Inter-channel Depolarization Impairments in 21.4-Gbit/s POLMUX OOK and DPSK Transmission

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We experimentally investigate the nonlinear tolerance of 21.4-Gbit/s POLMUX-RZ-OOK and POLMUX-RZ-DPSK modulation formats over an 800-km straight-line, for different numbers of co-propagating channels and channel spacing. We show that depolarization penalties are significantly reduced when POLMUX-RZ-DPSK is used, possibly making it a suitable modulation format for next-generation robust transmission systems.

Introduction

The emphasis in research for high-capacity transport links has shifted in recent years from achieving record capacities towards improvements in flexibility and robustness. Multi-level modulation formats are well known to boost tolerances towards chromatic- and polarization-mode dispersion at the same line rate as binary modulation [1]. The high robustness possibly eases deployment of 42.8-Gbit/s transmission over legacy fiber, which generally suffers from high polarization mode dispersion. Additionally, multi-level modulation formats have a narrow optical spectra allowing for cascaded optical filtering in 50-GHz spaced channels [2]. This is an important requirement since next generation wavelength division multiplexed (WDM) links are expected to operate on a 42.8-Gbit/s line rate and 50-GHz channel spacing.

Multi-level modulation can be realized by any combination of amplitude, phase and polarization modulation. Among the various possibilities, polarization multiplexing (POLMUX) is a straightforward and easily implemented technique to achieve the advantages of multi-level modulation, and has therefore been considered extensively. POLMUX doubles the capacity of a wavelength channel by transmitting two signals via orthogonal states of polarization. It has been successfully used in dense-WDM transmission experiments to achieve multi-Tbit/s transmission [3]. In long-haul transmission, POLMUX however suffers from cross phase modulation (XPM) which induces a polarization dependent nonlinear phase shift, or in other words depolarization [4, 5]. The detrimental influence of depolarization dominates over 'classic' XPM for POLMUX on-off-keying (OOK) and drastically influences polarization de-multiplexing at the receiver. As a result, POLMUX-OOK modulation is unsuitable for long-haul transmission. Differential phase shift keying (DPSK) on the other hand is less sensitive to XPM related impairments because the transmitted information is encoded in the phase of the signal. Ideally, the more constant power envelope reduces the influence of depolarization [6,7]. It has therefore been proposed that in POLMUX-DPSK the influence of depolarization should be reduced [8]. The results reported in [9] for POLMUX-NRZ-DPSK show that it can still suffer from depolarization impairments, although in lesser degree than observed for POLMUX-OOK modulation [5]. For POLMUX-RZ-DPSK modulation depolarization penalties should decrease even further, because of the more regular pulse shape.

In this paper we discuss the nonlinear tolerance of 21.4-Gbit/s POLMUX-RZ-DPSK and 21.4-Gbit/s POLMUX-RZ-OOK over an 800-km SSMF straight-line. We show that WDM depolarization penalties in POLMUX-RZ-DPSK are smaller than in 21.4-Gbit/s POLMUX-RZ-OOK modulation, possibly making it a suitable modulation format for long-haul transmission.

Experimental setup

The experimental setup is depicted in Fig. 1. The outputs of 1 to 9 external cavity lasers (ECL) on a 50-GHz grid (center wavelength at 1550.9 nm) are combined in a 16:1 coupler. A Mach-Zehnder modulator (MZM) driven with a 10.7-Gbit/s clock signal is used for pulse-carving with a 50% duty-cycle. A 10.7-Gbit/s 2^{31}-1 pseudo random bit sequence (PRBS) is used to drive a second MZM to generate either RZ-OOK or RZ-DPSK modulation, depending on the bias voltage and drive signal amplitude swing applied to the modulator. The signal is subsequently polarization-multiplexed by splitting the signal, delaying one tributary with 23 ns and then recombining both tributaries with orthogonal polarizations [10]. Before transmission, the channels are de-correlated with -510 ps/nm of pre-compensation. The transmission line consists of eight 100 km spans of standard single mode fiber (SSMF) and after each span a DCF module is used to compensate for the chromatic dispersion with an average under-compensation per span of 78.4 ps/nm. The loss of the SSMF spans and DCF varied between 21 dB…24 dB and 8 dB…11 dB, respectively. EDFA amplification is used to compensate for the fiber insertion loss. After transmission, the accumulated dispersion is compensated to approximately 0 ps/nm. Before the receiver a 0.3-nm channel selection filter (CSF) removes the out-of-band noise. POLMUX-RZ-DPSK and POLMUX-RZ-OOK modulation are manually polarization de-multiplexed using a polarization beam splitter (PBS) preceded by a polarization controller (PC). For RZ-DPSK the detector consists of a Mach-Zehnder delay interferometer (MZDI) with a 1-bit delay (93.5 ps) followed by balanced detection. For RZ-OOK normal direct detection is used. After clock recovery (CR), the transmission performance is assessed using a 10.7-Gbit/s BER tester.

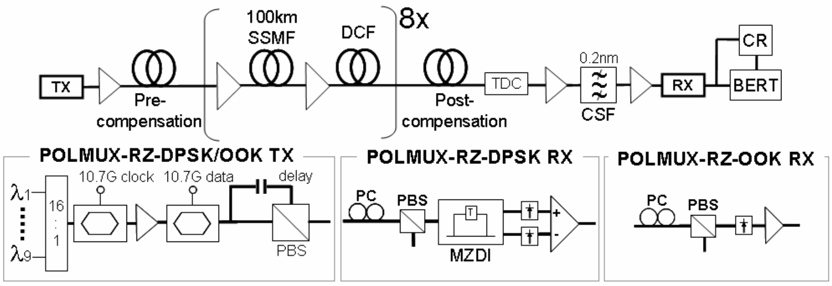

Fig. 1: Setup of the 800-km transmission line and 21.4-Gbit/s POLMUX-RZ-DPSK and POLMUX-RZ-OOK transmitter and receiver

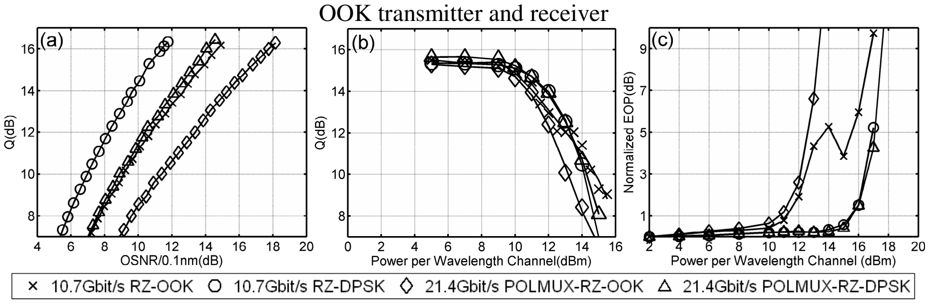

Fig. 2: (a) measured back-to-back sensitivity; (b) measured and (c) simulated nonlinear tolerance for single channel 800 km transmission.

Experimental results

For an 800-km long transmission link the effect of nonlinear impairments cannot be clearly observed in normal operation, hence their effect is increased by using high launch powers into the SSMF fiber. To exclude nonlinear impairments in the DCF the launch power is reduced by 10 dB with respect to the SSMF launch power with a minimum total launch power of 0 dBm.

Fig 2a show the back-to-back sensitivity of 10.7-Gbit/s RZ-OOK, 10.7-Gbit/s RZ-DPSK, 21.4-Gbit/s POLMUX-RZ-OOK and 21.4-Gbit/s POLMUX-RZ-DPSK. The RZ-DPSK modulation formats have a ~3-dB OSNR improvement over RZ-OOK. Doubling the data rate through POLMUX transmission reduces the sensitivity with about 2.5 dB; a 3-dB reduction resulting from the doubled data rate and a 0.5-dB sensitivity improvement due to the use of polarization sensitive detection. In order to compare the performance for different launch powers the optical signal-to-noise ratio (OSNR) is artificially kept constant at the receiver by noise loading. In the following measurements the received OSNR is chosen such that the back-to-back Q-factor is approximately 15.6 dB (10^{-9} BER). This results in 11 dB for 10.7-Gbit/s RZ-DPSK, 14 dB for 10.7-Gbit/s RZ-OOK and 21.4-Gbit/s POLMUX-RZ-DPSK and 17 dB for 21.4-Gbit/s POLMUX-RZ-OOK. The nonlinear tolerance is now defined as the channel launch power resulting in a 10-dB Q-factor.

Figures 2b and 2c show the measured and simulated single channel nonlinear tolerance with the same link parameters, respectively. In the simulations depicted in Fig. 2c an ideal signal shape is used, which does not take modulator imperfections and nonlinear phase noise interaction into account. Comparing Figures 2b and 2c shows that the simulated nonlinear tolerance for RZ-DPSK is higher than the measured tolerance, whereas simulations and measurement show a similar performance for RZ-OOK. Hence, the ideal simulated pulse shape has a large impact on RZ-DPSK whereas for RZ-OOK it still yields a good comparison with the measured results. However in both simulations and experiment the nonlinear tolerance of RZ-OOK and RZ-DPSK shows a penalty for RZ-OOK, which is a result of the more constant power envelope for RZ-DPSK, reducing the influence of self phase modulation (SPM). The fluctuations in nonlinear penalty for RZ-OOK with increasing launch powers are a result of quasi-soliton transmission in the single channel case. Where POLMUX-RZ-DPSK has a negligible measured penalty in comparison to RZ-DPSK, POLMUX-RZ-OOK suffers about a 2-dB penalty compared with RZ-OOK, which is a result of the quasi ‘3-level’ amplitude modulation in POLMUX-RZ-OOK. This increases the influence of SPM induced impairments and hence lowers the nonlinear tolerance [5].

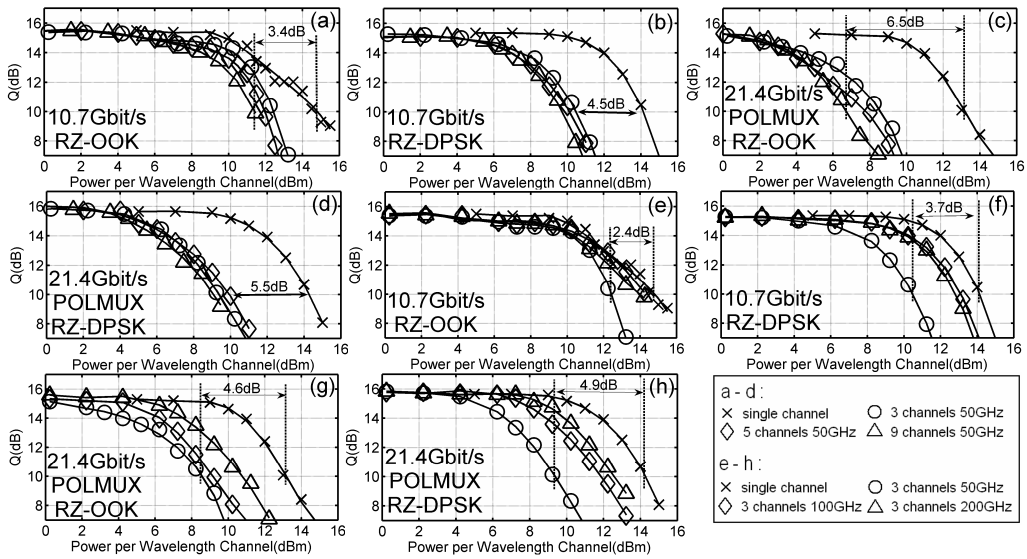

Fig. 3: Measured nonlinear tolerance (a-d) with 1, 3, 5 and 9 co-propagating channels on a 50-GHz grid and (e-h) with single channel and 3 co-propagating channels on a 50, 100 and 200-GHz grid.

Figures 3a-d shows the Q-factor as a function of the channel launch power for 9 co-propagating channels. Comparing transmission with a single channel and 9 co-propagating channels the nonlinear tolerance is decreased by 3.4 dB and 4.5 dB for RZ-OOK and RZ-DPSK,

respectively. This decrease results from inter-channel impairments such as XPM and crosstalk from neighboring channels due to the 16:1 coupler. For RZ-DPSK, the large inter-channel penalty could partially be a result of the high launch powers used in this comparison, enhancing the influence of XPM induced nonlinear phase noise. In long-haul transmission with lower launch powers per span these penalties might be further reduced. We now compare the nonlinear tolerance for nine co-propagating channels at 50-GHZ spacing between the different modulation formats. The measured results for RZ-OOK (Fig. 3a) and POLMUX-RZ-OOK (Fig. 3c) show a 2.9-dB difference. A comparison between RZ-DPSK (Fig. 3b) and POLMUX-RZ-DPSK (Fig. 3d) on the other hand shows only an additional 1-dB depolarization penalty for POLMUX-RZ-DPSK. This indicates the smaller depolarization influence for POLMUX-RZ-DPSK in comparison to POLMUX-RZ-OOK.
Figures 3e-h depict the nonlinear tolerance for 3 co-propagating channels with a 50-GHz, 100-GHz and 200-GHz channel spacing in order to compare the influence of different channel spacing. For both RZ-OOK (Fig. 3e) and RZ-DPSK (Fig. 3f) the largest inter-channel impairments are measured for a 50-GHz channel spacing, whereas for a larger channel spacing almost no penalty is observed. With POLMUX-RZ-OOK (Fig. 3g) and POLMUX-RZ-DPSK (Fig. 3h) on the other hand impairments are also measured at a 100-GHZ and 200-GHz channel spacing, where the influence of 'classic' XPM is minimal. This is a typical characteristic of the depolarization in POLMUX transmission; it can results in a decreased nonlinear tolerance for larger channel spacing. Comparing the nonlinear tolerance for a 100-GHz and 200-GHz channel spacing the difference is 1.6 dB for POLMUX-RZ-OOK. For RZ-OOK on the other hand almost no difference is measured, which shows the impact of depolarization in POLMUX transmission. POLMUX-RZ-DPSK shows merely some residual depolarization of the POLMUX signal and in comparison to RZ-DPSK only a 0.4 dB higher penalty is measured.

4. Conclusions

In this paper, we compared single and multi-channel nonlinear transmission penalties over an 800-km straight-line of SSMF for 21.4-Gbit/s POLMUX-RZ-OOK and POLMUX-RZ-DPSK. To assess the influence of polarization multiplexing on the respective nonlinear tolerance 10.7-Gbit/s RZ-OOK and RZ-DPSK are used as a reference.
For single channel transmission, both 10.7-Gbit/s RZ-OOK and RZ-DPSK modulation show a high nonlinear tolerance. However, where the introduction of POLMUX has a negligible penalty for RZ-DPSK, RZ-OOK suffers a 2-dB penalty when the signal is polarization-multiplexed. For multi-channel transmission only a small depolarization penalty is measured for 21.4-Gbit/s POLMUX-RZ-DPSK modulation, where POLMUX-RZ-OOK suffers from a significant reduction in nonlinear tolerance due to depolarization. We conclude that in combination with the 3-dB OSNR advantage of DPSK transmission, POLMUX-RZ-DPSK has more potential as a modulation format for future long-haul transmission systems.

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