All-Optical XOR Gate with Feedback using Highly Ge-Doped Nonlinear Fiber

Mable P. Fok[1], Wade Trappe[2], and Paul R. Prucnal[1]

[1]Lightwave Communication Research Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544 USA

[2]Wireless Information Network Laboratory, Department of Electrical and Computer Engineering, Rutgers University, 73 Brett Road, Piscataway, NJ 08854-8060

E-mail: mfok@princeton.edu

Abstract: We demonstrate an all-optical XOR gate with feedback using cross-polarization-rotation in a highly Ge-doped-nonlinear fiber. The optical feedback employs a TOAD to clean up signal and for wavelength conversion, resulting in a wide-open eye diagram.

OCIS codes: (230.3750) Optical logic devices; (190.4370) Nonlinear optics, fibers; (999.9999) Highly Ge-doped nonlinear fiber

1. Introduction

Ultrafast all-optical logic gates are important for future high-speed communication systems. The exclusive-OR (XOR) gate is a common component in optical signal processing, and is used in tasks like data encoding, high-speed pattern generation, optical correlation, and optical encryption. In particular, XOR gates have been applied to amplitude-shift keying and implemented via cross-phase modulation in a nonlinear loop mirror [1], cross-gain and cross-phase modulations via a semiconductor optical amplifier (SOA) [2]-[3], and cross-polarization rotation via a highly nonlinear fiber [4]. XOR gates are often used with feedback as the basis for correlation processing [5] and for building a variety of encryption schemes [6]. For example, combining XOR with feedback is essential in generating long key streams from smaller keys or initialization registers for enciphering in Vernam ciphers. Translating these building blocks to the optical domain and using them together in real applications requires that practical issues, such as noise accumulation and the propagation of undesirable logic levels, be dealt with carefully in the system design to ensure the accurate operation of these functions.

In this work, we exploit cross-polarization rotation in a highly Ge-doped nonlinear fiber (HDF) to demonstrate an all-optical XOR gate, and further show that optical feedback can be implemented effectively using a terahertz optical asymmetric demultiplexer (TOAD) [7]. The HDF is doped with 75 mol.% GeO_2, resulting in a large nonlinear coefficient of 35 $W^{-1}km^{-1}$ [8]. In our previous work, a 15-m HDF is used to demonstrate an optical thresholder [9]. Although HDF do not have an extremely high nonlinear coefficient and the fiber length is not ultra-short, this new type of highly nonlinear fiber is desirable because it is very compatible with standard single mode fibers. It can be directly spliced to standard single mode fiber using a standard fusion splicer with just 0.2 dB loss, and just like standard single mode fibers, HDF is very robust and can be easily put onto a 40-mm fiber spool. At the feedback path, a TOAD is used to serve two purposes: (i) to clean up imperfect bit levels, and (ii) to convert the output wavelength to the control wavelength. In our experiment, a widely opened eye diagram is observed from the HDF-based optical XOR gate with TOAD feedback.

2. Principle and Experimental Setup

The XOR logic with optical feedback is built using cross-polarization rotation in a highly Ge-doped nonlinear fiber and optical feedback is based on a TOAD. The schematic illustration of cross-polarization rotation using one control signal is depicted in Fig. 1(a). Cross-polarization rotation occurs when a strong control signal and CW signal are launched into a nonlinear media with linear polarization and have a 45° polarization difference.

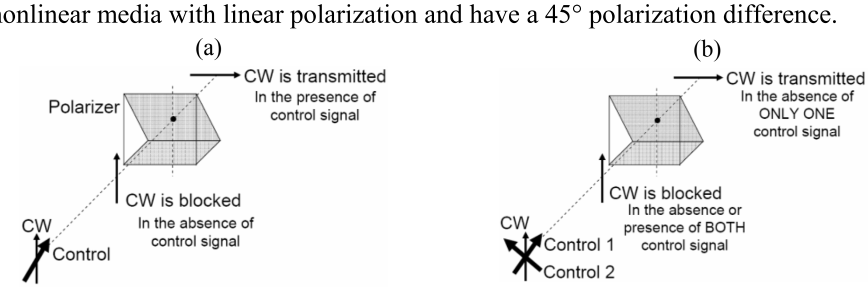

Fig. 1. Schematic illustration of cross-polarization rotation (a) with only one control signal (b) with two control signals.

The polarizer is oriented such that the CW signal is blocked in the absence of the control signal. When the control signal is present, a birefringence is induced in the nonlinear media. Thus, the CW signal polarization is rotated by an amount determined by the strength of control signal. The CW signal is blocked by the polarizer in the absence of the control signal when there is a polarizer that is 45° relative to the CW, while the CW signal is transmitted if a suitable level of control signal is present, as shown in Fig. 1(a). To build an optical XOR gate, two control signals are used, as illustrated in Fig. 1(b). Control 1 and Control 2 are orthogonally polarized and are at 45° to the CW. If only one control signal is present, the CW is transmitted through the polarizer (as in Fig. 1(a)), while if both control signals are present and at a sufficient power, the resulting polarization rotation is enough so that the CW signal is blocked by the polarizer. This results in an XOR logic operation, where a bit 1 results if and only if one of the controls has a bit 1.

Figure 2 shows the experimental setup of our all-optical XOR gate with feedback. The 5-Gb/s 1550-nm mode-locked fiber laser has three outputs, where two of them are intensity modulated using a 2^{31}-1 PRBS. The two modulated signals are Control 1 and Control 2, they are combined at a polarization beam splitter to ensure orthogonal polarization. The controls are combined with a CW light, amplified and launched into a 40-m HDF for cross-polarization rotation to occur. A polarizer is placed at the output of the HDF to observe the intensity change of the XOR output. Optical bandpass filters at λ_{cw} block the residue control signals. To complete the feedback loop for the XOR gate, the XOR output at point B is used to drive the TOAD. The TOAD will switch out the mode-locked laser output from point T1 to T2 in the presence of a bit 1 of the driving signal at point B. Optical bandpass filters block the residue of an imperfect XOR output at λ_{CW}, resulting in a clean XOR output at λ_{ML} at point C. Part of the clean XOR output is tapped and launched back to the XOR input as the feedback. The final XOR output is obtained at the system output port.

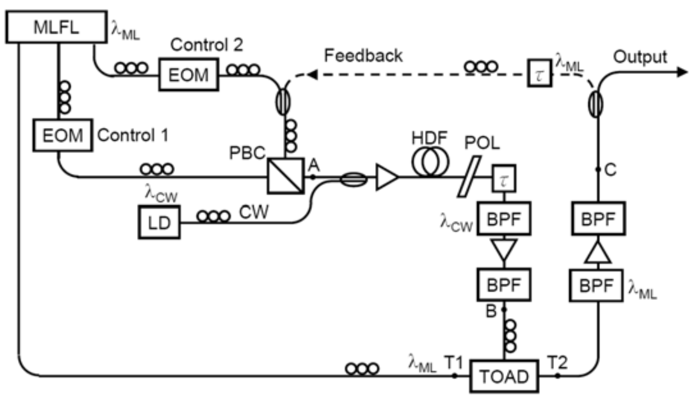

Fig. 2. Experimental setup of our all-optical XOR gate with feedback. MLFL: mode-locked fiber laser; EOM: intensity modulator; LD: CW laser diode; PBC: polarization beam combiner; HDF: highly Ge-doped nonlinear fiber; POL: polarizer; τ: tunable optical delay line; BPF: optical bandpass filter; TOAD: terahertz optical asymmetric demultiplexer.

3. Results and Discussion

In the experiment, we first opened the feedback path to verify our XOR gate. A pattern of "10101100" is used as control 1 and "01010110" is used as control 2, as shown in Fig. 3(a) and (b), respectively.

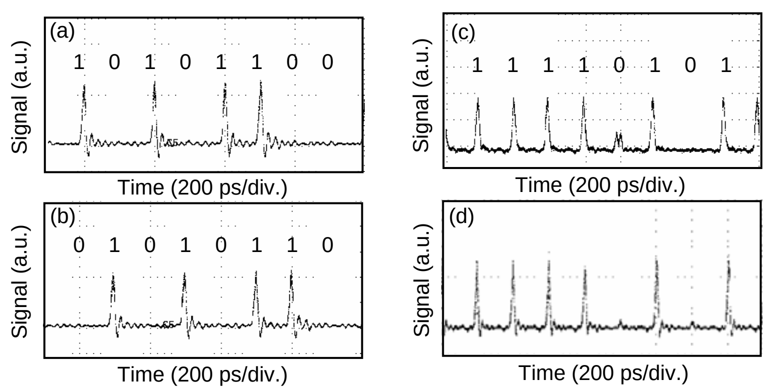

Fig. 3. Data pattern of the XOR gate without feedback: (a) Control 1, (b) Control 2, (c) Intermediate XOR , (d) XOR output after TOAD.

OWF7.pdf

After cross-polarization rotation in the HDF, the XOR output at point B is shown in Fig. 3(c). Correct XOR logic is successfully obtained except for a residual intensity at a bit 0 that resulted from an XOR of bit 1 in both the controls. Removing the residue from the imperfect XOR output is desirable for maintaining the correctness of XOR operations when used with optical feedback, and hence the intermediate XOR output at point B is passed through a TOAD, which cleans the bit levels and converts the wavelength to match with the XOR input. The clean XOR output from the TOAD is shown in Fig. 3(d). To demonstrate the XOR gate with optical feedback, part of the clean XOR output at λ_{ML} is tapped and launched to the polarization beam combiner. An optical coupler is used to couple the initial Control 2 and the XOR feedback. In practice, a decision device would be used to switch the XOR input from the initial Control 2 to the XOR feedback. In Fig. 4, we present the resulting XOR output when the control is driven by a 2^{31}-1 PRBS with optical feedback employed. The wide- open eye diagram indicates that our system has good performance.

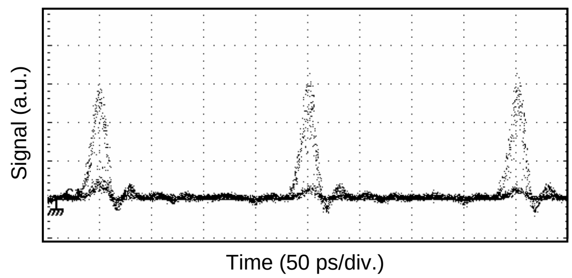

Fig. 4. Eye diagram of the XOR gate output in optical feedback mode.

4. Conclusion

We have experimentally demonstrated an all-optical XOR gate with optical feedback using cross-polarization rotation in highly Ge-doped nonlinear fiber, while the optical feedback is built using a TOAD. The highly Ge-doped nonlinear fiber is very compatible with standard single mode fiber, and can be directly spliced to standard single mode fiber with <0.2 dB loss. The TOAD in the feedback loop is used for cleaning up the XOR output to avoid the feedback of imperfect logic levels to the XOR gate. We experimentally showed that our XOR gate is correct, and further that the eye diagram obtained from the optical XOR gate in feedback mode indicates our system has good performance. XOR gates with feedback can be useful for correlation processing and as a fundamental building lock for many encryption schemes. Looking forward, we intend to explore the utility of our scheme as the basis for a practical optical security system.

Acknowledgment

This work was supported by Defense Advanced Research Projects Agency (DARPA) under SSC Pacific Grant N66001-07-1-2010.

References

[1] M. Jinno and T. Matsumoto, "Ultrafast all-optical logic operations in a nonlinear Sagnac interferometer with two control beams," Opt. Lett., vol. 16, pp. 220 – 222, February 1991.
[2] J. H. Kim, Y. M. Jhon, Y. T. Byun, S. Lee, D. H. Woo, and S. H. Kim, "All optical XOR gate using semiconductor optical amplifiers without additional input beam," IEEE Photon. Technol. Lett., vol. 14, pp. 1436 – 1438, October 2002.
[3] H. Soto, D. Erasme, and G. Guekos, "5-Gb/s XOR optical gate based on cross-polarization modulation in semiconductor optical amplifiers," IEEE Photon. Technol. Lett., vol. 13, pp. 335 – 337, April 2001.
[4] C. Y. Yu, L. Christen, T. Luo, Y. Wang, Z. Q. Pan, L. S. Yan, and A. E. Willner, "All-optical XOR gate using polarization rotation in single highly nonlinear fiber," IEEE Photon. Technol. Lett., vol. 17, pp. 1232 – 1234, June 2005.
[5] J. M. Martinez, J. Herrera, F. Ramos, and J. Marti, "All-optical correlation employing single logic XOR gate with feedback," Elect. Lett., vol. 42, pp. 1170 – 1171, September 2006.
[6] W. Trappe and L. C. Washington, "Introduction to cryptography with coding theory," 2nd edition, Prentice Hall, July 2005.
[7] J. P. Sokoloff, P. R. Prucnal, I. Glesk, and M. Kane, "A terahertz optical asymmetric demultiplexer (TOAD)," IEEE Photon. Technol. Lett., vol. 5, pp. 787 – 790, July 1993
[8] E. Dianov and V. Mashinsky, "Germania-based core optical fibers," J. Lightw. Tech., vol. 23, , pp. 3500 – 3508, November 2005.
[9] K. Kravtsov, P. R. Prucnal, and M. M. Bubnov, "Simple nonlinear interferometer-based all-optical thresholder and its applications for optical CDMA," Opt. Express, vol. 15, pp.13114 -13122, October 2007.