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# Transmission of 11 x 224-Gb/s POLMUX-RZ-16QAM over 1500 km of LongLine and pure-silica SMF

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**Abstract** *We demonstrate transmission of 11 x 224-Gb/s POLMUX-RZ-16QAM over 1500 km with a channel spacing of 50 GHz. A hybrid configuration of LongLine and pure silica fiber is used to optimize both nonlinear tolerance and Raman gain.*

## Introduction

Recent developments in transponder technology, such coherent detection and digital signal processing [1], have enabled solutions with close to optimum OSNR threshold and a near-perfect compensation of linear impairments. Such transponder therefore enable for the first time a performance close to theoretical limits and recently a great deal of research has therefore been dedicated to understanding the ultimate transmission capacity of single mode fiber [2]. In order to achieve a high spectral efficiency (SE) while not sacrificing too much transmission reach, several further development are required in the components and transmission technology of optical networks: (1) new single mode fiber (SMF) types with a large core size [3-5] and lower attanuation [6] to increase the OSNR margin and consequently increase the transmission distance, (2) more optimized amplifiers architectures with hybrid EDFA/Raman amplification in order to improve the received OSNR at the end of the link and finally (3) more advanced digital signal processing algorithms and forward error correction (FEC) codes [7].

A suitable candidate to realize both an ultra-high spectral efficiency, but still maintaining a sufficiently long feasible transmission distance is 28-GBaud (224 Gb/s) polarization-multiplexed, 16-level quadrature amplitude modulation (POLMUX-16QAM). Recently, transmission of 224-Gb/s POLMUX-16QAM has been demonstrated over 1200 km of SMF [4]. In this paper we show transmission of 11 x 224-Gb/s POLMUX-RZ-16QAM over 1500 km using a combination of LongLine (LL) [3] and pure silica core fiber (PSC) [6] in order to optimize both nonlinear tolerance and Raman gain.

## System Setup

The experimental setup is depicted in Fig. 1. As shown in the figure, ten distributed feed back (DFB) lasers and one external cavity laser (ECL) with wavelengths on the 50 GHz ITU grid, and ranging from 1548.5 nm and 1552.5 nm are grouped into odd and even channels using two array wave guides (AWG). The ECL laser is used for the channel under test and the DFB lasers are used for the co-propagating WDM channels. After the AWG, the two channels groups are first pulse carved using two Mach-Zehnder modulators (MZM) driven with a 28-GHz clock signal. Subsequently, the two wavelength combs are modulated with 28-GBaud 16QAM using two 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 a 4 level pulse amplitude modulated (PAM) signals, which are generated using the two bit DACs [4] shown in Fig. 1c. The input

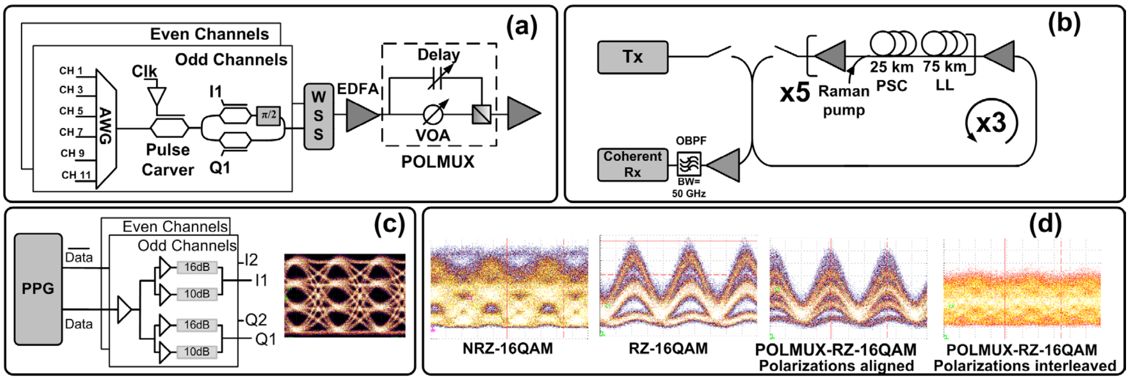

**Fig. 1:** Experimental setup; (a) Transmitter, (b) Re-circulating loop; (c)Generation of the 4-PAM driving signal (c) 16QAM eye diagrams

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signals to the DACs consist of 28-GBaud binary PRBS signals with a pattern length of $2^{15}$-1 bits. The amplitude of the 4-PAM signals is ~2.8 $V_{p-p}$. Due to the cascade of many discrete components in the DACs with an electrical bandwidth in the order of 25-26 GHz, the extinction ratio for the 28-GBaud 4-PAM signals is decreased significantly, and the rise and fall times are strongly increased. In order to alleviate this problem, we applied RZ pulse carving to the signal. The non-return to zero (NRZ) and RZ eye diagrams in Fig. 1d 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 polarization multiplexing stage, consisting from a 50/50 splitter a delay line and a polarization beam splitter (Fig. 1a), is used to polarization multiplex the signals at the output of the WSS. The two polarizations of the POLMUX signal are interleaved in order to enhance the signal's tolerance to nonlinear effects (Fig. 1d). Fig. 2 illustrates the optical spectrum of the eleven POLMUX-RZ-16QAM channels, at the transmitter side. The biasing point for the RZ pulse carver has been adjusted to confine the spectrum of each channel as evident from Fig. 2 which reduces slightly the cross-talk between the neighboring channels.

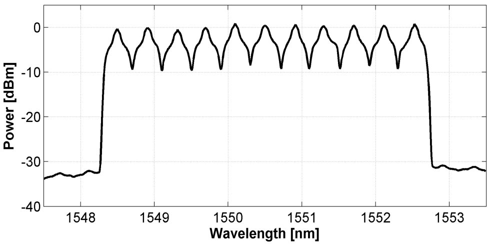

**Fig. 2:** 11 x 224-Gb/s POLMUX-RZ-16QAM optical spectrum

The optical transmission link consists of five spans of 100 km SMF built in a re-circulating loop. Each span in the loop is composed from 75 km of LL [3] fiber followed. by 25 km of PSC [6] fiber. Hybrid EDFA / Raman amplification scheme has been employed in this link (Fig. 1b) with an average ON/OFF Raman gain of ~10 dB. LL fiber has a core size of 120 $\mu m^2$ which reduces its nonlinear coefficient into ~0.8 1/W.km and consequently allows for higher launch powers. Therefore LL fiber is used directly after the EDFA amplifiers. However, this large core size results in a reduction in the Raman gain for the fiber. Consequently, we use a 25 km section of PSC (which is a conventional SSMF with a loss factor reduced to 0.168 dB/km) fiber in the end of each span to enhance the gain from the back-ward pumping Raman amplifier.

At the receiver a coherent detection is realized using an ECL local oscillator, and a polarization diversity IQ-mixer with balanced photodiodes. 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 (~4 x $10^6$ 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 four FIR filter banks in a butterfly structure. Each of these FIR filters has 21 taps, and their coefficients are first initialized using the constant modulus algorithm (CMA) followed by the least mean square algorithm (LMS). Phase lock loop (PLL) based carrier recovery is employed for the carrier and phased recovery.

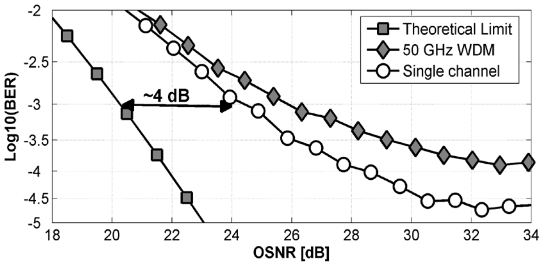

**Fig. 3:** Measured back-to-back OSNR requirement of POLMUX-RZ-16QAM

## Experimental Results

The back-to-back 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 dB at a bit error rate (BER) of $10^{-3}$ and has an error floor at around a BER of $2x10^{-5}$. 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 ohm 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 1.5 dB at a BER of $10^{-3}$ and furthermore the error floor shifts upwards to around $1x10^{-4}$. This penalty is due to the introduction of additional electrical components with a BW of 25 GHz in order to split the electrical driving signal between the two parallel modulators which further degrades the quality of the electrical driving signal. 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.

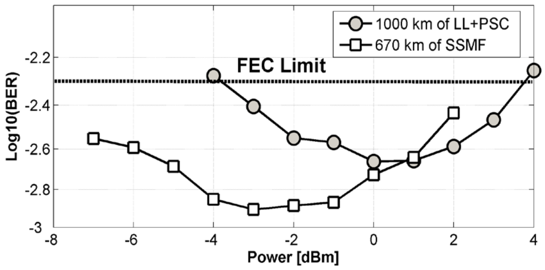

**Fig. 4:** Launch power variation results

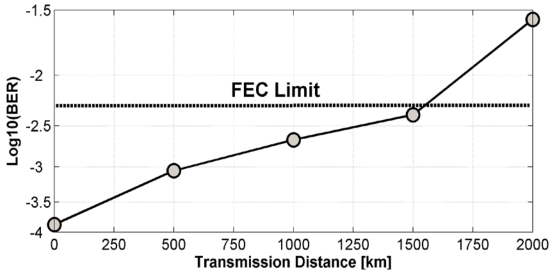

**Fig. 5:** BER results for the central channel versus transmission distance

In Fig. 4 the launch power for the 11 x 224-Gb/s POLMUX-RZ-16QAM channels is varied between -4 dBm and +4 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 of 1000 km. The optimum launch power is found to be around 0 dBm, which will be used for all of the following measurments to be reported in this paper. Transmission results for the same signal over a 670 km SSMF link with the same amplification technique are depicted as well in Fig. 4. It is evident from these results that the optimal launch power for the SSMF link is reduced by around 3 dB compared to the LL+PSC link which proves the ability of LL fiber to effectively reduce nonlinear effects and to increase transmission distance by around 50%. The BER of the received signal at a wavelength of 1550.52 nm is calculated at different transmission distances and reported in Fig. 5. The figure illustrates that a maximum transmission distance of 1500 km is feasible with a BER below the FEC limit [7]. The BER for the 11 channels has been measured after a transmission distance of 1500 km with the optimum launch power of 0 dBm (Fig. 6). During this measurement, the ECL laser has been switched such that it is used for each channel under test. The BER of all measured WDM results is below the FEC threshold (which is assumed to be at a BER of 5x$10^{-3}$ using a 7% overhead [7]).

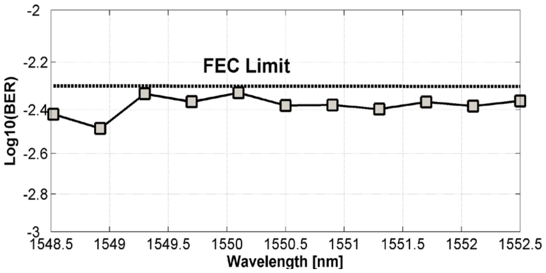

**Fig. 6:** BER results for the eleven channels after 1500-km transmission

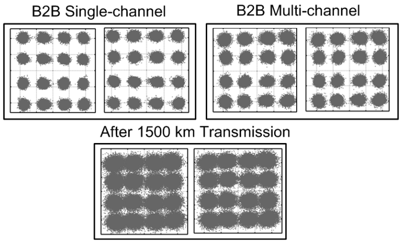

**Fig. 7:** POLMUX-RZ-16QAM constellation diagrams

Finally, the constellation diagrams for the POLMUX-RZ-16QAM signal are shown in Fig. 7 both in the single channel and multi-channel B2B configuration, as well as after 1500 km of transmission. The constellation diagram for the multi-channel B2B configuration confirms the degradation of the signal quality.

## Conclusions

In this paper, we demonstrate the transmission of 11 x 224-Gb/s polarization-multiplexed 16-level quadrature amplitude (POLMUX-RZ-16QAM) modulation over 1500 km of LongLine and pure silica core SMF, with a channel spacing of 50 GHz and a SE of 4.2 b/s/Hz. This shows the feasibility of ultra-high spectral efficiency transmission over a long-haul transmission distance.

## Acknowledgment

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