11 x 224 Gb/s POLMUX-RZ-16QAM transmission over 670 km of SSMF with 50-Ghz channel spacing

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11 × 224-Gb/s POLMUX-RZ-16QAM Transmission Over 670 km of SSMF With 50-GHz Channel Spacing

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***Abstract*—We demonstrate the generation and transmission of 11 channels with 224-Gb/s polarization-multiplexed return-to-zero 16-level quadrature amplitude modulation over 670 km of standard single-mode fiber (SSMF) with 50-GHz channel spacing and a spectral efficiency of 4.2 b/s/Hz. We report a penalty of around 4.3 dB in the performance at back-to-back in comparison to the theoretical limits, and a margin of 1 dB in Q-factor below the forward-error correction limit (assumed to be at a bit-error rate of 3.8×10^{-3}) after transmission over 670 km of SSMF.**

***Index Terms*—Coherent detection, polarization multiplexing (POLMUX), pulse amplitude modulation (PAM), 16-level quadrature amplitude modulation (16QAM).**

I. Introduction

THE combination of polarization-multiplexed (POLMUX) return-to-zero (RZ) quadrature phase-shift keying (QPSK), coherent detection, and digital signal processing has established itself in recent years as the most favorable solution to realize 100-Gb/s line rates on a 50-GHz channel grid [1]–[3]. This technology enables a transport capacity of up to 8 Tb/s on a single fiber in currently deployed C-band transmission systems. To allow a further scaling in the transport capacity of long-haul optical transmission systems beyond this figure, a further increase in the spectral efficiency (SE) represents the most attractive approach as long as a reasonable transmission reach can be maintained. This can be achieved either by increasing the line rate per wavelength channel [4]–[6] or by reducing the channel spacing between the wavelength-division-multiplexed (WDM) channels and consequently increasing the total number of transmitted WDM channels on a single fiber [6]–[9]. For the large installed base of transmission systems, only the increase of the line rate per WDM channel while maintaining the current 50-GHz channel spacing is a viable solution.

The most prominent modulation format to double the SE compared to 100-Gb/s POLMUX-QPSK modulation is polarization-multiplexed 16-level quadrature amplitude modulation (POLMUX-16QAM). WDM transmission of 112-Gb/s [7] and 171-Gb/s [5] POLMUX-16QAM has been demonstrated lately. Recently, Gnauck *et al.* proposed 224-Gb/s POLMUX-16QAM as a candidate modulation format to increase the line rate per WDM channel while maintaining the 50-GHz channel spacing [6]. In this letter, we describe transmission of 224-Gb/s POLMUX-16QAM over standard single-mode fiber (SSMF), which is used by the majority of currently deployed transmission systems. The 224-Gb/s POLMUX-16QAM consists of 208-Gb/s of payload as well as 7% of forward-error correction (FEC) overhead, resulting in an effective SE of 4.2-b/s/Hz. The 224-Gb/s POLMUX-16QAM modulation has the same symbol rate as 112-Gb/s POLMUX-RZ-QPSK, which means that it can take advantage from most of the optical and electrical components currently being developed for 112-Gb/s POLMUX-RZ-QPSK modulation.

In this letter, we show the generation of 224-Gb/s POMUX-RZ-16QAM modulation with a penalty of no more than 4.3 dB compared to the theoretical limits. Furthermore, we demonstrate the transmission of 50-GHz spaced 11 × 224-Gb/s POLMUX-RZ-16QAM modulated channels over 670 km.

II. System Setup

Our experimental setup is depicted in Fig. 1. As shown in Fig. 1(a), ten distributed-feedback (DFB) lasers and one external cavity laser (ECL) with wavelengths on the 50-GHz ITU grid, and ranging from 1548.5 and 1552.5 nm are grouped into odd and even channels using two arrayed waveguide gratings (AWGs). The ECL (with a linewidth of 100 KHz) is used for the channel under test at 1550.5 nm and the DFB lasers are used for the copropagating WDM channels. After the AWG, the two channel groups are first pulse carved using two Mach–Zehnder modulators (MZMs) driven with a 28-GHz clock signal. Subsequently, the two wavelength combs are modulated with 28-GBaud 16QAM using two in-phase, quadrature-phase (IQ) modulators. The Fujitsu FTM7961EX modulators used have a V_{pi} of ∼2.2 V as well as an optical bandwidth of >33 GHz. In order to generate the 28-GBaud 16QAM optical signal, the IQ modulators are driven with four-level pulse amplitude modulated (PAM) signals, which are generated using the two bit digital-to-analog converters (DACs) [6], [7] shown in Fig. 1(b). Fig. 1(b) shows two DAC configurations used for the generation of single- and multichannel 16QAM. The input signals to the DACs consist of 28-GBaud binary pseudorandom binary sequence (PRBS) signals with a pattern length of $2^{15}-1$ bits. The amplitude of the 4-PAM signals is ∼ 2.8 Vp-p. Due to the cascade of many discrete components in the DACs with an electrical bandwidth in the order of 25–26 GHz, the rise

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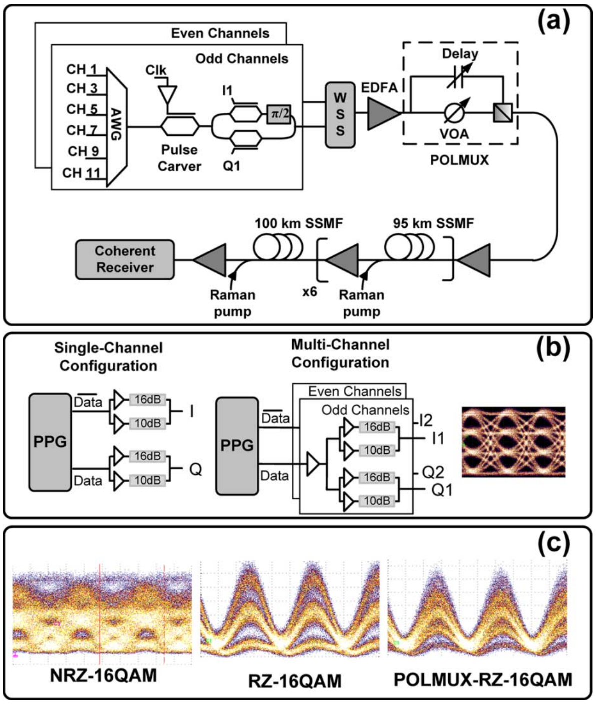

Fig. 1. Experimental setup. (a) Transmitter and transmission link. (b) Generation of the 4-PAM driving signal. (c) 16QAM eye diagrams. Clk: clock; VOA: variable optical attenuator; PPG: pulse pattern generator.

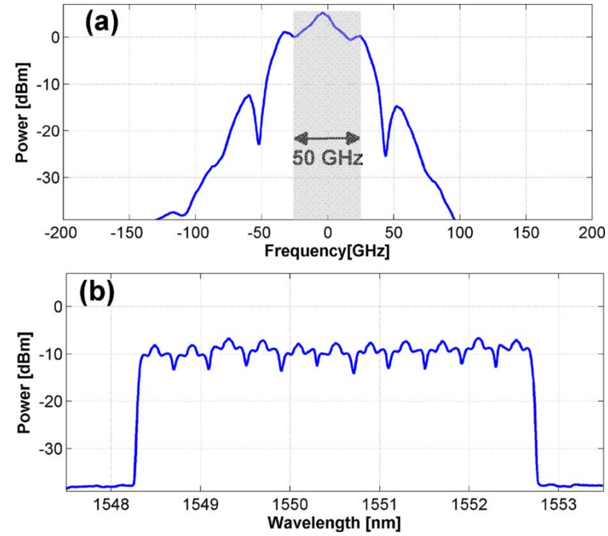

Fig. 2. POLMUX-RZ-16QAM optical spectrum: (a) single channel and (b) 11 WDM channels on a 50-GHz grid.

and fall times for the 28-GBaud 4-PAM signals are strongly increased. In order to alleviate this problem, we applied RZ pulse carving to the signal. The nonreturn-to-zero (NRZ) and RZ eye diagrams in Fig. 1(c) exhibit the improvement in the signal quality obtained through pulse carving.

The two wavelength combs of RZ-16QAM-modulated channels at the output of the two IQ modulators are combined on a 50-GHz channel grid using a wavelength-selective switch (WSS) which is used as well to equalize the channels powers. Finally, a POLMUX stage, consisting of a 50/50 splitter, a delay line, and a polarization beam splitter [Fig. 1(a)], is used to polarization-multiplex the signals at the output of the WSS. Fig. 2(a) and (b) illustrates the optical spectrum of the single- and eleven-channel POLMUX-RZ-16QAM, respectively, at the transmitter side.

The optical transmission link consists of six spans of 95 km of SSMF followed by a single 100-km span of SSMF with span losses varying between 18 and 20 dB. Hybrid erbium-doped fiber amplification (EDFA) and Raman amplification scheme has been employed in this link [Fig. 1(a)] with an average ON–OFF Raman gain of ∼11 dB. At the receiver side, a coherent receiver consisting of an ECL local oscillator, with a linewidth of 100 KHz, and a polarization diversity IQ-mixer with balanced photodiodes has been used [2], [4]–[7]. The four outputs from the coherent receiver are sampled at a sampling rate of 50 GSample/s using a real-time digital sampling scope [(DSA) 72004], and 10^6 samples ($\sim 4 \times 10^6$ bits) are saved for offline processing of each measuring point. In the offline processing, first a frequency-domain equalizer is used to compensate for the total accumulated chromatic dispersion (CD) on the received signal, and afterwards a time-domain equalizer is employed for equalizing all other linear effects in the signal. The time-domain equalizer consists of a bank of four finite-impulse response (FIR) filters in a butterfly structure. Each of these FIR filters has 13 taps, and their coefficients are first initialized using the constant modulus algorithm (CMA) followed by the decision directed least mean square algorithm (LMS). Feed-forward carrier phase estimation is used for the correction of local oscillator phase noise [10].

III. Experimental Results

The back-to-back (B2B) optical signal-to-noise ratio (OSNR) requirement for the 224-Gb/s POLMUX-RZ-16QAM signal is shown in Fig. 3 (OSNR measured within 0.1-nm resolution bandwidth). Compared to the theoretical limits, the measured OSNR sensitivity curve is shifted by approximately 4.3 dB at a bit-error rate (BER) of 10^{-3} and has an error floor at around a BER of 2×10^{-5}. We conjecture that this is the result of the electrical bandwidth limitation of the 4-PAM electrical driving signals, the nonlinearity in the MZM transfer function and to a small 50-Ω mismatch at the input of optical modulators. Fig. 3 shows as well the B2B sensitivity for the central WDM channel of the 50-GHz wavelength comb (at 1550.5 nm). Compared to the single-channel case, the WDM curve shows a penalty of 2.5 dB at a BER of 10^{-3}, and furthermore, the error floor shifts upwards to around 2×10^{-4}. This penalty is due to the introduction of additional electrical components with a bandwidth of 25 GHz in order to split the electrical driving signal between the two modulators of the odd and even channels as illustrated in Fig. 1(b). This further degraded the performance by affecting the quality of the electrical driving signal. Limited penalty has been introduced as well by linear crosstalk from neighboring channels. Note that in the single-channel configuration, a 50-GHz interleaver has been used to band limit the signal, and the difference between the single-channel and WDM configuration is, therefore, not due to narrowband optical filtering penalties.

In Fig. 4, the launch power for the 11×224-Gb/s POLMUX-RZ-16QAM channels is varied between −7 and +2 dBm, and the BER is calculated for the 1550.5-nm channel at each of the measured launch powers. This power variation measurement has been carried out after transmission distances

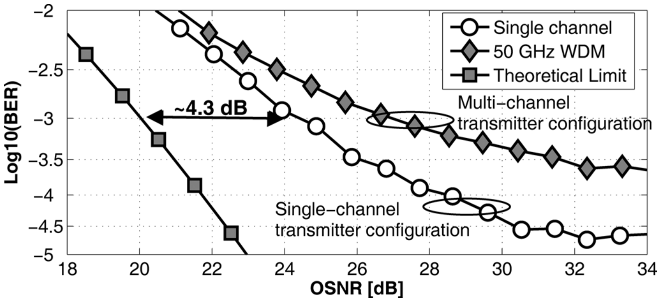

Fig. 3. Measured B2B OSNR requirement of POLMUX-RZ-16QAM.

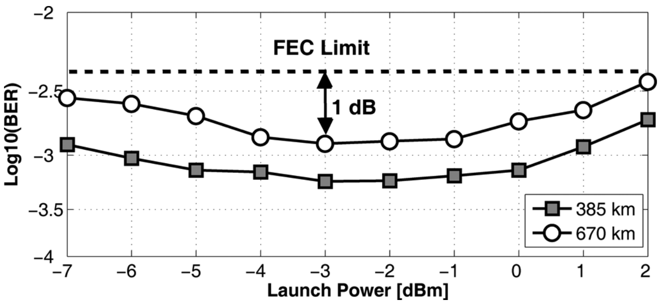

Fig. 4. Launch power variation results for the central transmitted channel.

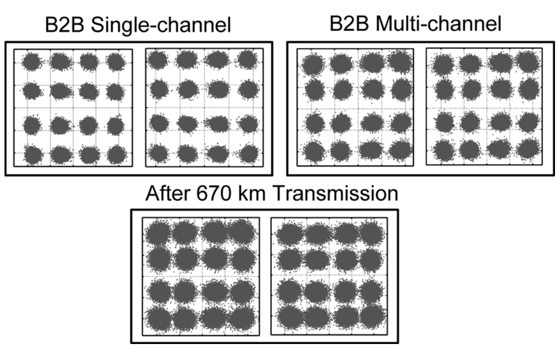

Fig. 5. POLMUX-RZ-16QAM constellation diagrams.

of 385 and 670 km. For both cases, the optimum launch power is found to be around -3 dBm. The constellation diagrams for the POLMUX-RZ-16QAM signal are shown in Fig. 5 both in the single-channel and multichannel B2B configuration, as well as after 670 km of transmission. Limited nonuniformity in the distribution of the constellation points can be noticed which results from the nonlinear transfer function of the MZMs. The constellation diagram for the multichannel B2B configuration confirms the degradation of the signal quality. After 670 km, the BER for the 11 channels has been measured at a launch power of -3 dBm (Fig. 6). During this measurement, the ECL has been switched such that it is used for each channel under test. The BER of all measured WDM results is well below the FEC threshold (which is assumed to be at a BER of 3.8×10^{-3} using a 7% overhead [2]).

IV. Conclusion

We demonstrated the generation and detection of a 224-Gb/s POLMUX-RZ-16QAM signal with around 4.3-dB penalty in comparison to the theoretical limits. Furthermore, we reported

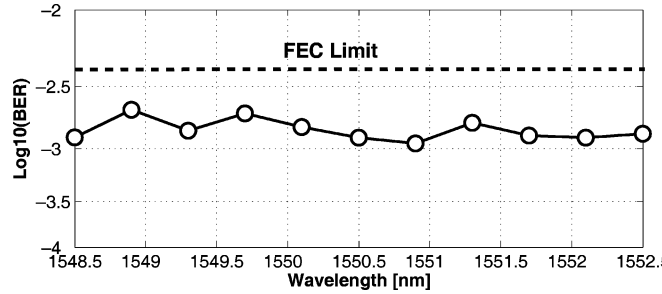

Fig. 6. BER results for the 11 channels after 670-km transmission.

the transmission of 11×224-Gb/s POLMUX-RZ-16QAM over 670 km of SSMF with a channel spacing of 50 GHz and an SE of 4.2 b/s/Hz.

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