112.8-Gb/s PM-RZ-64QAM optical signal generation and transmission on a 12.5GHz WDM grid

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Abstract: By employing a novel scheme we have generated 112.8-Gb/s polarization-multiplexed (PM)-RZ-64QAM optical signal. Transmission of 112.8-Gb/s PM-RZ-64QAM optical signal over 2×40km of SSMF has been demonstrated in an 8-channel WDM environment on a 12.5GHz grid.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications.

1. Introduction

Multi-level, multi-dimensional coding combined with digital signal processing (DSP) enabled coherent detection has shown to be an effective method to increase spectral efficiency (SE) and therefore overall fiber capacity [1-8]. By using single-carrier based polarization-multiplexed-return-to-zero 8QAM (PM-RZ-8QAM) modulation format, we recently demonstrated record 32Tb/s transmission over 580-km reach at a spectral efficiency of 4 bit/s/Hz, using EDFA-only optical amplification [6]. To be able to further increase fiber capacity and reduce the cost per transmitted bit, it is worthwhile to explore even higher spectral efficiency at 100-Gb/s (or above) per channel data rate. To our best knowledge, the demonstrated highest SE at data rate of 100-Gb/s per channel (or beyond) is 6.2 bit/s/Hz [5] using PM-16QAM nodulation format. PDM-64QAM is another very attractive modulation format aiming at even higher spectral efficiency. Generation of 240 Gb/s PM-64QAM with single channel back-to-back BER floor of about 10^{-2} has recently been reported by using hybrid integration of silica PLCs and LiNbO3 phase modulators [9]. In this paper, we report 112.4Gb/s PM-64QAM generation and transmission using a different 64QAM generation method. For this method, the high-speed 64QAM optical signal is generated by driving a single I/Q modulator with two eight-level electrical signals. The relatively high-quality eight-level electrical signal is produced through a novel E-O-E scheme. With this new 64QAM generation technique, we successfully transmitted a 112.8-Gb/s RZ-shaped PM-64QAM signal over 80km SMF-28 in an eight-channel WDM environment on a 12.5GHz grid. The measured BER of the middle channel is smaller than 2×10^{-3} after 2×40km SMF-28 transmission. This result demonstrates the feasibility of 100-Gb/s optical transmission at a record SE of 8 bit/s/Hz.

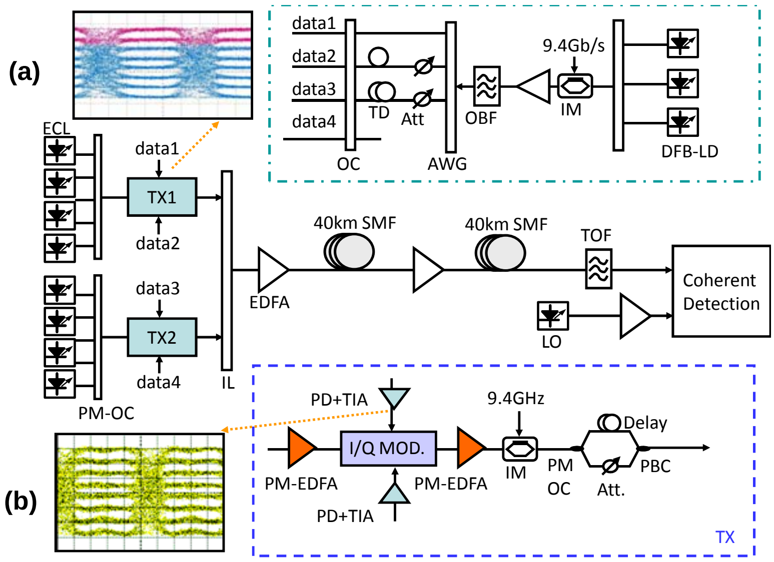

Fig. 1. Experimental setup. TD: time delay, Att: attenuator, IM: intensity modulator, PM-OC: polarization-maintained optical coupler, OBF; optical bandpass filter, MOD: optical modulator, AWG: arrayed waveguide grating, IL: 12.5/25GHz interleaver, TOF: tunable optical filter.

2. Experiment

The experimental setup is shown in Fig. 1. We have built two 112.8-Gbit/s PM-RZ-64QAM transmitters for odd and even channels, each modulating four 25GHz-spaced wavelengths. The odd and the even channels are combined by using a 12.5GHz flat-top interleaver with 0.5 and 2.5dB bandwidth of 8.4 and 10.9GHz, respectively. We use ECL lasers (full C-band tunable, linewidth <100kHz) for all the eight wavelength channels (1549.96~1550.67nm). The 64QAM optical signal is generated by using a π/2-biased dual-parallel Mach-Zehnder modulator (DP-MZM) driven by two eight-level electrical signals. The eight-level electrical signal is generated by a novel electrical-optical-electrical (E-O-E) method as illustrated in Fig. 1. Three DFB lasers at 1539.5, 1541.9 and 1554.3 nm (2.4nm channel spacing) are combined by a polarization-maintaining optical coupler (OC). The combined lightwaves are modulated by a MZ intensity modulator (IM) driven by a 9.4Gb/s electrical binary signal with a PRBS length of 2^{15}-1. The extinction ratio of the optical On/Off keying signal is optimized to be greater than 12dB. Then the three binary modulated wavelengths are de-multiplexed by using an optical AWG after being boosted by an EDFA and passing through a 9nm optical bandpass filter (OBF). Different attenuations (0, 3 and 6dB for wavelengths 1, 2 and 3, respectively) and time delays (for de-correlation) have been introduced to the three wavelengths. After that, we use a 4×4 optical power coupler to combine the three binary modulated signals. At the output of the 4×4 optical power coupler we obtain four identical eight-level (in terms of optical power) optical signals. The measured eye diagram of the eight-level optical signals (through a 65GHz optical sampling scope) is inserted in Fig. 1 as inset (a). After passing through different time delays for de-correlation, the four eight-level optical signals are detected by four identical 20GHz optical receivers with TIA. The eye diagram of the electrical signal received from the 20GHz optical receiver is inserted in Fig. 1 as inset (b). There is a little distortion in the middle. The electrical amplitude from the optical receiver is 0.7Vp-p when the input optical power is 0dBm. Each two of the four electrical signals (after different length fiber delays) are used to drive the DP-MZM. Each modulator in the DP-MZM is biased at the null point. No booster amplifier is used to drive the DP-MZM. The half-wave electrical voltage of the modulator is 2.1V. Because the modulators are driven at relatively low voltage to preserve good linearity during data modulation, the signal experiences a large loss after passing through the DP-MZM. We use a polarization-maintaining EDFA to boost the combined four CW lightwaves from the ECLs to 20dBm. The optical power after the DP-MZM is –8dBm. Then we employ another polarization-maintaining EDFA to boost the optical amplifier to 20dBm. To introduce RZ-pulse shaping, an intensity MZM is added after the second polarization-maintaining EDFA. The MZM intensity modulator is driven with a 9.4GHz clock to carve out ~ 50% duty cycle pulses. For RZ-pulse shaping, both the DC bias and the driving RF are carefully adjusted to optimize the spectral shape in order to reduce the crosstalk from the next neighboring channels due to the use of the same modulator for all the odd (or even) channels [1, 3]. The polarization-multiplexing is achieved by dividing and recombining the signal with 150 symbol delay before a polarization beam combiner. The odd and even channels are combined then by a 25/12.5 GHz optical interleaver.

The WDM optical signals are transmitted over 2×40km of SMF-28 (40km/span, span loss=8.7dB) and EDFA-only optical amplification. No optical dispersion compensation is used in this experiment. At the receiver, because only one fixed-frequency narrow linewidth (<400Hz) laser is available for the LO, we only measured the performance of the central channel located at 1550.36nm. The test channel is selected by a tunable optical filter with 3 and 20dB bandwidth of 0.1 and 0.24 nm, respectively. For the coherent receiver, polarization and phase-diverse coherent detection consists of a polarization-diverse 90-degree hybrid, a very narrow and fixed-frequency fiber laser based LO and four single-ended photodetectors. The distortion due to direct square-law detection of the signal component is mitigated by using a relatively high LO-to-signal power ratio (20dB in this experiment) combined with a recently proposed DSP algorithm [10]. The LO is within 10MHz of the transmit laser. The sampling and digitization (A/D) function is achieved by using a 4-channel digital storage scope with 50Gs/s sample rate and 9GHz electrical bandwidth. The captured data is then post-processed using a desktop PC.

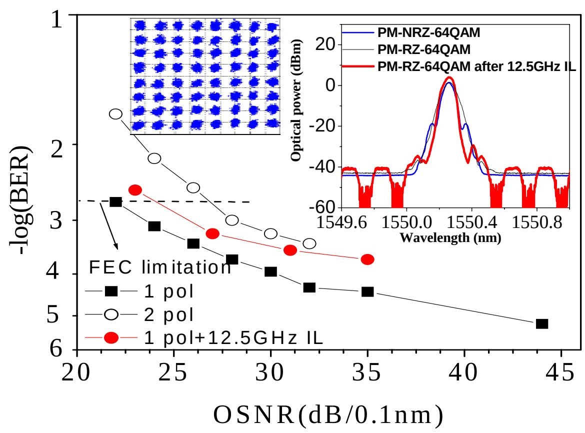

Fig. 2. The BER performance of the test single channel before transmission. Optical spectra and constellation for 112.8Gb/s PM-RZ-64QAM signal are shown as inserts.

For the DSP, electrical polarization recovery is achieved by using a three-stage blind equalization strategy: we first use the classic constant modulus algorithm [11] for first pre-equalization, and then use the recently proposed cascaded multi-modulus algorithm [6] for second pre-equalization (for simplicity, here we only use the three inner circles for error signal calculation) and finally we switch to the classic decision-directed least-mean square algorithm for final equalization. Carrier frequency and phase recovery is achieved by using a maximum likelihood based feedforward phase estimation method [12]. For this experiment, errors were counted over 12×10^6 bits (12 data sets, each data set contains 10^6 bits) and differential decoding has been used to solve the $\pi/2$ phase ambiguity problem.

Fig. 2 shows the measured BER performance of the single channel without transmission fiber. The required OSNR for the single and dual-polarization is 21 and 26.5dB, respectively. We observe excess 2.5dB PM penalty. There is 2dB OSNR degradation at a BER of 2×10^{-3} after passing through one 12.5GHz interleaver. Fig. 2 also shows the constellation of the generated single-polarization 56.4Gb/s 64QAM with an OSNR of 44dB. The measured BER is 6×10^{-6}. The optical spectra for single channel with or without pulse carving and with optical interleaver are inserted in Fig. 2. From this optical spectrum we can see that the optical power at 25GHz away is suppressed by more than 30dB, meaning that the crosstalk from the same transmitter is very small.

In Fig. 3, we show the measured BER of the test middle channel after transmission over 2×40km at different input powers into SMF-28. The corresponding optical spectrum after transmission with input power of -8dBm/per channel and the constellation of the test channel after transmission is shown as an insert. The OSNR of all channels after transmission is ~32dB (0.1nm noise bandwidth), and the measured BER of the test channel after transmission is 1.8×10^{-3} at the optimal input power of -8dBm per channel.

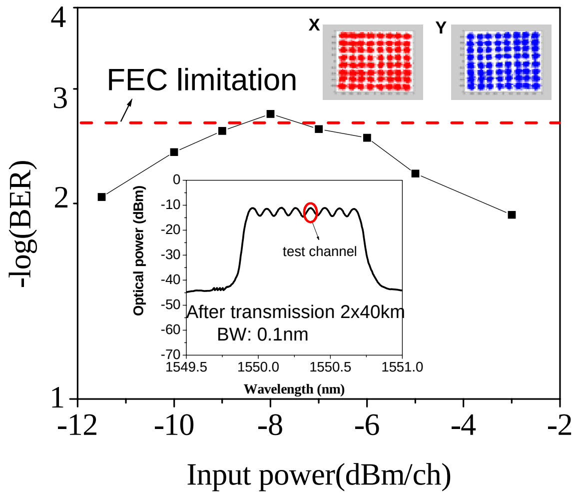

Fig. 3. BER performance of the 112.8Gb/s test channel after transmission in an 8-channel WDM system on a 12.5GHz grid at different input powers per channel. The X and Y-pol constellation of PM-RZ-64QAM signal of the test channel and optical spectrum after transmission are shown as inserts.

3. Conclusions

We have proposed and experimentally demonstrated a novel scheme to generate a high-speed eight-level electrical signal. This eight-level electrical signal is employed to generate a 64QAM optical signal. The generated 112.8Gb/s PM-RZ-64QAM optical signal has an OSNR requirement of 26.5dB at a BER of 2×10^{-3}. The BER of the middle test channel from the eight-channel WDM signals on a 12.5GHz grid after transmission over 80km SMF-28 is 1.8×10^{-3} at an optimal input power of -8dBm per channel. Our experimental results demonstrate the feasibility of 100-Gb/s optical transmission with a record spectral efficiency of 8 bit/s/Hz.

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