Ultrafast all-optical three-input Boolean XOR operation for differential phase-shift keying signals using periodically poled lithium niobate

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We propose and demonstrate that periodically poled lithium niobate (PPLN) can act as an ultrafast three-input XOR gate for differential phase-shift keying (DPSK) signals based on cascaded sum- and difference-frequency generation. PPLN-based all-optical three-input Boolean XOR operations for 20 Gbits/s return-to-zero DPSK (RZ-DPSK), 40 Gbits/s RZ-DPSK, and 20 Gbits/s non-return-to-zero DPSK signals are all successfully verified in the experiment. © 2008 Optical Society of America

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All-optical Boolean XOR operation is a crucial technology required in optical signal processing for functions such as pattern generation, label recognition and swapping, half- and full-adder, and half-subtracter. However, most existing all-optical XOR gates focused on conventional on–off keying (OOK) signals and were not suitable for the differential phase-shift keying (DPSK) modulation format. In the past few years, DPSK has attracted increased attention owing to its improved receiver sensitivity compared to OOK and higher tolerance against transmission impairments. DPSK exhibits better performance than OOK for high-speed long-haul transmission. To cope with the wide use of the optical DPSK modulation format, it is of great importance to investigate the all-optical Boolean XOR operation for DPSK signals. Previously, the all-optical XOR gate for two-input return-to-zero DPSK (RZ-DPSK) signals was demonstrated based on four-wave mixing (FWM) in a semiconductor optical amplifier (SOA), which suffered from a limitation in complicated applications requiring more input signals [1]. Although FWM-based all-optical three-input XOR gate for RZ-DPSK signals using an SOA was then implemented with impressive performance, the operation speed in the experiment was limited to 10 Gbits/s, and only RZ-DPSK input signals were adopted [2].

Recently, with the increasing research interest on another promising candidate used in optical signal processing called periodically poled lithium niobate (PPLN), all-optical PPLN-based Boolean logic operations have also been widely studied by using various second-order nonlinearities and their cascading [3–8]. We have demonstrated PPLN-based NOT [5], AND [6], switchable OR–XOR [7], and half-adder and -subtracter [8]. Nevertheless, all the suggested PPLN-based logic gates were limited to OOK signals [3–8] and operated at a relatively low speed [3,4]. So far, a PPLN-based XOR gate for DPSK signals has not yet been reported. In this Letter, by using cascaded sum- and difference-frequency generation (cSFG–DFG), we propose and experimentally demonstrate for the first time to the best of our knowledge, PPLN-based all-optical three-input Boolean XOR operation for RZ-DPSK signals at 20 and 40 Gbits/s, and for non-return-to-zero DPSK (NRZ-DPSK) signals at 20 Gbits/s.

Figure 1 illustrates the experimental setup and operation principle. Three tunable lasers (TL1–TL3) and two cascaded Mach–Zehnder modulators (MZMs) driven by a bit pattern generator (BPG) are used to generate three input pseudorandom binary sequence (PRBS) NRZ-DPSK or RZ-DPSK signals (A, B, and C). After being amplified by an erbium-doped fiber amplifier (EDFA), three input signals are separated by using a wavelength division multiplexer (WDM), and then delayed integral bit periods with each other by use of two optical delay lines (ODL1, ODL2). All three input signals are recombined together through an optical coupler (OC2), amplified using a high-power EDFA (HP-EDFA), polarization controlled by a polarization controller (PC), and finally launched into PPLN to participate in the cSFG–DFG nonlinear interactions. The commercial HP-EDFA offers a small-signal gain of 40 dB and a saturation output power of 30 dBm. A 50 mm long PPLN waveguide fabricated by the electric-field poling method and annealing proton-exchanged (APE) technique is employed in the experiment. It has a microdomain period of 14.7 μm and a quasi-phase-matching (QPM) wavelength of 1543.2 nm at room temperature.

As shown in Fig. 1, in the cSFG–DFG processes signal A interacts with signal B to generate a sum-frequency wave by sum-frequency generation (SFG). At the same time, signal C mixes with the sum-frequency wave to yield a converted idler wave by the subsequent DFG process. In general, the new generated idler wave takes the AND result of three-input signals with OOK modulation format [4,6,9]. However, in the case of three-input DPSK signals, it is interesting to find that the idler corresponds to the Boolean XOR operation, which can be explained as follows. Under the nondepletion approximation, by integrating the coupled-mode equations for

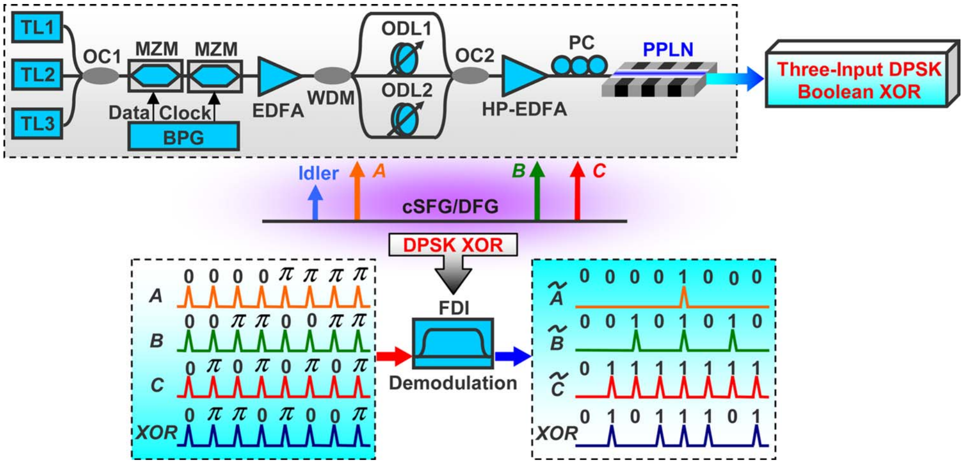

Fig. 1. (Color online) Experimental setup and operation principle of PPLN-based three-input XOR gate for DPSK signals.

cSFG–DFG we can derive an approximate analytical solution to the normalized complex amplitude of the converted idler wave (A_i), expressed as

$$A_i \approx -\omega_i \omega_{SF} \kappa_{SFG} \kappa_{DFG} A_A A_B A_C^* \left\{ \left[\frac{L}{\Delta} \sin(\Delta L) + \frac{\cos(\Delta L) - 1}{\Delta^2} \right] + i \left[\frac{\sin(\Delta L)}{\Delta^2} - \frac{L}{\Delta} \cos(\Delta L) \right] \right\}, \tag{1}$$

where A_A, A_B, and A_C denote the normalized complex amplitudes of the three-input signals, respectively. κ_{SFG} and κ_{DFG}, respectively, refer to the SFG and DFG coupling coefficients. Δ represents the phase mismatching for the DFG process. ω_i and ω_{SF} are the angular frequencies of the idler and sum-frequency wave. L is the length of PPLN.

Note that for the DPSK signal with constant optical power, the data information is carried by the phase of the optical field taking binary values of "0" or "π." Based on Eq. (1), we can further deduce the following phase relationship written by

$$\phi_i = \pi + \phi_A + \phi_B - \phi_C. \tag{2}$$

Taking into account the periodicity of 2π for optical phases, Eq. (2) indicates that the phase of the converted idler takes the XOR result of the phases of three-input signals, i.e., the Boolean XOR operation for three-input DPSK signals can be achieved as can be clearly seen in Fig. 1. A one-bit-delay fiber delay interferometer (FDI) is usually used to demodulate DPSK. It is interesting that the demodulation outputs from FDI also satisfy the three-input Boolean XOR operation, as shown in Fig. 1.

Figure 2 shows the typical optical spectra measured at the output of PPLN. As shown in Fig. 2(a), corresponding to 20 Gbits/s three-input Boolean XOR operation for RZ-DPSK signals, the wavelengths of signals A and B are set at 1535.7 and 1549.2 nm, respectively, to meet the SFG QPM condition. The signal C wavelength is tuned at 1554.5 nm, resulting in a new idler wave generated at 1530.6 nm via cSFG–DFG processes. Similarly, for three-input 40 Gbits/s RZ-DPSK and 20 Gbits/s NRZ-DPSK signals, the measured output optical spectra are shown in Figs. 2(b) and 2(c), respectively.

To further confirm the PPLN-based three-input Boolean XOR operation for DPSK signals, we observe the temporal waveforms for different optical waves using 2^7-1 PRBS. For 20 Gbits/s three-input RZ-DPSK signals, the demodulated waveforms at the output of FDI for three-input signals and converted idler (XOR) are displayed in Fig. 3. It is apparent that the observed waveforms successfully confirm the proposed Boolean XOR operation based on cSFG–DFG using a PPLN. Figure 4 depicts the demodulation outputs for three-input 40 Gbits/s RZ-DPSK signals and the corresponding converted idler taking the XOR result. For 20 Gbits/s three-input signals with NRZ-DPSK modulation format,

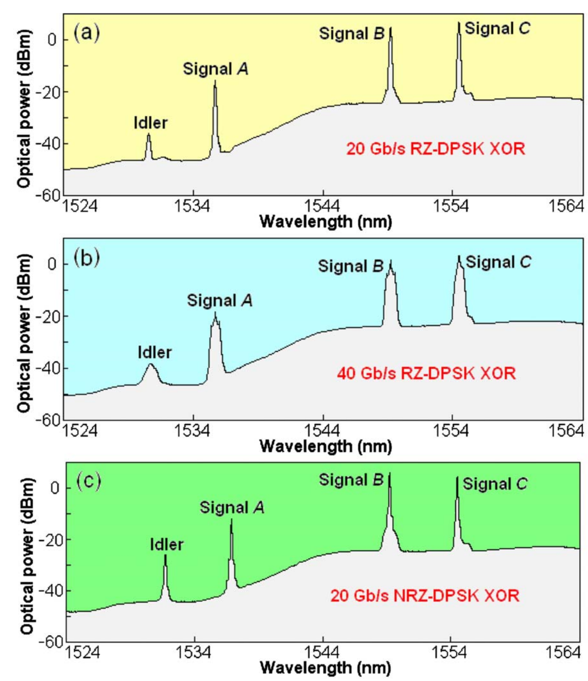

Fig. 2. (Color online) Measured optical spectra of PPLN-based three-input Boolean XOR operation for (a) 20 Gbits/s RZ-DPSK signals, (b) 40 Gbits/s RZ-DPSK signals, and (c) 20 Gbits/s NRZ-DPSK signals.

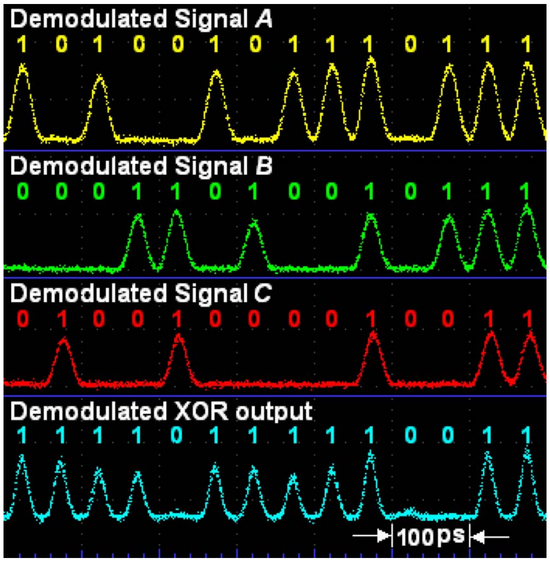

Fig. 3. (Color online) Demodulated waveforms of three-input signals and converted idler (XOR output) for three-input 20 Gbits/s RZ-DPSK Boolean XOR operation.

similar results can also be obtained as presented in Fig. 5. The obtained results shown in Figs. 3–5 indicate the successful implementation of the proposed ultrafast PPLN-based three-input Boolean XOR operation for both NRZ-DPSK and RZ-DPSK signals. Remarkably, the demonstrated three-input Boolean XOR operation for 20 Gbits/s RZ-DPSK signals has shown better operation performance compared with that for 40 Gbits/s RZ-DPSK and 20 Gbits/s NRZ-DPSK signals. The observed performance degradation could be mainly ascribed to the degraded quality of the original input 40 Gbits/s RZ-DPSK and 20 Gbits/s NRZ-DPSK signals adopted in the experiment. The optimization of the operation performance could be achieved in future by employing improved DPSK signal sources with better quality.

With further improvement, the proposed PPLN-based three-input Boolean XOR operation could also

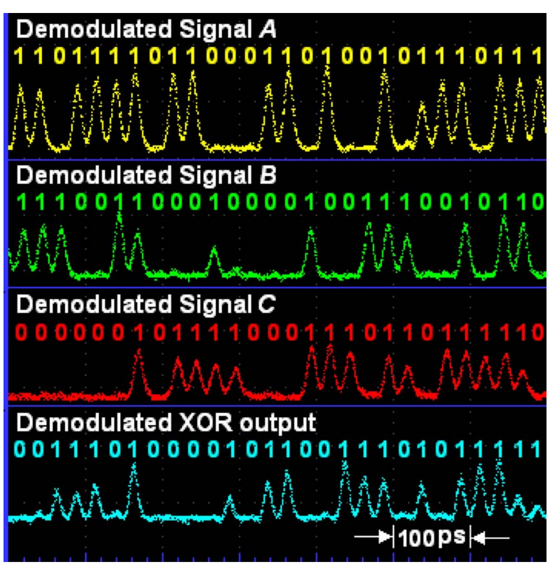

Fig. 4. (Color online) Demodulated waveforms of three-input signals and converted idler (XOR output) for three-input 40 Gbits/s RZ-DPSK Boolean XOR operation.

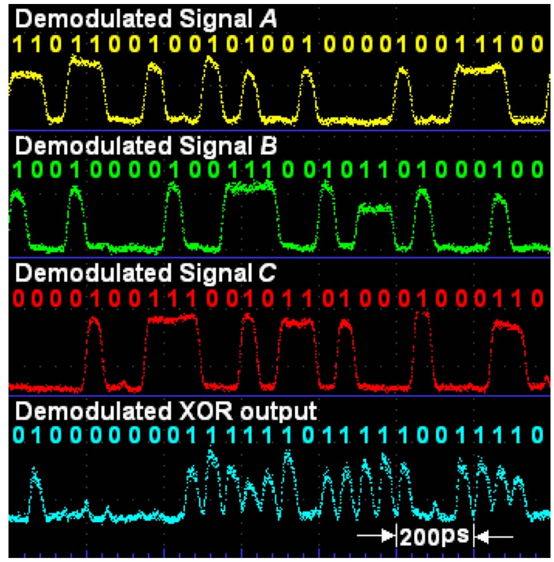

Fig. 5. (Color online) Demodulated waveforms of three-input signals and converted idler (XOR output) for three-input 20 Gbits/s NRZ-DPSK Boolean XOR operation.

be applied to the binary phase-shift keying format. Furthermore, owing to the ultrafast characteristic of PPLN, it is expected to perform the ultrafast PPLN-based three-input Boolean XOR operations for 160 and 320 Gbits/s DPSK signals.

In conclusion, we report a novel scheme of ultrafast all-optical three-input XOR gate for DPSK signals by using cSFG–DFG in a PPLN waveguide. Three-input Boolean XOR operations for 20 Gbits/s RZ-DPSK, 40 Gbits/s RZ-DPSK, and 20 Gbits/s NRZ-DPSK signals are all demonstrated in the experiment. It is expected that the proposed PPLN-based three-input Boolean XOR operation could also be applied to 160 and 320 Gbits/s DPSK signals.

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