of Polarization Mode Dispersion (PMD) requires long simulation times. For a given average Differential Group Delay (DGD) ⟨Δτ⟩, sufficiently many fiber samples must be synthesized for propagation, so as to have fibers with first- and higher-order PMD effects large enough to degrade performance significantly. We choose here Sensitivity Penalty (SP), evaluated @BER = 10^{-10}, as the performance indicator. Since such *strong PMD* fibers are rarely synthesized, propagation on most fibers yields SP values falling close to the modal SP value. Hence, one gets a poor definition in the tail of the SP distribution. Recently, importance sampling techniques have been proposed to increase the definition in the tail.[1] Here, we take a different approach.