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All-Optical Logic Gates Using Semiconductor Optical-Amplifier-Based Devices and Their Applications

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By using two main effects of cross-gain modulation and cross-phase modulation in semiconductor optical amplifier-based devices, many logic functions of logic AND, OR, XOR, NOR and XNOR are successfully demonstrated. Also, complex systems including all-optical half and full adders in a combination of multiple logic functions are successfully demonstrated. These functions will provide not only increased speed and capacity of telecommunication systems, but also various functionalities including optical packet switching, decision making, basic or complex optical computing, and many other optical signal-processing systems.

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I. INTRODUCTION

As the speed of telecommunication systems increases and reaches the limit of electronic devices, the demand for all-optical logic operations such as switching, decision-making, regenerating, and basic or complex computing is rapidly increasing. All-optical logic gates are essential elements for optical signal processors and networks.

Many researchers have reported their own logic gates, including NOR using a semiconductor optical amplifier (SOA) [1], OR with NOR using an ultrafast nonlinear interferometer (UNI) [2], XOR using a terahertz optical asymmetric demultiplexer (TOAD) [3], and so on. Even though logic gates using the UNI and the TOAD have the advantage of high speed, they are very complex and difficult to integrate with other logic gates. Contrary to these devices, SOA-based devices are compact, stable, integration-capable, and potentially independent of polarization and wavelength [4]. Also, they have the advantages of low switching energy and low latency [5]. In this paper, SOA-based devices are mainly employed to embody the fundamental logic functions.

II. VARIOUS ALL-OPTICAL LOGIC GATES USING XPM AND XGM

1. All-Optical AND Gate Using XPM

To accomplish an all-optical AND logic gate [6], an XPM wavelength converter (Alcatel 1901 ICM) has been utilized. The experimental setup is shown in Figure 1. Signals A and B with patterns 1100 and 0110 are coupled into the XPM wavelength converter to procure the AND

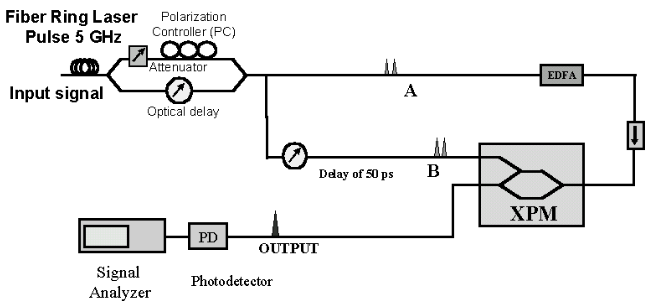

Fig. 1. Experimental setup for logic AND.

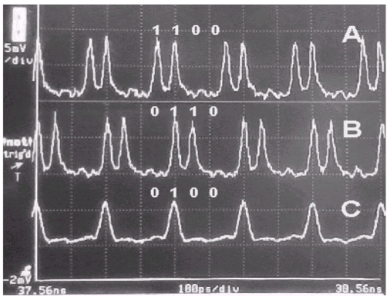

Fig. 2. Experimental results of logic AND.

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gate signal.

The input and output signals are configured in Figure 2. Overlapping signal A with signal B produces an output signal with the pattern 0100, which is the correct proof for characteristics of an AND logic gate. Therefore, the all-optical AND gate has been successfully demonstrated at 20 Gb/s. The all-optical XNOR gate has been realized by using the static characteristics of the XPM wavelength converter [7].

2. All-Optical NOR Gate Using XGM

By using cross-gain modulation (XGM), an all-optical NOR gate has been demonstrated at 10 Gb/s [8]. The configuration of the experimental setup is shown in Figure 3. Signals A and B with patterns 1100 and 0110 are added to form the signal A + B, which has the signal set of (1,0), (1,1), (0,1), and (0,0). A clock signal with repetition rate of 10 GHz is used as probe signal. Clock signal and signal A + B are simultaneously injected into the SOA. Due to the gain saturation effect of the SOA, the output signal has logic state 1 when only (0,0) of input appears. Input and output signals are seen in Figure 4. As shown in Figure 4, output is logic 1 when both inputs A and B are logic 0. Otherwise, output is logic 1. Since these results coincide with logic NOR, the all-optical NOR gate has been successfully demonstrated at 10 Gb/s. The all-optical OR gate can also be obtained with one additional SOA incorporated with the all-optical NOR gate [9].

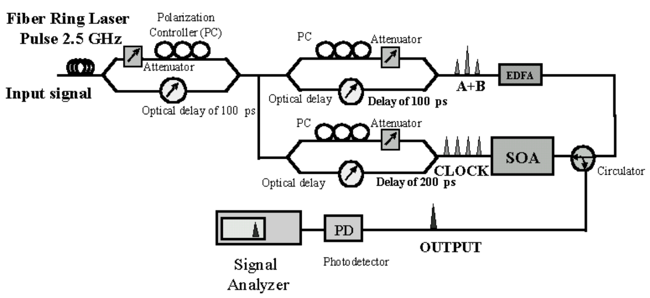

Fig. 3. Experimental setup for logic NOR.

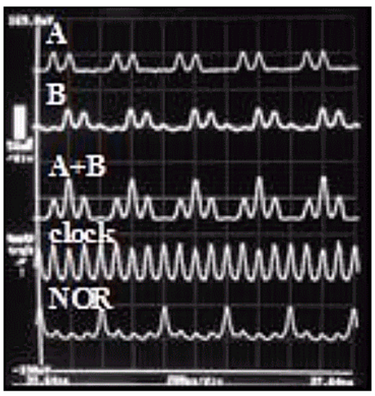

Fig. 4. Experimental results for logic NOR.

3. All-Optical XOR Gate Using XGM

By using two SOAs, an all-optical XOR gate has been demonstrated at 10 Gb/s [10]. Figure 5 shows the experimental setup for realizing the all-optical XOR gate. By passing signal A with the pattern 1100 as probe signal and signal B with the pattern 0110 as pump signal into SOA-1, Boolean $\boldsymbol{A\bar{B}}$ with the pattern 1000 has been obtained. Also, by switching the roles of signal A and B for SOA-2, Boolean $\boldsymbol{\bar{A}B}$ with the pattern 0010 has been acquired. After combining Boolean $\boldsymbol{A\bar{B}}$ and $\boldsymbol{\bar{A}B}$ with the 50:50 coupler, the output signal has been detected and displayed on the signal analyzer. Figure 6 depicts the added signal of Boolean $\boldsymbol{A\bar{B}}$ and $\boldsymbol{\bar{A}B}$, which is Boolean $\boldsymbol{A\bar{B}} + \boldsymbol{\bar{A}B}$ with the pattern 1010. As shown in Figure 6, the output signal is logic 1 when either signal A or B is logic 1. When both signals A and B have the same logic state, the output signal is logic 0. These results coincide with logic XOR. Therefore, the all-optical XOR gate at 10 Gb/s has been successfully realized.

4. All-Optical AND Gate using XGM

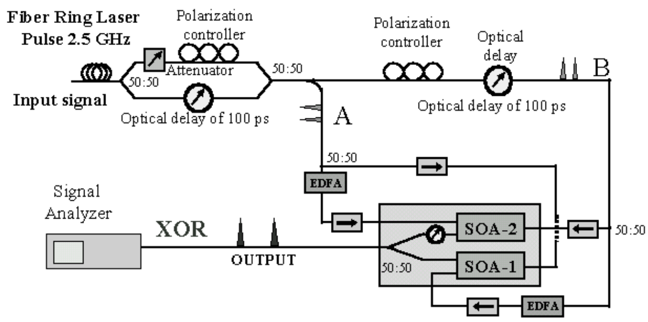

Fig. 5. Experimental setup for logic XOR.

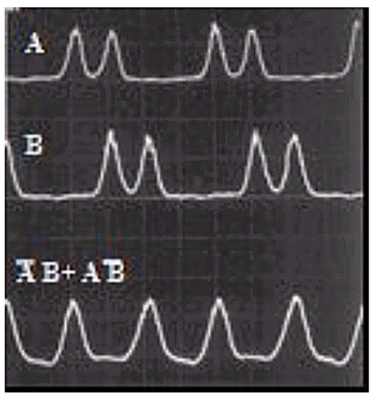

Fig. 6. Experimental results for logic XOR.

To compose the all-optical AND gate, two SOAs are required [11]. The experimental setup is shown in Figure 7. Firstly, by passing signal A as probe signal and signal B as pump signal into SOA-2, Boolean $\boldsymbol{A\bar{B}}$ can be obtained [2]. Then, clock signal as probe signal and signal B as pump signal are simultaneously injected through SOA-1 to produce the gain inversion of signal B, which is Boolean $\boldsymbol{\bar{B}}$. Boolean B out of $\boldsymbol{A\bar{B}}$ is substituted by the output of SOA-1 to obtain Boolean AB, which coincides with logic AND. Figure 8 shows the input and output signals.

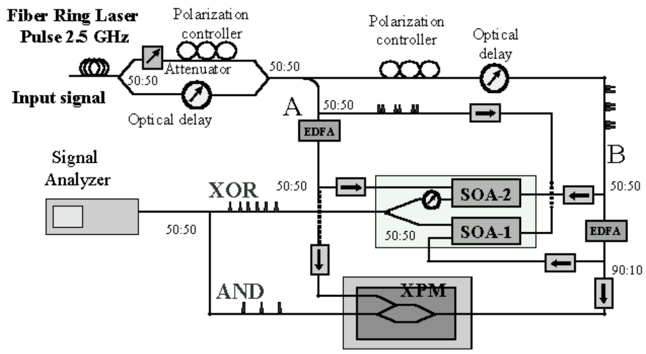

Fig. 9. Experimental setup for the all-optical half adder.

III. COMPLEX LOGIC SYSTEMS: ALL-OPTICAL HALF ADDER AND FULL ADDER

By using the SOA-based devices, an all-optical half adder as a simple example of further complex systems has been demonstrated [12]. To realize logic SUM and CARRY of the half adder, the all-optical XOR and AND gates are utilized, respectively. Figure 9 shows the experimental setup for realizing the all-optical half adder. Figure 10 depicts logic SUM and CARRY of the half adder. Both logic SUM and CARRY are simultaneously performed to prove the half-adder operation at 10 Gb/s.

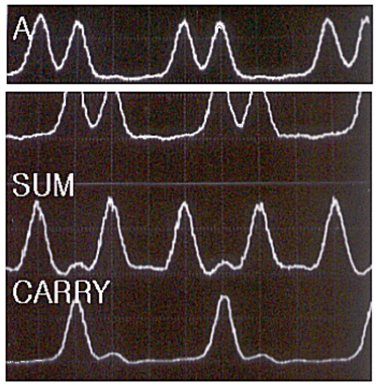

Fig. 10. Experimental results of half adder.

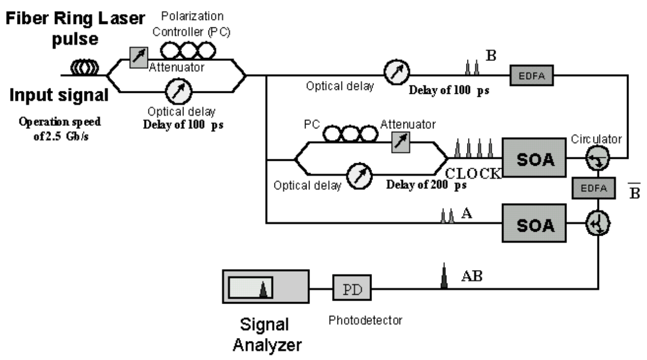

Fig. 7. Experimental setup for the all-optical AND gate.

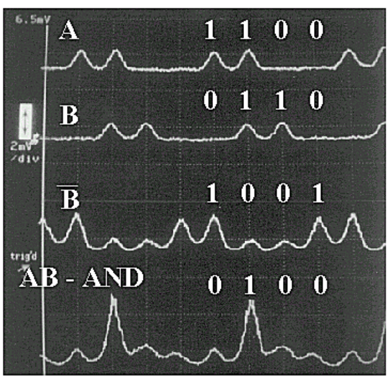

Fig. 8. Input and output signals of the all-optical AND gate.

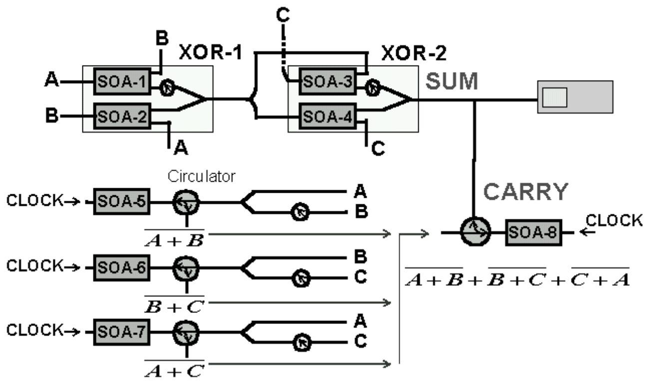

Fig. 11. Experimental setup for all-optical full adder including SUM and CARRY.

The all-optical full adder requires much higher complexity than the all-optical half adder [13]. A total of 8 SOAs are required. To realize SUM and CARRY, two XOR gates and four NOR gates are utilized. The experimental setup to implement the all-optical XOR and NOR gates for SUM and CARRY is shown in Figure 11. By injecting signals A and B through the first XOR gate, Boolean $\boldsymbol{A\bar{B}} + \boldsymbol{\bar{A}B}$ is obtained. By injecting signals $\boldsymbol{A\bar{B}} + \boldsymbol{\bar{A}B}$ and C through the second XOR gate, signal SUM of full adder is obtained.

By injecting signals A + B and clock through SOA-

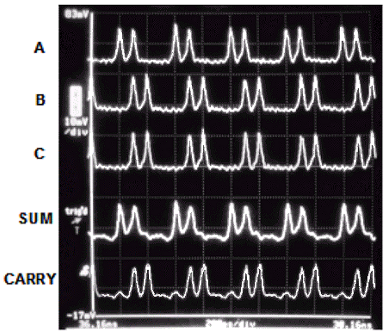

Fig. 12. Experimental results of the all-optical full adder.

5, all-optical NOR operation of A + B, Boolean $\overline{\boldsymbol{A}+\boldsymbol{B}}$ is obtained. With the same methods but with variation of input signals, NOR operation of B + C and C + A is also obtained. The added signal of these outputs is injected with the clock signal through SOA-8 to obtain the signal CARRY of the all-optical full adder. The input and output signals are shown in Figure 12.

IV. CONCLUSION

In this paper, the fundamental all-optical logic gates including AND, OR, NOR, XNOR, and XOR by using the SOA-based devices are demonstrated. Also, the all-optical half adder and full adder as examples of further complex systems are demonstrated. The operation speed of the all-optical logic gates is limited to around 10 Gbps, except for the AND gate using XPM. This low speed is due to the carrier recovery time in SOA. To overcome this problem, two cascaded SOAs and a much longer SOA are good alternatives [14,15]. Realization of the all-optical logic gates will provide not only increased speed and capacity of telecommunication systems, but also various functionalities including optical packet switching, add/drop, decision making, bit exactraction, regenerating, and basic or complex optical computing.

REFERENCES

[1] A. Sharaiha, H. W. Li, F. Marchese and J. Le Bihan, Electron. Lett. **33**, 323 (1997).
[2] N. S. Patel, K. L. Hall and K. A. Rauschenbach, Opt. Lett. **21**, 1466 (1996).
[3] A. J. Poustie, K. J. Blow, A. E. Kelly and R. J. Manning, Opt. Commun. **156**, 22 (1998).
[4] T. Fjelde, D. Wolfson, A. Kloch, B. Dagens, A. Coquelin, I. Guillemot, F. Gaborit, F. Poingt and M. Renaud, Electron. Lett. **36**, 1863 (2000).
[5] K. Vlachos, K. Zoiros, T. Houbavlis, A. Hatziefremidis and H. Avramopoulos, Proc. LEOS **768**, 2 (1999).
[6] B. K. Kang, J. H. Kim, Y. T. Byun, S. Lee, Y. M. Jhon, D. H. Woo, J. S. Yang, S. H. Kim, Y. H. Park and B. G. Yu, Japan J. of Applied Physics **41**, L568 (2002).
[7] S. C. Lee, J. W. Park, K. C. Lee, D. S. Eom, S. Lee and J. H. Kim, Japan J. of Applied Physics **41**, L1155 (2002).
[8] Y. T. Byun, J. H. Kim, Y. M. Jhon, D. H. Woo, S. Lee and S. H. Kim, CLEO-Europe, CJ3M (2003).
[9] Y. T. Byun, J. H. Kim, Y. M. Jhon, D. H. Woo, S. Lee and S. H. Kim, PS 2002, (Je-Ju, Korea, 2002), p. 21
[10] J. H. Kim, Y. M. Jhon, Y. T. Byun, S. Lee, D. H. Woo and S. H. Kim, IEEE Photonics Technology Letters **14**, 1436 (2002).
[11] J. H. Kim, B. C. Kim, Y. T. Byun, Y. M. Jhon, M. C. Park, S. Lee, D. H. Woo, S. H. Kim, Y. W. Choi and T. H. Yoon, Optical Amplifiers and their Applications (OAA) **2003**, 106 (2003).
[12] J. H. Kim, Y. T. Byun, Y. M. Jhon, S. Lee, D. H. Woo and S. H. Kim, Optics Communications **218**, 345 (2003).
[13] J. H. Kim, B. C. Kim, Y. T. Byun, Y. M. Jhon, S. Lee, D. H. Woo and S. H. Kim, ECOC 2003 (Accepted).
[14] C. Joergensen, S. L. Danielsen, K. E. Stubkjaer, M. Schilling, K. Daub, P. Doussiere, F. Pommerau, P. B. Hansen, H. N. Poulsen, A. Kloch, M. Vaa, B. Mikkelsen, E. Lach, G. Laube, W. Idler and K. Wunstel, IEEE Journal of Selected Topics in Quantum Electronics **3**, 1168 (1997).
[15] A. D. Ellis, A. E. Kelly, D. Nesset, D. Pitcher, D. G. Moodie and R. Kashyap, IEEE Electronics Letters **34**, 1958 (1998).