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PMD and Nonlinearity-Induced Penalties on Polarization-Multiplexed Transmission

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***Abstract*—We investigate penalties induced by polarization-mode dispersion (PMD) and the interaction between PMD and fiber nonlinearity on polarization-multiplexed transmission through both simulations and experiment. We find that controlling the phase difference between polarization channels can enhance the PMD tolerance in polarization-multiplexed transmission.**

***Index Terms*—Fiber nonlinearity, nonlinearity tolerance, polarization-mode dispersion (PMD), polarization multiplexing (POLMUX).**

I. INTRODUCTION

INCREASING the spectral efficiency of optical transmission in order to increase total capacity of state-of-the-art transmission systems is a topic which received considerable research interest in recent years. Polarization multiplexing (POLMUX) is a well-known technique to increase spectral efficiency and can be used to effectively double fiber capacity. It has been used successfully in record breaking laboratory experiments [1]–[3] as well as field trails [4].

However, POLMUX has so far not found its way into commercial optical transmission systems. This is partly due to the vulnerability of POLMUX to polarization-mode dispersion (PMD) as initially shown in [5] and [6], where a factor of five lower tolerance is reported relative to non-POLMUX transmission. Here, we investigate in more detail PMD tolerance when fiber nonlinearity is included using POLMUX signals with a total line rate of 2 $\times$ 10 Gb/s. We will show a tolerance up to 20-ps differential group delay (DGD) for the worst-case scenario with even further improvements possible through control of the phase difference between both polarization channels.

The lower tolerance of POLMUX signals to PMD is a result of interchannel interference through both first- and second-order PMD (SOPMD) and the influence of PMD-induced coherent crosstalk on transmission. However, even in the absence of PMD the birefringence in optical fibers induces an unpredictable rotation to the state of polarization (SOP). This rotation must be corrected for at the receiver side in order to separate both polarization channels during transmission of POLMUX signals. The received current from a single polarization channel can be written as (1) [7], where ψ is the polarization misalignment angle between polarization channels and an ideal polarization beam splitter (PBS), φ the phase difference between the polarization channels, and b_1 and b_2 the bits transmitted in each of the respective polarization channels. In the absence of PMD, the polarization can be perfectly aligned, ψ equals zero, and no penalty is induced. However, in the presence of PMD, ideal compensation of the polarization rotation is not possible and this results in a power penalty

$$I \approx \frac{b_1 \cos^2 \psi}{2} + \frac{b_2 \sin^2 \psi}{2} + 2 b_1 b_2 \cos\varphi \sin\psi. \qquad (1)$$

To minimize the influence of PMD, the leading edge of the bits in both polarization channels are synchronized at the transmitter. First-order PMD (DGD) results in a change of the SOP on the bit-time scale when the POLMUX channels are not coupled into the principle states of polarization (PSP). Consider the case when the bits in both polarization states are at a high level and in the subsequent bit-slot one is high and one is low. Due to DGD, the pulses partly overlap and the SOP of the pulses are then different near the edge with respect to the center of the pulses. The polarization control in front of the receiver minimizes the crosstalk between both POLMUX channels, but cannot change the SOP on the bit-time scale. The alignment with the PBS is not optimal $(\psi \neq 0)$ in the overlapping part of the bit which results in coherent crosstalk. In the received eye, this results in an over- or undershoot between adjacent bits, as shown in Fig. 1(a). Note that when both polarization channels are not synchronized, the over- or undershoot occurs more near the center of the eye, which results in far lower PMD tolerance.

The DGD also induces a periodic change of the SOP with wavelength. Additionally, SOPMD results in a change of the DGD as a function of wavelength [8]. The polarization controller aligns the received signal only for the center wavelength, which contains the major part of the optical channel power. This results in crosstalk between both polarization channels. In addition to the influence of PMD, POLMUX signals are further degraded due to standard nonlinear effects and the POLMUX specific effect of cross-polarization phase modulation, a cross-phase-modulation (XPM)-like effect between polarization channels at the same wavelength.

II. SIMULATION RESULTS

Through simulations of transmission with POLMUX nonreturn-to-zero (NRZ) signals and nonlinear effects, the source of PMD penalties is investigated and the PMD tolerance is determined. A single wavelength channel at 10 Gb/s per polarization channel is simulated over a 100-km standard single-mode fiber

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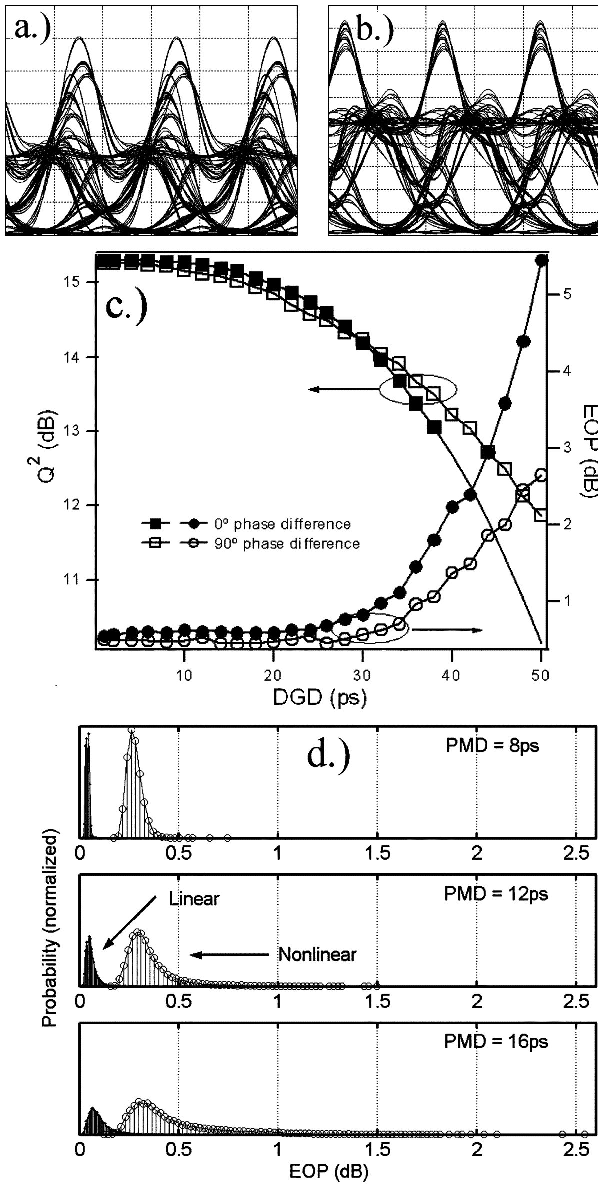

Fig. 1. Simulation results of POLMUX transmission; eye diagrams show (a) zero and (b) $\pi/2$ phase difference between polarization channels with 50-ps DGD. (c) EOP and Q^2 versus DGD for both 0 and $\pi/2$ phase difference between polarization channels. In order to simulate only the influence of DGD, the waveplate angles are chosen such that SOPMD is minimal. (d) Monte Carlo simulation (10 000 simulations) of the EOP probability for several average PMD values, dots denote linear and circles denote nonlinear simulations.

(SSMF) fiber link with −510-ps/nm predispersion and zero accumulated dispersion. A high 15-dBm launch power into the SSMF and 5 dBm into the dispersion-compensating fiber is used in order to produce sufficient nonlinear interactions without relying on long-haul transmission. The short 100-km fiber link is used in both simulation and experiment because then a deterministic amount of DGD can be added in order to measure the DGD tolerance. The influence of amplified spontaneous emission noise is neglected in the simulations. Here we report only single-channel simulations and the influence of XPM is, thus, not determined.

PMD influence is simulated through random coupling between 1000 waveplate sections in the SSMF fiber (pseudorandom binary sequence $2^6 - 1$). In order to simulate worst-case PMD influence, the signal is launched at a 45° angle with respect to the PSPs for all simulations discussed here. To study the influence of a change in φ, the PMD influence is simulated for a $\varphi = 0$ and $\varphi = \pi/2$ phase shift between polarization channels. The eye opening penalty (EOP) and Q^2 value from a single polarization channel are depicted in Fig. 1(c), clearly showing the higher tolerance of the $\varphi = \pi/2$ phase difference to PMD. Results obtained by Monte Carlo simulations, where the waveplate angles are chosen randomly for each simulation, are depicted in Fig. 1(d) to show the difference between linear and nonlinear transmission. In order to obtain worst-case results for the simulations the phase difference between polarization channels is kept constant at $\varphi = 0$. A number of conclusions can be drawn from these simulations:

1) As shown in (1) and Fig. 1(c), a $\pi/2$ phase difference between the polarization channels enhances PMD tolerance due to helpful coherent interference. Additional simulations show larger EOP differences between the two cases considered, $\varphi = 0$ and $\varphi = \pi/2$, at high power values and/or high PMD values. This suggests the phase difference is at least partly preserved under the influence of fiber nonlinearity.

2) For low average PMD values (PMD < 12 ps), the main penalty for POLMUX signals is due to first-order PMD. Even for the worst case scenario, ~30-ps DGD results in an EOP smaller than 1 dB. Compared to DGD, the influence of SOPMD is small. In a statistical back-to-back simulation, a 1800-ps² SOPMD value results in a 1-dB EOP. This value is unrealistically high for the average PMD values discussed here.

3) Nonlinear penalties together with DGD drastically increases the EOP penalty compared with the EOP penalty of DGD alone [Fig. 1(d)]. At low DGD values, the increase is small, resulting in 0.3-dB EOP for a 15-dBm input power. However, nonlinear penalties are enhanced in the presence of high DGD values as is visible through the extended tail for the nonlinear case in comparison to the linear case.

4) The polarization-sensitive detection used in POLMUX systems results in different interaction between nonlinear effects and DGD compared with non-POLMUX systems. The beneficial influence of a small DGD value, as observed in non-POLMUX transmission [9], is not observed in POLMUX transmission.

III. Experiments and Results

In order to verify the improvement of the EOP due to a phase difference between polarization channels as found through simulations, we measured the back-to-back sensitivity of NRZ POLMUX signals in the presence of DGD while controlling the phase. The experimental setup is depicted in Fig. 2. The principle behind the POLMUX modulator is discussed in more detail in [4]. A measurement with polarization-maintaining fiber between transmitter and receiver was chosen to determine the back-to-back DGD tolerance for several DGD values (PRBS $2^{31} - 1$), as shown in Fig. 3(a). A value of about 20-ps DGD for a 45° coupling with respect to the PSP results in a 1-dB power penalty. As expected, the power penalty increases significantly for high DGD values and the eye diagram in Fig. 3(b)

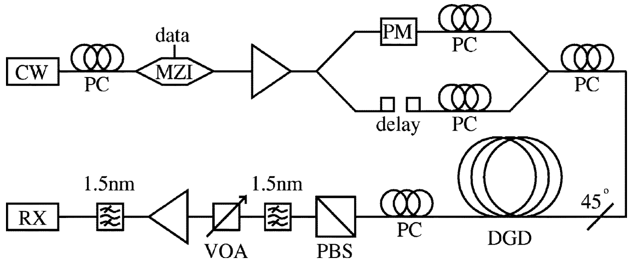

Fig. 2. Experimental setup. PM: phase modulator. VOA: variable optical attenuator. PC: polarization controller.

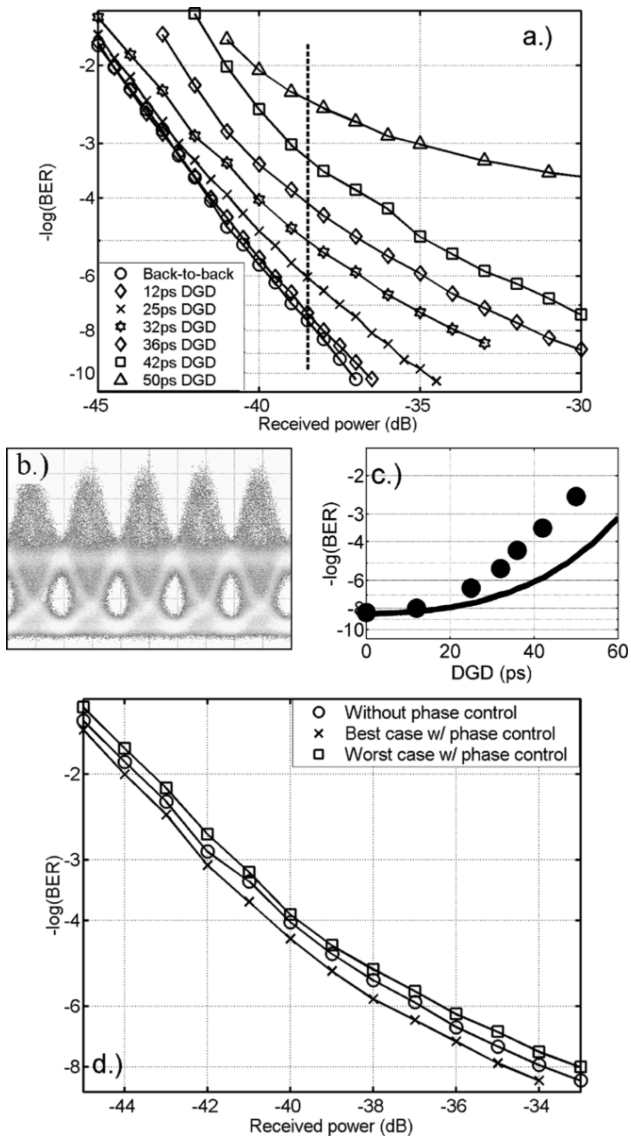

Fig. 3. (a) Measured power penalties for several values of the DGD in back-to-back transmission, vertical line denotes a received power of −38.5 dBm. (b) Measured eye diagram at 50-ps DGD. (c) Measured values taken from Fig. 2(a) at a received power of −38.5 dBm (dots) and simulation results (solid line). (d) Change in the bit-error rate measured through phase control at the transmitter for a 32-ps DGD.

shows an overshoot near the edge of the pulse similar to the simulated eye diagram in Fig. 1(a). The difference between measurement and simulation results, as shown in Fig. 3(c), is believed to be a result of jitter and noise in the crossing of the eye, which is not present in the simulation and enlarges the DGD induced penalty in the experiments. For 32-ps DGD, the phase influence is measured using a phase modulator in one of the transmitter arms and shown in Fig. 3(d). Unfortunately, the phase difference is complicated to control due to both manual phase control and polarization demultiplexing, so only the best- and worst-case bit-error rates could be determined. In order to maintain the same bit-error rate (10^{-7}), there is a difference in the received power of 1.5 dB between the best and worst cases when controlling the phase. This indicates a significant improvement can be made by controlling the transmitter phase in POLMUX transmission.

IV. Conclusion

We have shown through simulations and measurements the influence of PMD on POLMUX systems. Neglecting nonlinear effects, we find that the DGD dominates the penalty and the influence of SOPMD is minimal. In a back-to-back measurement, a DGD value of about 20 ps for the worst-case scenario is found to result in a 1-dB power penalty. The maximum DGD value is approximately a third of the maximum allowable value of non-POLMUX systems at a double line rate. This DGD penalty is smaller than previously reported, and the difference is believed to be a result of the lower influence of SOPMD for 2×10 Gb/s transmission in comparison with POLMUX transmission at a higher line rate, as reported in [5]–[7]. We have also shown the additional penalty for POLMUX systems when combining PMD and nonlinear effects which greatly increases the effort for using POLMUX as a transmission format. PMD and nonlinear effects cannot be studied separately since there is a large interaction which limits system performance. Furthermore, we experimentally verified that a $\varphi = \pi/2$ phase difference between POLMUX channels enhances the PMD tolerance.

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