280-Gb/s 320-km Transmission of Polarization-Division Multiplexed QAM-PAM with Stokes Vector Receiver

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Abstract: We propose a novel three-dimensional modulation scheme on Stokes space for metro and regional optical transmissions. Based on this scheme, 320-km transmission of 280-Gb/s 16QAM-PAM2 signals using a Stokes vector receiver is experimentally demonstrated.

OCIS codes: (060.2330) Fiber optics communications; (230.4110) Modulator; (230.0040) Detectors;

1. Introduction

The capacity demand of optical networks continues to grow rapidly, especially for data center interconnects (DCIs). Coherent optical systems have been deployed as the mainstream technology for long-haul networks [1, 2], attributed to its high spectral efficiency and high channel impairment tolerance. On the other hand, intensity modulation-direct detection (IM/DD) systems have also received significant attentions for short reach applications such as intra-DCI connections because of its low cost, small footprint and low power consumption [3]. Recently, Stokes vector based direct detection (SV-DD) system attracted rising interest because of the multi-dimensional modulation and distinguished channel linearization capabilities [4-7], and it is considered as an intermediate solution between coherent and IM/DD systems. In the self-coherent SV-DD system in [4], complex signal is modulated on one polarization, and a laser tone is sent on the other polarization as a phase reference at receiver. Later, polarization-division multiplexed (PDM) SV-DD systems were proposed to further exploit the potential capacity of SV-DD systems [5-7]. However, since the phase reference is removed, the SV-DD systems in [6,7], which achieve higher spectral efficiency, cannot compensate chromatic dispersion (CD) and thus are only suitable for short reach applications.

In this paper, we propose a novel SV-DD system, which increases spectral efficiency while maintaining CD compensation ability. 280 Gb/s 16QAM-PAM2 signals using the proposed SV-DD modulation and demodulation is transmitted over 320 km standard single mode fiber (SSMF) with a bit error rate (BER) below the 20% soft-decision forward-error-correction (SD-FEC) threshold. In particular, this system achieves 25% additional spectral efficiency relative to [4], and additional 300 km of fiber transmission with respect to [5-7]. This is the longest reach that has been reported for 200 Gb/s per wavelength and beyond using SV-DD.

2. QAM-PAM Stokes modulation and demodulation

The architecture of the employed transmitter is depicted in Fig. 1(a). Particularly, a continuous wave from an external laser source is fed to a dual-polarization IQ modulator (DP-IQM). A complex QAM signal $\mathrm{E}_\mathrm{X}^\mathrm{t}$ is generated on X-polarization. For Y-polarization, modified PAM2 format on the magnitude of the signal $\mathrm{E}_\mathrm{Y}^\mathrm{t}$ with a fixed phase ø is mapped. Since we have to bias the MZMs at null in order to enable CD pre-compensation, a four-level signal is required to enable the modified PAM2 format assuming the used digital-to-analog-converters (DACs) are AC-coupled,. To generate this four-level signal, the equivalent two levels of the electric field is toggled in phase such that even symbols have phase $ø$ and odd symbols have phase $ø + \pi$. In order to keep the interphase difference between the two polarizations fixed, we also add a π phase shift to the odd QAM symbols on the X-polarization. With the available field at the transmitter for CD pre-compensation, the signals are polarization multiplexed with transmitted Stokes vector represented as $\mathrm{S}_0 = |\mathrm{E}_\mathrm{X}^\mathrm{t}|^2 + |\mathrm{E}_\mathrm{Y}^\mathrm{t}|^2$, $\mathrm{S}_1 = |\mathrm{E}_\mathrm{X}^\mathrm{t}|^2 - |\mathrm{E}_\mathrm{Y}^\mathrm{t}|^2$, $\mathrm{S}_2 = 2\mathrm{Re}[\mathrm{E}_\mathrm{X}^\mathrm{t}\mathrm{E}_\mathrm{Y}^{\mathrm{t}*}]$, $\mathrm{S}_3 = 2\mathrm{Im}[\mathrm{E}_\mathrm{X}^\mathrm{t}\mathrm{E}_\mathrm{Y}^{\mathrm{t}*}]$ where $*$, Re, Im denote complex conjugation, real and imaginary parts of a complex number, respectively. The received signals are detected in the Stokes space with a well-reported SV-DD receiver in the literature, as illustrated in Fig. 1(b) [4-5]. To recover the transmitted signals, the $|\mathrm{E}_\mathrm{Y}^\mathrm{t}|^2$ need to be detected first through a real 4x1 multiple-input-single-output (MISO) equalizer as

$$|E_Y^t|^2 = m_{12}|E_X^r|^2 + m_{22}|E_Y^r|^2 + m_{32}\, Re[E_X^r E_Y^{r*}] + m_{42}\, Im[E_X^r E_Y^{r*}] \tag{1}$$

where m_{12}, m_{22}, m_{32} and m_{42} are the real equalizer taps. The next step is to retrieve the transmitted S_2 and S_3 via a 4x2 multiple-input-multiple-output (MIMO) equalizer as

$$\begin{bmatrix} \mathrm{S}_2 \\ \mathrm{S}_3 \end{bmatrix} = \begin{bmatrix} \mathrm{m}_{13} & \mathrm{m}_{23} & \mathrm{m}_{33} & \mathrm{m}_{43} \\ \mathrm{m}_{14} & \mathrm{m}_{24} & \mathrm{m}_{34} & \mathrm{m}_{44} \end{bmatrix} \begin{bmatrix} |\mathrm{E}_\mathrm{X}^\mathrm{r}|^2 \\ |\mathrm{E}_\mathrm{Y}^\mathrm{r}|^2 \\ \mathrm{Re}[\mathrm{E}_\mathrm{X}^\mathrm{r}\mathrm{E}_\mathrm{Y}^{\mathrm{r}*}] \\ \mathrm{m}[\mathrm{E}_\mathrm{X}^\mathrm{r}\mathrm{E}_\mathrm{Y}^{\mathrm{r}*}] \end{bmatrix} \tag{2}$$

where $m_{13},\ldots, m_{43}, m_{14},\ldots, m_{44}$ are real equalizer taps. Finally, the QAM signal on the X-polarization can be recovered from

$$\begin{bmatrix} Re(E_X^t) \\ Im(E_X^t) \end{bmatrix} = \begin{bmatrix} \mathrm{S}_2 \\ \mathrm{S}_3 \end{bmatrix} ./|E_Y^t| \tag{3}$$

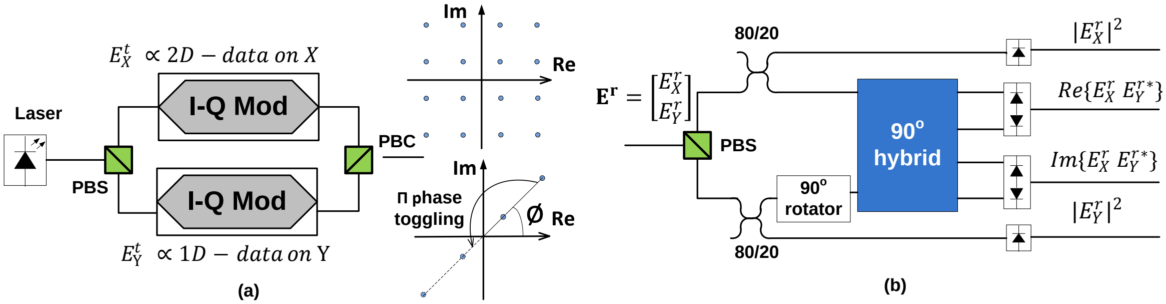

Fig. 1. Schematic diagram of the proposed SV-DD transceiver including (a) transmitter with constellations of dual polarization signals and (b) receiver.

3. Experiment and results

Fig. 2 depicts the experiment setup, where the output of a 100 kHz linewidth external cavity laser (ECL) operating at 1550.12 nm with 15.5 dBm optical power was fed into an InP-based Dual Polarization IQ modulator. An AC-coupled 8-bit DAC operating at 84 GSps generated four electrical signals which were amplified using four discrete radio-frequency (RF) amplifiers, each having a 3 dB bandwidth of 50 GHz. The four RF amplifiers were followed by RF delay lines for synchronization before driving the DP-IQM. The generated optical signal contained the QAM modulation on X-pol and the modified PAM modulation on Y-pol, as described previously in Fig. 1(a). The output signals of the DP-IQM were boosted by an Erbium-doped fiber amplifier (EDFA) and the optical power was controlled by a variable optical attenuator (VOA) before the signals entered a re-circulating loop. The loop comprised four spans of 80 km SSMF, four EDFAs, and a tunable filter used after the second span with a bandwidth of 2 nm. After the loop, the signals were filtered and amplified before entering the SV-DD receiver as plotted in Fig 1. (b) with the received power of 13 dBm. Both PDs and BPDs had 3-dB bandwidths of 40 GHz. Then the signals were digitized by four 63 GHz ADC channels sampling at 160 GSps from two synchronized real-time oscilloscopes

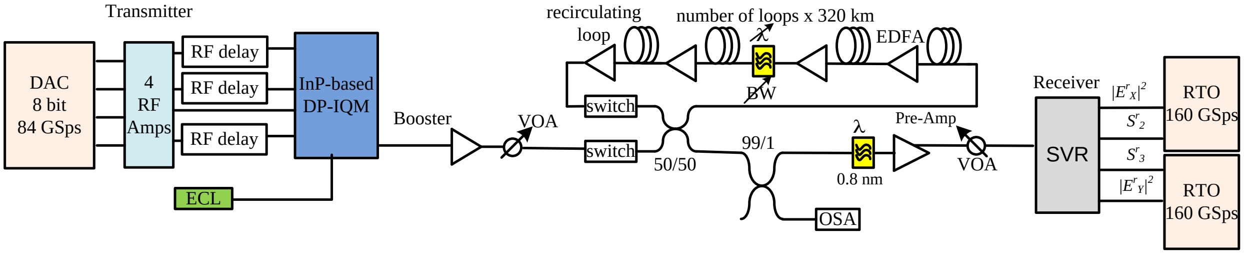

Fig. 2. Experiment setup for 56 Gbaud QAM-PAM SV-DD transmissions.

The transmitter side DSP blocks consisted of symbol generation for QAM and PAM, raised-cosine (RC) pulse shaping with a roll-off factor of 0.1, CD pre-compensation, and pre-emphasis to compensate the transmitter frequency response. The pre-emphasis equalizer was obtained experimentally to achieve an optimal performance for 56 Gbaud signals. At the receiver side, the off-line processing started with resampling to 2 samples per symbol followed by synchronization using training symbols. Afterwards, the direct detection term $|\mathrm{E}_\mathrm{Y}^\mathrm{t}|^2$ was recovered using least-mean square (LMS) based MISO as described in Eq. (1). Next, the two transmitted SV S_2 and S_3 were obtained by a LMS based MIMO as described in Eq. (2). Before symbol demapping for BER counting, the QAM signal on X-pol was retrieved using Eq. (3).

Fig. 3 shows the BER as a function of transmission distance for 56 Gbaud PDM 16QAM-PAM2, 8QAM-PAM2 and QPSK-PAM2 signals, respectively. A bit rate of 280 Gb/s is achieved using 56 Gbaud 16QAM-PAM2, and after 320 km transmission the BER is 1.36 x 10^{-2}, which is below the SD-FEC threshold of 2 x 10^{-2}. Also, 224 Gb/s at 640 km and 168 Gb/s at 1280 km are achieved at BERs below the SD-FEC threshold using 56 Gbaud 8QAM-PAM2 and QPSK-PAM2, respectively. High order QAM such as 8QAM and 16QAM have larger BER compared to PAM2 as shown in Fig. 3(a). Fig. 3(b) shows that QPSK has similar BERs as PAM2 since both formats have the same two levels of decision thresholds at the receiver as explained earlier. The use of PAM4 together with 16QAM is possible and will be left for future investigations.

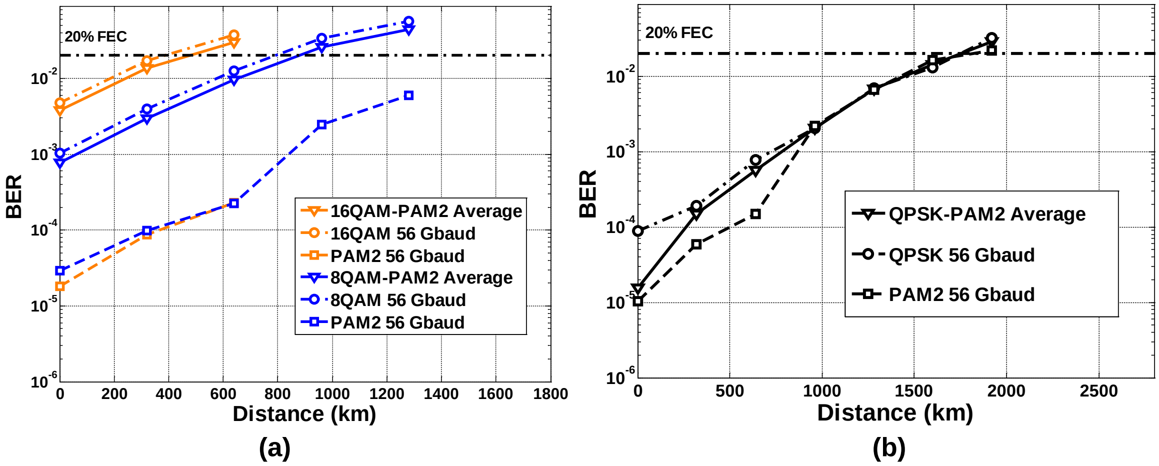

Fig. 3. BER vs. distance for PDM QAM-PAM signals: (a) 16QAM-PAM2, 8QAM-PAM2 and (b) QPSK-PAM2.

Fig. 4(a) plots the back-to-back detected constellations of 16QAM, 8QAM, QPSK and PAM2 signals. Fig. 4(b) shows the impact of received power on SV-DD performance for 16QAM-PAM2 after 320 km transmission. Due to the 10 dB loss of optical hybrid and the lack of power boost from LO as in coherent detection, the larger received power offers better BER for both X-pol and Y-pol signals, indicating that optical pre-amplification is beneficial for the proposed SV-DD systems.

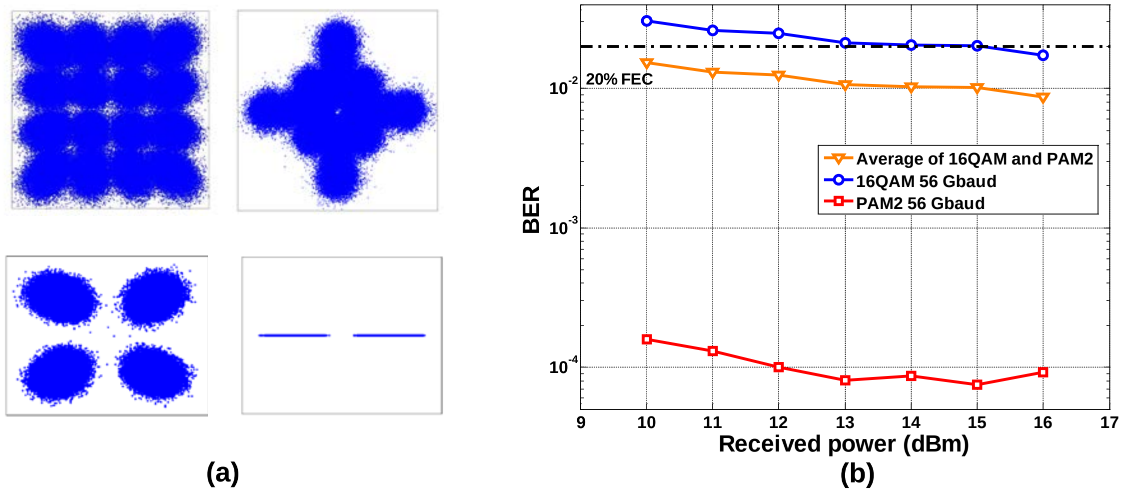

Fig. 4: (a) Received constellations after B2B transmission. (b) BER vs. received power for 16QAM-PAM2 after 320 km transmission.

4. Conclusion

We demonstrate a transmission of 280 Gb/s 16QAM-PAM2 signals over 320 km fibers based on a novel Stokes-vector direct detection (SVDD) scheme. Different from previous SVDD systems, the proposed scheme offers both high spectral efficiency (5 bits/s/Hz) per carrier and CD compensation capability.

5. References

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