20-Gbit/s all-optical XOR gate by four-wave mixing in semiconductor optical amplifier with RZ-DPSK modulated inputs

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Abstract: We demonstrate an all-optical XOR gate at 20-Gbit/s using FWM in an SOA, with RZ-DPSK modulated input signals. The scheme is inherently simple, robust, and free of pattern effect. It is feasible for ultrahigh-speed operation.

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OCIS codes: (060.2330) Fiber optics communications; (190.4360) Nonlinear optics, device;

Introduction

All-optical signal processing has attracted much attention in the past decade as the system line rate has advanced beyond the bandwidth of the available electronics circuit. Boolean exclusive-OR (XOR) is one of those common logic operations required in data packet processing. In future high-speed packet networks, all-optical XOR gate enables bit-serial header/label processing, thus the packet header and the label can be recognized, erased and replaced at the network nodes, all-optically. Previously, by using semiconductor optical amplifier (SOA), all-optical XOR gate was realized by utilizing cross gain modulation (XGM) [1] and cross-polarization modulation (XPolM) [2] at relatively low speed. Higher speed operation was reported by utilizing cross-phase modulation (XPM) in an SOA with differential inputs and in different configurations, including terahertz optical asymmetric demultiplexer (TOAD) [3], ultrafast nonlinear interferometer (UNI) [4] and SOA Mach-Zehnder interferometer (SOA-MZI) [5].

In this paper, we propose an all-optical XOR gate by four-wave-mixing (FWM) in an SOA with return-to-zero differential phase shifted keying (RZ-DPSK) modulated input signals. In addition to its simplicity and ability to alleviate patterning effect due to the constant intensity envelope, it can potentially support much higher speed operation than the XPM-based schemes since the intraband processes, such as carrier heating (CH) and spectral hole burning (SHB), leading to FWM have much shorter scattering than the interband process. We have successfully demonstrated all-optical XOR operation using FWM in an SOA at both 10-Gb/s and 20-Gb/s RZ-DPSK input signals. Higher speed operation can also be achieved with sufficiently narrow optical pulses.

Principle of FWM-based XOR gate

FWM is a third-order nonlinear process, by which a new field is created in a medium that depends on the product of three electrical fields present. In a SOA, three input fields beat to produce gain and phase gratings, which scatter the input fields to generate upper and lower sidebands as described by the equation:

\[ E_{132} = (A_1 \cdot A_3) r(\omega_1 - \omega_3) A_2 \exp[j(\omega_1 + \omega_2 - \omega_3)t + (\phi_1 + \phi_2 - \phi_3)] \]  

where \( A_i \) (\( i = 1, 2, 3 \)), \( \omega_i \) and \( \phi_i \) are the respective input field amplitudes, angular frequencies and phases, \( r(\omega_1 - \omega_3) \) describes the conversion efficiency and \( E_{132} \) is the FWM-generated field. With the phase of the input fields taking values either “0” or “\( \pi \)”, the possible phases of the generated new field will be “0”, “\( \pi \)”, “2\( \pi \)” or “-\( \pi \)”. Due to the periodicity of the phases, a phase of “\( \pi \)” is equivalent to “-\( \pi \)”, and similar property applies to the phases of “2\( \pi \)” and “0”. By assuming Boolean values “0” and “1” as the signal phases of “0” and “\( \pi \)”, respectively, the FWM process can be regarded as a three-input XOR Boolean operation in the phase domain, i.e. \( \phi_{132} = \phi_1 \oplus \phi_2 \oplus \phi_3 \).
To achieve FWM-based Boolean operation, we employ RZ-DPSK as the modulation format of the input signals, by which the “0” and the “1” bits are represented in form of phase change between adjacent optical pulses. A three-input XOR gate can be realized with the input fields $E_1(A_1, \omega_1, \phi_1)$, $E_2(A_2, \omega_2, \phi_2)$ and $E_3(A_3, \omega_3, \phi_3)$ all of which are RZ-DPSK modulated, i.e.

$$k_{1,i} \Rightarrow \phi_{1,i} \oplus \phi_{1,(i+1)}; \quad k_{2,i} \Rightarrow \phi_{2,i} \oplus \phi_{2,(i+1)} \quad \text{and} \quad k_{3,i} \Rightarrow \phi_{3,i} \oplus \phi_{3,(i+1)}$$

where $k_{1,i}$ (either “0” or “1”) is the binary value and $\phi_{1,i}$ (either “0” or “π”) is the phase value for the $i^{th}$ RZ-DPSK coded optical pulse, $i$ is the input wavelength index. When FWM occurs in the SOA with three input fields, one of the generated fields will be at an angular frequency of $(\omega_1 + \omega_2 - \omega_3)$, and a resultant phase of $(\phi_1 \oplus \phi_2 \oplus \phi_3)\pi$. After demodulation using a delayed-interferometer (DI), the output binary value, $k_{132,i}$, of the $i^{th}$ optical pulse is:

$$k_{132,i} = (\phi_{1,i} \oplus \phi_{2,i} \oplus \phi_{3,i}) \oplus (\phi_{1,(i+1)} \oplus \phi_{2,(i+1)} \oplus \phi_{3,(i+1)}) \Rightarrow k_{1,i} \oplus k_{2,i} \oplus k_{3,i}$$

That is, the output of the DI represents the XOR Boolean operation between respective binary value of the input fields $E_1(A_1, \omega_1, \phi_1)$, $E_2(A_2, \omega_2, \phi_2)$ and $E_3(A_3, \omega_3, \phi_3)$. Hence, all-optical XOR Boolean operation can be realized by FWM of RZ-DPSK modulated input signals.

**Experiment and Results**

The experimental setup is shown in Fig. 1. For simplicity, two-input FWM was performed in this experiment, the modified equation (1) became

$$E_{z1} = (A_1 \cdot A_2) \cdot \exp[j(2\omega_1 - \omega_2)t + (2\phi_1 - \phi_2)]$$

Using a pair of electroabsorption modulators (EAM), the RZ pulse streams were generated at 1547 nm and 1551 nm respectively. The optical pulses had a pulsewidth of about 15 ps and a repetition rate of 10.61 GHz. The pulse streams were then phase-encoded separately via optical phase modulators using 10.61-Gbit/s PRBS. As only two input signals were present for FWM, the input field at the shorter wavelength $(\omega_1)$ was modulated with a depth of “π/2”, instead of “π”, according to equation (4). After having amplified by the EDFAs, the DPSK coded pulse streams were then combined using a 3-dB fiber coupler. The average power launched into the SOA was about 6 dBm, with the two inputs at similar power level. From the output of the SOA, the FWM-generated signal at 1543 nm achieved conversion efficiency larger than 20 dB. It was then extracted by a 1-nm (FWMH) optical bandpass filter before being DPSK-demodulated via a DI with a relative delay of 94 ps. The output waveform was recorded using a 45-GHz p-i-n detector.

The observed waveforms are shown in Fig. 2. Fig. 2(a) and (b) show the demodulated bit patterns for the first input signal (“101110111”) and the second input signal (“011100010”). Fig. 2(c) shows the demodulated output from the proposed all-optical XOR gate (“110010101”). The obtained result verified the effectiveness of the XOR operation by the proposed FWM method. The unsatisfactory extinction ratio could be caused by possible amplitude fluctuation at “1” and “0” levels at the modulator driver output,
which led to inaccurate phase modulation during the DPSK encoding. To verify that the proposed all-optical XOR gate could be operated at high speed, the input signals were multiplexed to 21.22 Gbit/s, before being launched into the SOA. The corresponding obtained XOR output was shown in Fig. 3. The degraded waveform could be explained by the inter-channel crosstalk during optical time division multiplexing as a result of insufficient pulse extinction ratio and relatively broad signal pulsewidth.

We have also performed bit-error-rate measurement for the 10.61-Gbit/s input signals by switching off the phase modulation on the first signal at 1547 nm, such that the XOR gate functioned as a wavelength converter. The second input signal at 1551 nm was modulated with $2^{31-1}$ RZ-DPSK PRBS. The measured results showed only negligible power penalty (< 0.1 dB).

Summary

In this paper, an all-optical XOR gate operating up to 20-Gbit/s was demonstrated based on FWM in an SOA with input RZ-DPSK modulated signals. The proposed scheme is proved to be not only structurally simple and robust, but also able to effectively alleviate patterning induced degradation in the SOA as a result of employing the constant intensity modulation format. With sufficiently narrow optical pulses, our proposed FWM-based all-optical XOR gate with RZ-DPSK modulated inputs is feasible to be operated at ultrahigh speeds.

References