All-optical reconfigurable multi-logic gates based on nonlinear polarization rotation effect in a single SOA

Lilin Yi (义理林)*, Weisheng Hu (胡卫生), Hao He (何 浩), Yi Dong (董 毅), Yaohui Jin (金耀辉), and Weiqiang Sun (孙卫强)

State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

**Corresponding author: lilinyi@sjtu.edu.cn*

Received September 4, 2010; accepted November 15, 2010; posted online February 21, 2011

We demonstrate an all-optical reconfigurable logic gate based on dominant nonlinear polarization rotation accompanied with cross-gain modulation effect in a single semiconductor optical amplifier (SOA). Five logic functions, including NOT, OR, NOR, AND, and NAND, are realized using 10-Gb/s on-off keying signals with flexible wavelength tunability. The operation principle is explained in detail. By adjusting polarization controllers, multiple logic functions corresponding to different input polarization states are separately achieved using a single SOA with high flexibility.

OCIS codes: 060.4510, 250.3750.
doi: 10.3788/COL201109.030603.

Future high-speed optical packet switching (OPS) networks are expected to process signals mainly in the optical domain to avoid optoelectronic conversions. Optical logic gates are key elements for realizing all-optical functions such as header recognition, label swapping, and parity checking for future OPS networks. Previously, all-optical logic functions are mainly achieved using nonlinear effects in highly nonlinear fibers[1−3], nonlinear optical materials, and semiconductor optical amplifiers (SOAs)[4−10]. Among them, the logic gates based on semiconductor devices feature the advantages of compactness, monolithic integration, low power consumption, and low cost. The SOA-based logic operations have been demonstrated by employing cross-gain modulation (XGM)[4], cross-phase modulation (XPM)[5,6], cross-polarization modulation[7], and four-wave mixing (FWM)[8−10]. Recently, multi-logic operations in the same logic device, namely, reconfigurable logic gates, have attracted much interest from research communities because of their flexibilities[6,8−10]. Logic functions including XOR, NOR, OR, and NAND are realized based on XPM in a complex SOA-based Mach-Zehnder interferometer structure[6]. To reduce the complexity of the SOA-based reconfigurable logic gate, a single SOA needs to be used. In most single SOA-based reconfiguration logic gates, FWM is the dominant effect required to realize reconfigurable logic operation, such as FWM accompanied by XGM in Ref. [8], by polarization-encoded signal in Ref. [9], and by transient XPM in Ref. [10]. FWM has the advantage of bit-rate independence; however, the degraded optical signal-to-noise ratio (SNR) of the logic operation can be the main limitation for its applications, aside from the requirement that input data wavelengths must be close enough to enable the FWM effect. The logic operations can only work at specified wavelengths, which limit their flexibilities—the most important characteristics of the reconfigurable logic gate.

In this letter, we demonstrate a reconfigurable logic gate based on dominant nonlinear polarization rotation (NPR) effect accompanied by XGM in a single SOA. Multi-logic operations including NOT, OR, NOR, AND, and NAND are successfully realized with 10-Gb/s non return-to-zero (NRZ) on-off keying signals. In this logic gate, all the logic operations are obtained at the same output of the device. The multi-logic operation state can be switched by simply adjusting polarization controllers and the signal power in the setup, and the operating wavelength of the logic functions can be flexibly tuned by changing the wavelength of the probe light. This reconfigurable logic gate with high flexibility and low complexity will be desired in future OPS networks.

Table 1 shows seven basic logic operations (NOT, OR, NOT, AND, NAND, XOR, and XNOR). Other more sophisticated logic operations can be realized based on their combinations. Except for the NOT operation, the "01" and "10" input of D1D2 lead to the same output value. Therefore, the four input states (00, 01, 10, 11) of D1D2 correspond to three different optical power states, namely 0, 1, and 2 if D1 and D2 have the same polarization states. In the following explanation, we will use the different power states (0→1→2) of a continuous-wave (CW) light to represent the four input states of D1D2. The power difference from 0 to 1 corresponds to the extinction ratio (ER) of the input data, and that from 1 to 2 refers to a 3-dB power increase.

Figure 1 depicts the principle of the logic operations based on NPR in an SOA. The CW pump light represents D1 and D2 having the same polarization orientations,

Table 1. Basic Logic Operations

D1	D2	NOT(D1)	OR	NOR	AND	NAND	XOR	XNOR
0	0	1	0	1	0	1	0	1
0	1	1	1	0	0	1	1	0
1	0	0	1	0	0	1	1	0
1	1	0	1	0	1	0	0	1

which are in parallel with one of the principle axes of the SOA (TE or TM mode). The polarization state of the CW probe light is adjusted by 45° with respect to the principle axes of the SOA to achieve the best operating performance. The projections of the probe light at TE and TM modes experience different gains and refractive index variations because of the different total optical powers in the two modes. Thus, the phase variations experienced by the two projections are also different. The variations in phase difference in the two axes leads to the polarization rotation of the probe light, and the rotation radian increases with pump power. This is the principle of nonlinear polarization rotation. Multi logic operations can be obtained by tuning the polarization state of the probe light exiting from the SOA using a polarization controller (PC) and a polarizer, as shown in Fig. 1. If the original polarization state (without the pump) of the output probe light is aligned with the polarizer, the output power is the maximum, corresponding to the operation result of "1". With the pump power increasing (0→1→2), the transmitted power first decreases to the minimum and then somewhat increases because of the polarization rotation of the probe light. We set two equal powers close to the minimum as the operation results of "0"; therefore, the corresponding power variation in the probe light is 1→0→0, which achieves NOR operation. Tuning the original polarization states of the output probe light can realize OR, AND, NAND, XNOR, and XOR operations based on a similar process. XNOR and XOR operations require larger nonlinear polarization rotation radian than do other logic operations.

Figure 2 shows the experimental setup for demonstrating the proposed reconfigurable logic operations. A laser diode operating at 1561.59 nm is modulated by an intensity modulator (IM) driven with a 10-Gb/s NRZ data from a pulse pattern generator (PPG). The modulated signal power is boosted by an erbium-doped fiber amplifier (EDFA), and then the amplified spontaneous emission (ASE) noise is filtered out using a tunable filter (TF). A variable optical attenuator is employed to adjust the signal power. The signal is then divided into two paths by a 50/50 coupler, and one of them is delayed using a tunable delay-line (TDL) to ensure the bit-synchronization of the two channels. The two channels are treated as D1 and D2, which are launched into a commercial polarization-independent SOA (CIP-SOA-NL-OEC-1550, CIP, UK) from the opposite direction

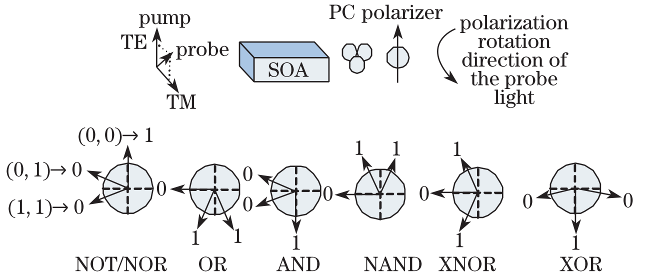

Fig. 1. Schematic of the logic operations based on NPR in a SOA. In the six operations, the arrows represent the polarization states of the probe light existing from the PC, where the bold arrow is the original polarization state without the pump, corresponding to the input state of "00". The numbers on the arrows represent the operation results.

to avoid the interference of the two data. The SOA has a maximal gain of 30 dB at 300-mA bias current, a 3-dB gain bandwidth of 50 nm, and a decay time constant of 15 ps. A probe laser operating at 1550 nm is amplified by EDFA2 and then combined with D1 by a 90/10 coupler. The power of the probe light launched into the SOA is about 0 dBm. After amplification and polarization rotation processes in the SOA, the probe light exits from an optical circulator and is then filtered from the signal power by TF2. PC5 and a polarizer with a 35-dB extinction ratio are used to vary the original polarization state of the output probe light to realize the different logic operations depicted in Fig. 1.

To verify the logic operations, we first measure the power variation in the probe light when changing the CW pump power for different logic operations, as shown in Fig. 3. When the original polarization state of the output probe light is aligned with the polarizer, the NPR and XGM effects play the same role in the power variation in the probe light (Fig. 3(a)), that is, the probe power decreases with the pump power increasing, which can realize NOT gate or the so-called inverted wavelength conversion. If the original polarization state of the output probe light is aligned with the "off" state of the polarizer, the transmitted power first increases with pump power owing to NPR and then remains almost unchanged when pump power exceeds 0 dBm as XGM counteracts NPR. The non-inverted wavelength conversion can be realized based on the power variation in Fig. 3(b). By varying PC5, the original output power of the probe light changes accordingly. In Figs. 3(c) and (e), the probe power first decreases with the pump power increasing owing to the NPR, and achieves the lowest value. Then, the power starts to increase as NPR effect becomes stronger than XGM. Therefore, NOR and AND logic operations can be obtained by setting the appropriate signal power. In Fig. 3(d), probe power first increases and then decreases with the pump power increasing as XGM outperforms NPR. OR gate can be achieved based on the power variation. In Fig. 3(f), when pump power exceeds 2 dBm, the strong XGM plays the same role as NPR in the probe power variation. Thus, probe power drastically decreases with the pump power increasing, which achieves NAND gate.

In principle, XNOR and XOR operations can also be obtained; however, the simultaneous XGM effect and the small polarization rotation radian in our used SOA make them difficult to realize in the experiment. They can be realized using a SOA with stronger nonlinearity. For NOT, NOR, OR, AND, and NAND operations, with the pump power increasing, the XGM effect will also affect the power variation in the transmitted probe light, and show different effects on the output power in different logic operations. Therefore, the combination of NPR and XGM effects lead to the desired logic operation results.

Finally, we modulate the signal with a fixed pattern at 10-Gb/s bit rate and observe the multi logic operations, as shown in Fig. 4. The bit sequences of D1 and D2 are "110110000011011000" and "000110110000011011". All operations with the input of 00, 01, 10, and 11 are obtained. By carefully tuning PC4, PC5, and the total power of D1 and D2, optimal performance can be achieved. In practice, one can first record the

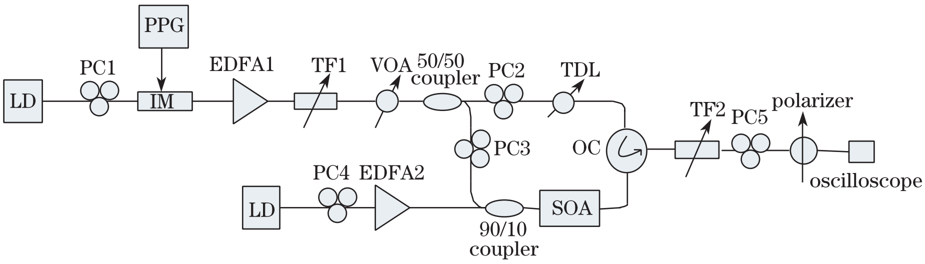

Fig. 2. Experimental setup.

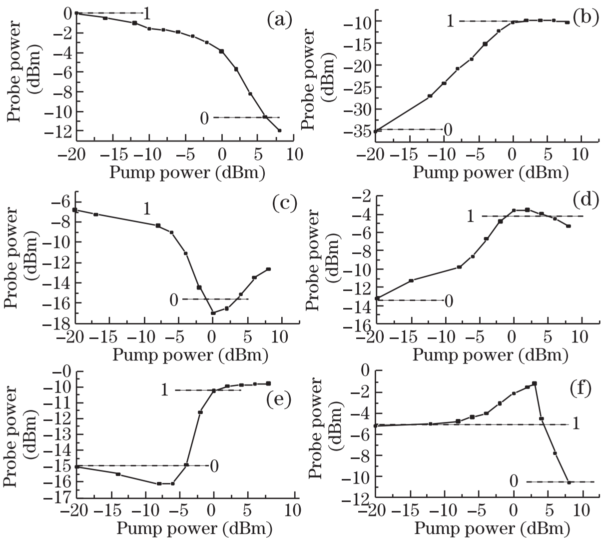

Fig. 3. Power variation in the probe with the pump light for the logic operations and wavelength conversion: (a) NOT (inverted wavelength conversion), (b) non-inverted wavelength conversion, (c) NOR, (d) OR, (e) AND, and (f) NAND.

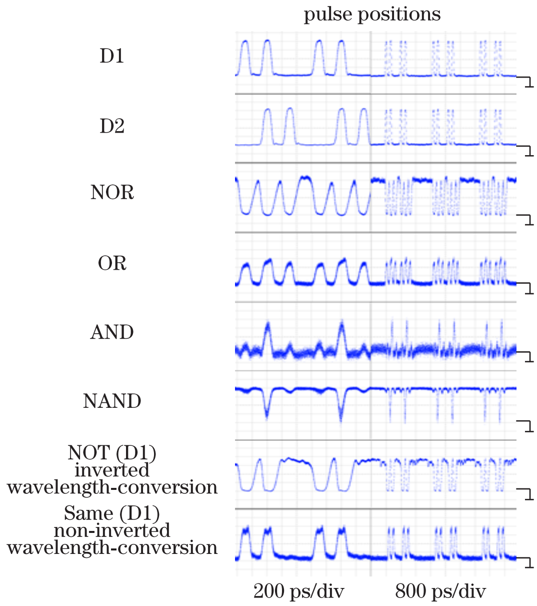

Fig. 4. Results of the logic operations.

optimum working state of each logic operation by employing the digitally controllable PC and the gain-tunable EDFA, and then choose the corresponding state based on the requirement to realize the switching of different logic operations. NOR, OR, AND, NAND, NOT, and non-inverted wavelength conversion are implemented correctly. No noticeable pattern effects are observed even though the SOA is deeply saturated, as the SOA exhibits a fast recovery time (45 ps). The power fluctuations at the high and low levels and the different pulse widths for some logic operations are mainly due to the non-ideal tuning of the pump power and the TDL. The output powers and ERs of the logic operations are different, which can also be seen in Fig. 3. As explained above, the ER can be improved using a SOA with stronger nonlinearity. We obtained multi-logic operations at the same output port of the logic device rather than at different output ports as in Refs. [8–10], and the different logic operation can be switched by tuning the PCs and the signal power, which is a desired reconfigurable logic gate in some practical network applications. Furthermore, the operating wavelength can be flexibly tuned by varying the wavelength of the probe light, which is different with the FWM-based reconfigurable logic gates[8−10], in which the wavelength of logic operations is limited by the incoming signals. Therefore, once the input wavelengths are fixed, the logic operating wavelength cannot be tuned.

To evaluate the signal quality of the logic operations, we measured the ER of the different logic results (Fig. 5). As NPR and XGM effects have different effects on logic operations, the ERs of the logic gates are therefore different. The ERs of the signals from AND, NAND, OR, NOR, and NOT are 5, 6, 9, 9, and 11 dB, respectively. To achieve the same Q-factor, the low ER requires higher SNR. Therefore, the low ERs for some logic operations will affect the signal quality and the cascading performance of the logic gates, which can be improved by employing a SOA with stronger nonlinearity to increase the polarization rotation radian.

In this experiment, we demonstrate only 10-Gb/s reconfigurable logic operations for proof-of-concept because of the lack of data source with higher bit rates. The

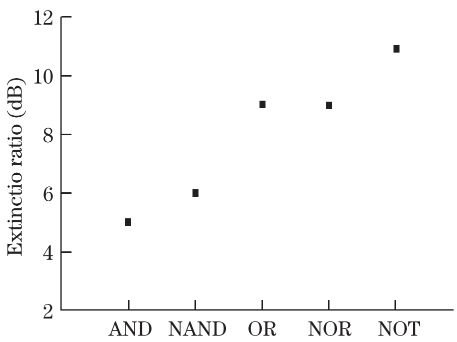

Fig. 5. Extinction ratio of different logic operation results.

operation speed is mainly limited by the recovery time of the used SOA, but higher operation speed can be achieved using a SOA followed by a detuning bandpass optical filter[10,11].

In conclusion, a compact, flexible, and reconfigurable all-optical multi-logic gate has been demonstrated based on simultaneous NPR and XGM effects in a single SOA. NOT, OR, NOR, AND, and NAND operations at 10-Gb/s bit rate are successfully realized. All the logic operations are obtained from the same output port of the logic gate and can be switched by tuning the polarization controllers and the signal power. Furthermore, the operating wavelength of the logic operation can be flexibly tuned according to practical requirements. Such a reconfigurable logic gate with high flexibility and low complexity will be a potential candidate in future OPS networks.

This work was supported by the National Natural Science Foundation of China (Nos. 61007041, 60825103, and 60632010), the National "973" Project of China (No. 2010CB328205), the National "863" Program of China, and the Program of Shanghai Subject Chief Scientist (No. 09XD1402200).

References

1. J. H. Lee, T. Nagashima, T. Hasegawa, S. Ohara, N. Sugimoto, and K. Kikuchi, Electron. Lett. **41,** 1074 (2005).
2. B. S. Robinson, S. A. Hamilton, S. J. Savage, and E. P. Ippen, in *Proceedings of Optical Fiber Communication Conference* 561(2002).
3. Y. J. Jung, S. Yu, H. Yu, S. Han, N. Park, J. H. Kim, Y. M. Jhon, and S. Lee, in *Proceedings of Pacific Rim Conference on Lasers and Electro-Optics* TuB4-3 (2009).
4. J. H. Kim, Y. M. Jhon, Y. T. Byun, S. Lee, D. H. Woo, and S. H. Kim, IEEE Photon. Technol. Lett. **14,** 1436 (2002).
5. R. P. Webb, R. J. Manning, G. D. Maxwell, and A. J. Poustie, Electron. Lett. **39,** 79 (2003).
6. J. Y. Kim, J. M. Kang, T. Y. Kim, and S. K. Han, Electron. Lett. **42,** 303 (2006).
7. H. Soto, D. Erasme, and G. Guekos, IEEE Photon. Technol. Lett. **13,** 335 (2001).
8. G. Berrettini, A. Simi, A. Malacarne, A. Bogoni, and L. Poti, IEEE Photon. Technol. Lett. **18,** 1341 (2006).
9. Z. Li and G. Li, IEEE Photon. Technol. Lett. **18,** 917 (2006).
10. J. Dong, X. Zhang, Y. Wang, J. Xu, and D. Huang, Electron. Lett. **43,** 884 (2007).
11. Y. Liu, E. Tangdiongga, Z. Li, S. Zhang, H. de Waardt, G. D. Khoe, and H. J. S. Dorren, J. Lightwave Technol. **24,** 230 (2006).