# 10x224-Gb/s POLMUX-16QAM transmission over 656 km of large-Aeff PSCF with a special efficiency of 5.6 b/s/Hz

# 10 × 224-Gb/s POLMUX-16QAM Transmission Over 656 km of Large-$A_{eff}$ PSCF With a Spectral Efficiency of 5.6 b/s/Hz

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***Abstract*—The authors demonstrate the successful transmission of 10 channels with 224-Gb/s POLMUX-16QAM modulation (28 GBaud) on a 37.5-GHz wavelength grid. Using large-$A_{eff}$ pure-silica-core fibers they show a 656-km transmission distance with a spectral efficiency of 5.6 b/s/Hz. They report a back-to-back performance penalty of 3.5 dB compared to theoretical limits at the forward-error correction (FEC) limit (bit-error rate of $3.8 \cdot 10^{-3}$), and a margin of 0.5 dB in Q-factor with respect to the FEC limit after 656 km of transmission.**

***Index Terms*—Coherent detection, polarization multiplexing (POLMUX), quadrature amplitude modulation (QAM).**

## I. Introduction

THE rapid increase in popularity of bandwidth-consuming applications such as internet video, cloud storage and social networking requires large volumes of data to be transmitted over long distances. This has fueled the historically exponential growth of data traffic volumes in the worldwide telecommunication network, and based on current trends it is likely to continue to drive an unsurpassed need for transmission capacity over the next decade. The industry-wide drive to develop the optical components, subsystems and systems required to upgrade long-haul and ultra long-haul networks to 100 G line rates is a key development to facilitate the need for more capacity in core networks. Polarization-multiplexed quadrature phase shift keying (POLMUX-QPSK) [1] has emerged in recent years as the most suitable modulation format for 100 G line rates, as it is compatible with the standardized 50-GHz channel spacing. This allows for a spectral efficiency of 2.0 b/s/Hz, scaling C-band transmission systems to a total capacity of between 8 and 10 Tb/s.

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With 100 G transport solution now well established and first commercial deployments ongoing, there is strong need to understand how long-haul transmission systems can evolve to 400 G line rates. Increasing the spectral efficiency by using higher-order modulation formats is the most effective method to realize higher transmission capacities at a comparable or lower cost per transmitted bit. Transponder technologies developed for 100 G line rates such as the optical components for dual-polarization QPSK modulation can be largely reused when scaling to denser modulation formats. Based on such technologies several transmission experiments have been reported using 16-level quadrature amplitude modulation (POLMUX-16QAM) [2], [3], or even denser constellations such as POLMUX-32QAM [4], POLMUX-64QAM [5], [6] or POLMUX-128QAM [7]. However, this research showed as well that the increase in optical signal-to-noise (OSNR) threshold coupled with a decreased nonlinear threshold makes it tremendously challenging to transport such formats over long-haul distances.

The strongly reduced transmission margin for dense constellations limits the spectral efficiency that can be used for long-haul transmission [8], making it very hard to transport 400 G within a 50-GHz WDM grid [4]. This underlines the need for an optimized infrastructure to improve the feasible transmission distance of next-generation transport systems while maintaining the maximum possible spectral efficiency. One solution is the use of flexi-grid technology, which allows a flexible scaling of channel spacing across the transmission band [9], [10]. This permits 400 G line rates to use a spectral band broader than 50 GHz, and enables a trade-off between transmission distance and spectral efficiency depending on network topology and physical layer infrastructure. Dual-carrier modulation, with both carriers being 200 G POLMUX-16QAM modulated, is a particularly promising approach to realize 400 G line rates, as this allows for the use of components with a lower optical and/or electrical bandwidth. For this purpose we investigated in this letter the transmission of 224-Gb/s POLMUX-16QAM on a 37.5-GHz grid over 656 km of large-$A_{eff}$ pure-silica-core fiber [11]. This allows for a 5.6 b/s/Hz spectral efficiency, and demonstrates the feasibility of next-generation 400 G transport using flexi-rate technology on an optimized fiber infrastructure.

## II. Experimental Setup

Fig. 1 depicts the setup used in the transmission experiment. At the transmitter (Fig. 1(a)), two combs of 5 lasers with a

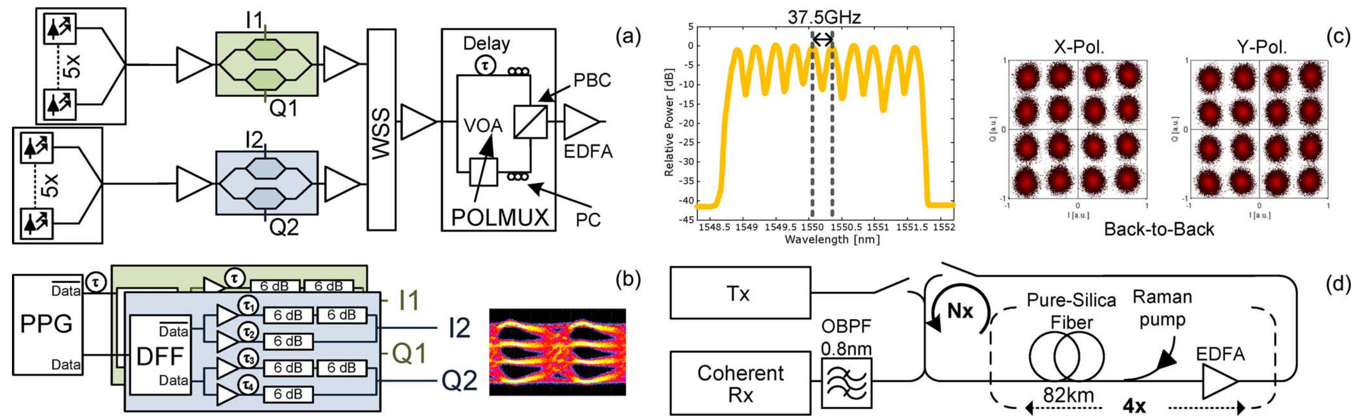


Fig. 1. Experimental setup. (a) Transmitter (Tx). (b) Generation of electrical 4-PAM driving signal. (c) Spectrum and recovered back-to-back constellations for both polarizations. (d) Recirculating loop setup.

wavelength spacing of 75 GHz are coupled together using a passive coupler. The two combs consist of a mix of ECL and DFB lasers, and the relative wavelength spacing between both combs is 37.5 GHz. The output signals of both combs are subsequently 112-Gb/s 16-QAM modulated with two IQ-modulators, with a $\mathrm{V_{pi}}$ of $\sim$2.2 V. Two outputs of a pulse pattern generator (PPG), generating $2^{15}$ PRBS sequences at a 28-Gbaud symbol rate, are first cleaned up using two D flip-flops (DFF). Each of the DFF outputs is subsequently split, amplified and delayed for de-correlation (Fig. 1(b)). One of the paths is 6 dB attenuated and afterwards the two paths are combined to create an electrical 4-PAM signal [3]. Two 4-PAM signals are used to drive the In-phase and Quadrature inputs of the IQ-modulators. An additional attenuation of 6 dB has been used to reduce the impact of the reflections from the IQ-modulator and amplifiers, resulting in 4-PAM signal with a voltage swing of $\sim 1.6\ \mathrm{V_{pp}}$ [2]. The 112-Gb/s 16-QAM modulated signals are first amplified separately and subsequently multiplexed using a flexi-grid wavelength selective switch (WSS, Waveshaper 4000S) with 37.5-GHz channel spacing. The resulting optical spectrum is shown in Fig. 1(c). The combined signal is subsequently fed into a polarization-multiplexing (POLMUX) stage. In this stage the incoming optical signal is split up in two equally powered tributaries, one delayed for de-correlation, and subsequently recombined using a polarization beam combiner (PBC), resulting in 224-Gb/s POLMUX-16QAM modulation.

The transmission link consists of a recirculating loop (Fig. 1(d)) with four spans of 82-km large-$\mathrm{A_{eff}}$ pure-silica-core fiber. The average loss of the fiber is 0.161 dB/km, the chromatic dispersion coefficient is 21.0 ps/nm/km at a wavelength of 1550 nm, and the dispersion slope equals 0.061 $\mathrm{ps/nm^2/km}$. The average effective area of the large-$\mathrm{A_{eff}}$ fiber is 133 $\mu\mathrm{m}^2$, which results in a nonlinear coefficient of 0.6 $\mathrm{W^{-1} \cdot km^{-1}}$. The average total loss of each of the 82-km spans is 14 dB, which is a combination of the fiber loss and the splice losses between standard single-mode fiber and the large-$\mathrm{A_{eff}}$ fiber. The span loss is compensated for by hybrid EDFA/Raman amplification using backward-pumping with an average ON/OFF Raman gain of 6.5 dB at the maximum pump power. The Raman gain is reduced due to the core size of the large-$\mathrm{A_{eff}}$ fiber, but the low fiber loss at the Raman pump wavelengths (0.20 dB/km at 1450 nm) ensures that a sufficiently high Raman gain is still obtained at moderate pump level (650 mW).

After transmission, the channels of interest are filtered out using a de-multiplexing filter with a 100-GHz bandwidth and subsequently fed to a polarization-diversity 90° optical hybrid. The signal is mixed with a local oscillator (LO) with 100-kHz linewidth, which selects the channel under test by coherent channel selection (tuned within $+/-60$ MHz of the channel wavelength). The four outputs of the 90° optical hybrid are converted to the electrical domain using balanced photodiodes, and subsequently digitized using a 50-Gsamples/s real-time digital sampling scope (DSA72004B). A sequence of one million samples, corresponding to 4.48 million bits is subsequently used for offline digital signal processing. Per measurement point, the average BER of two 224-Gb/s POLMUX-16QAM channels, selected by the de-multiplexing filter, are presented in the results section. The average BER is calculated from eight shots, four shots of both channels separately, at different time instances. Offline digital signal processing is used to demodulate the resulting samples as described in [2]. During the measurements no cycle slips were observed, and therefore no differential decoding was used.

## III. Results

The back-to-back measured BER of the 224-Gb/s POLMUX-16QAM modulated signal, single channel and multiplexed on a 37.5-GHz grid, as a function of the OSNR is shown in Fig. 2. At a BER of $10^{-3}$, the required OSNR for single channel 224-Gb/s POLMUX-16QAM modulation is 25.4 dB. A 5.1-dB penalty with respect to the theoretical OSNR requirement of a 224-Gb/s POLMUX-16QAM modulated signal is observed. At the FEC-threshold at a BER of $3.8 \cdot 10^{-3}$ the difference between the measured and theoretical required OSNR is reduced to 3.5 dB (19.0 dB versus 22.5 dB). In the WDM configuration the required OSNR for a BER of $10^{-3}$ is equal to 27.1 dB. The 1.7-dB OSNR penalty between the single channel and WDM configuration is resulting from the linear crosstalk between the WDM signals, due to the tight channel spacing [3].

Fig. 3 shows the measured average BER as a function of the launch power for the center two 224-Gb/s POLMUX-16QAM channels (channels 5 and 6) after transmission over 656 km of

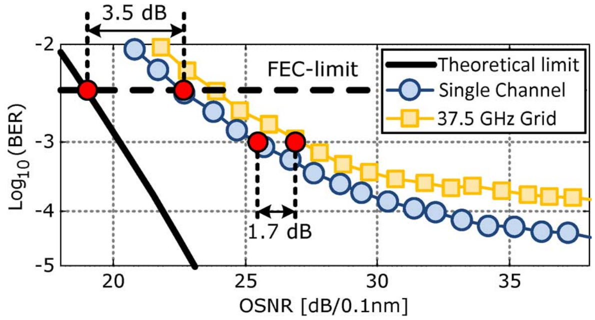


Fig. 2. Measured back-to-back BER curves for 224-Gb/s POLMUX-16QAM.

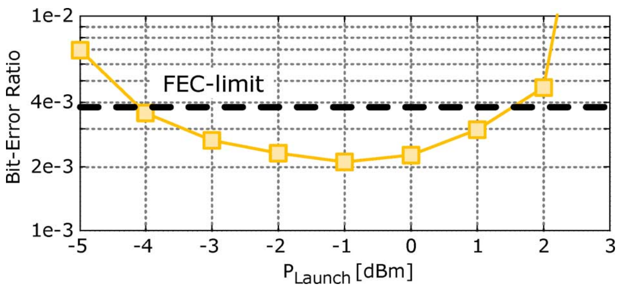


Fig. 3. Launch power variation versus average BER for the center two 224-Gb/s POLMUX-16QAM channels after 656 km of transmission.

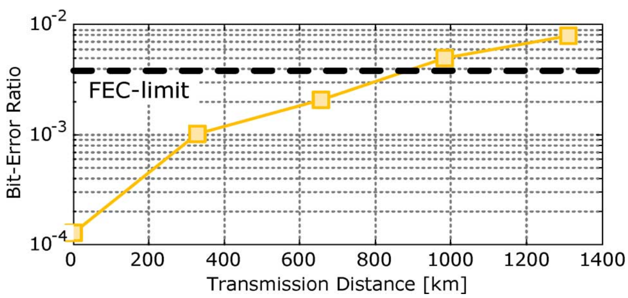


Fig. 4. Average BER results for the center two 224-Gb/s POLMUX-16QAM channels versus transmission distance.

large-$A_{eff}$ pure-silica-core fiber. The optimal launch power is $-1$ dBm per 224-Gb/s POLMUX-16QAM channel, which confirms the significant benefit of large core fiber to improve the nonlinear tolerance of high spectrally efficient modulation formats such as POLMUX-16QAM modulation. Fig. 4 shows the measured BER as a function of transmission distance for the center two 224-Gb/s POLMUX-16QAM modulated channels, and at the launch power of $-1$ dBm per channel. After 656 km of large-$A_{eff}$ pure-silica-core fiber (2 recirculating loops) an average BER of $2.1 \cdot 10^{-3}$ is measured. This translates into a margin of approximately 0.6 dB in Q-factor with respect to an FEC-limit of $3.8 \cdot 10^{-3}$. After 3 recirculating loops (984 km) the measured BER has degraded to $5 \cdot 10^{-3}$.

Fig. 5 shows the measured BER for each of the ten 224-Gb/s WDM channels after 656 km transmission and at the optimum launch power. For each of the measurements, the ECL-lasers are tuned from the center channel to the channel under test to ensure a low enough laser linewidth for carrier phase estimation. The transmission results depicted in Fig. 5 confirm that all the 224-Gb/s channels have nearly the same performance, and

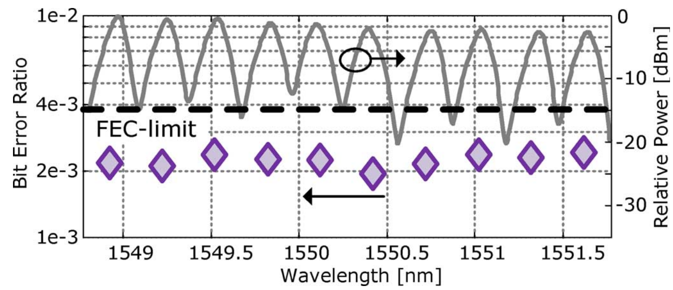


Fig. 5. BER results for the ten 224-Gb/s POLMUX-16QAM channels after 656 km of transmission.

the worst measured channel has a margin of 0.5 dB in Q-factor (BER of $2.4 \cdot 10^{-3}$) with respect to the FEC-limit.

## IV. Conclusion

We have shown transmission of ten 224-Gb/s POLMUX-16QAM modulated channels on a 37.5-GHz flexible grid, resulting in a spectral efficiency of 5.6 b/s/Hz. A total capacity of 2 Tb/s has been transmitted over 656 km of large-$A_{eff}$ pure-silica-core fiber with a margin of 0.5 dB in Q-factor with respect to the FEC-limit for the worst channel.

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