Demonstration of 30Gbit/s QPSK-to-PAM4 Data-Format and Wavelength Conversion to Enable All-Optical Gateway from Long-haul to Datacenter

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Abstract: A tunable optical QPSK to PAM4 converter is experimentally demonstrated. The proposed method maps four symbols of QPSK signal to four different amplitude levels which can be directly detected in photo-diode. Open eyes are obtained for the detected PAM4 signal.
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1. Introduction

Higher-order modulation formats have been of great importance for longer-distance optical communications systems due to their higher system capacity, increased spectral efficiency, and lower speed of electronics [1-2]. One of the most common data formats is quadrature-phase-shift-keying (QPSK), and relatively-complex coherent techniques are required to receive such signals [3].

More recently, simpler and less-costly direct-detection approaches have gained much interest in the data center and short-haul application space. For example, multi-amplitude-level pulse-amplitude-modulation (PAM) can: (a) have higher capacity and spectral efficiency as compared to conventional on-off keying, and (b) be received using relatively simple and cost-effective direct-detection components [4-5]. Note that PAM4 corresponds to QPSK in terms of number of data symbols but does not exhibit the same high system performance as QPSK.

A challenge arises for data channels traversing a network to be compatible with the data format being used optimally at different points. For example, a data signal propagating from a long-haul network into a data center may need to be converted from QPSK into PAM4. There may be advantages to performing this operation at the access point in an all-optical fashion in order to avoid the optical-electrical-optical conversion. Although deaggregation of a 16-QAM channel into two PAM4 channels was accomplished previously, those approaches used coherent elements and not direct-detection components [6-7].

In this paper, we demonstrate all-optical format and wavelength conversion of 20-30Gbit/s QPSK-to-PAM4 by using to enable an optical interface gateway from long-haul to datacenter. In our proposed scheme, the constellation of the input QPSK signal is rotated and coherently added by a CW pump laser with an appropriate complex weight. Then this signal is sent to a photo detector to detect PAM4 signal. Open eyes are obtained for received PAM4 signal and BER measurements are also shown for 20-30Gbit/s signals. Wavelength tunability of the converted PAM4 is investigated as well

2. Concept

The concept of QPSK to PAM4 modulation format conversion is shown in Fig.1. As it is shown in Fig.1(a), four

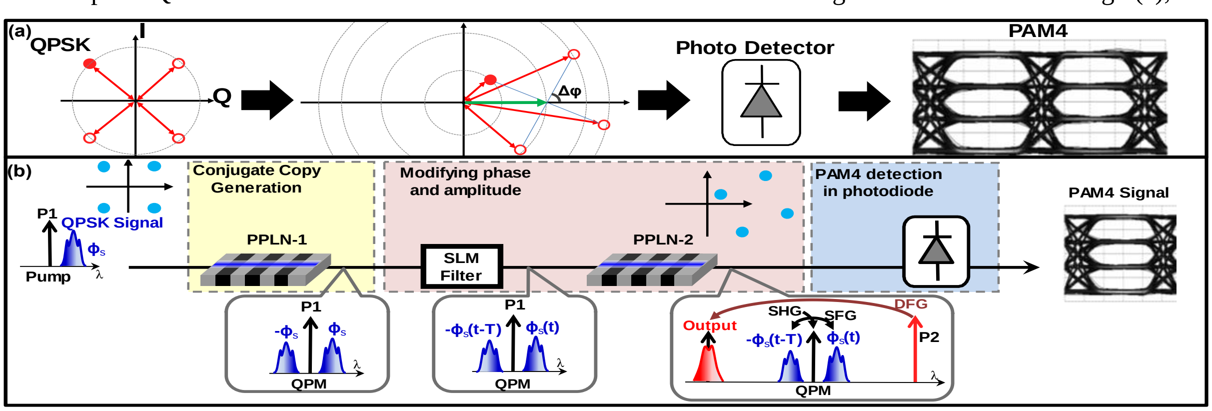

Fig. 1: (a) concept of optical QPSK to PAM4 conversion, (b) conceptual block diagram of QPSK to PAM4 conversion using nonlinear stages.

data symbols of QPSK signal have the same amplitude; however, they have four different phases. In this case, if direct detection is used, the encoded phase data will be vanished. Therefore, to detect a transmitted QPSK signal from long-haul network into a data center using direct detection, we need to map four symbols of QPSK signal to four different amplitude levels regardless of phase information. To perform this task, we can add a CW signal to QPSK signal and apply phase rotation to the constellation. In this way, a 4-level signal will be created (see Fig.1(a)). In this manner, each amplitude corresponds to a specific symbol in QPSK signal. By sending this signal to a photodetector, the PAM4 signal will be detected.

Figure 1(b) depicts the conceptual block diagram of converting QPSK signal to PAM4 using all optical signal processing in two nonlinear stages. In the first stage, an incoming QPSK signal along with a CW pump is injected into a periodically-poled-lithium-niobate (PPLN-1) waveguide to produce a phase conjugate copy of the original signal. The signal and its conjugate copy are then sent into an in-line spatial light modulator (SLM) phase and amplitude programmable filter to apply appropriate delays, amplitudes, and relative phases. Here, one symbol delay is required to be applied between signal and its conjugate which leads to phase locking between the first injected CW signal and the final output [8]. After that, these signals (i.e., original signal, the conjugate copy, and the CW pump) along with another CW pump are sent to the second nonlinear stage (PPLN-2). In this stage, since the first CW pump is set to the PPLN quasi-phase matching (QPM), it interacts with itself through second harmonic-generation (SHG), and creates the mixing term in $2\times f_{QPM}$. Also, signal multiplies with its conjugate through sum-frequency-generation (SFG) and creates the mixing term in $2\times f_{QPM}$. Therefore, the signal and CW pump can be added coherently since they are frequency and phase locked. This mixing processes followed by the difference-frequency-generation (DFG) which converts back the signals on $2\times f_{QPM}$ into C-band by employing the second CW pump.

3. Experimental Setup

The experimental setup is illustrated in Fig.2. A nested Mach-Zehnder modulator is used to generate the 20-30Gbit/s QPSK data (PRBS 2^{15}-1) at 1552.8 nm. The signal and a CW pump at 1550.7 nm are amplified, combined in a 50/50 coupler, and then sent together into PPLN-1. The conjugate of the signal is generated at the output of PPLN-1 (Fig.2(a)). A 100 m DCF and SLM filter are used to induce one symbol delay between signal and its conjugate. Also, we apply relative phases in the SLM. The SLM output is amplified in EDFA3 (1.2 W), passed through 5-nm filter, coupled with a CW pump (P2 at 1554.6 nm and 550 mW power from EDFA4) and sent to second stage PPLN. The spectrum at the output of PPLN-2 is illustrated in Fig.2(b). The QPM wavelength of the both PPLNs are tuned by temperature controllers to be at the same wavelength of the first pump. The multiplexed signal is then filtered, amplified and sent to a photodetector to capture the eye diagram. Please note that since the QPSK signal is multiplied with its delayed conjugated signal, a differential QPSK (DQPSK) is generated.

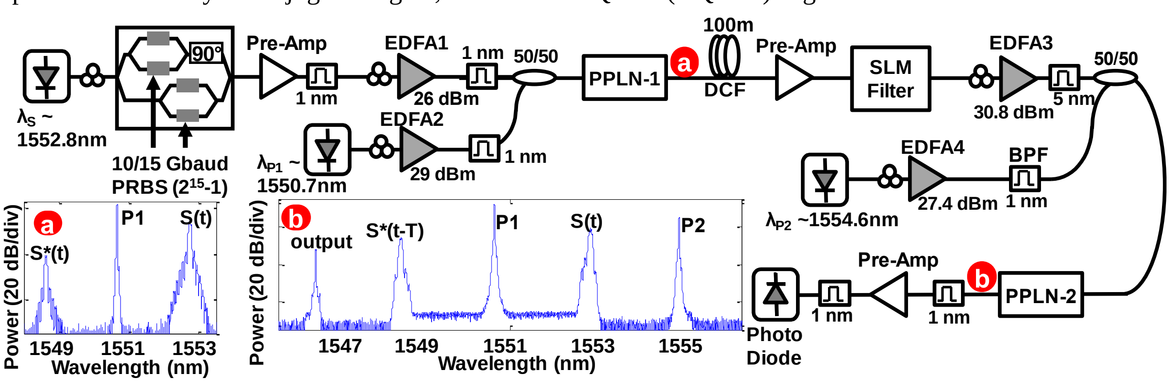

Fig. 2: Experimental setup (a) spectrum of the output of PPLN-1 (b) spectrum of the output of PPLN-2.

4. Results and discussion

The performance of the system is assessed by implementing the proposed method on 20 and 30 Gbit/s QPSK signals. In Fig. 3, the resultant eye diagrams of the output signal, after sending to photodiode, are shown. The eye diagrams are depicted for both simulation and experimental results. The impact of the applied phase rotation to the incoming QPSK signal can be perceived by comparing Fig.3 (a), (b) and (c). If $\Delta\varphi=45^\circ$, the photodiode detects a 2-level signal since there are just two different amplitude levels. In fact, this is the in-phase component of the original QPSK signal. Therefore, if we apply 90° more of relative phase, the quadrature component can be detected. Fig.3(b) indicates by setting $\Delta\varphi=90^\circ$, a 3-level signal will be detected in photodiode. In this case, two symbols of QPSK signal are merged and distorted and they cannot be recovered in the receiver. The case of interest is illustrated in

Fig.3(c) in which PAM4 signal is detected when we set Δφ≈71̊. In this case, each level of PAM4 signal corresponds to each symbol of QPSK signal. It can be seen that for 20Gbit/s signal, the eye is more open and clear than 30Gbit/s signal. However, the PAM4 signal is still detectable in 20G/s case that assures the baud rate tunability of the proposed method.

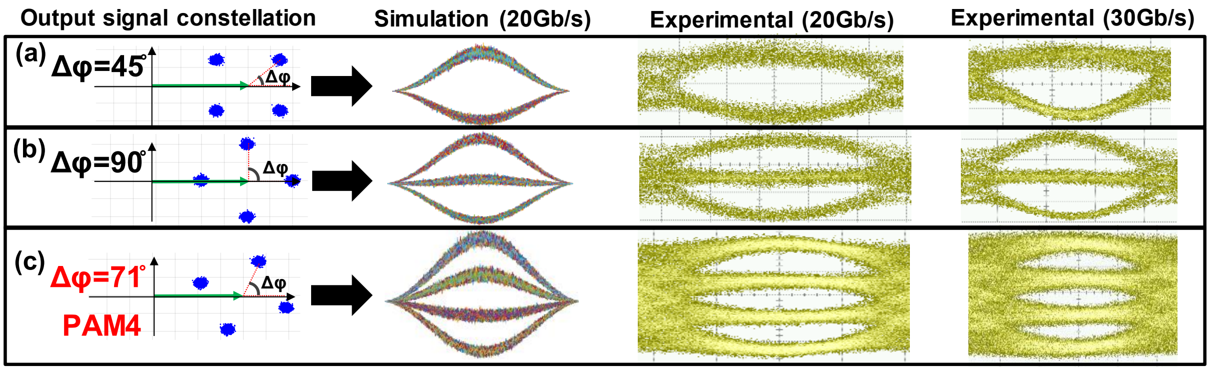

Fig. 3: The simulation and experimental result of sending output signal to direct detection by tuning the relative phase.

Fig.4(a) shows bit error rate (BER) measurements for the input QPSK signal and the output PAM4 signal versus OSNR for both 20 and 30Gbit/s. At BER of 1e-3, the OSNR difference between input QPSK signal and output PAM4 signal is ~22dB. Although it may show a huge gap between QPSK and PAM4, this is mainly because of the added CW pump to the QPSK signal. In order to show this fact, we also measured the BER of the received signal without adding the CW pump by employing coherent receiver. This signal shows ~3dB OSNR difference with the transmitted QPSK signal. For comparison of the quality of the generated PAM4, the BER of back to back (B2B) PAM4 is also measured.

In Fig.4(b-c) we show the wavelength tunability of the converted PAM4 in the output. In this case, the wavelength of the second stage CW pump is changed form 1554.6nm to 1558.2nm which leads to PAM4 wavelength conversation to the lower wavelength. The detected PAM4 eyes have almost the same quality. Hence, in our proposed technique, the incoming QPSK signal from long-haul network can be converted to a desirable wavelength in the output. For instance, the wavelength of 850 nm and 1310 nm attract attentions in data centers. Our system could potentially convert the input wavelength of 1550 nm to 850 nm or 1310 nm range along with converting data format from QPSK to PAM4.

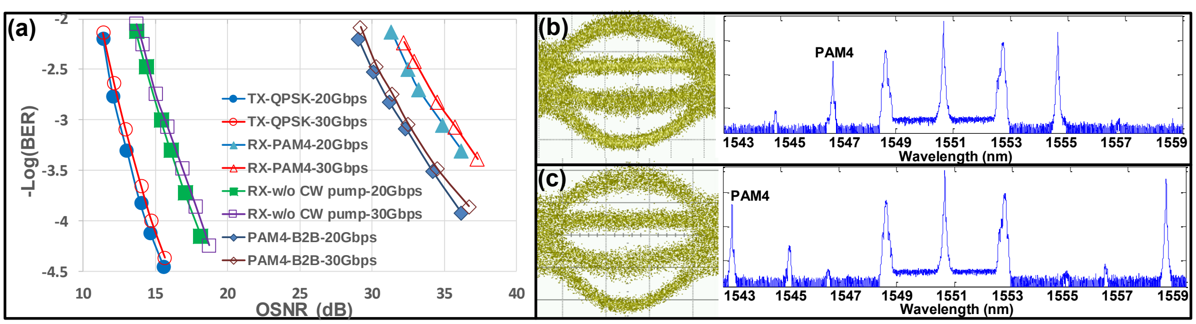

Fig. 4: (a) BER performance (b-c) wavelength tunability of the converted PAM4 signal in the output.

5. Acknowledgments

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6. References

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