40-Gbaud/s (120-Gbit/s) Octal and 10-Gbaud/s (40-Gbit/s) Hexadecimal Simultaneous Addition and Subtraction Using 8PSK/16PSK and Highly Nonlinear Fiber

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Abstract: Employing 8PSK and 16PSK modulation formats, non-degenerate four-wave mixing (FWM) in a single highly nonlinear fiber (HNLF), and coherent detection, we experimentally demonstrate 40-Gbaud/s (120-Gbit/s) octal and 10-Gbaud/s (40-Gbit/s) hexadecimal simultaneous addition (A+B) and bidirectional subtraction (A-B, B-A).
OCIS codes: (200.4560) Optical data processing; (190.4380) Nonlinear optics, four-wave mixing

1. Introduction

Many electronic digital signal processors utilize addition and subtraction of two hexadecimal or octal numbers as key building blocks. In general, optical signal processing has the potential for high-speed operation of these two functions when using optical nonlinearities, such that two data streams can be added to and subtracted from each other at high speed.

Optical nonlinearities have been used to add/subtract two binary on-off-keyed (OOK) data streams at 160-Gbit/s using second-order nonlinear interactions in a periodically poled lithium niobate (PPLN) waveguide [1]. However, given that optical data can be encoded in the I/Q plane such that many different phases (m-ary) can be represented in a single symbol time, it is possible to add/subtract many different possible values within one symbol. This can provide dramatically increased spectral efficiency and lower electronic baud rates. This approach was shown recently for adding/subtracting two 50-Gbaud/s (100-Gbit/s) 4-ary data streams using differential quadrature phase-shift-keyed (DQPSK) modulation format and employing non-degenerate four-wave mixing (FWM) in a direct detection system [2]. Beyond quaternary addition/subtraction, a laudable goal would be to further develop addition/subtraction for even higher-base (i.e., octal/hexadecimal) numbers. It is possible to use higher-order multi-level modulation formats (i.e., 8PSK and 16PSK) to represent higher-base numbers (i.e., 8-ary and 16-ary). Although 8PSK has been widely used in spectrally-efficient, high-speed (100 Gbit/s and above) optical transmission [3-5], so far as we know there has been little research using 8PSK/16PSK format for optical processing functions, such as optical addition/subtraction.

In this paper, we show optical octal and hexadecimal simultaneous addition and subtraction using 8PSK and 16PSK modulation formats, non-degenerate FWM in a single highly nonlinear fiber (HNLF), and coherent detection. 10/40-Gbaud/s (30/120-Gbit/s) octal and 10-Gbaud/s (40-Gbit/s) hexadecimal simultaneous addition (A+B) and bidirectional subtraction (A-B, B-A) are demonstrated with optical signal-to-noise ratio (OSNR) penalties of less than 2.8/4.5 dB and 5 dB at a bit-error rate (BER) of 2e-3 (enhanced forward error correction (EFEC) threshold [4]).

2. Concept and principle

Fig. 1(a) depicts a conceptual diagram of octal/hexadecimal addition and subtraction. 8PSK with 8-level phase and 16PSK with 16-level phase are respectively used to represent octal (0, 1, 2, …, 7) and hexadecimal (0, 1, 2, …, a, b, c, d, e, f) numbers. For input two octal/hexadecimal numbers (A, B), output simultaneous addition (A+B) and bidirectional subtraction (A-B, B-A) are expected, which can be achieved using non-degenerate FWM in a single HNLF. As illustrated in Fig. 1(b), the working principle relies on three non-degenerate FWM processes as two input 8PSK/16PSK signals and a continuous-wave (CW) pump are fed into the HNLF. Three converted idlers are generated (idler1~idler3), following linear phase relationships expressed as $\Phi_{i1}=\Phi_A+\Phi_B-\Phi_{CW}$, $\Phi_{i2}=\Phi_A-\Phi_B+\Phi_{CW}$, and $\Phi_{i3}=\Phi_B-\Phi_A+\Phi_{CW}$ [2], where the CW pump phase Φ_{CW} is a constant, Φ_A, Φ_B, Φ_{i1}, Φ_{i2} and Φ_{i3} are the phase information carried by input signal A, signal B, output idler 1, idler 2, and idler3, respectively. For 8PSK/16PSK modulation formats using 8/16-level phase as octal/hexadecimal numbers, the three converted idler 1, idler 2 and idler 3 respectively correspond to the octal/hexadecimal addition (A+B) and bidirectional subtraction (A-B, B-A) thanks to the phase-wrapping characteristic with a periodicity of 2π.

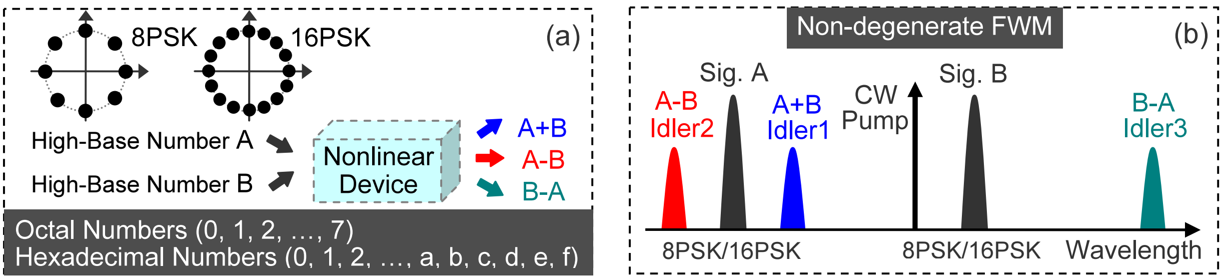

Fig. 1. (a) Concept and (b) principle of octal and hexadecimal addition and bidirectional subtraction using 8PSK/16PSK and non-degenerate FWM.

3. Experimental setup

Fig. 2 shows the experimental setup for 10/40-Gbaud/s octal and 10-Gbaud/s hexadecimal addition and bidirectional subtraction using 8PSK/16PSK, non-degenerate FWM in an HNLF, and coherent detection. The 8PSK/16PSK transmitter consists of a QPSK modulator which is a π/2-biased dual-parallel Mach-Zehnder modulator or I/Q modulator, two phase modulators (PM1, PM2), and an amplitude modulator (AM). 10/40-Gbaud/s QPSK is first generated after the QPSK modulator driven by two 10/40-Gbit/s data streams. 10/40-Gbaud/s 8PSK is then obtained after PM1 which is driven by the third 10/40-Gbit/s data stream to provide (0, π/4) phase modulation. Another PM2 driven by the fourth 10-Gbit/s data stream, providing (0, π/8) phase modulation, is employed for the 10-Gbaud/s 16PSK generation. The AM is driven by a 10/40-GHz clock to carve out 50%-ducy-cycle return-to-zero (RZ) pulses. Two CW lasers are sent to the 8PSK/16PSK transmitter, after which the generated two 8PSK/16PSK signals are separated by band-pass filters (BPFs) and relatively delayed integral symbols using a tunable optical delay line (ODL). Two 10/40-Gbaud/s 8PSK or 10-Gbaud/s 16PSK signals (A, B), together with a CW pump, are launched into a 520-m piece of HNLF with a nonlinear coefficient of 20 $W^{-1}\cdot km^{-1}$, a zero-dispersion wavelength (ZDW) of ~1555 nm, and a dispersion slope of ~0.026 $ps/nm^2/km$. Three non-degenerate FWM processes perform the octal/hexadecimal addition and bidirectional subtraction. At the receiver, coherent detection of 8PSK/16PSK is adopted using an Agilent optical modulation analyzer (N4391A) together with a Tektronix real-time sampling scope with a 50-Gs/s sample rate and a 20-GHz electrical bandwidth. Due to the bandwidth (20 GHz) limitation of the sampling scope, 40-to-10 Gbaud/s demultiplexing using an electroabsorption modulator (EAM) driven by a 10-GHz clock, is employed for 40-Gbaud/s octal addition and subtraction before the coherent detection.

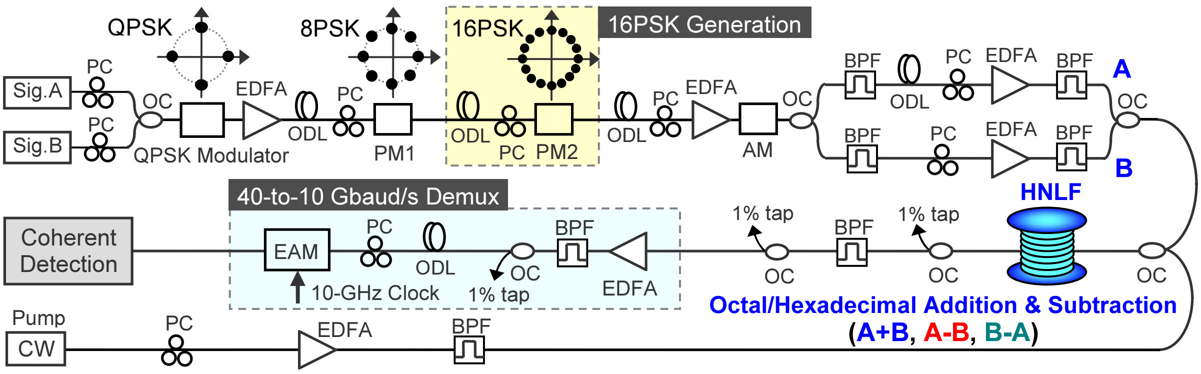

Fig. 2. Experimental setup for 10/40-Gbaud/s octal and 10-Gbaud/s hexadecimal simultaneous addition and bidirectional subtraction.

4. Experimental results and discussions

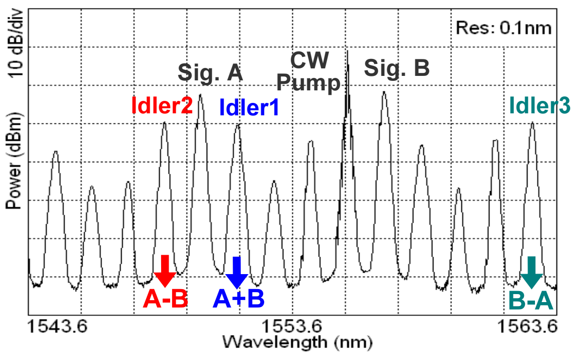

Fig. 3. Spectrum for 10-Gbaud/s octal addition and subtraction.

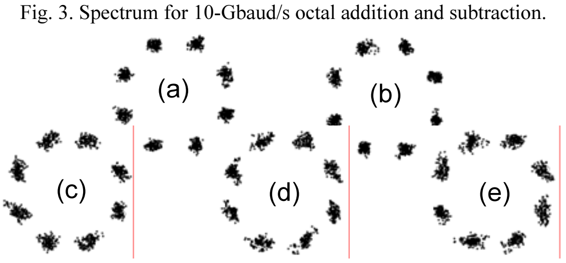

Fig. 4. Constellations for 10-Gbaud/s octal addition and bidirectional subtraction (OSNR>35 dB). (a) Input Signal A (EVM: 8.3). (b) Input Signal B (EVM: 8.6). (c) A+B (EVM: 11.6). (d) A-B (EVM: 11.7). (e) B-A (EVM: 12.0).

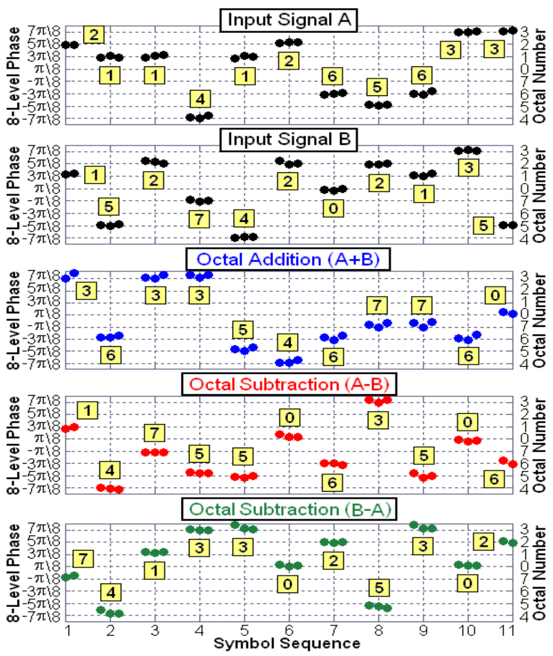

Fig. 5. Measured phase of symbol sequence with coherent detection for 10-Gbaud/s octal addition and bidirectional subtraction.

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Fig. 3 shows the measured spectrum for 10-Gbaud/s octal addition and subtraction. The power of two 10-Gbaud/s 8PSK signals (A: 1550.12 nm, B: 1557.01 nm) and CW pump (1555.62 nm) fed into the HNLF is about 10.8, 10.9 and 14.9 dBm, respectively. It can be seen that three idlers (idler 1: 1551.50 nm, idler 2: 1548.74 nm, idler 3: 1562.56 nm) are generated by three non-degenerate FWM processes. Fig. 4 depicts observed constellations with OSNR>35 dB, from which we can clearly distinguish the 8-level phase for octal addition and subtraction. The error vector magnitude (EVM) is also measured for input signals (A: 8.3, B: 8.6) and output octal addition (A+B: 11.6) and subtraction (A-B: 11.7, B-A: 12.0). In order to further verify the octal addition and bidirectional subtraction, we measure the phase of symbol sequence for two input signals and three converted idlers as shown in Fig. 5. 8-level phases represent octal (8-ary) numbers. It can be confirmed from Fig. 5 that simultaneous octal addition (A+B) and bidirectional subtraction (A-B, B-A) are successfully implemented using 8PSK, non-degenerate FWM, and coherent detection. Fig. 6(a) plots BER performance for 10-Gbaud/s octal addition and subtraction. The observed OSNR penalty at a BER of 2e-3 for octal addition (A+B) and bidirectional subtraction (A-B, B-A) is measured to be about 2.3, 2.6, and 2.8 dB, respectively. Shown in Fig. 6(b) is the BER as a function of the relative time offset between two signals (signal offset/symbol time) with an OSNR of ~20 dB. It is noted that the BER is kept below the EFEC threshold of 2e-3 [4], showing good tolerance to the signal offset (+/-35%). Fig. 6(c) and (d) depict the dynamic range of input pump and signal powers. A measurable dynamic range of ~28 dB for pump power and ~20 dB for signal power is obtained with the achieved BER below the EFEC threshold of 2e-3.

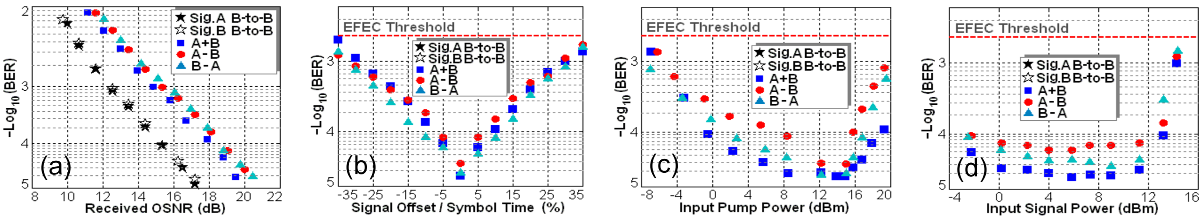

Fig. 6. (a) BER curves. (b) BER vs. Signal offset/symbol time. (c) BER vs. Input pump power. (d) BER vs. Input signal Power. (b)-(d) OSNR: ~20dB.

Fig. 7 shows the results for 40-Gbaud/s octal addition and bidirectional subtraction (A: 1550.12 nm, B: 1563.08 nm, pump: 1552.58 nm). The measured OSNR penalty at a BER of 2e-3 for octal addition (A+B) and bidirectional subtraction (A-B, B-A) is about 4.0, 4.5, and 3.6 dB, respectively. Fig. 8 further presents the results for 10-Gbaud/s hexadecimal addition and bidirectional subtraction (A: 1550.12 nm, B: 1557.01 nm, pump: 1555.62 nm). As shown in Fig. 8(a)-(e), 16-level phases denoting hexadecimal (16-ary) numbers are observed. The hexadecimal addition and bidirectional subtraction functions are verified using the similar figure to Fig. 5 which is not shown here. The measured OSNR penalty at a BER of 2e-3 for hexadecimal addition (A+B) and bidirectional subtraction (A-B, B-A) is about 5.0, 4.3, and 4.8 dB, respectively.

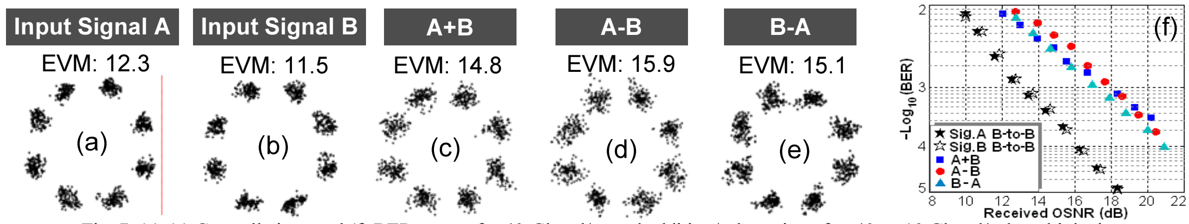

Fig. 7. (a)-(e) Constellations and (f) BER curves for 40-Gbaud/s octal addition/subtraction after 40-to-10 Gbaud/s demultiplexing.

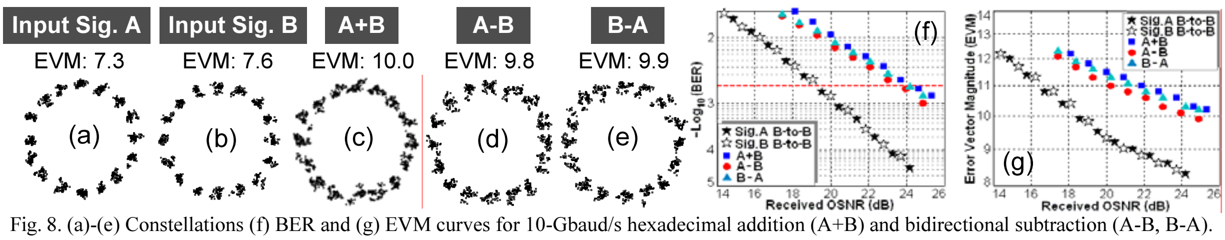

Fig. 8. (a)-(e) Constellations (f) BER and (g) EVM curves for 10-Gbaud/s hexadecimal addition (A+B) and bidirectional subtraction (A-B, B-A).

5. Acknowledgement

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6. References

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