Transmission of 240 Gb/s PM-RZ-D8PSK over 320 km in 10 Gb/s NRZ-OOK WDM System

E. Tipsuwannakul, M. Sköld, M. Karlsson, P. Andrekson
Dept. of Microtechnology and Nanoscience (MC2), Photonics Laboratory, Chalmers University of Technology, SE – 412 96 Gothenburg, Sweden, ekawit@chalmers.se

Abstract: We present the first demonstration of 40 Gbaud PM-RZ-D8PSK and its successful transmission in a 100 GHz-spaced 10 Gb/s NRZ-OOK WDM system over a 320-km transmission link along with the studies of WDM nonlinear crosstalk.

OCIS codes: (060.4510) Optical communication; (060.5060) Phase modulation

1. Introduction

In recent years, a lot of research has focused on multilevel Phase Shift Keying (PSK) using both coherent and differential detections due to its spectral efficiency and robustness towards fiber nonlinearity [1]. While coherent detection benefits from electronic post processing e.g. Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) compensations, the limited bandwidth of real time digital signal processing restricts most of the studies to be conducted using offline processing [2]. Differential detection, on the other hand, offers online capability at very high baud-rates e.g. 53.5 Gbaud differential quadrature PSK (DQPSK) [3]. Higher order formats such as differential 8-level PSK (D8PSK) have also been reported but at lower baud-rate [4,5]. Combined with its lower receiver complexity and cost (potentially in the order of DQPSK) [6], this detection scheme can be more attractive for near term commercialization.

In this paper, 240 Gb/s Polarization Multiplexed (PM) Return to Zero (RZ) D8PSK, with a corresponding record baud-rate of 40 Gbaud, is for the first time experimentally demonstrated along with the studies of the BER performance in a single wavelength back-to-back transmission and the WDM nonlinear crosstalk induced by four co-propagating 10 Gb/s NRZ On/Off Keying (OOK) channels over a 320 km transmission link. Furthermore, we also compare the performance with 40 Gbaud PM-RZ-DQPSK (corresponding to 160 Gb/s) using the same setup.

2. Experimental Setup

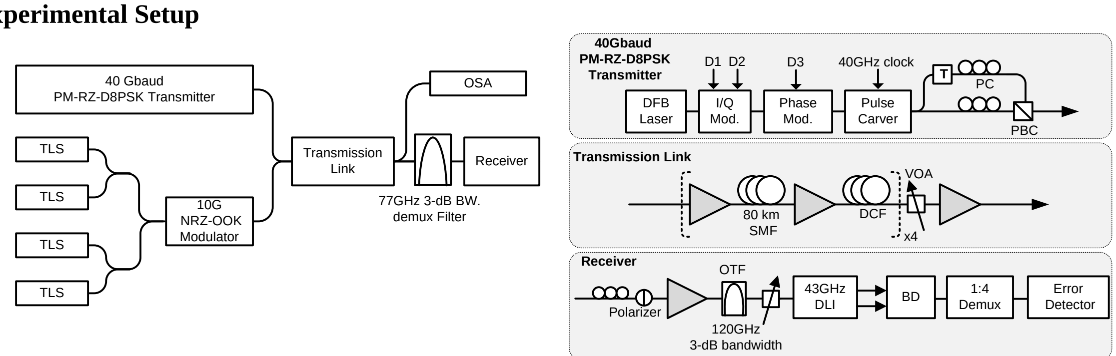

Fig. 1. Experimental setup of the investigated system

As illustrated in Fig. 1, the PM-RZ-D8PSK transmitter consisted of a 1 MHz linewidth DFB laser followed by a 31 GHz I/Q modulator, a 35 GHz phase modulator, and a chirp-free Mach-Zehnder Modulator (MZM) for 50% duty cycle pulse carving. The I/Q modulator was driven by two of 40 Gb/s binary data streams (D1 and D2), providing 40 Gbaud DQPSK signal at the output. The following phase modulator was driven by the third 40 Gb/s binary data stream (D3) creating a $\pi/4$ phase shift to generate the D8PSK signal. Polarization multiplexing was realized by a 3-dB coupler, a variable optical delay, two Polarization Controllers (PCs), and a Polarization Beam Combiner (PBC). All data streams (D1, D2, and D3) were decorrelated Pseudo Random Bit Streams (PRBS) with a length of 2^{11}-1.

The transmission link was realized by four spans of an 80 km standard single mode fiber (SSMF) and double-stage Erbium-doped fiber amplifiers (EDFAs) with a dispersion compensation fiber (DCF) in between. The average loss of SSMFs and DCFs in each span were 18 and 12 dB respectively. A variable optical attenuator (VOA) and the EDFA located after the four spans were used to vary the optical to noise ratio (OSNR) into the receiver. A demux filter (77 GHz 3-dB bandwidth flat top filter) was used to demultiplex the phase modulated signal into the receiver.

At the receiver, the signal was polarization demultiplexed by a polarizer. A delay line interferometer (DLI) with a free spectral range (FSR) of 43 GHz performed differential demodulation and the demodulated signal was detected by a 40 GHz balanced detector. The detected signal were electronically demultiplexed by a 1:4 demultiplexer and fed into the error detector programmed with the expected differentially demodulated bit patterns. The signal power into the balanced detector was kept constant by the second VOA in front of the DLI.

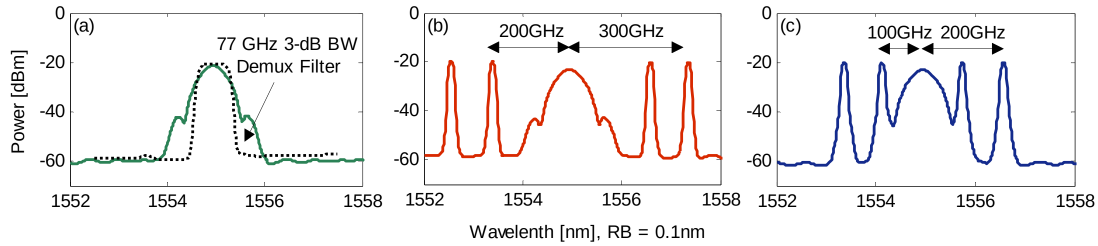

Fig. 2. The transmitted spectra of 40 Gbaud PM-RZ-D8PSK signal in (a) a single wavelength system, 100 GHz-spaced WDM systems with (b) 200 GHz, and (c) 100 GHz separation to the nearest channels.

Fig.2 depicts the transmitted signal spectra of 40 Gbaud PM-RZ-D8PSK in three different scenarios: (a) the single wavelength system, 100 GHz-spaced WDM systems with (b) 200 GHz, and (c) 100 GHz separation to the nearest channels. The co-propagating signals were realized by introducing four of 10 Gb/s NRZ-OOK signals in the adjacent channels via a 3-dB coupler. These neighboring signals were generated using four tunable laser sources (TLSs) followed by a MZ modulator, which was driven by 10 Gb/s PRBS 2^{31}-1 data stream. The power per WDM channel per polarization was adjust to be equal.

3. Back-to-back performance

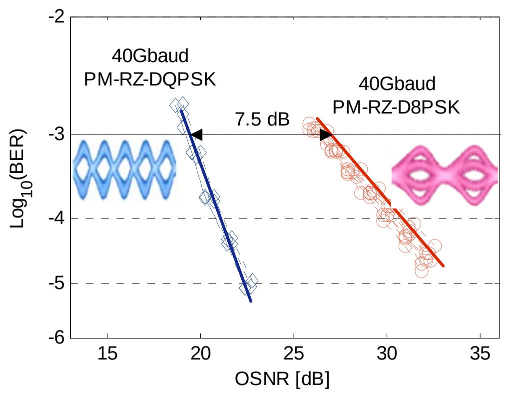

Fig. 3. BER as a function of OSNR in back-to-back transmission of 40 Gbaud PM-RZ-DPQSK/D8PSK without the demux filter together with eye diagrams (insets).

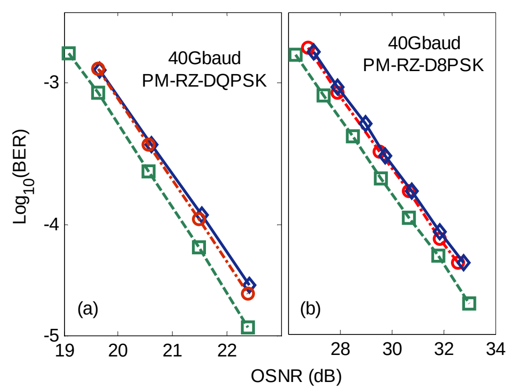

Fig. 4. BER as a function of OSNR in back-to-back transmission of 40 Gbaud PM-RZ-DPQSK/D8PSK in the single wavelength system with (circles) and without (squares) the demux filter and in the WDM system (diamonds) with 100 GHz separation to the nearest channels.

Fig. 3 shows the experimental results of 40 Gbaud PM-RZ-D8PSK in the single wavelength back-to-back transmission without the demux filter in comparison to 40 Gbaud PM-RZ-DQPSK. The dashed lines represent the measured error rates corresponding to binary decision thresholds as a function of OSNR of all tributaries for the two modulation formats. Each tributary was measured individually by applying phase offsets to one arm of the DLI ($\pm\pi/4$ for DQPSK, and $\pm\pi/8$, $\pm 3\pi/8$ for D8PSK) on the orthogonal polarizations, resulting in 4 and 8 curves for polmux system, respectively. By assuming that Gray coding is implemented and symbol errors only occur between nearest neighbors, BER (solid lines) of the system is the average of the dashed lines for DQPSK but the average multiplied by 4/3 for D8PSK [4].

The required OSNR at the Forward Error Correction (FEC) threshold (BER = 10^{-3}) are found to be 19.5/27.0 dB for 40 Gbaud PM-RZ-DQPSK/D8PSK. These sensitivities are 1.6 and 3.5 dB (1.5 and 3.2 dB theoretically) higher than those of 28 Gbaud DQPSK and 18.7 Gbaud D8PSK in [5]. According to theory, the asymptotic difference in sensitivity between DQPSK and D8PSK is estimated to be 6.4 dB [7]. The excess penalty found in this experiment (1.1 dB for BER = 10^{-3} and 3.6 dB for BER = 10^{-4}) is likely caused by the extra phase modulator and the 1:4 demultiplexer, which is designed for binary rather than multi-level input signal as is in the D8PSK system.

The impact of the demux filter and linear crosstalk from adjacent channels in the back-to-back transmission is illustrated in fig. 4. The lines marked with circles and squares represent the BER performances of the two modulation formats with and without the demux filter in the single wavelength system. The lines marked with diamonds correspond to those of the two formats in the WDM system as shown in fig. 2c. The penalty caused by the demux filter at the FEC threshold are found to be 0.3/0.7 dB for 40 Gbaud PM-RZ-DQPSK/D8PSK. The impact of linear crosstalk from co-propagating channels is, however, negligible for both modulation formats. The slightly smaller filtering tolerance of the D8PSK system is due to narrower angular distance between symbols.

4. WDM Nonlinear Crosstalk

For the WDM nonlinear crosstalk, three different configurations as shown in fig. 2 were investigated. The input powers into DCFs were kept 5 dB lower than those into SSMFs, which is a compromise between OSNR and nonlinearity. The power per WDM channel per polarization was adjusted to be equal. The BER and required OSNR curves depicted in fig.5 are computed from the measured error rates from all tributaries as mentioned in section 3.

Fig 5a shows the result of the BER performance as a function of launch power per channel per polarization of 40 Gbaud PM-RZ-D8PSK along with the corresponding curves in the single polarization (SP) system. The curves illustrate the optimal launch power, which represents the trade-off between OSNR and the impact of nonlinearity. It also shows that the WDM nonlinear crosstalk decreases with increasing channel spacing. This is due to that the cross phase modulation (XPM)-induced nonlinear phase shift grows with the walk-off distance. In addition, it depicts less tolerance to nonlinearity in the polmux system (compared to the single-pol system), which is partly due to 3 dB higher total launch power. Nevertheless, BER performances for all cases at the optimal launch power are below the FEC threshold (BER = 10^{-3}).

Fig 5b presents the required OSNR for BER = 10^{-3} of the 40 Gbaud D8PSK/DQPSK as a function of launch power per channel per polarization in both single-pol and polmux systems. Due to narrower angular distance between symbols of D8PSK, less robustness (compared to DQPSK) to WDM nonlinear crosstalk can be observed from the figure in both single-pol and polmux systems.

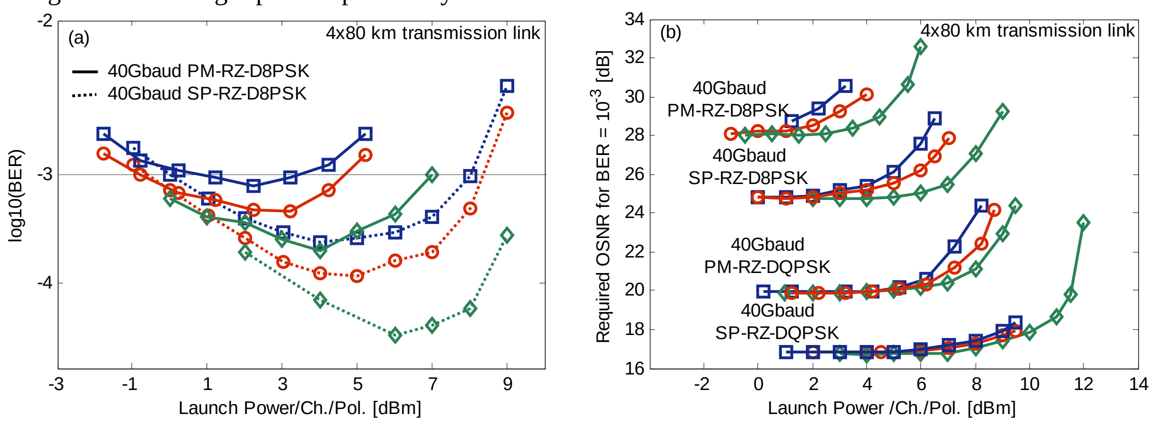

Fig. 5. (a) BER, and (b) required OSNR for BER = 10^{-3} of 40 Gbaud PM-RZ-D8PSK as a function of launch power per channel per polarization over 320 km along with other modulation formats in three different configuration: (diamonds) the single wavelength system, 100 GHz-spaced WDM systems with (circles) 200 GHz, and (squares) 100 GHz to the nearest channels.

5. Conclusion

We experimentally demonstrated, for the first time, 40 Gbaud (FEC included) PM-RZ-D8PSK along with PM-RZ-DQPSK at the same baud-rate and the feasibility of its transmission in a 100 GHz-spaced 10Gb/s OOK WDM system over a 320 km transmission link. We also show that the impact of WDM nonlinear crosstalk on the phase modulated signals decreases with increasing channel spacing. In addition, we found that D8PSK is more sensitive to nonlinearity compared to the DQPSK in both single polarization and polarization multiplexing systems. This work was supported by Swedish Foundation for Strategic Research (SSF), the Swedish Governmental Agency for Innovation Systems (VINNOVA) within the 100 GET program, and the Knut and Alice Wallenberg Foundation.

4. References

[1] P. J. Winzer et al.," Advanced Optical Modulation Formats", Proc. IEEE 94 (5), 2006, pp.952-985

[2] P. J. Winzer et al.,"56-Gbaud PDM-QPSK: Coherent Detection and 2,500-km Transmission", ECOC, 2009, PD2.7

[3] H. Hu et al.,"107 Gb/s RZ-DQPSK Signal Transmission over 108 km SMF Using Optical Phase Conjugation in an SOA", OFC, 2009, OThF6

[4] C. Kim et al., "WDM Transmission over 320 km EDFA-Amplified SSMF Using 30 Gb/s Return-To-Zero Optical Differential 8-Level Phase-Shift-Keying (OD8PSK)", Opt. Express 13 (11), 2004, pp. 4044 – 4049

[5] E. Tipsuwannakul et al.,"Comparison of 112 Gb/s PM-RZ-DQPSK and PM-RZ-D8PSK in Terms of OSNR Requirement and Transmission Impairments", to appear in Photon. Technol. Lett.

[6] Y. Han et al.,"Simplified receiver implementation for optical differential 8-level phase-shift keying", El. Lett. 40 (2), October, 2004

[7] R. F. Pawula et al.,"Distribution of the Phase Angle Between Two Vectors Perturbed by Gaussian Noise", *IEEE Trans. Commun.*, COM-30 (8), 1982, pp. 1828 – 1841.