PMD induced transmission penalties in polarization multiplexed transmission

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

PMD-Induced Transmission Penalties in Polarization-Multiplexed Transmission

D. van den Borne, *Student Member, IEEE*, N. E. Hecker-Denschlag, G. D. Khoe, *Fellow, IEEE*, and H. de Waardt

Abstract—In this paper, we investigate for the first time chromatic dispersion and nonlinearity tolerances in the presence of polarization-mode dispersion (PMD) for polarization-multiplexed (POLMUX) 2 × 10-Gb/s nonreturn-to-zero (NRZ) transmission. In polarization-multiplexing, the interaction between fiber nonlinearity and PMD can lower the nonlinear tolerance beyond the tolerances evident when considering both transmission penalties separately; the combined penalties are significantly worse than in the case for non-POLMUX transmission. In this paper, we show, through simulations comparing POLMUX with non-POMUX transmission in the presence of nonlinearity, a reduction of about a factor of three in PMD tolerance. In addition, we show that the dispersion tolerance of POLMUX transmission is severely limited in the presence of PMD. For example, a 40-ps differential group delay (DGD) with worst case coupling of the polarization channels into the fiber lowers the dispersion tolerance, resulting in a 1-dB eye-opening penalty (EOP), from 1200 to 450 ps/nm. We conclude that the interaction between PMD, chromatic dispersion, and nonlinearity leads to the worst signal impairments in POLMUX transmission and increases the effort of using polarization-multiplexing as a modulation format.

Index Terms—Dispersion tolerance, fiber nonlinearity, fiber-optics communication, nonlinearity tolerance, optical transmission, polarization-mode dispersion (PMD), polarization multiplexing (POLMUX).

I. INTRODUCTION

POLARIZATION-MULTIPLEXING doubles the capacity of a wavelength channel and the spectral efficiency by transmitting two signals via orthogonal states of polarization (SOPs). Hence, doubling fiber capacity through polarization-multiplexing has been very promising in optical communication.

For an ideal optical fiber, this allows for multiplexing of two channels without a decrease in transmission tolerances. Initial research into polarization-multiplexing focused on soliton transmission [1], [2], and it has been used as early as [3] in wavelength-division-multiplexing (WDM) transmission experiments. Further experiments using polarization-multiplexing continue to show the advantage in spectral efficiency and used it successfully in both record-breaking laboratory experiments [4], [5] as well as field trails [6].

Although polarization-multiplexing is considered interesting for increasing the transmitted capacity, it suffers from decreased polarization-mode dispersion (PMD) tolerance, due to the polarization-sensitive detection [7]–[9] used to separate the polarization-multiplexed (POLMUX) channels. This greatly increases the effort of using polarization-multiplexing in commercial systems.

In this paper, the interaction between PMD, chromatic dispersion, and nonlinear transmission impairments is discussed. The paper is organized as follows; Section II discusses the influence of birefringence and PMD in POLMUX transmission. In Section III, the nonlinear transmission penalties in POLMUX transmission are discussed in more detail. PMD is added in order to study the interaction between PMD and nonlinearity. The interaction between PMD and nonlinearity in POLMUX transmission compared with non-POLMUX transmission is discussed for both 10- and 20-Gb/s non-POLMUX transmission. Finally, the influence of narrowband filtering and PMD compensation on transmission penalties is examined in detail. Subsequently, in Section IV, the dispersion tolerance of POLMUX transmission is discussed. In simulations and measurement, a decreased dispersion tolerance is shown and the influence of narrowband filtering and PMD compensation is discussed. At the end of the section, measurement results are compared with simulation results. We conclude our results in Section V.

II. PMD PENALTIES IN POLMUX TRANSMISSION

The random birefringence in optical fibers induces an unpredictable rotation to the SOP. Because POLMUX transmission makes use of both orthogonal SOPs, this unpredictable rotation must be corrected in order to avoid misalignment penalties with the polarization-sensitive receiver. The polarization-sensitive receiver consists of an automatic polarization controller (PC) followed by a polarization beam splitter (PBS). The PC dynamically rotates the polarization of the signals in order to obtain the correct SOP necessary for the separation of the two polarization channels at the PBS. The PC functions by measuring the strength of interaction between the two polarization signals using a pilot tone or a low-frequency phase modulation, which is added at the transmitter to one of the polarization channels. This principle makes it possible to control the SOP on a microsecond basis, which should be fast enough to track the change in SOP induced by a varying fiber birefringence. Demultiplexing of the polarization channels is then

ideal, and fiber capacity can be doubled without a sensitivity penalty.

In the presence of differential group delay (DGD), i.e., PMD to the first order, the delay between both principal states of polarization (PSP) results in a change of the SOP at the leading and falling edge of the pulse. This can be understood most easily by considering the SOP as the sum vector of the SOP of both POLMUX channels. The transmitted SOP for POLMUX signals is dependent on the bit sequence in both channels, i.e., when two "1" are transmitted, the SOP is different then when a "1" and a "0" are transmitted. Hence, a POLMUX signal does not have a slowly varying SOP, as is the case for non-POLMUX signals, but would appear to a slow control algorithm as a depolarized signal. Note that to minimize the changes in SOP, both polarization channels should be synchronized such that for the two signals, the rising and falling of the bits always occurs at the same time. When the POLMUX channels are coupled into the PSPs of the fiber, the DGD simply results in a time delay. The PC matches the axes of the PBS with the carrier frequency of the POLMUX channels, which now coincide with the PSPs, and no demultiplexing penalty is introduced.

When the polarization channels are not coupled into the PSPs, demultiplexing does suffer from a DGD-induced penalty. Consider again the case that in subsequent bit slots, different symbols are transmitted, for example, two "1"s in the first bit slot and a "1" and a "1" in the subsequent bit slot. Due to DGD, the pulses partly overlap and the SOP of the overlapping part changes with respect to the SOP of the center part of the pulses. The PC 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 near the edge of the pulse, which results in suboptimal demultiplexing and the introduction of coherent crosstalk. In the received signal, the suboptimal demultiplexing is visible through an over- or undershoot between adjacent bits. The DGD also induces a periodic change of the SOP with frequency, as is well known from PMD theory [10]. The polarization control aligns the received signal such that crosstalk is minimized. In effect, the SOP of the carrier wavelength, which contains the majority of the transmitted power, is aligned with the axes of the PBS. In the presence of a DGD or second-order PMD (SOPMD), this results in crosstalk between both polarization channels for all other components of the signal spectrum. At a higher line rate (e.g., 40 Gb/s), this has a larger contribution due to the broader optical spectrum of the signal and leads to an even lower PMD tolerance of POLMUX compared with non-POLMUX transmission [7]–[9], especially when no nonlinear impairments are considered. Additionally, SOPMD results in a change of the DGD as a function of wavelength [11].

In this paper, we study for the first time the combined effects of DGD, chromatic dispersion, and nonlinearity in POLMUX transmission. We show that polarization-multiplexing suffers from decreased nonlinear and dispersion tolerances in the presence of a DGD, significantly beyond the combined degradation observed in non-POLMUX transmission. The reduction of DGD, nonlinear, and dispersion tolerances combined is significantly larger than the effect of the pulse degradations separately.

III. NONLINEAR PENALTIES IN POLMUX TRANSMISSION

In POLMUX transmission, coherent crosstalk can be a result of the influence of fiber nonlinearity in the absence of DGD. Nonlinear interaction between both polarization channels of a single wavelength channel results in an XPM-like effect that induces coherent coupling between the polarization channels, and thus, degrades the POLMUX signal, increasing transmission penalties. Note that POLMUX modulation can be considered a pseudo "three-level"-intensity modulation, which further indicates the source of the increased nonlinear interaction in comparison to non-POLMUX signals. Considering WDM, polarization scattering through XPM-induced depolarization becomes an important penalty to consider [12]. We limit the study in this paper, however, to the interaction of the various transmission penalties in single-channel transmission. The influence of XPM-induced depolarization has been studied in [13].

A. Statistical Simulations

The interaction between DGD and nonlinearity significantly influences transmission penalties. Similar to the over- and undershoots induced through the influence of DGD, a nonlinear phase shift induced by self-phase modulation (SPM) also results in pulse shaping. Combining both edge effects increases transmission penalties in POLMUX transmission. The precise interaction between DGD and fiber nonlinearity depends on the statistical evolution of the SOP in the fiber. Depending on the SOP, the power in each of the PSPs of the fiber is different. This results in different nonlinear interaction between both polarization channels, which again leads to a different interaction between DGD and nonlinearity.

As a first step to study this interaction, statistical simulations using a Monte Carlo approach are used to investigate the interaction between both transmission impairments. Since only the interaction between nonlinearity and DGD is considered, amplified-spontaneous-emission (ASE) noise is neglected in the simulations and the performance is evaluated using the eye-opening penalty (EOP). The EOP is defined as twice the mean signal intensity divided by the maximum eye opening available for 20% of the bit period. Note that the 1-dB EOP penalty is used to compare our simulation results. The EOP does not infer that the optical signal-to-noise ratio (OSNR) penalty is the same. For instance, in [14], the authors point out that the EOP is lower than the OSNR penalty by about a factor of two.

A 100-km standard single-mode fiber (SSMF) fiber link with a module dispersion of 1700 ps/nm, a 510-ps/nm predispersion, and zero accumulated dispersion is used in the simulations. The fiber parameters are depicted in Table I. Both polarization components consist of a 10-Gb/s nonreturn-to-zero (NRZ) signal, modulated with a $2^6 - 1$ pseudorandom bit sequence (PRBS) and zero chirp after the modulator. The total launch power into the SSMF equals 30 mW, and into the DCF is 3.5 mW. The high launch power is used to study the interaction between nonlinear transmission impairments and DGD, and is not representative of true launch powers in single spans. Based on results in [15], we can simply scale the high per-channel input powers for low span counts to lower powers for more spans in order to

TABLE I
PARAMETERS OF THE SIMULATION MODEL

	SSMF	DCF	unit
Insertion loss (α)	-0.2	-0.5	dB/km
Dispersion (D)	17	-102	ps/km/nm
Dispersion slope (S)	0.057	-0.34	ps/km/nm^2
Nonlinearity (γ)	1.2993	2.9534	1/W/km
Channel frequency		193.1	THz
Receiver bandwidth		100	GHz

obtain a figure of merit for long-haul transmission. The effect of DGD is simulated through random coupling of the wave plates in the SSMF [16]. In the simulations, the average PMD is kept constant while the wave plates in the SSMF change for each simulation, which approximates a Maxwellian PMD distribution. The signal is launched at a 45° angle with respect to the PSPs to simulate worst-case DGD impairments. At the receiver side, the polarization channels are demultiplexed using an ideal PBS, and perfect alignment of the polarization at the carrier frequency with the PBS is assumed. Both polarization channels have a slightly different EOP, which could be due to the influence of SOPMD or the limited simulated PRBS length. Unless noted otherwise, the worst case from both channels is used in the figures presented here.

In Fig. 1(a), the EOP probability distribution for both linear and nonlinear simulations is depicted. For the linear simulations, the average EOP does not increase significantly for an increasing average PMD. The EOP tail does become longer, which is due to an increased probability for high DGD at a higher average PMD. This is a result of the square relation [11] between the PMD variance and the average PMD $|\tau|$ (1a). The nonlinear simulations show a transmission penalty that has only a slight dependence on the average PMD, but a significantly enlarged tail due to interactions between PMD and fiber nonlinearity.

$$\mathrm{var}\,(|\tau|) = 3\pi/8 \cdot |\tau|^2 \tag{1a}$$

$$|\tau_\omega| \approx 0.5831 \cdot |\tau|^2. \tag{1b}$$

The enlarged variance due to interaction with fiber nonlinearity is also evident when for a 12-ps average PMD, the launch power into the SSMF is increased, as shown in Fig. 1(c). The average EOP penalty shows a strong increase for higher launch powers, but it is the variance in EOP that increases drastically with a factor of 10 and severely limits the PMD tolerance.

The increased tail length for a higher average PMD is partly related to SOPMD, which is also present in the statistical simulations. Similar to the DGD variance, the statistical-average SOPMD $|\tau_\omega|$ is dependent on the square of the statistical average value (1b), and the variance of the SOPMD is related to the fourth power of the average PMD. This makes it evident that the influence of SOPMD becomes more important for high average PMD. However, assuming moderate launch powers
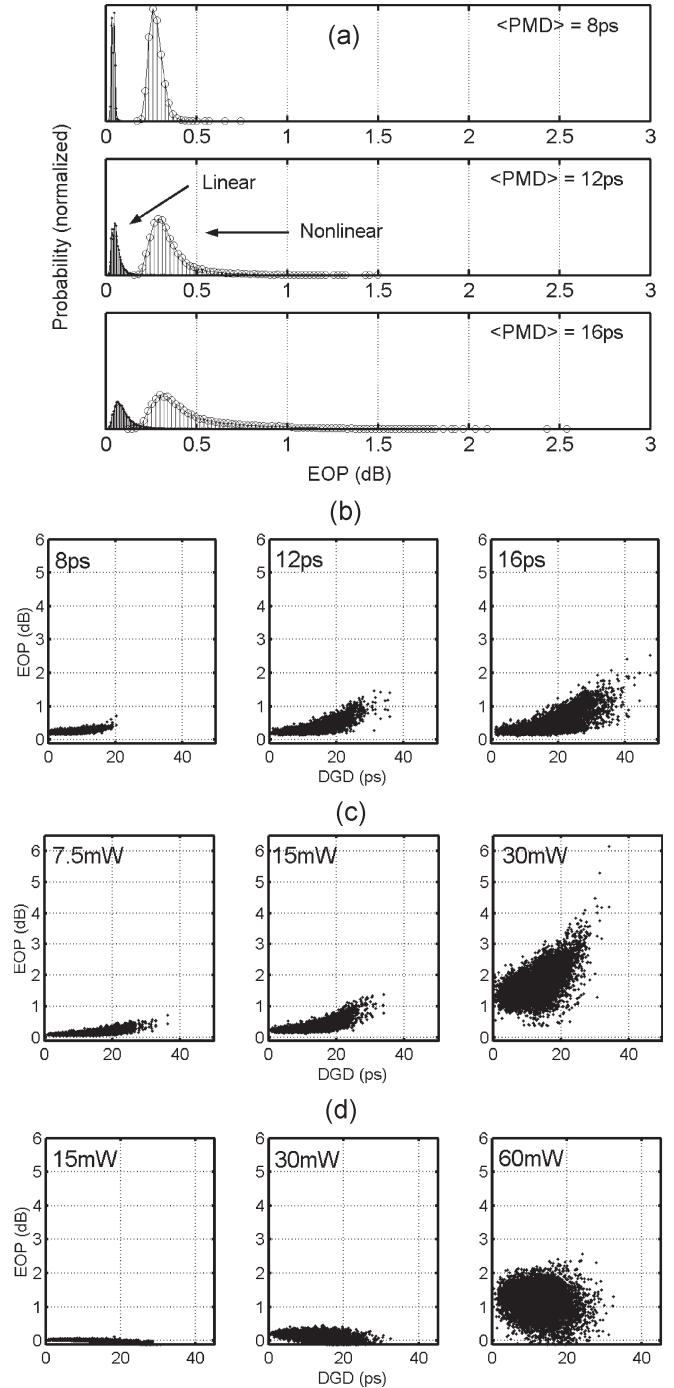
Fig. 1. Statistical simulation results of POLMUX transmission. (a) Monte-Carlo simulation (10 000 simulations) of the EOP probability for several amounts of average PMD; dots denote linear and circles denote nonlinear simulations for a 15-mW input power per polarization channel. (b) Scatter plots for several amounts of average PMD; SSMF input power is equal to 15 mW per polarization channel. (c) Scatter plots for various launch powers per polarization channel; average PMD is equal to 12 ps. (d) Scatter for the same total launch powers for non-POLMUX transmission; average PMD is equal to 12 ps. All simulations assume worst case coupling with respect to the PSP.

even for the worst case scenario, about 30-ps DGD can be tolerated so that the EOP is less than 1 dB. In comparison, a 500 ps^2 SOPMD results in a 1-dB EOP for similar statistical simulations with DGD compensation. Thus, for low average PMD ($<$ 12 ps), the main penalty for 2 $\times$ 10-Gb/s POLMUX signals is due to the DGD, while the SOPMD-related penalties

are small. Comparing Fig. 1(b) and (c), POLMUX transmission shows a much steeper increase in EOP for increasing input power than for increasing average PMD. Hence, it can be concluded that for high launch powers, the influence between DGD and fiber nonlinearity dominates the transmission penalty in POLMUX transmission rather than those due to DGD alone. In contrast, when the relation between DGD and nonlinearity is considered for 10-Gb/s non-POLMUX transmission, no interaction between DGD and nonlinearity is observed, as shown in Fig. 1(d). For low input powers, even a slight decrease of EOP is observed for an increasing DGD [17].

B. Simulations With a Fixed SOP Evolution

In the previously discussed simulations, statistics are used to characterize the random evolution of the SOP along the fiber link. In the simulations discussed in this section, a fixed set of coupling angles between birefringent fiber sections is used, and the strength of the birefringence is varied to simulate different amounts of DGD. Similar to the statistical simulations, the polarization channels are launched with a worst case 45° angle with respect to the PSP. This simplification allows us to study the interaction between DGD and nonlinearity with significantly reduced computation effort and neglecting the influence from the statistical behavior. For a certain DGD and input power, a single EOP value is now obtained instead of a probability distribution. Note that due to the fixed evolution of the SOP along the fiber link, the results represent only an average case with respect to DGD and nonlinear tolerance in comparison to the worst case statistical results. Due to the wave-plate model used to simulate the DGD in the fiber link, a small SOPMD is present in the simulations. For the chosen set of coupling angles used in these simulations, SOPMD is 0.228 ps^2 for a 1-ps DGD, and therefore, can be neglected.

Fig. 2 shows the EOP as a function of both input power into the SSMF and DGD in the fiber link. In order to compare penalties, both 2 × 10-Gb/s POLMUX NRZ [Fig. 2(a)] and non-POLMUX NRZ transmission with 10 and 20 Gb/s [Fig. 2(b) and (c)] line rates are depicted. Comparing the influence of DGD and nonlinearity on 2 × 10-Gb/s POLMUX versus 10-Gb/s non-POLMUX transmission is useful to understand transmission penalties associated with POLMUX transmission. However, in order to determine the suitability of POLMUX transmission as a modulation format, it should be compared with 20-Gb/s non-POLMUX transmission, since it has the same total line rate as 2 × 10-Gb/s POLMUX transmission.

Comparing 2 × 10-Gb/s POLMUX and 10-Gb/s non-POLMUX transmission clearly shows the decreased DGD tolerance of POLMUX transmission. A DGD of, respectively, 54 and 42 ps results in a 1-dB EOP in the absence of nonlinear interaction. Moreover, POLMUX transmission shows a clear dependence between DGD and input power into the SSMF. The increase in transmission penalties via an interaction between DGD and fiber nonlinearity also becomes evident through the eye diagrams presented in Fig. 3. Both DGD and high launch powers show an overshoot near the edge of the pulse. However, the center of the pulse is only strongly affected when both
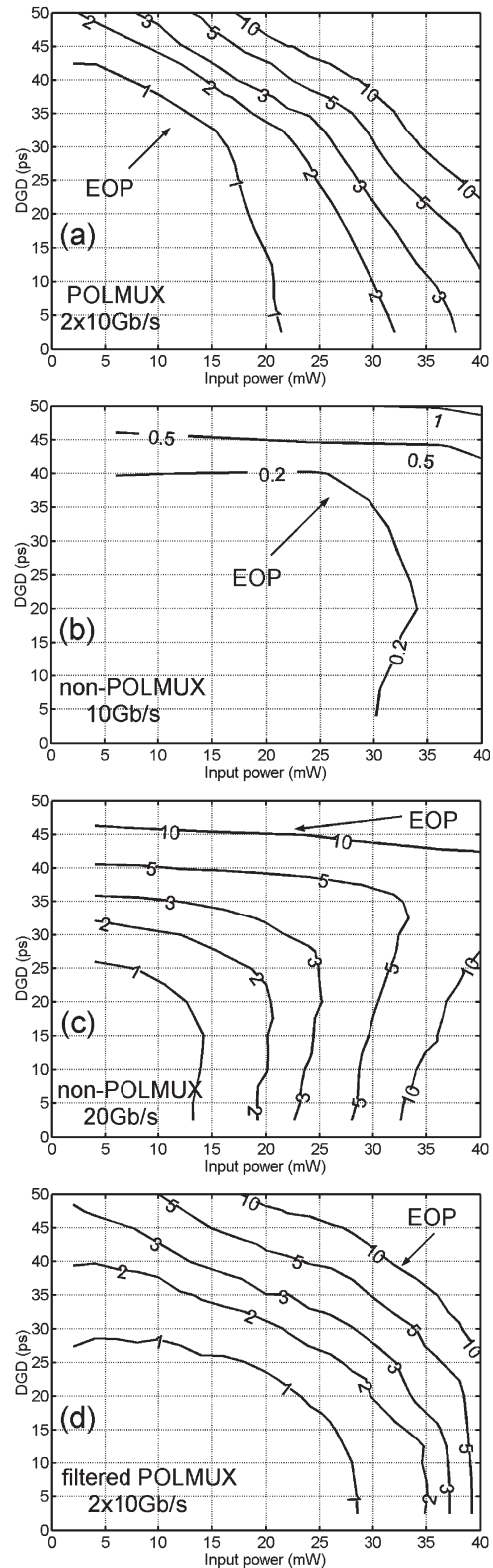
Fig. 2. Worst-case DGD versus launch power per polarization channel for transmission over 100-km SSMF. (a) 2 × 10-Gb/s POLMUX transmission. (b) Non-POLMUX 10-Gb/s NRZ transmission. (c) Non-POLMUX 20-Gb/s NRZ transmission. (d) 2 × 10-Gb/s POLMUX transmission with narrowband 20-GHz optical filtering at the receiver.

effects are combined, resulting in a higher EOP. This shows that POLMUX transmission with high launch powers is less tolerant to DGD-induced penalties than non-POLMUX transmission,

Fig. 3. Eye diagrams of the 0° channel for POLMUX transmission after 100-km transmission. (a) 40-ps DGD and 1-mW launch power. (b) 0-ps DGD and 15-mW launch power. (c) 40-ps DGD and 15-mW launch power. (d) 10-Gb/s non-POLMUX transmission with 40-ps DGD and 15-mW launch power. The box in the center of the eye is used to determine the EOP.
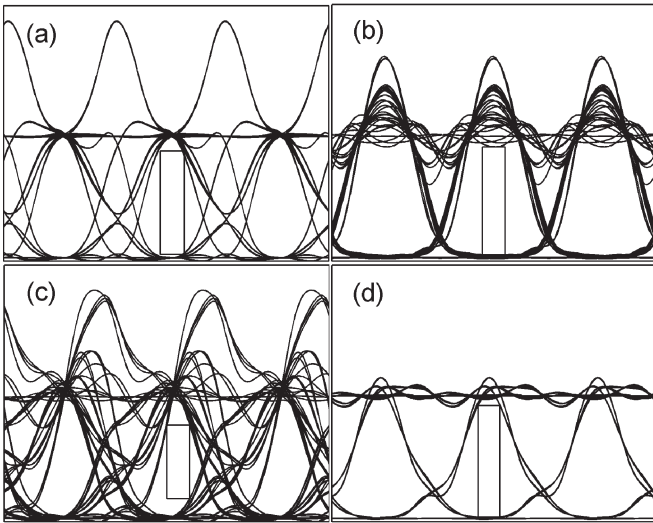
even for a DGD on the order of 10 ps. In the case of non-POLMUX transmission, the DGD only starts to affect the EOP for a DGD larger than 40 ps. Compared to the observation in the statistical simulations, a small DGD can even slightly enhance transmission, as visible in Fig. 2(b) and (c).

In addition to a larger DGD tolerance, 10-Gb/s non-POLMUX transmission also shows a significantly higher nonlinear tolerance when compared with POLMUX transmission. In the absence of significant DGD, a launch power of 22 and 56 mW results in a 1-dB EOP for POLMUX and non-POLMUX transmission, respectively. The difference in nonlinear tolerance is a result of the influence of nonlinear interaction between both polarization components. This results in overshoots near the center and undershoots near the edge of the pulse, which is evident from the eye diagram in Fig. 3(b) and (d).

In Fig. 2, POLMUX and non-POLMUX transmission are compared for the same launch power per polarization channel, hence, the total launch power is doubled for POLMUX compared with non-POLMUX transmission. When compared for the same total launch power in the absence of DGD, it is clear that the nonlinear impairments in POLMUX transmission are only slightly larger in POLMUX in comparison to non-POLMUX transmission. This can be attributed to the pseudo "three-level"-intensity modulation in POLMUX transmission. Hence, it is not the power per polarization component, but the power in each wavelength channel that characterizes the impact of the nonlinear impairments.

A comparison between 2×10-Gb/s POLMUX and 20-Gb/s non-POLMUX transmission shows a much different picture with respect to DGD and nonlinear tolerances. As expected, the DGD tolerance of 20-Gb/s non-POLMUX transmission is approximately halved, because the bit period is a factor of two smaller. The nonlinear tolerances show an even stronger decrease when compared with 10-Gb/s non-POLMUX transmission. This indicates that 2×10-Gb/s POLMUX has

an advantage over 20-Gb/s non-POLMUX transmission in both DGD and nonlinear tolerances. The DGD tolerance of 2×10-Gb/s POLMUX transmission is 42 ps compared with 26 ps for 20-Gb/s non-POLMUX transmission and the nonlinear tolerance equals 21 and 14 mW, respectively. Only for high launch powers and high DGD combined, where 2×10-Gb/s POLMUX transmission suffers from an interaction between DGD and fiber nonlinearity, does it appear that 20-Gb/s non-POLMUX transmission can have an advantage over 2×10-Gb/s POLMUX transmission.

It has been shown previously that narrowband filtering at the receiver can increase tolerances to transmission penalties [18], [19]. In POLMUX transmission, the influence of SOPMD-related penalties can be lowered because narrowband filtering removes the part of the spectrum that induces the worst polarization misalignment penalties. Here, we investigate the influence of narrowband filtering on both nonlinear and DGD tolerance. In back-to-back simulations, a 20-GHz optical filter bandwidth is found to result in the lowest EOP, and when Fig. 2(a) and (d) are compared, it shows a higher nonlinear tolerance at low EOP values. However, for high launch powers, the narrower received spectrum due to filtering results in additional penalties, because pulse distortions related to the nonlinear effects broadens into the center of the pulse. The higher nonlinear tolerance for narrowband filtering also comes at the cost of a decrease in DGD tolerance with 42-ps versus 28-ps DGD resulting in a 1-dB EOP. This indicates that in PMD-limited POLMUX transmission, narrowband filtering decreases signal quality.

C. Influence of DGD Compensation

Normally, in a PMD-compensated linear transmission link, no penalties are associated with the demultiplexing of POLMUX channels, assuming perfect PMD compensation of all orders. We have found that the decreased PMD tolerance of POLMUX transmission can be mitigated by PMD compensation, even in the presence of nonlinearities. Here, we discuss only simple first-order DGD compensation, since we find in our simulations that the DGD dominates transmission penalties in 10-Gb/s NRZ POLMUX transmission. The PMD compensation thus reduces the DGD for the carrier frequency of the POLMUX channel to zero, and any influence of higher order PMD is not compensated. For this specific case, we investigate the demultiplexing penalties in the presence of interaction between DGD and fiber nonlinearity along the transmission link.

Fig. 4 depicts the EOP for increasing launch power and DGD with DGD compensation. Because the EOP is not dependent on the DGD, we find that the influence of DGD and the associated transmission penalties due to edge effects are fully compensated for low input powers. For low DGD, the simulated EOP is similar for the case with and without DGD compensation, which is evident by comparing Figs. 2(a) and 4. Hence, with DGD compensation, the EOP is only dependent on the nonlinear interaction along the transmission link. Only for a combination of both high launch powers and high DGD do the simulations in Fig. 4 show an increasing EOP for increasing
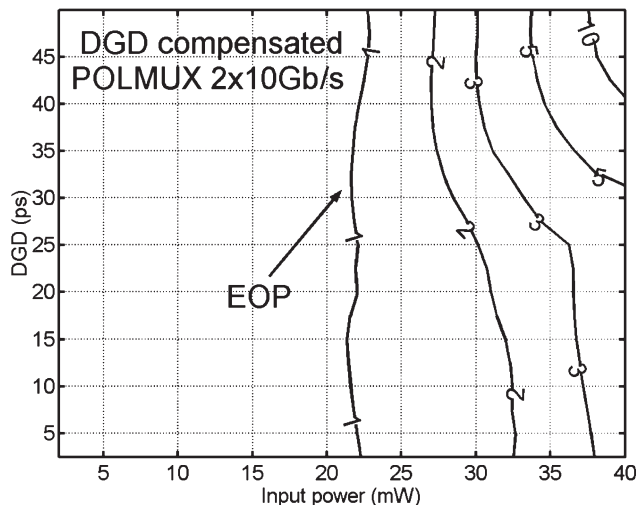
Fig. 4. Input power versus DGD for transmission over 100-km SSMF with DGD compensation at the receiver. The SOP evolution used in the simulations is equal to Fig. 2.

DGD. This is likely due to an interaction between higher order PMD, which scales with the DGD in the simulations, and nonlinearity. The constant EOP for increasing DGD indicates that in a DGD-compensated transmission link, PMD and nonlinear effects can be treated independently for low transmission powers, similar to that observed in Fig. 2(b) and (c) for non-POLMUX transmission.

The negative impact of PMD on POLMUX transmission can thus be successfully mitigated via DGD compensation. This shows that a transmission link employing a combination of POLMUX transmission and DGD compensation can be a suitable technique to double channel capacity and spectral efficiency.

A final consideration is that in POLMUX transmission, PMD compensation is required before polarization demultiplexing. Hence, the implementation cannot be based on SOP measurement, as is common for non-POLMUX transmission. An alternative control scheme that has previously been reported with POLMUX transmission is spectral monitoring of the electrical spectrum to obtain a feedback signal [20].

D. Experimental Results

The interaction between DGD and nonlinearity is investigated in experiments using the setup depicted in Fig. 5. A Mach–Zehnder interferometer is used for 9.95328-Gb/s NRZ data coding with a $2^{31} - 1$ PRBS. The NRZ signal is separated into two polarization components with equal power. One polarization component is delayed with respect to the other to create pseudoindependent channels [6]. A low-frequency phase modulation is added to one of the polarization channels for proper polarization demultiplexing [21].

Before transmission, various polarization-maintaining fibers are used to add DGD to the POLMUX signal. This is in contrast to the simulations where the DGD is added along the fiber link. However, the simulations discussed in Section III-A and B show that the interaction between DGD and nonlinearity can be treated independently in transmission, and the penalties

occur when demultiplexing the POLMUX channels. Hence, the penalties are associated with the change of the SOP on the bit time scale, which results in suboptimal demultiplexing of the polarization channels. This indicates that when DGD is added before transmission, similar transmission penalties as the ones discussed in the simulations are reproduced, allowing for a comparison between measurement and simulations results. The signal is transmitted over 100 km of SSMF and matching DCF. A high input power into the SSMF is used in the experiments to put in evidence of nonlinear effects, and a change in the input power is used to investigate the interaction between PMD and fiber nonlinearity. For high input powers, the influence of stimulated Brillouin scattering can have a slight influence on the measured nonlinear degradation; however, this should not affect the comparison between POLMUX and non-POLMUX transmission. At the receiver side, the polarization channels are manually demultiplexed and a noise-loading experiment is performed. Both bandpass filters used in the setup have a full-width at half-maximum (FWHM) band of 1.6 nm. Thus, no narrowband filtering has been applied.

The results of the sensitivity measurements are depicted in Fig. 6. Measurements are carried out for both POLMUX and non-POLMUX transmission, and with and without a DGD. To understand the experimental results, the large power penalty for POLMUX transmission in the presence of 32-ps DGD is first of all investigated. It was observed during the measurements that the eye closure comes from the side in PMD-limited POLMUX transmission instead of eye closure from the top, which is the case for OSNR and nonlinear penalties. We believe that the increased penalty is therefore partly due to the influence of timing jitter and suboptimal demultiplexing of the POLMUX channels in the measurements. This could indicate that for PMD-limited POLMUX transmission, timing jitter is more detrimental, and it should be further investigated in order to obtain better agreement between simulations and experiments.

In the case of non-POLMUX transmission, there is virtually no penalty when transmission with 0-ps and 32-ps DGD are compared. For a 10^{-5} BER, the difference between a 15-mW and 50-mW input power is 2 dB in the absence of DGD, and 3.5 dB in the presence of 32-ps DGD for 10-Gb/s non-POLMUX transmission. For low-launch-power values and 32-ps DGD, the sensitivity is slightly increased (-38 dBm versus -39.2 dBm), as predicted by simulations [Fig. 2(b)]. Only for measurements at a 50-mW launch power is a significant decrease in sensitivity observed. In contrast to non-POLMUX transmission, POLMUX transmission shows a large penalty when 32-ps DGD is added. For a 10^{-5} BER, the difference between a 15-mW and 50-mW input power is 3 dB in the absence of DGD, and 7.8 dB for POLMUX transmission with a 32-ps DGD. This underlines the decreased PMD tolerance of POLMUX transmission. When the measurements for different input powers are compared in Fig. 6, the increase in power penalty is stronger in the presence of DGD. This shows the predicted interaction between PMD and fiber nonlinearity for POLMUX transmission that is not present for non-POLMUX transmission. It should be noted that total launch powers into the SSMF are the same for both POLMUX and non-POLMUX
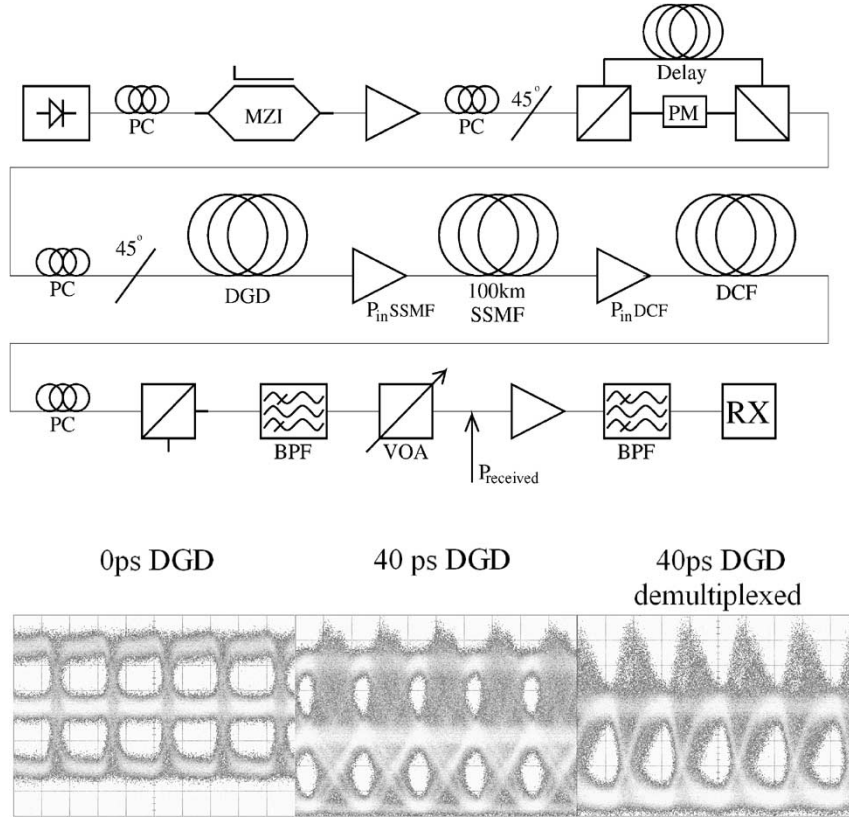
Fig. 5. In the experimental setup for nonlinear-interaction measurements, both in front of the polarization multiplexer and the DGD fiber, the SOP is equal to 45° to ensure proper multiplexing and coupling into the DGD fiber, respectively. BPF (bandpass filer), VOA (variable optical attenuator), PC (polarization controller), and PM (phase modulator). Eye diagrams show POLMUX signal with, respectively, 0- and 40-ps DGD and demultiplexed POLMUX signal with 40-ps DGD.

measurements. This implies that the launch power per channel is twice as high for non-POLMUX transmission. When comparing our simulation and experimental results, we find in both cases that there is only a small power penalty between POLMUX and non-POLMUX transmission in the absence of DGD, which we attribute to increased nonlinear transmission penalties.

IV. DISPERSION TOLERANCE IN POLMUX TRANSMISSION

In addition to the influence of nonlinearity, chromatic dispersion is also detrimental. The edge effects induced by DGD translate to pulse distortions in the center of the pulse in the presence of an accumulated dispersion at the receiver. This implies that in the presence of DGD, the chromatic-dispersion tolerance of POLMUX transmission is lower compared with non-POLMUX transmission at the same line rate.

A. Back-to-Back Dispersion Tolerance

It is well known that in the case of non-POLMUX NRZ transmission, nonlinear penalties can be reduced by using a suitable dispersion map with undercompensation at the end of the transmission link [22]. The strong influence of PMD on POLMUX transmission results in significant pulse distortions. Thus, it is reasonable to assume that the dispersion tolerance, and hence, the optimal accumulated dispersion changes in the presence of PMD. It must be noted that the simulations

and experiments discussed in the previous section assume a zero accumulated dispersion after transmission. In this section, the influence of a nonzero accumulated dispersion is investigated, both for back to back and for transmission over a single span. Two important parameters are discussed: the optimal accumulated dispersion and the dispersion tolerance. The dispersion tolerance determines the tolerance of POLMUX transmission to suboptimal dispersion maps that may occur in a field environment.

First of all, the back-to-back dispersion tolerance of a 2×10-Gb/s POLMUX signal is simulated for several DGD values. Fig. 7(a) shows the relation between simulated accumulated dispersion and EOP in the presence of a DGD. The optimal accumulated dispersion is zero as can be expected for linear transmission. However, for high DGD, an accumulated dispersion results in a large penalty. Because of the combined effects of DGD and dispersion, the EOP is too large at a zero accumulated dispersion to use the 1-dB EOP as a definition for the dispersion tolerance. Therefore, to compare the dispersion tolerance in the presence of DGD, we now define the dispersion tolerance as a 1-dB increase of the EOP over the EOP for a zero accumulated dispersion. The dispersion tolerance then shows a strong decrease with increasing DGD. Whereas the dispersion tolerance for 1-ps DGD is about 1600 ps/nm, the dispersion tolerance decreases to 400 ps/nm for 40-ps DGD. The decreased dispersion tolerance is also evident from the eye diagrams in Fig. 7(b)–(e) and shows the pulse degradation for an increasing accumulated dispersion. Similar to the interaction
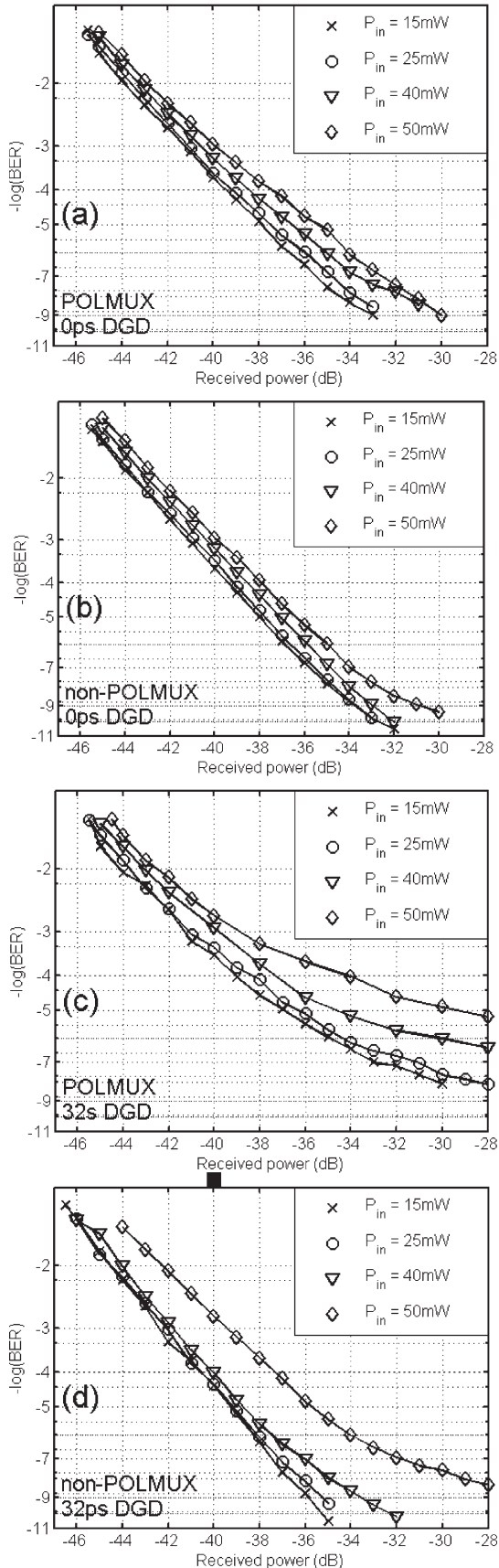
Fig. 6. Sensitivity measurements for various SSMF input powers; input power denotes the total launch power for both polarization components. With [(a) and (b)] 0-ps DGD and [(c) and (d)] 32-ps DGD and for [(a) and (c)] POLMUX and [(b) and (d)] non-POLMUX transmission.
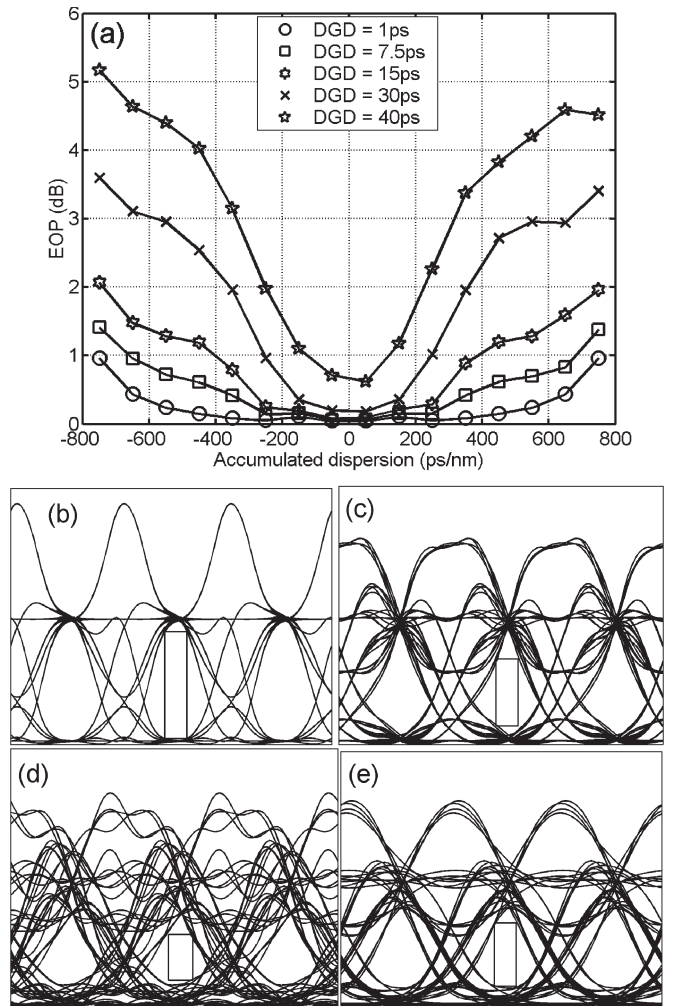

Fig. 7. (a) Back-to-back dispersion tolerance for 2×10-Gb/s POLMUX transmission with various amounts of DGD. Eye diagrams of the $0°$ channel for POLMUX transmission with 40-ps DGD and (b) 0-ps/nm, (c) 400-ps/nm, (d) 800-ps/nm accumulated dispersion, and (e) 800-ps/nm accumulated dispersion with narrowband filtering.

between DGD and fiber nonlinearity, the pulse degradation is a result of the DGD induced over- and undershoots near the edge of the pulse. Due to the dispersion-induced pulse broadening, the distorted edge squeezes into the center of the pulse, which results in a decreased pulse quality.

The influence of narrowband filtering on the dispersion tolerance in the presence of a DGD becomes evident when eye diagrams in Fig. 7(d) and (e) are compared. In Fig. 7(e), an optical filter with a 20-GHz bandwidth is used that clearly improves pulse quality in the presence of a significant accumulated dispersion. Narrowband filtering removes the frequency components most affected by the accumulated dispersion, which includes the frequency components resulting in an overshoot near the edge of the pulse.

B. Dispersion Tolerance in the Presence of Nonlinearity

In POLMUX transmission, signal impairments arise through a combination of fiber nonlinearity, dispersion, and DGD. Their combination will give rise to the worst case DGD-induced

transmission penalties. For example, DGD-induced edge effects increases nonlinear transmission penalties, and in the presence of an accumulated dispersion, these effects decrease pulse quality near the pulses' center. Fig. 8 shows the dispersion tolerance after transmission over a single span with a launch power into the SSMF of 15 mW per polarization channel and worst case coupling between POLMUX channels and the fiber's PSP. For low DGD and the same total launch power, the dispersion-induced transmission penalties is similar to that of non-POLMUX transmission.

When Fig. 8(a) and (b) are compared, it is evident that for an equal launch power per polarization channel, 2 × 10-Gb/s POLMUX transmission is strongly affected by nonlinear interaction than 10-Gb/s non-POLMUX transmission. The interaction between DGD and dispersion is small for non-POLMUX transmission. Only for 40-ps DGD does non-POLMUX transmission show a slight decrease in dispersion tolerances, which is evident due to DGD-related penalties. From Fig. 8(b), it is further evident that for 10-Gb/s non-POLMUX transmission, a positive accumulated dispersion is optimal to partially compensate for the influence of nonlinearity [22]. However, as is evident from Fig 8(a), this advantage disappears with 2 × 10-Gb/s POLMUX transmission due to the DGD-induced penalty. Hence, a zero accumulated dispersion is optimal in the presence of DGD.

Fig. 8(d) shows that the DGD-related decrease in dispersion tolerance for POLMUX transmission is mitigated when DGD, compensation is applied. Even for high DGD no penalties are observed, and the dispersion tolerance is comparable with 10-Gb/s non-POLMUX transmission for the same total launch power. This underlines the observation that the DGD-related penalties are a result of changes in the SOP on the bit time scale, which results in suboptimal demultiplexing at the receiver side. Comparing Fig. 8(b) and (d) also shows the influence of nonlinear impairments on the dispersion tolerance through an increased penalty in the case of undercompensation.

C. Dispersion-Tolerance Measurements

Using a similar setup as described for the nonlinear measurements (Fig. 5), the accumulated dispersion tolerance of POLMUX transmission in the presence of a DGD is measured. After the POLMUX transmitter, DGD is added to the signal, which is subsequently transmitted over 50 km of SSMF with a module dispersion of 831 ps/nm. The launch power into the SSMF is about 5 dBm, in order to reduce the influence of fiber nonlinearity. After the SSMF, a tunable dispersion compensator is used with a dispersion tuning range of −800 to +800 ps/nm. Effectively, the accumulated dispersion is thus changed between nearly zero and +1600 ps/nm. After tunable dispersion compensation, the POLMUX signal is demultiplexed with a PBS and detected with a standard receiver for bit-error-rate measurement.

The dispersion-tolerance measurements with a low DGD (12 ps) show only a slight decrease in tolerance compared with the dispersion tolerance in the absence of DGD, as evident from Fig. 9(a). For a large DGD (32 ps), a significant penalty is
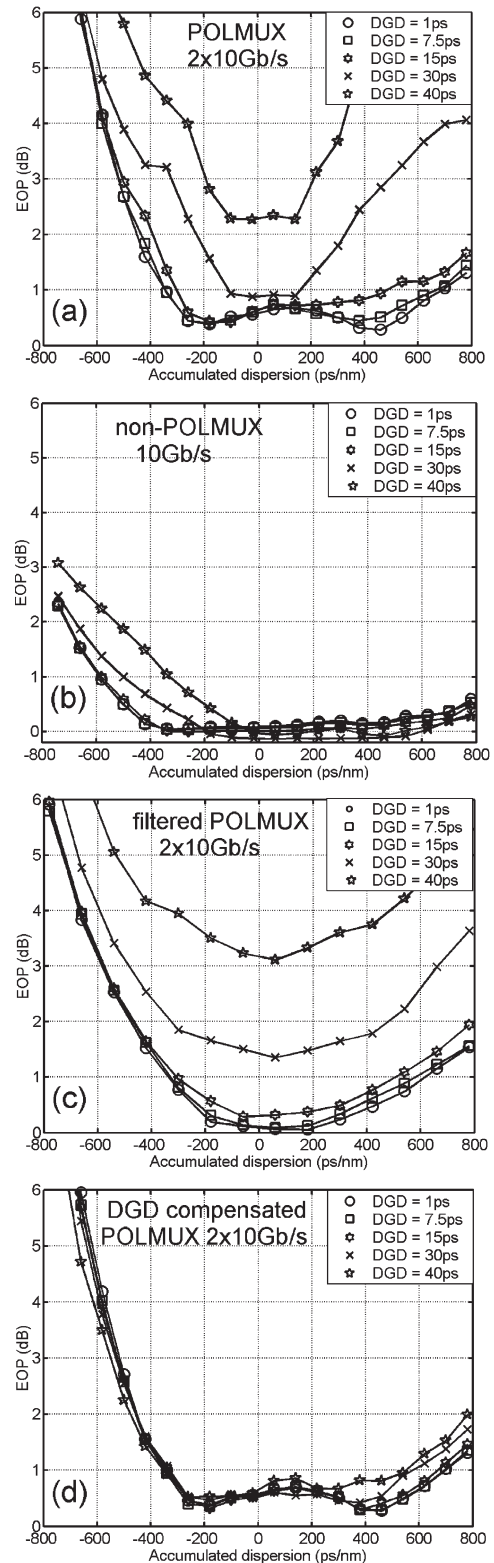

Fig. 8. Dispersion tolerance for various amounts DGD after 100-km transmission and 15-mW input power per polarization channel. (a) 2 × 10-Gb/s POLMUX transmission. (b) 10-Gb/s non-POLMUX transmission. (c) 2 × 10-Gb/s POLMUX transmission with narrowband filtering at the receiver. (d) 2 × 10-Gb/s POLMUX transmission with DGD compensation after transmission.

introduced, making a comparison of the dispersion tolerance difficult. For a 32-ps DGD, the received power is therefore adjusted to −30 dBm, to obtain a similar BER ($1 \cdot 10^{-8}$) for
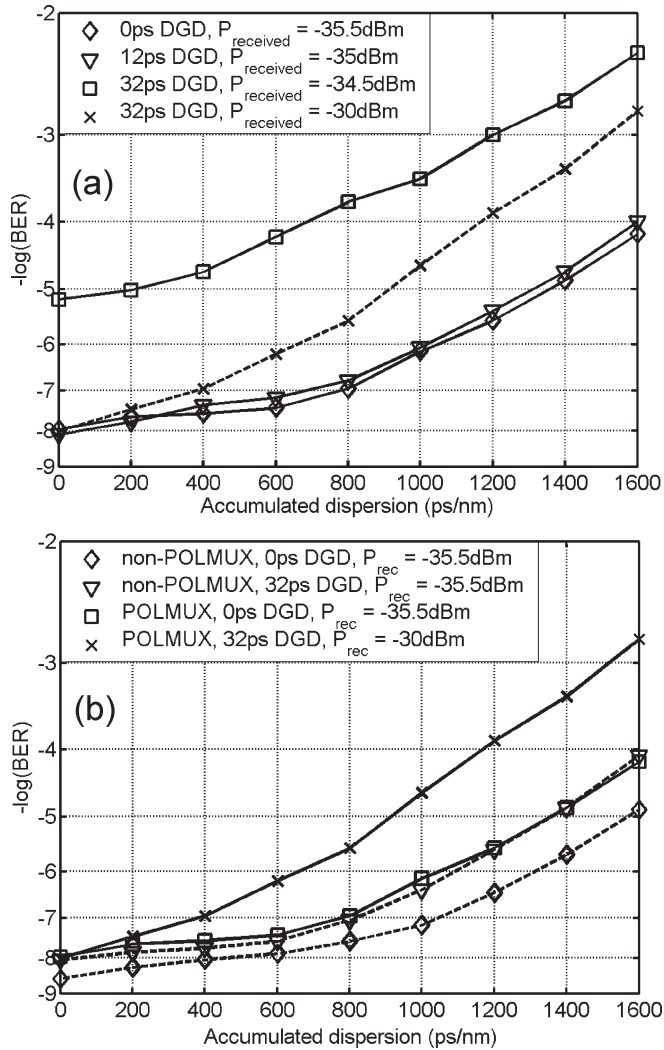
Fig. 9. (a) Measured dispersion tolerance for various amounts of DGD and a received power of about −35 dBm. For 32-ps DGD, also the dispersion tolerance at a received power of −30 dBm is added for comparison. (b) Accumulated dispersion tolerance for POLMUX and non-POLMUX transmission for both 0-ps and 32-ps DGD.

zero accumulated dispersion as measured in the absence of DGD. Comparing the measured dispersion tolerance without DGD and in the presence of 32-ps DGD for the same BER in the absence of accumulated dispersion, a lower dispersion tolerance in the presence of DGD is evident. Fig. 9(b) compares the accumulated dispersion tolerance for both POLMUX and non-POLMUX transmission in the presence of 32-ps DGD. For non-POLMUX transmission, only a small penalty is measured for a 32-ps DGD and the accumulated dispersion tolerance is virtually unaffected, as expected from the simulation results. This shows that the tendency of the experiments is in good agreement with the simulations discussed in Section IV-A and IV-B.

V. CONCLUSION

In the absence of polarization-mode dispersion (PMD), transmission tolerances of polarization-multiplexed (POLMUX) sig-

nals are lowered through nonlinear interaction between the polarization components. However, in this paper we showed for the first time through simulations and experiments, a decreased tolerance of POLMUX transmission with respect to fiber nonlinearity and chromatic dispersion in the presence of PMD. The nonlinear tolerances are decreased in the presence of differential group delay (DGD) due to the cumulative edge effects of DGD and self-phase modulation (SPM), which induce serious signal impairments in POLMUX transmission. This causes even a minimal DGD to increase transmission penalties. Statistical simulations show that the interaction between PMD and fiber nonlinearity also significantly enlarges the eye-opening penalty (EOP) probability tail, which imposes severe limits on the PMD tolerance of POLMUX transmission.

In the presence of PMD, the dispersion tolerance of POLMUX transmission is lowered significantly, decreasing from 1200 ps/nm in the absence of DGD to 450 ps/nm in the presence of a 40-ps DGD. The reduced dispersion tolerance is a result of the DGD-induced overshoot near the edge of the pulse. The accumulated dispersion results in a decreased pulse quality because the pulse broadening shifts the DGD-induced edge overshoot from the edge of the pulse to the center of the pulse.

The interaction between PMD, fiber dispersion, and nonlinearity brings out the worst impairments for POLMUX transmission. Further research should be dedicated to understanding worst case penalties resulting from the detrimental interaction between DGD and nonlinearity in POLMUX transmission. However, the results discussed in this paper do show that the polarization-sensitive detection adds a new level of complexity to understanding transmission penalties in polarization-multiplexed optical transmission links.

Comparing 2 × 10-Gb/s POLMUX with 20-Gb/s non-POLMUX transmission shows that polarization-multiplexing can enhance transmission characteristics, which adds to the inherently higher spectral efficiency of POLMUX transmission. In addition, at a lower line rate, for example, POLMUX 2 × 5-Gb/s, the advantages of POLMUX transmission are expected to be even larger. However, the comparison between POLMUX and non-POLMUX transmission is only strongly in favor of POLMUX transmission when the DGD of the transmission link is compensated. We expect that only combining POLMUX transmission and DGD compensation can make POLMUX transmission feasible, resulting in transmission with both a high spectral efficiency and high tolerances to transmission impairments.

REFERENCES

[1] S. R. Evangelides, Jr., L. Mollenauer, J. Gordon, and N. Bergamo, "Polarization multiplexing with solitons," *J. Lightw. Technol.*, vol. 10, no. 1, pp. 28–35, Jan. 1992.

[2] K. Iwatsuki, K. Suzuki, S. Nishi, and M. Saruwatari, "80 Gb/s optical soliton transmission over 80 km with time/polarization division multiplexing," *IEEE Photon. Technol. Lett.*, vol. 5, no. 2, pp. 245–248, Feb. 1993.

[3] A. R. Chraplyvy, A. Gnauck, R. Tkach, *et al.*, "1 Tb/s transmission experiment," *IEEE Photon. Technol. Lett.*, vol. 8, no. 9, pp. 1264–1266, Sep. 1996.

[4] T. Ito, K. Fukuchi, K. Sekiya, *et al.*, "6.4 Tb/s (160 × 40 Gb/s) WDM transmission experiment with 0.8 b/s/Hz spectral efficiency," presented at the Eur. Conf. Optical Communication (ECOC), Munich, Germany, 2000, Paper PD1.1.

[5] Y. Frignac, G. Charlet, W. Idler, *et al.*, "Transmission of 256 wavelength-division and polarization-division-multiplexed channels at 42.7 Gb/s (10.2 Tb/s capacity) over 3 × 100 km of Teralight fiber," in *Proc. Optical Fiber Communication (OFC)*, Anaheim, CA, 2002, pp. FC5-1–FC5-3.

[6] N. E. Hecker, E. Gottwald, K. Kotten, *et al.*, "Automated polarization control demonstrated in a 1.28 Tb/s (16 × 2 × 40 Gb/s) polarization multiplexed DWDM field trail," in *Proc. Eur. Conf. Optical Communication (ECOC)*, Amsterdam, The Netherlands, 2001, pp. 86–87.

[7] L. E. Nelson, T. Nielsen, and H. Kogelnik, "Observation of PMD-induced coherent crosstalk in polarization-multiplexed transmission," *IEEE Photon. Technol. Lett.*, vol. 13, no. 7, pp. 738–740, Jul. 2001.

[8] L. E. Nelson and H. Kogelnik, "Coherent crosstalk impairments in polarization multiplexed transmission due to polarization mode dispersion," *Opt. Express*, vol. 7, no. 10, pp. 350–361, Nov. 2000.

[9] S. Hinz, D. Sandel, F. Wüst, and R. Noé, "Polarization multiplexed 2 × 20 Gb/s RZ transmission using interference detection," in *Proc. Optical Fiber Communication (OFC)*, Anaheim, CA, 2001, pp. WM4-1–WM4-3.

[10] S. Song, C. Allen, K. Demarest, and R. Hui, "A novel method for measuring polarization-mode dispersion using four-wave mixing," *J. Lightw. Technol.*, vol. 17, no. 12, pp. 2530–2533, Dec. 1999.

[11] L. E. Nelson and R. Jopson, "Introduction to polarization mode dispersion in optical systems," in *Proc. Venice Summer School Polarization Mode Dispersion*, Venice, Italy, 2002, pp. 1–22.

[12] L. F. Mollenauer, J. P. Gordon, and F. Heismann, "Polarization scattering by soliton–soliton collisions," *Opt. Lett.*, vol. 20, no. 20, pp. 2060–2062, Oct. 1995.

[13] D. van den Borne, N. E. Hecker-Denschlag, G. D. Khoe, and H. de Waardt, "Cross phase modulation induced depolarization penalties in 2 × 10 Gb/s polarization-multiplexed transmission," in *Proc. Eur. Conf. Optical Communication (ECOC)*, Stockholm, Sweden, 2004, pp. 102–103, Paper Mo4.5.5.

[14] H. Kogelnik, L. E. Nelson, and P. J Wintzer, "Second-order PMD outage of first-order compensated fiber systems," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 1053–1055, Apr. 2004.

[15] J. P. Elbers, A. Färbert, and C. Scheerer *et al.*, "Reduced model to describe SPM-limited fiber transmission in dispersion-managed lightwave systems," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 2, pp. 276–281, Mar./Apr. 2000.

[16] A. O. Dal Forno, A. Paradisi, R. Passy, and J. P. von der Weid, "Experimental and theoretical modeling of polarization mode dispersion in single-mode fibers," *IEEE Photon. Technol. Lett.*, vol. 12, no. 3, pp. 296–298, Mar. 2000.

[17] B. S. Marks and C. R. Menyuk, "Polarization-mode dispersion enhancements of nonlinear propagation," presented at the Eur. Conf. Optical Communication (ECOC), Rimini, Italy, 2003, Paper Mo3.7.1.

[18] A. Hodžić, M. Winter, B. Konrad, *et al.*, "Optimized filtering for 40-Gb/s/Ch-based DWDM transmission systems over standard single-mode fiber," *IEEE Photon. Technol. Lett.*, vol. 15, no. 7, pp. 1002–1004, Jul. 2003.

[19] G. Bosco, A. Carena, V. Curri, *et al.*, "On the use of NRZ, RZ, and CSRZ modulation at 40 Gb/s with narrow DWDM channel spacing," *J. Lightw. Technol.*, vol. 20, no. 9, pp. 1694–1704, Sep. 2002.

[20] D. Sandel, F. Wüst, V. Mirvoda, and R. Noé, "Standard (NRZ 1 × 40 Gb/s, 210 km) and polarization multiplex (CS-RZ, 2 × 40 Gb/s, 212 km) transmissions with PMD compensation," *IEEE Photon. Technol. Lett.*, vol. 14, no. 8, p. 1181, Aug. 2002.

[21] R. Noé, S. Hinz, D. Sandel, and F. Wüst, "Crosstalk detection schemes for polarization division multiplexed transmission experiments," *J. Lightw. Technol.*, vol. 19, no. 10, pp. 1469–1475, Oct. 2001.

[22] J.-P. Elbers, A. Farbert, C. Scheerer, *et al.*, "Reduced model to describe SPM-limited fiber transmission in dispersion-managed light wave systems," *J. Sel. Topics Quantum Electron.*, vol. 6, no. 2, pp. 276–281, Mar./Apr. 2000.

D. van den Borne (S'04) was born in Bladel, The Netherlands, on October 7, 1979. He received the B.Sc. and M.Sc. degree (*cum laude*) in electric engineering from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 2001 and 2004, respectively. He performed his master's thesis work in collaboration with Siemens AG, Munich, Germany, on polarization-mode-dispersion (PMD)-related transmission penalties in polarization-multiplexed transmission. He recently started pursuing the Ph.D. degree in advanced modulation formats at Eindhoven University of Technology in collaboration with the Siemens AG, Munich.

He previously worked at Fujitsu Laboratories, Ltd., Kawasaki, Japan, on supercontinuum generation and pulse compression.

N. E. Hecker-Denschlag was born in Farmington, MI, USA, on June 23, 1966. She received the B.S. degree in physics from the University of Michigan, Ann Arbor, in 1988, with her bachelor's thesis work on pattern formation. In 1994, she obtained the Ph.D. degree in physics from Harvard University, Cambridge, MA, in vibrations in high-Tc superconductors.

She was a Lise Meitner Fellow at the University of Innsbruck, and continued postdoctoral work there until 1998, working in the field of ultrafast optical spectroscopy of semiconductors and surface plasmon enhancement of photoluminescence. As an Alexander von Humboldt Fellow, she moved to the Ludwig-Maximilians-Universität, Munich, Germany, working in the field of terahertz spectroscopy, and continued working there as a Universitäts Assistant until 2001. She joined the Advanced Technology Research Group at Siemens in December 2001, working on high-capacity optical-transport systems, focusing on polarization multiplexing (POLMUX) and alternative modulation formats. Recently, she has moved within Siemens AG to the System Engineering Department, where she is leading a team of engineers in developing the next generation of Siemens' optical-transport product.

G. D. Khoe (S'71–M'71–SM'85–F'91) was born in Magelang, Indonesia, on July 22, 1946. He received the degree of Elektrotechnisch Ingenieur (*cum laude*) from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 1971.

He began his research career at the Dutch Foundation for Fundamental Research on Matter (FOM) Laboratory on Plasma Physics, Rijnhuizen, The Netherlands. In 1973, he moved to the Philips Research Laboratories in order to research into the area of optical-fiber communication systems. In 1983, he was appointed as Part Time Professor at Eindhoven University of Technology, became a Full Professor at the same University in 1994, and is currently Chairman of the Department of Telecommunication Technology and Electromagnetics (TTE). He is one of the Founders of the Dutch Communication Technology Basic Research and Applications (COBRA) University Research Institute. In 2001, he brought four groups together to start a new international alliance called the European Institute on Telecommunication Technologies (eiTT). Most of his work has been devoted to single-mode fiber systems and components. Currently, his research programs are centered on ultrafast all-optical signal processing, high-capacity transport systems, and systems in the environment of the users. He has more than 40 U.S. patents and has authored and coauthored more than 100 papers, invited papers, and chapters in books. He has been involved in journal activities, as Associate Editor, as a Member of the Advisory Board, or as Reviewer. In Europe, he is closely involved in Research Programs of the European Community and in Dutch national research programs, as Participant, Evaluator, Auditor, and Program Committee Member.

Mr. Khoe's professional activities include many conferences, where he has served in technical committees, management committees, and advisory committees as a Member or Chairman. Recently, he was General Cochair of European Conference on Optical Communication (ECOC) 2001. He is currently serving as Associate Editor of IEEE JOURNAL OF QUANTUM ELECTRONICS (JQE). He has served in various positions in IEEE/Lasers and Electro-Optics Society (LEOS). He was a Founder of the LEOS Benelux Chapter. In 2003, he was appointed President of LEOS. He received the micro-optics conference (MOC)/graded-index optical systems (GRIN) award in 1997.

H. de Waardt was born in Voorburg, The Netherlands, on December 1, 1953. He received the M.Sc. and Ph.D. degrees in electrical engineering from the Delft University of Technology, Delft, The Netherlands, in 1980 and 1995, respectively.

In 1981, he joined the Department of Physics, Koninklijke PTT Nederland (KPN) Research, Leidschendam, The Netherlands, where he was engaged in research on the performance aspects of long-wavelength semiconductor-laser diodes, LEDs, and photodiodes. In 1989, he moved to the Department of Transmission, where he has been working in the fields of high bit-rate direct-detection systems, optical preamplification, wavelength-division multiplexing (WDM), dispersion-related system limitations, and the system application of resonant optical amplifiers. He contributed to (inter)national standardization bodies and to the EURO-COST activities 215 and 239. In October 1995, he was appointed as Associate Professor at the Faculty of Electrical Engineering, University of Eindhoven (TU/e), Eindhoven, The Netherlands, in the area of high-speed trunk transmission. His current research interests are in applications of semiconductor optical amplifiers, high-speed optical time-division multiplexing (OTDM) transmission, and WDM optical networking. He was active in European research programs, such as ACTS BLISS, ACTS Upgrade, and ACTS APEX. At present, he coordinates TU/e activities in the European projects IST METEOR and IST FASHION. He is a Member of the Project Management Committee of the national project BTS RETINA. He (co)authored more than 70 refereed papers and conference contributions.