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1650-km transmission of 50-Gb/s NRZ and RZ-DQPSK signals generated using an electroabsorption modulators-silica planar lightwave circuit hybrid integrated device

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Abstract: We demonstrate long-haul transmission of 50-Gb/s RZ and NRZ-DQPSK signals generated using an electroabsorption-based optical vector modulator. Transmission over 1650 km is achieved with less than 1.2 dB OSNR penalty relative to back-to-back performance.
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1. Introduction

Quadrature phase shift keying (QPSK) have been subjects of extensive research [1,2] as it is the simplest spectrally-efficient modulation format for upgrading the optical transport capacity. For example, four bits of information can be encoded per symbol when QPSK is used in conjunction with polarization multiplexing. The increased spectral efficiency does however entail more complex transmitters and receivers. Majority of QPSK transmission experiments have been carried out using lithium niobate nested Mach-Zehnder modulators (MZMs). However, higher degree of integration using semiconductor devices may be desirable to realize smaller device form factor and reduced drive voltage requirement, and hence reduced power consumption [3-6]. In addition, integration could facilitate generation of modulation formats more complex than QPSK .

Recently, we have demonstrated a hybrid optical vector modulator consisting of an array of four AlGaInAs/InP electroabsorption modulators (EAMs) and a 1x4 multi-mode interferometer (MMI) on a silica planar lightwave circuit (PLC) for generation of high spectral efficiency modulation formats [5, 6]. Using the hybrid modulator, we generated 50-Gb/s single-polarization NRZ and RZ-DQPSK signals whose back-to-back bit error rate (BER) performance was shown to be comparable to the best obtained using lithium niobate modulators.

In this paper, we investigate the long-haul transmission performance of DQPSK signals generated using the EAM-hybrid vector modulator. It is well known that amplitude modulation using EAMs induces optical frequency chirp. The impact of the chirp on transmission of on-off-keyed (OOK) signals has been well investigated [7]. For example, EAMs are mostly used in short to medium-haul (< 100 km) transmission of 10-Gb/s OOK signals where the effect of chirp can be tolerated without per-channel dispersion compensation. However, the effect of chirp on long-distance QPSK transmission is yet to be examined. Of practical interest is whether EAM-generated QPSK signals with a symbol rate higher than 25-Gbaud can be transported over 1000 km with small penalties, as these would be typical requirements in the next-generation 100-Gb/s long-haul terrestrial optical transmission systems. In this paper, we demonstrate transmission of NRZ and RZ-DQPSK signals generated using the EAM-vector modulator over 1650 km of standard single mode fiber (SSMF) with transmission penalties less than ~ 1.2 dB compared to the back-to-back performance.

2. Experimental Setup

A schematic of the EAM-hybrid optical vector modulator is given in Fig. 1(a). We use an array of four InP EAMs as low drive voltage data modulation elements. The monolithic InP chip also integrates an array of semiconductor optical amplifiers (SOAs) to compensate for optical coupling losses. For implementing an optical interferometer requisite for generating the advanced modulation formats, we choose a low-loss silica PLC technology containing a 1x4 MMI. The two components are butt-coupled as illustrated in Fig. 1(a), where the incoming CW light is first modulated by the EAMs and reflected at the high-reflector side of the EAM device and modulated again by the same set of data drives before it exits the device via a circulator. For illustration purpose, we show a transmissive geometry in (b), which is topologically equivalent to the reflective geometry in (a) used for the actual experimental demonstrations. Figs. 1(b) and 1(c) illustrate how a QPSK constellation can be generated by push-pull on-off keyed (*OOK)* modulation of the EAM elements (A, B, C, D). We note that RZ-QPSK signals can be generated without having to use an external pulse carver [5]. Further details of the device and its operation can be found in [5, 6], wherein the back-to-back BER performance of 50-Gb/s NRZ and RZ-DQPSK signals are also shown.

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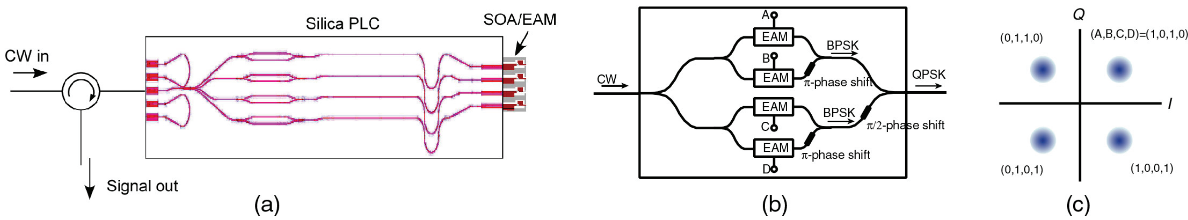

Fig. 1.(a) A layout of the EAM-silica hybrid. (b) A transmissive device equivalent to the reflective one in (a). (c) QPSK constellation.

Fig. 2 shows the experimental set up of the transmission experiment. The electronic data bit sequences driving the EAM-silica hybrid QPSK modulator are derived from a 2^{15}-1 bit-long 25-Gb/s pseudo-random bit sequence (PRBS) and its delayed replica. The amplitude of the drive signals is less than $2.9V_{pp}$($2.6\ V_{pp}$) for NRZ(RZ) signals, respectively. Along with the QPSK signal (λ_5=1559.77 nm), we inject seven CW laser outputs to load the Erbium-doped amplifiers (EDFAs) in the re-circulating loop. The CW channels (λ_4, λ_6) nearest to the DQPSK signal (λ_5) are separated from it by 200-GHz to facilitate the measurement of optical signal-to-noise ratios (OSNRs) while the frequency spacing among the CW channels is 100 GHz. The CW channels are combined using a 1x8 fiber optical coupler, and the CW channels and the signal channel are multiplexed using a 3-dB power combiner. The re-circulating loop consists of four 82.5-km spans of SSMF. The span losses range from 18 to 21 dB. The average dispersion is 17 ps/nm/km and the residual dispersion of each span is roughly 42.5 nm/ps at 1550 nm. A pre-compensation of –514 ps/nm is used. A wavelength selective switch having a free spectral range (FSR) of 100 GHz and a 3-dB per channel optical bandwidth of 78 GHz is used as a dynamic gain equalizing filter (DGEF). At the end of the loop, the signal is switched and any residual chromatic dispersion is compensated using a tunable optical dispersion compensator (TODC) implemented using a periodic group-delay device. The demodulation of the DQPSK signals is accomplished using a delay line interferometer (DLI) having 25-GHz FSR. The demodulated signals are then detected using a balanced photo detector. Bit error rates of the detected signal are measured after 2:1 demultiplexing triggered by the 25 GHz clock recovered using a high-Q clock recovery circuit.

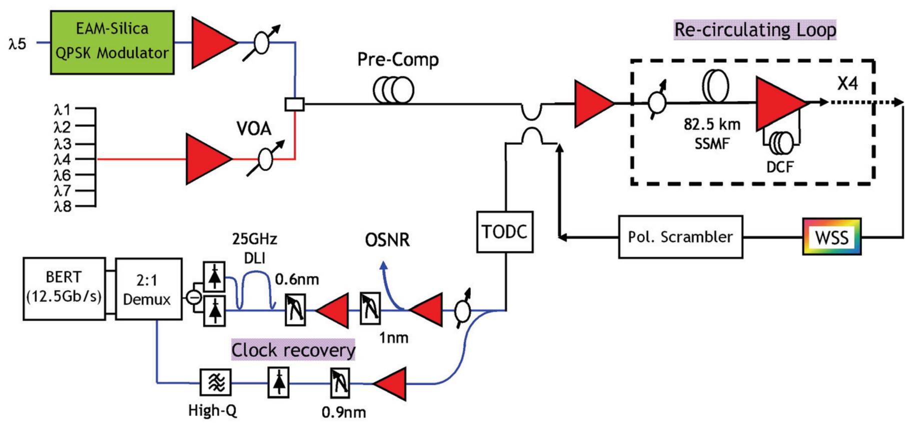

Fig. 2. Schematic of the transmission experiment set up.

3. Experimental Results

We first optimized the launch powers by measuring the required OSNR at a BER of 10^{-3}, at a given distance. For NRZ-DQPSK (RZ-QPSK) transmission, we optimized the launch powers after transmitting over 990 km (1320 km), respectively. Plotted in Fig. 3(a) are the required OSNRs (referred in 0.1 nm bandwidth) as a function of the average signal power in each span. The measurements shown in Fig. 3(a) are made on one phase (I or Q) only. We observe that RZ-DQPSK is substantially more tolerant to the nonlinear penalties than NRZ-DQPSK, as anticipated from its wider optical bandwidth and consequent faster temporal pulse spreading. The signal power for a 1-dB OSNR penalty is measured to be 2 dBm for NRZ-DQPSK at 990 km and 3 dBm for RZ-DQPSK at 1320 km. These levels of signal power for an EAM-based transmitter compare reasonably well with those obtained using lithium niobate based transmitters [1], indicating the minimal influence of chirp in such a dispersion-managed transmission link. Signal power of 0 dBm is chosen for both formats to ensure minimizing the nonlinear penalties while maintaining the ability to deliver sufficient OSNR.

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In Fig. 3(b), we show the required OSNR as a function of transmission distance for input signal power of 0 dBm. The plotted symbols are the average values of the required OSNRs for I and Q phases. The transmission penalties relative to the back-to-back cases are 1.2 dB for NRZ-DQPSK and 1.1 dB for RZ-QPSK after transmission over 1650 km. The modest penalties are of comparable magnitude to those measured using lithium niobate DQPSK modulators at similar data rates [1] and show that the chirp induced by the EAMs can be compensated without significant degradation of transmission performance. Since only quadratic spectral chirp can be compensated using the tunable optical dispersion compensator in this experiment, coherent detection with electronic signal processing should be able to handle the chirp equally well or better.

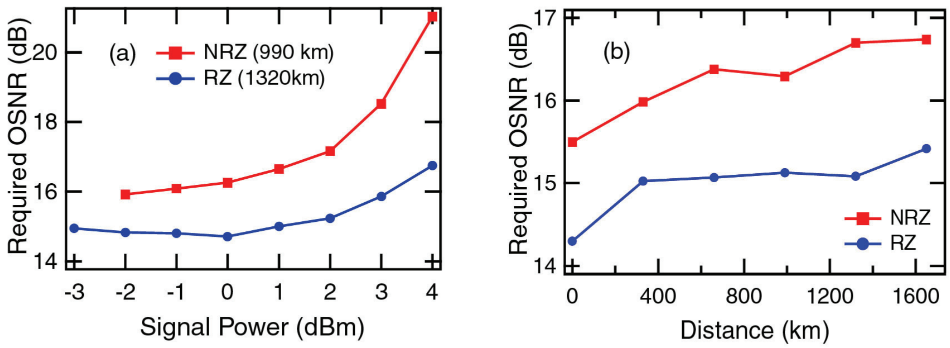

Fig. 3. (a) Required OSNR for a BER of 10^{-3} as a function of input signal powers. (b) Required OSNR as a function of transmission distances.

In Fig. 4, we show some of the received eye diagrams of NRZ-DQPSK and RZ-DQPSK signals after demodulation. Shown in Fig. 4(a) is an eye diagram of NRZ-DQPSK signals transmitted over 1320 km with a BER of 7×10^{-5} and an OSNR of 20.3 dB. In Fig. 4(b), we show an eye diagram of RZ-DQPSK signals transmitted over 1650 km with a BER of 5×10^{-5} and an OSNR of 18.4 dB.

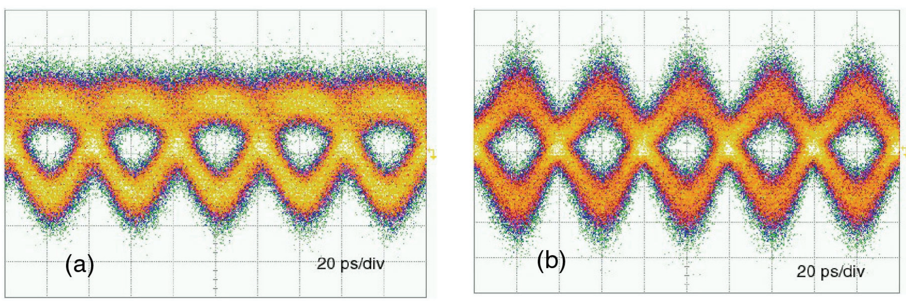

Fig. 4. (a) Eye diagram of demodulated NRZ-DQPSK after 1320 km. (b) Eye diagram of demodulated RZ-DQPSK after 1650 km.

4. Summary

We have confirmed the ability to transmit over long distance multi-level phase modulated signals generated using an EAM-based vector modulator. Both NRZ-DQPSK and RZ-DQPSK signals generated using the hybrid integrated device have been transmitted over 1650 km in a dispersion-managed SSMF loop. Our results suggest the potential benefits of using such integrated EAM-based vector modulators for applications involving higher-order multi-level modulation formats owing to the small form factors and small drive voltage requirements.

5. References

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