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40 Gb/s all-optical logic NOR and OR gates using a semiconductor optical amplifier: Experimental demonstration and theoretical analysis

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Abstract

We experimentally and theoretically demonstrate 40 Gb/s all-optical logic NOR and OR gates based on a semiconductor optical amplifier (SOA) and a blue shifted optical bandpass filter (OBF). Two kinds of data formats are discussed, namely return-to-zero (RZ) format and nonreturn-to-zero (NRZ) format. The logic NOR and OR functions of RZ format are realized at the OBF detuning of −0.22 nm and −0.44 nm, respectively. The logic NOR function of NRZ format is realized at the OBF detuning of −0.24 nm. The simulation is in good agreement with the experimental results when the linewidth enhancement factor is 5.5. The simulation also shows that the SOA with large linewidth enhancement factor is preferred to achieve NOR and OR functions with good performance. The input data signal is of good pulsewidth-tolerance for NOR function, whereas not for OR function. The high *Q* factor could be obtained at narrow pulses injection.

Keywords: All-optical logic gate; Semiconductor optical amplifier (SOA); Cross phase modulation (XPM)

1. Introduction

All-optical logic elements will be required to achieve high speed performance at data rates beyond 40 Gb/s because of the speed limitation set by the traditional electrical circuits [1]. Nonlinearities in semiconductor optical amplifier (SOA) have attracted considerable interest for realizing various logic gates. A variety of logic gates (including XOR, NOR, OR and HAND) based on cross phase modulation (XPM) have been presented [2] with advantages of high extinction ratio (ER) at the cost of complex interferometer configurations. Logic gates based on cross gain modulation (XGM) employing two-cascaded SOAs have been reported, such as AND logic and XOR logic with its application in half adders [3], AND logic and NOR logic realized by different power level control [4,5]. However the operation speed of XGM-based schemes is limited by the slow gain recovery time of the SOA. An effective solution to accelerate the gain recovery is with assistance of optical bandpass filter (OBF). Cho firstly presented the improved wavelength conversion (WC) scheme with a fiber Bragg grating filter [6,7]. Based on this approach high speed WC at 320 Gb/s has been demonstrated [8]. Moreover, multi-logic functions with AND, OR, and XOR gates at 10 Gb/s have been proposed with single SOA followed by a narrow OBF [9], and 40 Gb/s NOR function has been demonstrated as well [10]. However, data signals with ultrashort pulses (∼3 ps) are rigidly required to induce large phase shifts and chirp.

In this paper, we experimentally and theoretically demonstrate 40 Gb/s logic NOR and OR gates based on a single SOA and a blue shifted OBF. The NOR function of return-to-zero (RZ) and nonreturn-to-zero (NRZ) formats is obtained with the XGM effect of the SOA. However a

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blue shifted OBF at a detuning of about −0.22 nm is necessary to accelerate the gain recovery since the gain recovery time is much longer than single bit duration. The OR function of RZ format is obtained with the transient XPM effect of the SOA. In this case, the blue shifted OBF at a detuning of −0.44 nm is used to select the blue-shifted spectrum of the probe signal and convert the phase modulation to the intensity modulation. The Q factor of the NOR and OR functions dependent on the SOA α value and input pulsewidth is analyzed in numerical simulation. The simulation is in good agreement with the experimental results when α value is 5.5. The simulation shows that the NOR function has the potential advantages of pulse-width-tolerance.

2. Operation principle and experimental setup

The operation principle of the proposed logic functions is described in Fig. 1. Input signals with RZ and NRZ formats are illustrated in Fig. 1a and b, respectively. In Fig. 1a, two data signals with RZ format (Data A, Data B), combined with a continuous wave (CW) probe signal, are injected into the SOA. Due to XGM and XPM, the leading/trailing edge of the inverted probe signal is red/blue shifted. Hence the probe spectrum is broadened. The subsequent OBF is used to reshape the probe spectrum at a central wavelength of $\lambda_{cw} + \Delta\lambda_{det}$, which is different from the probe signal λ_{cw}. Our previous work showed that both inverted and non-inverted WC at 40 Gb/s could be obtained by adjusting the OBF detuning $\Delta\lambda_{det}$ properly [11]. Inspired by this work, we could obtain both OR logic and NOR functions with proper OBF detuning if two channels of the input data are launched into the SOA.

When the OBF detuning is set to be properly large (negative), the OBF is used to reject the probe carrier and select the blue-shifted spectrum. Either Data A or Data B or both launched into the SOA will induce blue shifted spectrum, which fits in the OBF passband. If both Data A and Data B are absent, the OBF will block the probe carrier without blue shifted spectrum. Therefore the output is logic OR function. When the OBF detuning is small (negative), the XGM effect remains dominant in the SOA since the probe carrier is not suppressed. Hence either Data A or Data B or both launched into the SOA will induce polarity-inverted output, which is logic NOR function. The blue shifted OBF with small detuning is useful to accelerate the SOA gain recovery. In our scheme, the SOA recovery time is much longer than the single bit period. If a single channel of input data can operate the XGM effect, the output will be the logic NOT of the input.

In Fig. 1b, we replace Data A and Data B with NRZ format. The operation principle of NOR logic is similar to the case of RZ data signal injection. Note that the blue shifted OBF with small detuning is also useful to accelerate the SOA gain recovery even under NRZ signal injection. The output becomes logic NOT function of the input if a single NRZ data can operate the SOA. Unlike the case of RZ signal injection, one cannot observe the logic OR function of NRZ signal, because the NRZ amplitude keeps constant under consecutive bit "1"s injection, which could not induce wavelength shifts of the probe signal.

The experimental setup for the proposed logic functions is shown in Fig. 2. The wavelengths of three CW beams generated by LD1, LD2, and LD3 are 1563.5 nm (λ_A), 1549.5 nm (λ_B), and 1557.32 nm (λ_{cw}), respectively. The data signals (λ_A and λ_B) are modulated by two Mach–Zehnder Modulators (MZMs) at 40 Gb/s to form 2^{31}-1 RZ pseudo random binary sequence (PRBS) signals. The duty cycle of these RZ pulses is 33%. The RZ format can be easily changed to NRZ format by removing the MZM driven by clock (CLK) signal. Then an erbium-doped fiber amplifier (EDFA1) and an attenuator (ATT) are used to adjust the RZ output peak power. Two data signals will be separated by the wavelength division multiplexer (WDM) and one of them is delayed for several bit periods by an optical delay line (ODL). Therefore, two data signals with different data pattern are obtained at the output of the optical coupler (OC2). The average power measured at the SOA input is −3.1 dBm (λ_A), −3.3 dBm (λ_B), −2.7 dBm (λ_{cw}), respectively. The SOA, manufactured by Kamelian Inc, is biased at 200 mA. No polarization devices are required because of the low polarization dependence (<0.5 dB). The SOA recovery time is about 90 ps, which is much longer than one bit period. A tunable OBF1 with 0.32 nm 3 dB-bandwidth has a detuning to the probe signal. Another EDFA2 and an OBF2 with 1 nm bandwidth are used to further amplify the converted signal power

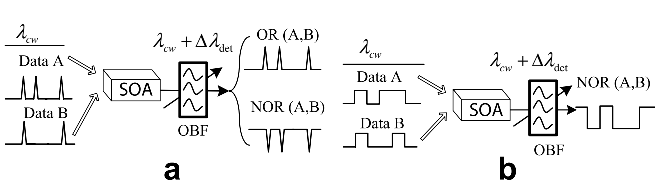

Fig. 1. Schematic diagram of the logic functions based on a single SOA and a filter, (a) logic OR/NOR with RZ format, (b) logic NOR with NRZ format.

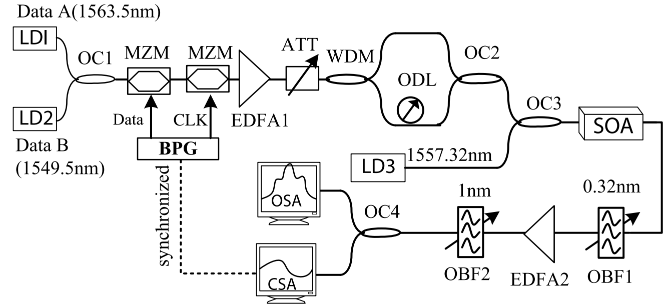

Fig. 2. Experimental setup of the proposed logic functions, BPG: bit pattern generator; MZM: Mach–Zehnder Modulators; ATT: attenuator; OC: optical coupler; ODL: optical delay line; OBF: optical bandpass filter; OSA: optical spectrum analyzer; CSA: communication signal analyzer.