All-Optical Three-Input Simultaneous Multicasted Quaternary Addition/Subtraction Using Non-degenerate FWM in a Silicon Waveguide and 20 Gibt/s QPSK Signal

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Abstract: By exploiting multiple non-degenerate four-wave mixing (FWM) and quadrature phase-shift keying (QPSK) signals, we experimentally demonstrate three-input (A, B, C) simultaneous multicasted quaternary addition/subtraction (A+C-B, A+B-C, B+C-A) at 20 Gbit/s based on a silicon waveguide. Alignment tolerance of three input signals is also evaluated in the experiment.

OCIS codes: (130.3120) Integrated optics devices; (200.4560) Optical data processing; (190.4380) Nonlinear optics, four-wave mixing.

1. Introduction

Addition and subtraction are considered to be fundamental building blocks of digital signal processing which are ubiquitous in microprocessors for arithmetic operations. However, the processing speed is limited by the electronic bottleneck. It might be valuable to implement high-speed arithmetic operations of addition and subtraction in the optical domain. Optical nonlinearities are potentially candidates to enable various optical digital signal processing functions, such as logic gate, switching, optical computing, and coding/decoding [1]. Previously, optical binary logic gates were reported in various platforms for on-off keying (OOK) and phase-shift keying (PSK) modulation formats, including highly nonlinear fiber (HNLF), semiconductor optical amplifier (SOA), periodically poled lithium niobate (PPLN) waveguide, and chalcogenide (As_2S_3) waveguide [2-4].

With unabated exponential growth of data traffic, the using of m-ary phase-shift keying (m-PSK) and m-ary quadrature amplitude modulation (m-QAM) in coherent systems have become a key technique for efficient increase the transmission capacity and spectral efficiency of optical communication systems [5, 6]. In addition, multi-level modulation formats with multiple constellation points in I/Q plane can be also used to represent high-base (quaternary, octal, hexadecimal) numbers [7]. Hence, there might be interesting to enable optical digital signal processing for high-base numbers using multi-level modulation formats. Recently, we demonstrated optical arithmetic operations for high-base numbers using HNLFs [7-9]. Compared to HNLFs, Silicon-on-Insulator (SOI) based waveguides can offer some distinct advantages: (1) in silicon waveguides, high-contrast index leads to tight light confinement, which will greatly enhance the nonlinearities; (2) silicon waveguides also feature broad bandwidth, high speed, low power consumption, and complementary metal-oxide-semiconductor (CMOS) compatibility. In addition, multiple-input arithmetic operations are expected to increase the processing throughput and capability beyond conventional two-input functions. In this scenario, it is highly desirable to perform multiple-input addition/subtraction operation for high-base numbers in SOI platform.

In this paper, using QPSK signals with four-phase levels (π/4, 3π/4, 5π/4, 7π/4) to represent quaternary base numbers (0, 1, 2, 3), we experimentally demonstrate all-optical three-input (A, B, C) optical quaternary addition/subtraction (A+C-B, A+B-C, B+C-A) by exploiting multiple non-degenerate four wave mixing (FWM) processing in a silicon waveguide.

2. Concept and operation principle

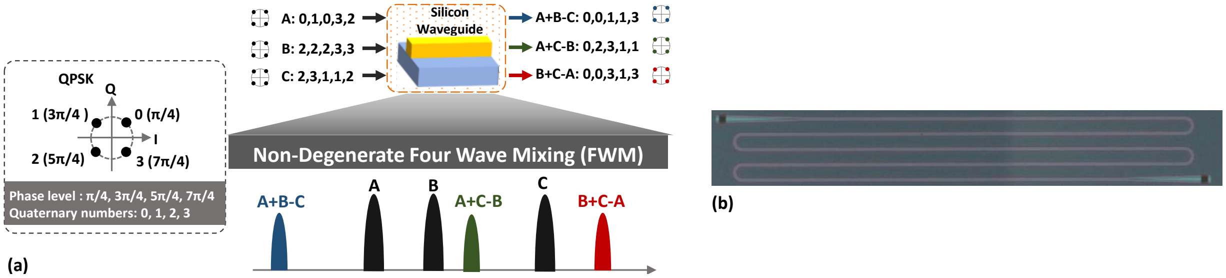

Fig. 1. (a) Concept principle of three-input optical quaternary addition/subtraction. (b) Photomicrograph of the silicon waveguide.

Figure 1(a) illustrates the concept of three-input quaternary addition/subtraction. Quaternary numbers (0, 1, 2, 3) are represented by 4 phase levels (0, $\pi/4$, $3\pi/4$, $7\pi/4$) of QPSK. Three input quaternary numbers (A, B, C) are injected into a silicon waveguide. Multicasted three outputs are achieved carrying quaternary addition/subtraction results (A+C-B, A+B-C, B+C-A). The photomicrograph of the used silicon waveguide is shown in Fig. 1(b).The silicon waveguide employed in the experiment is a 6-mm-long SOI waveguide with dimensions of 500 nm width and 220 nm thick. Vertical grating couplers are used to couple light in/out of the Si waveguide and ensure operation with TE-polarized light. The grating coupling loss is about 6 dB per facet. And the transmission loss of the waveguide is estimated to be 3~4 dB/cm.

3. Experiment

The experimental setup for silicon waveguide based all-optical three-input (A, B, C) optical quaternary addition/subtraction is shown in Fig. 2. The wavelength of three input QPSK signal fed into silicon waveguide is 1548.52 nm, 1550.12 nm, and 1552.52 nm, respectively. At the transmitter, the CW outputs from three external cavity laser (ECL1-3) serve as the signal light for the FWM. The signal light is then modulated with QPSK at 10 Gbaud by an optical I/Q modulator. An arbitrary waveform generator (AWG) is used to produce the electrical signal. The modulated signal is then amplified by an erbium-doped optical fiber amplifier (EDFA1). Afterwards, a wavelength selective switch (WSS) is used to separate three signals for symbol alignment. The three signals are then combined by an optical coupler (OC2) and amplified by anther EDFA (EDFA2) before launched into the silicon chip. Polarization controllers (PC4, PC5 and PC6) are used to adjust the polarization states of the three input signal to achieve optimized conversion efficiency of FWM. After wavelength conversion, the desired idler is selected using two stage optical filtering (TBF1, TBF2). The CW output from ECL4 serves as a reference light for coherent detection.

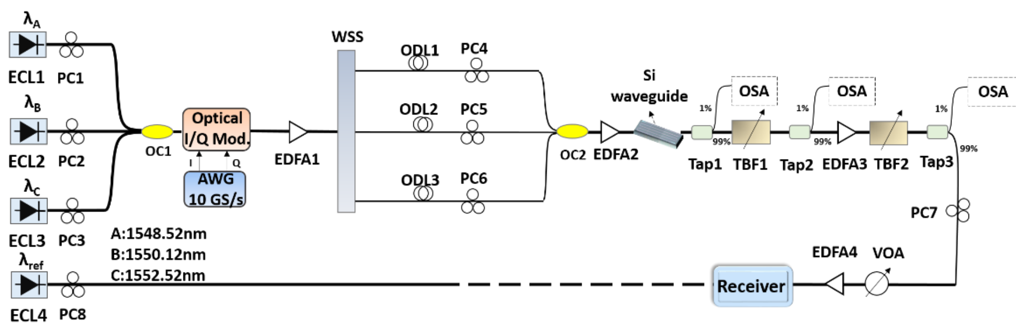

Fig. 2. Experimental setup for silicon waveguide based all-optical three-input (A, B, C) quaternary addition/subtraction. ECL, external cavity laser; AWG, arbitrary waveform generator; PC, polarization controller; WSS, wavelength selective switch; OC, optical coupler; TBF, tunable bandpass filter; OSA, optical spectrum analyzer; VOA, variable optical attnuator.

The measured spectrum for non-degenerate FWM is shown in Fig. 3. When three QPSK signals are coupled into the waveguide, three converted idlers (idler 1: 1546.12 nm, idler 2: 1550.92 nm, idler 3: 1554.12 nm) are generated by three non-degenerate FWM processes with their electrical fields (phase relationships) expressed as $E_{i1} \propto E_A E_B E_C^*$ $(\Phi_{i1}=\Phi_A+\Phi_B-\Phi_C)$, $E_{i2} \propto E_A E_C E_B^*$ $(\Phi_{i2}=\Phi_A+\Phi_C-\Phi_B)$ and $E_{i3} \propto E_B E_C E_A^*$ $(\Phi_{i3}=\Phi_B+\Phi_C-\Phi_A)$ [10]. Owing to the 2π phase wrap characteristic, the linear phase relationships indicate that three converted idlers correspond to module 4 operations of quaternary addition/subtraction of A+C-B, A+B-C, and B+C-A, respectively.

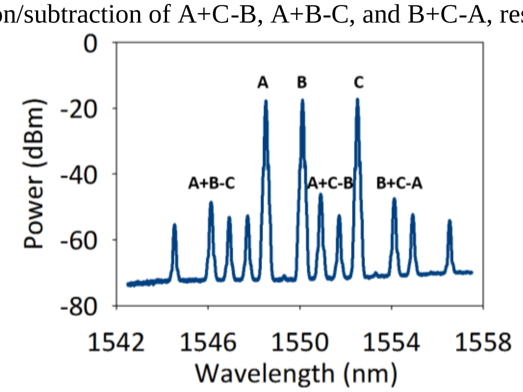

Fig. 3. Measured spectrum for non-degenerate FWM.

Figure 4 shows the measured symbol sequence for three-input optical quaternary addition/subtraction. The measured bit-error rate (BER) performance as a function of received optical signal-to-noise ratio (OSNR) is shown in Fig. 5(a). The OSNR penalty is around 6 dB at a BER of 2e-3 (enhanced forward error correction (EFEC) threshold). From Fig. 5(b), the measured constellations of three converted idlers (three-input optical quaternary addition/subtraction (A+C-B, A+B-C, B+C-A)) are also QPSK formats. The obtained results shown in Figs. 4 and 5 confirm the successful implementation of simultaneous quaternary addition/subtraction (A+C-B, A+B-C, B+C-A) using QPSK, non-degenerate FWM, and coherent detection.

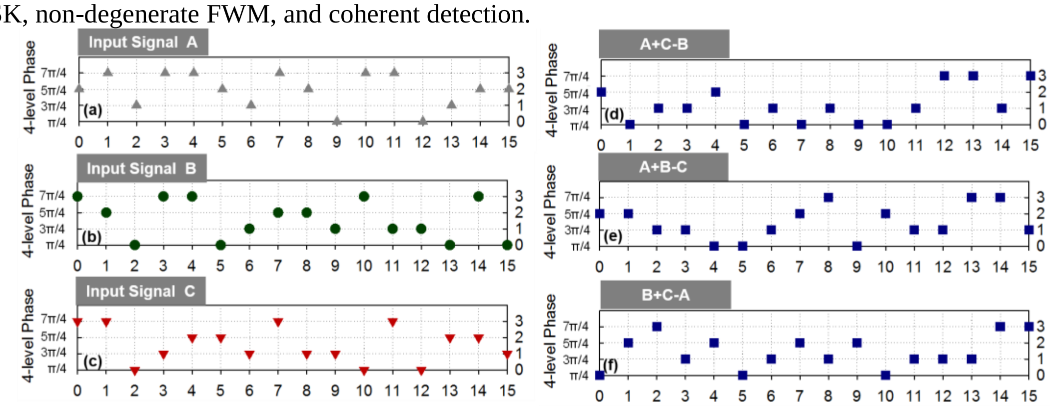

Fig. 4. Measured symbol sequence for (a)-(c) three-input optical quaternary signal and their (c)-(e) addition/subtraction.

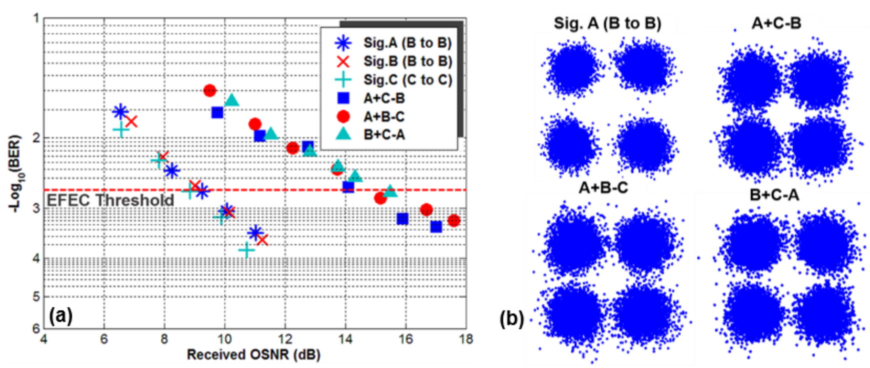

Fig. 5. Measured (a) BER curves and (b) constellations for three-input optical quaternary addition/subtraction (A+C-B, A+B-C, B+C-A).

The imperfect alignment between input signal A, B, and C will introduce degeneration of the output idlers (A+C-B, A+B-C, B+C-A). We measured the BER with different signal offset, as shown in Fig. 6. For each idler, we changed the offset of signal A and B, and evaluate the BER performance of the idlers. About 30 ps signal offset tolerance is observed at EFEC threshold for all idlers.

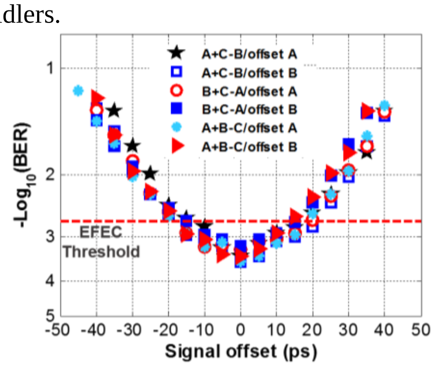

Fig. 6. Measured BER curves as functions of signal offset.

4. Acknowledgements

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