WDM Transmission of 152-Gb/s Polarization Multiplexed RZ-16QAM Signals with 25-GHz Channel Spacing over 15×80-km of SSMF

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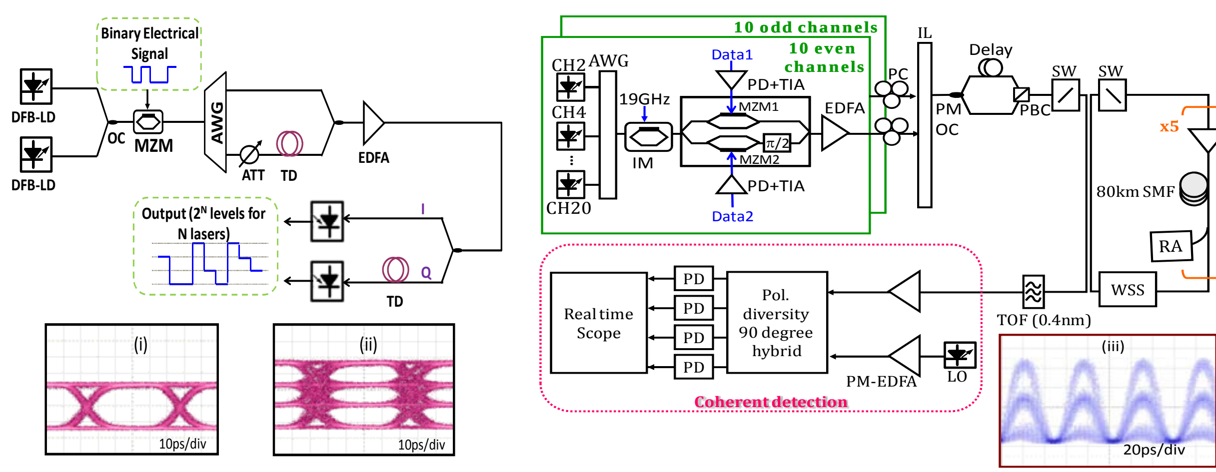
Abstract: We demonstrate transmission of 20×152-Gb/s PolMux-RZ-16QAM at a channel spacing of 25 GHz (5.68 b/s/Hz) over 15×80-km spans of SSFM. Coherent detection was used to recover the transmitted data and we achieved BER below 3.8×10^{-3}.

OCIS codes: (060. 2330) Fiber optical communications; (060.2360) Fiber optics links and subsystems

1. Introduction

Demand for ever greater capacity over a single fiber is driving demand for higher spectral efficiency in long-haul 100GbE systems. Recent experiments for 100-Gb/s dense wavelength-division multiplexing (DWDM) systems have used different modulation formats and detection schemes [1−6]. In particular, high-level modulation formats such as 8-PSK, 8-QAM and 16-QAM encoding information in multiple amplitude and/or phase levels have gained increasing interest. Ultimately, the achieved spectral efficiency is a function of both the number of bits encoded per symbol [3−6], and the bandwidth allocated to each WDM channel. Reducing the channel spacing enables a larger number of transmitted WDM channels on a single fiber [5−6]. Dual-polarization (DP) 16-QAM is an attractive format for beyond 100-Gb/s systems as it is a logical progression from DP-QPSK, doubling spectral efficiency while keeping the optical signal-to-noise ratio (OSNR) requirement reasonable. Recent experiments for beyond-100G systems employing DP-16QAM have included 224-Gb/s DP-16QAM at 50-GHz spacing (4.48 b/s/Hz) transmitted over 12×100-km spans of ultra-large-area fiber (ULAF) [3], 171-Gb/s at 25-GHz spacing (6.84 b/s/Hz) over 240 km of ULAF [4], 112-Gb/s at 25 GHz (4.48 b/s/Hz) over 1022 km of SSMF [5], and 224-Gb/s at 50-GHz spacing (4.48 b/s/Hz) over 670 km of SSMF [6]. In this paper, we report the generation and WDM transmission of 20×152-Gb/s polarization multiplexed return-to-zero 16QAM (PolMux-RZ-16QAM) on a 25-GHz grid, achieving a spectrum efficiency of 5.68 bit/s/Hz over 15×80-km spans of standard single-mode fiber (SSMF) without inline dispersion compensation. The bit-error rate (BER) measured at the receiver was below the error threshold for forward-error coding (FEC) with 7% overhead [7]. To our knowledge, this result achieves the highest spectral-efficiency-distance product (6,818 b/s/Hz-km) to date for PolMux-RZ-16QAM transmission over SSMF.



(a) (b)

Fig. 1: (a) Four-level electrical signal generation. (a) Experimental setup. (MZM: Mach-Zehnder modulator. AWG: arrayed waveguide grating. ATT.: attenuator. TD: time delay. IL: interleaver. SW: acousto-optic switch. TOF: tunable optical filter. WSS: wavelength selected switch. LO: local oscillator. RA: Raman amplifier. PD: photodetector.)

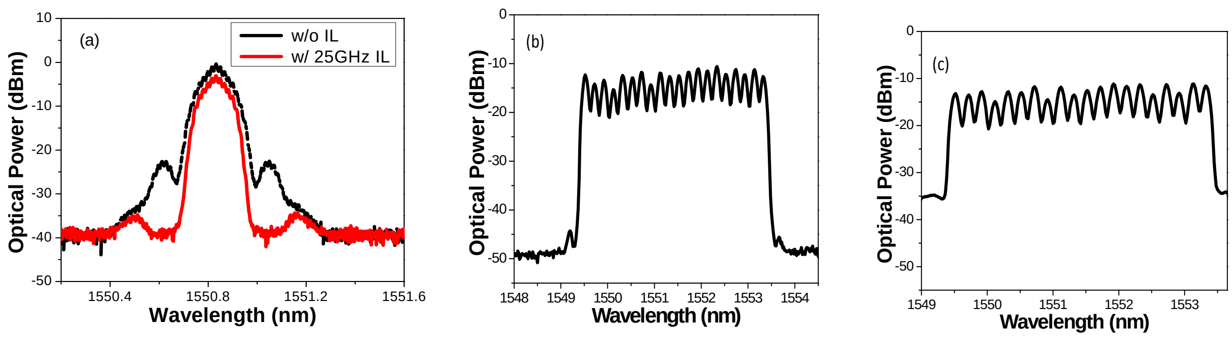


Fig. 2: Received optical spectra. (a): single channel w/ and w/o a 25-GHz IL. (b) and (c): all channels before and after 15×80-km SSMF.

2. Experimental configuration

Fig. 1 (a) shows the setup used to generate high-quality four-level electrical drive signals at 19 Gbaud [8,9]. Two distributed feedback (DFB) lasers were combined and modulated with a Mach-Zehnder intensity modulator (MZM) driven by a 19-Gb/s binary electrical. The modulated wavelengths are separated and re-combined using an optical arrayed waveguide grating (AWG) and an optical coupler. One of the λ's is attenuated by 3-dB and delayed by 672 baud intervals for decorrelation. The insets in Fig. 1(a) show the optical intensity eye diagrams measured when (i) λ_2 is turned off (yielding a two-level signal), and when (ii) both λ_1 and λ_2 are on (yielding a four-level signal). After re-amplification, the signal is split into two paths before detection by 50-GHz photodiodes (PD), yielding two uncorrelated four-level electrical signals at 19 Gbaud. Fig. 1(b) shows the experimental setup. Two identical transmitters (Tx) were used to generate signals for the odd and even channels. In each Tx, ten external cavity lasers (ECLs) spaced 50 GHz apart were combined with an arrayed waveguide grating (AWG). This was followed by a sine-wave driven MZM carving out 50% RZ pulses, and a dual-parellel I/Q modulator driven with the 19 Gbaud four-level signals produced in Fig. 1(a). The resulting single-polarization 16-QAM signals in the odd and even channels were then combined in a 25-GHz flat-top optical interleaver (IL). Two polarization controllers (PC) are used to ensure co-polarization between the channels since the IL is not polarization maintaining. Finally, the signal was split; one of the signals was delayed by 150 symbols and rotated to the orthogonal polarization before the two signals were combined in a polarization beam combiner (PBC), yielding the desired PolMux-RZ-16QAM signals spaced at 25-GHz from 1549.61 to 1553.53 nm. Fig. 1(iii) shows optical intensities diagrams for the 16-QAM signal before the polarization multiplexer. The optical spectrum after polarization multiplexing is shown in Fig. 2(b). We transmitted the 152-Gb/s PolMux-RZ-16QAM signals over a re-circulating loop consisting of five 80-km spans of SSMF with hybrid erbium-doped fiber amplification (EDFA) and Raman amplification after each span. No dispersion compensation fibers (DCF) was used (dispersion unmanaged transmission). A wavelength selected switch (WSS) was inserted in the loop to simulate switching in an optical network. The data was circulated through three loops (1,200 km), and the optical spectrum after transmission is shown in Fig. 2(c). Coherent detection was used to recover the transmitted data. The front-end of the receiver is a polarization-diversity 90-degree balanced hybrid combining the received signal with a tunable ECL local oscillator (LO). The outputs of the hybrid are detected with four balanced PD, yielding electrical signals corresponding to the I and Q of the *x*-and *y*- polarizations. These were sampled and digitized by a four-port LeCroy digital storage scope with sampling rates of 40 GSa/s and electrical bandwidths of 16 GHz. The captured data was processed offline using a desktop PC. We captured five data sets of 38,000 symbols (2 μs duration), and computed the BER and signal-to-interference-and noise (SINR) of the recovered constellation from the second-half of the captured data after convergence of the adaptive filter (3.8×10^6 bits per data point).

3. Experimental results

Fig. 2(a) shows optical spectra of our 152-Gb/s PolMux-RZ-16QAM signal before transmission, measured at a bandwidth resolution of 0.01-nm resolution, with and without a 25-GHz IL. Fig. 3 shows the SINR in back-to-back (BTB) transmission as a function of OSNR at 0.1-nm resolution bandwidth for the cases of: (i) single-λ BTB, (ii) single-λ BTB with a 25-GHz IL and (iii) WDM BTB with IL. It is observed that the signal performance doesn't degrade when a 25-GHz IL is used. For the WDM system, crosstalk from neighboring channels degraded performance by about 1 dB, and the required OSNR to achieve an SINR of 16.5 dB is 25 dB. The insets in Fig. 3 show constellation diagrams measured at an OSNR of 32 dB.

System performance after transmission over 15×80-km spans of SSMF is shown in Fig. 4, where we swept the launch power from −8 dBm to −1 dBm to find the optimal transmitter setting. It is observed that the optimal launch power is −5 dBm, above which self-phase modulation (SPM) degrades system performance. The insets show constellation diagrams measured at −8, −5 and −3 dBm, respectively. Fig. 5 shows the BER measured for the odd WDM channels after 15×80-km with the launch power set to −5 dBm per channel. It is observed that all channels achieved BER below the FEC limit of 3.8×10^{-3} corresponding to the hard-decision code 7% overhead [7]. Constellation diagrams for CH1 (1549.61 nm), CH9 (1551.32 nm) and CH19 (1553.33 nm) are also shown in the insets of Fig. 5.

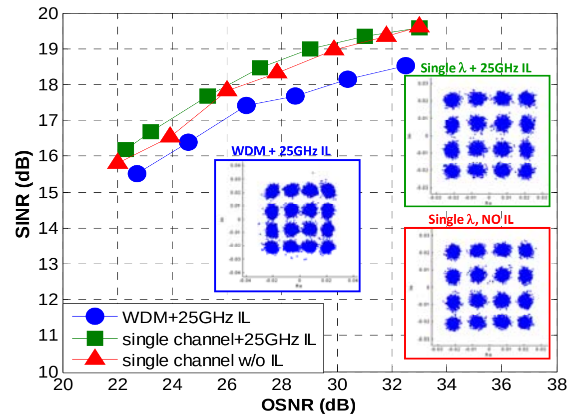


Fig. 3: Back-to-back performance.

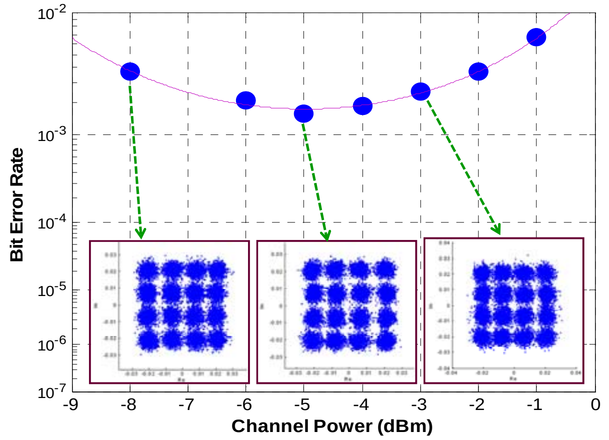


Fig. 4: System performance versus launch power measured for CH9 (1551.32nm) after transmission over 15×80-km spans of SSMF.

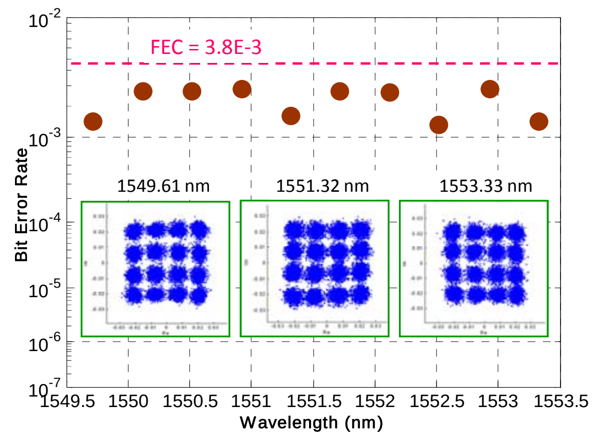


Fig. 5: System performance measured for odd channels at −5 dBm/λ after transmission over 15×80-km spans of SSMF.

4. Conclusion

We demonstrated DWDM transmission of 20×152-Gb/s PolMux-RZ-16QAM at 25-GHz channel spacing over 15×80-km spans of SSFM with hybrid EDFA and Raman amplification after each span and no inline dispersion compensation. Experimental results were presented, showing an optimum launch power was −5 dBm per channel. All of the channels recovered achieved BER below the FEC limit at the optimal launch power. To our knowledge, by employing SSMF as transmission medium, our result achieves the highest spectral-efficiency-distance product (6,818 b/s/Hz-km) to date for PolMux-RZ-16QAM transmission.

5. References

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