Influence of Pulse Shape in 112-Gb/s WDM PDM-QPSK Transmission

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***Abstract*—In this work, we investigated the influence of pulse shape on the transmission performance of polarization-division-multiplexed quadrature-phase-shift keying modulation format at 112 Gb/s in a ten-channel wavelength-division-multiplexed (WDM) transmission experiment with 50-GHz channel spacing. Nonreturn-to-zero (NRZ) and return-to-zero with 50% duty cycle (RZ50) were compared. RZ50 was found to have better performance in both single-channel and WDM experiments. Compared with NRZ, the use of RZ50 yielded an increase in reach from 6560 to 7760 km in the single-channel experiment (corresponding to an increase in reach by 18%); in the case of WDM. the reach was extended from 5920 to 7360 km (corresponding to a 24% increase in reach).**

***Index Terms*—Advanced modulation formats, coherent optical communications, digital signal processing.**

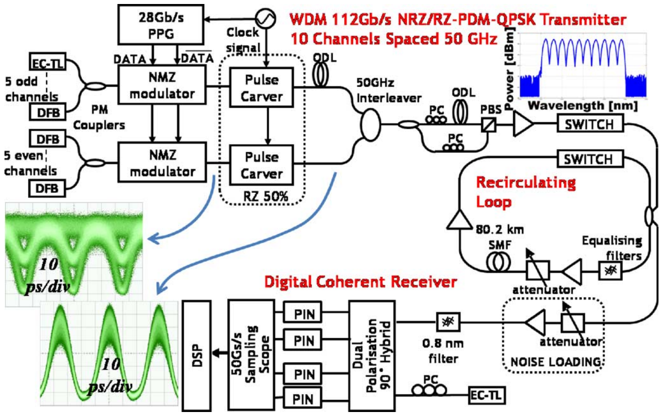

Fig. 1. Experimental setup for 112-Gb/s PDM-QPSK WDM transmission with NRZ and RZ50 pulse shapes.

I. INTRODUCTION

ADVANCED modulation formats in combination with wavelength-division multiplexing (WDM) and coherent detection are key enablers to achieve longer reach, larger capacity, and higher spectral efficiency. Much focus has been devoted to quadrature-phase-shift keying (QPSK) as a modulation format to obtain 100-Gb/s rates, essential for future optical networks. QPSK can be generated with relatively low complexity using commercially available modulators driven with binary signals, and is noise and nonlinearity tolerant, compared with multilevel modulation formats.

Although various research groups have demonstrated high performance transmission results for QPSK at 100 Gb/s and higher, both in terms of maximum reach and capacity [1]–[3], little investigation into the impact of pulse shapes on QPSK transmission has been carried out. An advantage of using RZ-QPSK instead of nonreturn-to-zero (NRZ)-QPSK stems from its wider spectrum, which reduces phase-matching between adjacent frequency components during propagation through dispersive media, and increases the tolerance to nonlinearity [4]. This effect has been experimentally demonstrated in [5], where for a fixed transmission distance of 1600 km over dispersion-managed link the use of WDM RZ-QPSK did not affect the maximum Q-factor, but improved the Q-factor margin. For a single channel, the results in [6] demonstrated that RZ-QPSK with interleaved polarizations performed better than NRZ-QPSK with aligned polarizations for a fixed distance of 1200 km over dispersion-managed link with low dispersion fiber.

In this work, we have carried out an investigation of transmission performance of 112-Gb/s single-channel and WDM NRZ and return-to-zero with 50% duty cycle (RZ50) polarization-division-multiplexing (PDM)-QPSK over an uncompensated link, focusing on the maximum achievable reach.

II. 112-Gb/s WDM PDM-QPSK TRANSMISSION SETUP

figThe experimental setup used for WDM-PDM-QPSK transmission is shown in Fig. 1. First, a WDM comb with 50-GHz spacing between the wavelengths was generated using nine distributed-feedback (DFB) lasers and an external cavity laser (EC-TL) with a linewidth of 100 kHz (measured using a self-heterodyne technique), acting as a central channel under test. To generate the odd and even QPSK channels four 28-Gb/s data outputs of the pulse pattern generator (PPG) were amplified to 7 Vp-p to drive two nested Mach–Zehnder (NMZ) modulators over 2 $V\pi$. The pattern length of the PPG was set to $2^{15} - 1$; I and Q parts were decorrelated by 42 symbols. The generated NRZ-QPSK signals at 28 Gbaud were then

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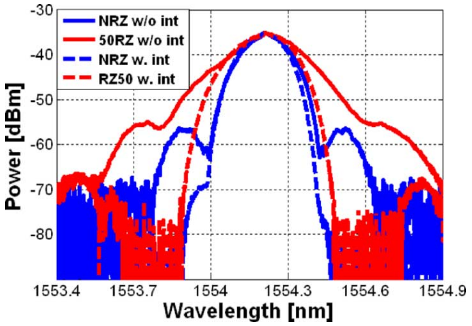

Fig. 2. Measured spectrum for 112-Gb/s NRZ and RZ50 PDM-QPSK (solid curve—without interleaver; dashed curve—with interleaver).

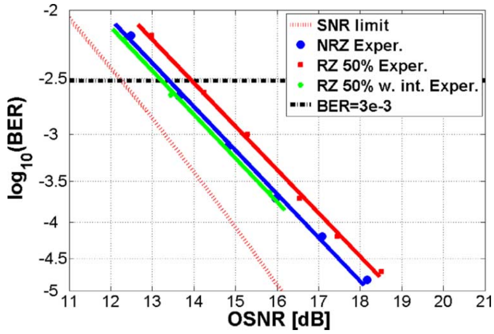

Fig. 3. Back-to-back receiver sensitivity for 112-Gb/s single-channel NRZ and RZ50 PDM-QPSK.

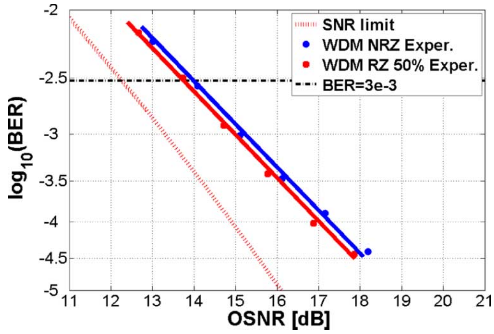

Fig. 4. Back-to-back receiver sensitivity for 112-Gb/s WDM NRZ and RZ50 PDM-QPSK (measured for the central channel).

passed through an optional block of pulse carving. To generate RZ50-QPSK, the MZ modulators were driven with a full clock (28 GHz) with $Vp\text{-}p = 5$ V ($V\pi$ of the MZ modulator) with a bias point set in the middle point (in terms of amplitude) of the modulator transfer function. Odd and even channels were then decorrelated by several hundreds of symbols via additional optical fiber (ODL) and combined using a 50-GHz interleaver (with a 3-dB bandwidth of 30 GHz). Spectra of 112-Gb/s NRZ- and RZ50-QPSK with and without the interleaver are shown in Fig. 2. To obtain a PDM-QPSK signal, a passive delay-line stage with adjustable states of polarization (PC) for signals in each arm was used; the two QPSK signals were decorrelated by 63 symbols and recombined via a polarization beam splitter (PBS).

The resultant 112-Gb/s QPSK WDM signal was launched into a recirculating loop consisting of 80.2 km of single-mode fiber (SMF) span with a chromatic dispersion of 1347 ps/nm and 15.4-dB loss (the total loop loss was 23.5 dB per recirculation). The noise figure of the erbium-doped fiber amplifiers (EDFAs) in the loop was ~4.5 dB. Within the loop, the gain flattening MZ-type filters were used to equalize a WDM signal after each recirculation. After the loop we used an optical filter with a bandwidth of 0.8 nm to limit the power at the input of the photodiodes (PINs). For the back-to-back measurements, a noise-loading stage was also used to set the received OSNR. A polarization- and phase-diverse coherent receiver was then used to detect the in-phase and quadrature components of two orthogonal polarizations. The power difference between the signal and the local oscillator (LO) (linewidth measured to be 80 kHz) was set to 20 dB, as described in [7]. The beating signal was detected with single-ended PINs with a bandwidth of 30 GHz, digitized using a Tektronix real-time scope at 50 GSamples/s (with an analog bandwidth of 16 GHz), and processed offline in Matlab.

For the digital signal processing (DSP), linear algorithms similar to those described in [8] were used. Chromatic dispersion was compensated using finite impulse response (FIR) filters. Adaptive equalization was performed to invert the channel frequency response and recover the clock phase using a constant modulus algorithm (CMA) with a least mean square (LMS) tap weight update. We used *a priori* knowledge of clock frequency at the transmitter and sampling rate of the ADCs; this estimation which was sufficiently accurate over the length of the measurement window. Carrier phase estimation was performed using a modified Viterbi & Viterbi algorithm [9], [10]. Transmission measurements were performed assuming a forward error correction rate of 3×10^{-3}.

III. Transmission Results and Discussion

First the receiver sensitivity for the single-channel QPSK experiment was characterized and is shown in Fig. 3 where the bit-error rate (BER) is plotted as a function of optical signal-to-noise ratio (OSNR). In the case of NRZ-QPSK the implementation penalty (at $\mathrm{BER} = 3 \times 10^{-3}$) was measured to be 1.2 dB; for RZ50, the implementation penalty increased to 1.8 dB. This difference can be attributed to the limited analog bandwidth (16 GHz) of the analog-to-digital converters (ADCs). For a 28-Gbaud QPSK signal lower duty cycles result in wider spectra, which means that RZ50-QPSK is affected more by the ADC bandwidth limitation, compared with NRZ-QPSK. When using an interleaver we saw an improvement in the RZ50-QPSK back-to-back performance by 0.8 dB (the use of interleaver did not affect the back-to-back performance for NRZ). This is due to the fact that the narrow optical filtering at the transmitter converts an RZ pulse into a high quality NRZ signal with less intersymbol interference, compared with a conventional NRZ signal subjected to narrow optical filtering [11]. In the case of WDM implementation penalties of 1.6 and 1.8 dB were measured for RZ50-QPSK and NRZ-QPSK, respectively (Fig. 4).

Next, the maximum achievable distances as functions of power were measured for the single-channel transmission and the results are shown in Fig. 5 for the two pulse shapes. For lower input powers the transmission performance was limited due to ASE noise accumulation in the loop; for higher input powers the performance was limited due to intrachannel nonlinearity. The optimum launch power was found to be −3.5 dBm

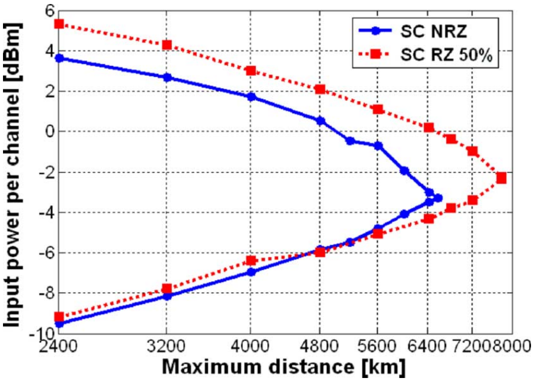

Fig. 5. Maximum distance as function of fiber input power in 112-Gb/s single-channel PDM-QPSK transmission experiment with NRZ and RZ50 pulse shapes.

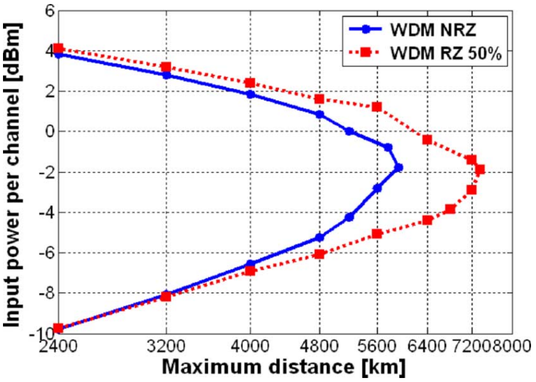

Fig. 6. Maximum distance as a function of the input launch power in a 112-Gb/s WDM-PDM-QPSK transmission experiment with NRZ and RZ50 pulse shapes (measured for the central channel).

for NRZ-QPSK and -2 dBm for RZ50-QPSK. An increased optimum launch power for RZ50-QPSK is due to its higher tolerance to intrachannel nonlinearity. The relative back-to-back penalty between NRZ-QPSK and RZ50-QPSK was translated into the linear part of the transmission curve, e.g., 0.6-dB difference in the required OSNR between NRZ-QPSK and RZ50-QPSK results in a similar difference in the required input power for a fixed distance. Overall, the use of RZ50-QPSK led to an increase in the maximum reach from 6560 to 7660 km, compared with NRZ-QPSK.

Next, WDM PDM-QPSK measurements were carried out also focusing on the maximum reach, with the results shown in Fig. 6. These measurements were performed for the central WDM channel (channel 6); however, for the case of NRZ-QPSK transmission we also measured the BER on every channel, which was found to be less than the FEC of 3×10^{-3} for every channel. For low input powers (e.g., -10 dBm) WDM-QPSK performs slightly better than QPSK in a single-channel configuration; this is due to the different operating point of the EDFAs in single-channel and WDM experiments. The optimum launch power for both pulse shapes was found to be approximately -2 dBm. We also observed a smaller difference between NRZ- and RZ50-QPSK performances in the nonlinear part of the reach curve, compared to the single-channel experiment. This can be attributed to the presence of interchannel nonlinearities, which are the dominant source of impairments in the case of WDM transmission. However, similar to a single-channel experiment, RZ50-QPSK has a higher nonlinear threshold, compared to NRZ-QPSK. Therefore, the use of RZ50-QPSK in WDM transmission yielded improved overall performance and resulted in an increase in the maximum reach from 5920 to 7360 km, compared with NRZ-QPSK.

IV. CONCLUSION

The impact of pulse shapes in a 112-Gb/s single-channel and ten-channel WDM PDM-QPSK transmission has been investigated. We found that RZ50 yields an improvement in terms of maximum reach in both single- and WDM transmission experiments. In the case of a single-channel experiment, the use of RZ50-QPSK allowed to increase the maximum reach from 6560 to 7760 km (18% increase) compared with NRZ-QPSK. In the case of WDM, the maximum reach was increased from 5920 to 7360 km (24% increase). Despite an additional pulse carver for RZ50-QPSK and potential disadvantages associated with its wider spectrum (reduced spectral efficiency, increased linear WDM crosstalk, lower tolerance to optical add–drop multiplexer concatenation and the need for higher speed ADCs at the receiver), its use is justified by the improvement in the transmission margin in both single-channel and WDM configurations.

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