All-optical two-channel polarization-multiplexing format conversion from QPSK to BPSK signals in a silicon waveguide

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All-optical two-channel format conversion is proposed and experimentally demonstrated from a 40 Gbit/s polarization multiplexing (Pol-MUX) non-return-to-zero quadrature phase-shift keying (QPSK) signal to Pol-MUX binary phase-shift keying (BPSK) signals by using phase-doubled four-wave mixing effects with two polarization-angled pumps in a silicon waveguide. The eye diagrams and constellation diagrams of the original QPSK sequences and the converted BPSK sequences of each channel are clearly observed on the two polarization states. Moreover, the bit error rates (BERs) of the two converted idlers are measured. The power penalties of all these converted BPSK sequences on both X and Y polarization states are less than 3.4 dB at a BER of 3.8×10^{-3}.

OCIS codes: (060.5060) Phase modulation; (070.4340) Nonlinear optical signal processing; (190.4380) Nonlinear optics, four-wave mixing; (190.4390) Nonlinear optics, integrated optics.
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1. INTRODUCTION

In optical communication networks, many kinds of modulation formats will be used for various applications. These modulation formats can be classified to be amplitude-shift keying (ASK) signals [on–off keying (OOK), etc.], phase-shift keying (PSK) signals [binary PSK (BPSK) and differential binary PSK (DPSK), etc.], and polarization-shift keying (PolSK) signals. Different modulation formats are suitable for different networks, and format conversion becomes essential at the nodes to exchange data between two optical communication links with different modulation formats. In particular, all-optical signal processing has been considered a promising technology in future optical communications to avoid optical–electrical–optical conversion, which can provide flexible management and interface, increase bandwidth utilization, improve efficiency, and ease data traffic. In the past, many format conversion schemes based on nonlinear effects such as cross-gain modulation (XGM) [1,2], cross-phase modulation (XPM) [2–6], and four-wave mixing (FWM) [3,4] have been reported in highly nonlinear fibers (HNLFs) [3,5], semiconductor optical amplifiers (SOAs) [1,2], and semiconductor waveguides [4,6] from non-return-to-zero (NRZ) to return-to-zero (RZ) signals [3,4], from NRZ to carrier-suppressed RZ signals [2], from RZ to NRZ signals [1], or from OOK to BPSK signals [5,6].

In next-generation optical networks, high-order and spectrally efficient modulation formats such as quadrature PSK (QPSK) and quadrature amplitude modulation (QAM) are considered to be candidates to enhance the transmission capacity and improve spectral efficiency. In addition, the spectral efficiency and data capacity can be doubled by using the polarization multiplexing (Pol-MUX) technique to combine two polarization channels with the same wavelength [7]. All-optical format conversion has been demonstrated involving single-polarization or Pol-MUX high-order modulation formats, such as from OOK to QPSK/Pol-MUX QPSK [8,9], 8PSK [10,11], or QAM [12] signals, from NRZ-QPSK to RZ-QPSK signals [13], and from QPSK to QAM signals [14,15]. Also, there have been attempts to convert high-order modulation formats to low-order modulation formats, such as from QPSK to BPSK [16,17] or DPSK signals [18], and from QAM to QPSK signals [19].

In these nonlinear effects, FWM has exhibited its special advantages in all-optical signal processing due to its ability to deal with advanced modulation formats, since the amplitude and phase information can be completely transferred from the signal light to the idler light. In particular, silicon waveguides have emerged as ideal integrated nonlinear media for their tight mode confinement ability and high nonlinear coefficients. In silicon waveguides, FWM-based all-optical signal processing, such as wavelength conversion and multicasting [7,20], format conversion [4], and logic gate [21], have been investigated. In this paper, we propose and experimentally demonstrate an integrated all-optical 40 Gbit/s Pol-MUX QPSK to Pol-MUX BPSK format conversion scheme by utilizing the phase-doubled FWM process in a silicon waveguide. Two-channel format conversion is realized by adopting two incident pumps with suitable polarization angles. The conversion performance is studied by measuring the eye diagrams and constellation diagrams of the X- and Y-polarization states. The bit error rate (BER) results are also measured, and the power penalties of both orthogonal polarization states are limited to less than 3.4 dB at a BER of 3.8×10^{-3}.

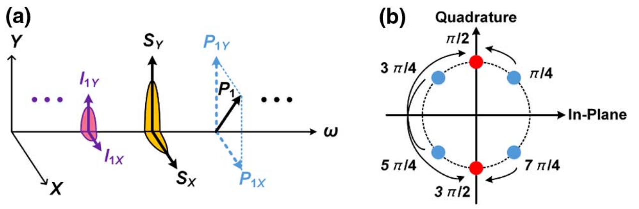

Fig. 1. Principle of the format conversion from a Pol-MUX QPSK signal to Pol-MUX BPSK signals based on phase-doubled FWM in a silicon waveguide. (a) Phase-doubled FWMs with polarization-angled pumps, and (b) phase change between the QPSK signal and the BPSK idler via the phase-doubled FWM process.

2. PRINCIPLE

Figure 1 shows the principle for format conversion of a Pol-MUX QPSK signal to a Pol-MUX BPSK signal in a silicon waveguide. Here we take one converted channel as an example. As shown in Fig. 1(a), the input Pol-MUX QPSK signal is generated by modulating two QPSK sequences on the two orthogonal polarization states (denoted as S_X and S_Y, and they are polarized along with the TE and TM modes of the waveguide, respectively) of an optical carrier S. The pump P_1 is injected into the silicon waveguide with an angle between the TE (or TM) axis, and it will be decomposed to the TE and TM modes, which are denoted as P_{1X} and P_{1Y} [7,20]. The pump components P_{1X} (or P_{1Y}) can interact with the polarization S_X (or S_Y) of the Pol-MUX QPSK signal via degenerate FWMs $P_{1X} - S_X - S_X - I_{1X}$ and $P_{1Y} - S_Y - S_Y - I_{1Y}$. An idler will be generated on the signal side with two orthogonal components denoted as I_{1X} and I_{1Y}. Its frequency equals $\omega_{I1} = 2\omega_S - \omega_{P1}$ and its phase satisfies $\varphi_{I1} = 2\varphi_S - \varphi_{P1}$ [20]. As the pump P_1 is a continuous wave (CW), it is reasonable to suppose the phase of the pump as $\varphi_{P1} = 0$ for demodulation. Thus, the phase-modulation depth of the idler is doubled compared to the original Pol-MUX QPSK signal, which can be depicted as $\varphi_{I1} = 2\varphi_S$. As shown in Fig. 1(b), when the signal is modulated by a Pol-MUX QPSK sequence with four phase levels, the signal phase will be doubled to two phase levels on the generated idler, which means a Pol-MUX BPSK signal. Therefore, Pol-MUX QPSK can be successfully converted to Pol-MUX BPSK through the all-optical phase-doubled FWM scheme. It is noted that the vector FWMs $P_{1Y} - S_Y - S_X - I_{1X}$ and $P_{1X} - S_X - S_Y - I_{1Y}$ will occur simultaneously [22], which will introduce phase noises and cause crosstalk. If multiple pumps $(P_1, P_2, P_3, \ldots)$ are adopted, multiple phase-doubled FWM processes will occur in parallel to generate multiple idlers on the signal side, and each idler will also carry the Pol-MUX BPSK sequences. This means that the number of format-converted channels can be increased just by providing more incident pumps.

3. EXPERIMENTAL SETUP

Figure 2 shows the experimental setup for the proposed format conversion scheme from Pol-MUX QPSK to Pol-MUX BPSK signals. The QPSK signal is generated by modulating a 10 Gbit/s $2^{15} - 1$ pseudorandom binary sequence (PRBS) on the optical carrier from a distributed feedback laser (Koheras Bootik E15 with a linewidth <1 kHz) with a wavelength of 1549.25 nm via an in-phase quadrature modulator (IQM). Then, the signal is split into two paths: an optical delay is introduced to one path to eliminate their correlation, and an

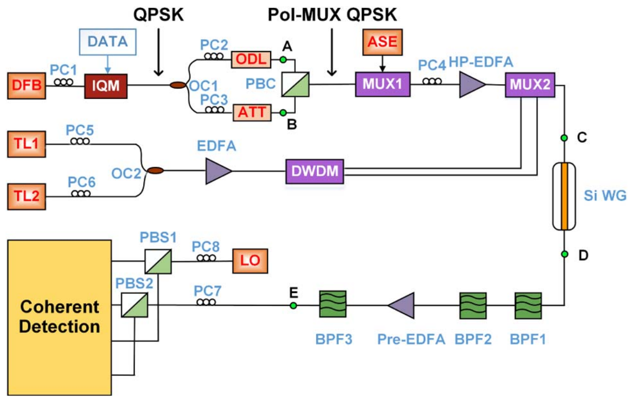

Fig. 2. Experimental setup of the two-channel format conversion from Pol-MUX QPSK to Pol-MUX BPSK signals based on phase-doubled FWM in a silicon waveguide.

optical attenuator is used in another path to balance their powers. By adjusting polarization controllers PC2 and PC3, their polarization states are tuned orthogonal to each other. Thereafter, the two paths are recombined using a polarization beam combiner (PBC) to generate the 40 Gbit/s Pol-MUX QPSK signal S. An amplified spontaneous emission (ASE) noise source is introduced via a multiplexer (MUX1) to change the input signal's optical signal-to-noise ratio (OSNR) for performance measurement.

In our experiment, two pumps are adopted to demonstrate the multichannel performance of the proposed format conversion scheme. The two CW pumps, P_1 and P_2, are provided by two tunable lasers (TL1 and TL2, Agilent N7714A with a linewidth of around 100 kHz). Their wavelengths are tuned to be 1548.42 and 1551.62 nm, respectively. The amplified pumps and signal are combined using MUX2 and launched into a 3 μm × 3 μm silicon waveguide, whose length is about 17 mm, effective mode area is about 5 μm^2, and nonlinear parameter is about 11 $W^{-1} m^{-1}$. The dispersions of the TE and TM modes are both about −830 ps/(km · nm) at 1550 nm [23]. Here the polarization state S_X (or S_Y) of the Pol-MUX QPSK signal is aligned to the TE (or TM) axis by adjusting PC4. By adjusting PC5 and PC6, the two pump polarizations are tuned to a suitable angle with respect to the waveguide's TE axis to make the efficiencies on the two polarizations almost the same. In the silicon waveguide, a phase-doubled FWM process occurs between the signal S and the two pumps, P_1 and P_2. The two idlers, I_1 (at 1550.11 nm) and I_2 (at 1546.89 nm), generated on the signal side from FWM between S and P_1 or P_2 will carry the Pol-MUX BPSK sequences.

The needed idlers are filtered by 0.8 nm bandpass filters (BPFs), pre-amplified, and demodulated by using digital coherent detection. A tunable laser (Santec TSL-210 with an approximate 200 kHz linewidth) is utilized as the local oscillator (LO). By adjusting PC7 and PC8, the two orthogonal polarization components of the LO and each converted idler are obtained at the two outputs of PBS1 and PBS2. After digital coherent detection, the demodulated constellation diagrams can be drawn and the BERs can be calculated. For comparison, the incident Pol-MUX QPSK signal and the converted two-channel Pol-MUX BPSK signals are both demodulated.

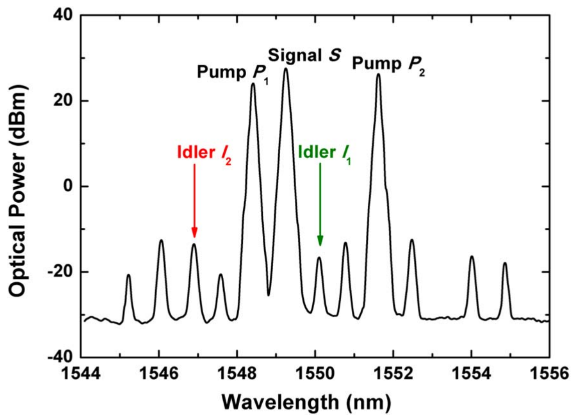

Fig. 3. Measured optical spectrum of the FWM processes for two-channel format conversion at the end of the silicon waveguide.

4. RESULTS

Figure 3 shows the measured optical spectrum of the two-channel format conversion from Pol-MUX QPSK to Pol-MUX BPSK signals at the end of the silicon waveguide using an optical spectrum analyzer (Ando AQ6317B), which is measured at point D, as shown in Fig. 2. The power of the signal is 29.6 dBm, and the powers of the two pumps are 26.1 and 28.2 dBm, before being injected into the silicon waveguide (measured at point C). The total loss of the waveguide is about 1.5 dB. The two needed idlers with the converted Pol-MUX BPSK sequences are at 1550.11 (I_1) and 1546.89 nm (I_2), and their corresponding powers are −16.6 and −13.7 dBm, with calculated conversion efficiencies of −44.7 and −41.8 dB, respectively.

The eye diagrams of the input signal (at points A and B) and the two format-converted idlers (at point E) are observed by a 40 GHz bandwidth oscilloscope (OSC, Agilent 86100A), as depicted in Fig. 4. Figures 4(a) and 4(b) are for the X and Y polarizations of the incident Pol-MUX QPSK signals, while Figs. 4(c)–4(f) are for the X and Y polarizations of the two converted Pol-MUX BPSK idlers I_1 and I_2. The eye diagrams of the converted data on the two polarizations of the generated idlers are clear, which shows that the two-channel format conversion from a Pol-MUX QPSK signal to a Pol-MUX BPSK signal is successfully realized.

Figure 5 shows the constellation diagrams of the input Pol-MUX QPSK signal and the two converted idlers. Figures 5(a) and 5(b) represent the input QPSK signals on the X and Y polarizations. The root-mean-square (RMS) error vector magnitudes (EVMs) of the X- and Y-polarization components are calculated to be 9.20% and 9.13%, respectively. Figures 5(c)–5(f) are for the X and Y polarizations of the Pol-MUX BPSK signal on idlers I_1 and I_2. The RMS EVMs of the X and Y polarizations of idler I_1 are 15.24% and 15.12%, respectively and they are 15.61% and 15.54% for idler I_2. Because of noise introduced in the conversion process, such as amplifier noise and vector FWM, the RMS EVMs increases less than 6.41% and 6.11% of the X and Y polarizations, respectively, compared to the input QPSK signals. By employing advanced digital signal processing (DSP) [24], the constellation distortion and EVM degradation introduced by the format conversion can be limited to a low level.

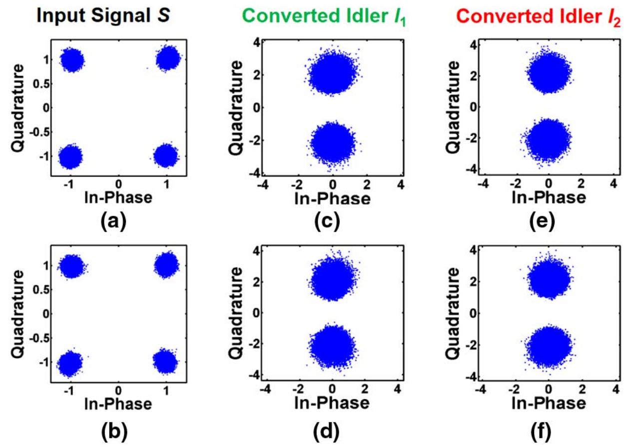

Fig. 5. Measured constellation diagrams of the Pol-MUX QPSK signal on signal S and the two-channel format-converted Pol-MUX BPSK signals on idlers I_1 and I_2: (a) S_X, (b) S_Y, (c) I_{1X}, (d) I_{1Y}, (e) I_{2X}, and (f) I_{2Y}.

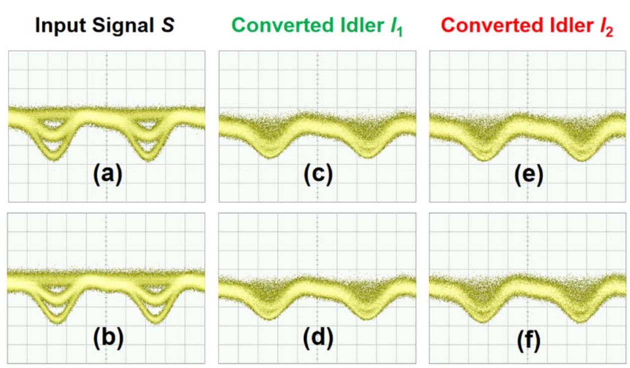

Fig. 4. Measured eye diagrams of the Pol-MUX QPSK signal: (a) S_X, and (b) S_Y. Format-converted Pol-MUX BPSK signals on idlers I_1 and I_2: (c) I_{1X}, (d) I_{1Y}, (e) I_{2X}, and (f) I_{2Y} (20 ps/div).

The BERs are measured to quantitatively estimate the quality of the format conversion. Figure 6 shows the BERs, as functions of the signal OSNR (in 0.1 nm reference bandwidth), for the incident Pol-MUX QPSK signal, the two converted Pol-MUX BPSK signals, and also a directly modulated Pol-MUX BPSK signal for comparison. The Pol-MUX QPSK signal is back-to-back (BTB) measured before the silicon waveguide,

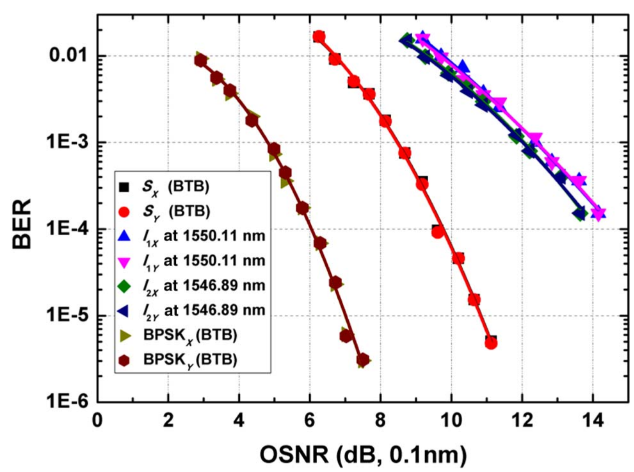

Fig. 6. Measured BERs as functions of the OSNR for the incident BTB signals and the two-channel format-converted idlers.

and the signal OSNR is tuned by the ASE source. Similarly, the BERs of the format-converted Pol-MUX BPSK signals are measured after the silicon waveguide. As shown in Fig. 6, the required OSNRs for the X- and Y-polarization states of the input Pol-MUX QPSK signal are both 7.6 dB at BER of 3.8×10^{-3}, while the required OSNRs increase to 11.0 and 10.9 dB, respectively, for idler I_1 and 10.6 and 10.5 dB for idler I_2. The power penalties caused by the format conversion are less than 3.4 dB for the X-polarization states and 3.3 dB for the Y-polarization states. We measure that the BTB Pol-MUX QPSK signal has a 3.7 dB degradation compared to the BTB Pol-MUX BPSK signal, which agrees well with the theoretical analysis in [25]. As a result, the signal degradation of the format conversion will be about 7.1 dB compared to the directly modulated Pol-MUX BPSK signals.

5. CONCLUSION

We have proposed and experimentally demonstrated an all-optical multiple-channel format conversion method from Pol-MUX QPSK signal to Pol-MUX BPSK signal by using the FWM processes in a silicon waveguide. A 40 Gbit/s Pol-MUX QPSK signal is generated and successfully converted to two-channel Pol-MUX BPSK signals with the cooperation of two incident pumps. The eye diagrams and constellation diagrams of the converted Pol-MUX BPSK signals are clear, which reveals the feasibility of the method. A format-converted power penalty lower than 3.4 dB is achieved for both the X- and Y-polarization components measured at BER of 3.8×10^{-3}. Furthermore, this scheme has the potential to be extended to higher-order modulation formats and higher bit rate processing, which shows great potential for future optical networks.

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