Simultaneous four-wave mixing and cross-gain modulation for implementing an all-optical XNOR logic gate using a single SOA

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Abstract: We report on an all-optical XNOR-gate using simultaneous Four-Wave Mixing (FWM) and Cross-Gain Modulation (XGM) in a semiconductor optical amplifier (SOA). FWM generates the bitwise AND output corresponding to the two input data streams while XGM is used to generate the NOR output. These two outputs are combined using a coupler to obtain the final XNOR output. Error-free operation for RZ data with <2dB power-penalty is reported.

OCIS codes: (060.2330) Fiber optics communications; (070.4560) Optical data processing

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#69773 - $15.00 USD Received 7 April 2006; revised 1 June 2006; accepted 4 June 2006

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1. Introduction

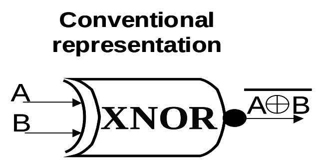
It can be envisioned that future high-speed optical networks could employ all-optical data processing in order to assist electronic modules in performing certain functions where purely electronic solutions may encounter a bottleneck. Many data processing functions e.g. time-to-live field decrementing [1], and checksum verification require digital logic capabilities and implementing such functions in the optical domain necessitates the development of optical logic gates. All-optical versions of various logic gates have been demonstrated [2-5]. All-optical exclusive-OR gates, commonly called XOR gates [3-5] are of particular interest. XOR gates can enable a diverse set of processing functions, including (i) comparison of data patterns for address recognition and subsequent packet switching [6], (ii) basic or complex computing as a component of digital-addition modules, (iii) optical generation of pseudorandom patterns [7], (iv) data encryption/decryption, and (v) parity checking [8]. However, the complementary function of the XOR, the XNOR, has not been investigated extensively. Since the XOR and XNOR provide logically inverted outputs, one may be able to replace the other in specific applications. For example, a pattern-matching module that uses an XOR gate will generate output pulses for all the bits that do not match, while one operating using an XNOR gate will produce output pulses for all the bits that do match. Thus a threshold detector looking for an output pulse signals a pattern-mismatch using an XOR gate, but the same functionality can be obtained by using an XNOR gate with a threshold detector looking for a missing pulse at the output.

Semiconductor optical amplifiers (SOAs) are popular candidates for use as nonlinear elements in optical logic gates. They provide high nonlinearity with a small footprint and possess the potential for integration. Various nonlinearities in SOAs including cross-gain modulation (XGM), four-wave mixing (FWM), and cross-phase modulation have been exploited for implementing optical gates. Earlier proposals for all-optical XNOR gates based on semiconductors include (i) using semiconductor micro-ring resonators [9], and (ii) using a semiconductor optical amplifier-based Mach-Zehnder interferometer [10].

We report on an all-optical XNOR gate [11] utilizing simultaneous four-wave mixing and cross-gain modulation in a single SOA. The FWM performs the AND operation and XGM is used to implement a NOR gate. These two outputs are then combined to produce the XNOR output. Error free operation was observed for RZ data with <2 dB power penalty. Since the module utilizes only one nonlinear optical element, it is quite simple in design. This has been made possible by exploiting simultaneous nonlinear processes in a single SOA. The module is inherently stable in operation but sensitivity to timing-mismatch between the input signals is observed. Also, the module is polarization dependent due to the FWM process involved in generating the AND component of the output. The module may potentially be used as an all-optical serial bit-wise half adder since it generates the AND and XNOR outputs simultaneously which correspond to the CARRY and inverted-SUM outputs of a half adder.

2. Concept

As shown in Fig. 1, an XNOR gate operates on two serial data streams (A and B). The output is ‘on’ if both the input bits are ‘on’ (AND operation) or if both the input bits are ‘off’ (NOR operation). The FWM process [12] is equivalent to the logic AND operation between the two input signals while the XGM process [13] can be used to implement the NOR logic. The truth table in Fig. 1 shows that the XNOR logic corresponds to an OR operation between the AND and NOR outputs. For our optical system, this is simply equivalent to coupling together the FWM and XGM outputs as shown in Fig. 2.



Truth Table

A	B	NOR	AND	XNOR
0	0	1	0	1
0	1	0	0	0
1	0	0	0	0
1	1	0	1	1

Fig. 1. Truth table of an XNOR gate. The XNOR logic is equivalent to combining the results obtained from a NOR operation and an AND operation.

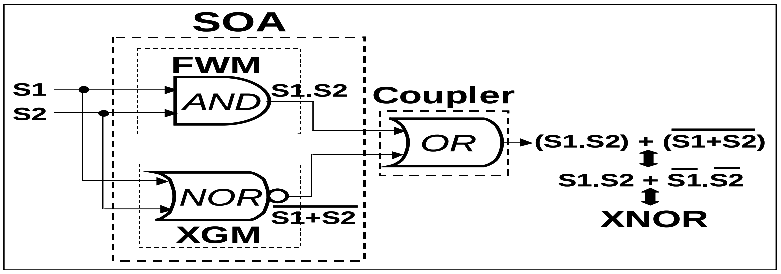


Fig. 2. Optical equivalent circuit for XNOR gate. FWM in the SOA generates the AND output while the NOR is obtained using XGM. These two outputs are combined using a coupler to obtain the XNOR output.

The two input signals (at λ_1 and λ_2, respectively) between which the XNOR operation is to be performed are synchronized, amplified and injected into the SOA. A lower power pulse train (probe signal) at λ_p, synchronized with the signal pulses is also injected. The two high power signals at λ_1 and λ_2 undergo FWM, which results in products at λ_a and λ_b. The product signals have a pulse only when pulses are present on both the input signals simultaneously. This corresponds to the AND operation. On the other hand each of the amplified input signals acts as a pump for the XGM process. Whenever a pulse is present on either of the input signals, it saturates the SOA's gain and as a result the corresponding pulse on λ_p sees a reduced gain while traveling through the SOA. Only those pulses on λ_p that have no corresponding pulses on λ_1 or λ_2 emerge at the output. This is equivalent to a NOR operation between the input signals. The NOR output on λ_p and AND output on λ_a are filtered, amplified to equal power levels and recombined to produce the XNOR output. Figure 3. depicts the propagation of the signals through the module leading to the generation of the final XNOR output.

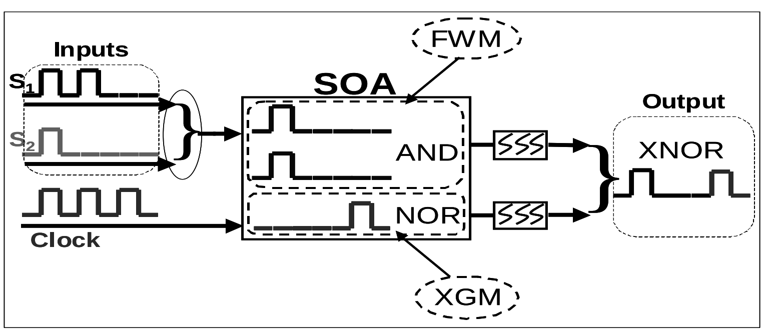


Fig. 3. Signal flow through the XNOR gate. FWM in the SOA generates the AND output while the NOR output is obtained from the XGM process. The two outputs are combined to generate the final XNOR signal.

#69773 - $15.00 USD Received 7 April 2006; revised 1 June 2006; accepted 4 June 2006

Even though in the reported demonstration, the XNOR output is comprised of pulses on two different wavelengths, it may be possible to use a probe wavelength that coincides with one of the FWM product wavelengths. The probe could be injected into the SOA with a polarization orthogonal to the FWM product (to minimize coherent crosstalk) and both the NOR output and the AND output could be filtered out together. Coherent crosstalk may be further suppressed by the fact that the FWM output is generated only when the probe pulses are strongly suppressed due to XGM from both the input signal pulses. However, in such a mode of operation the NOR and AND outputs cannot be separated by filtering and thus their respective pulse amplitudes cannot be equalized through relative amplification/attenuation after exiting the SOA. As a result one needs to ensure that the pulses obtained from the NOR operation (via XGM) are equal in amplitude to those generated from the AND operation (via FWM) at the SOA's output itself. Achieving this condition will possibly impose more stringent optimization of the power levels of the SOA inputs than is observed for the case when the NOR and AND outputs can be separated by filtering and individually attenuated/amplified before being recombined such that all pulses in the final XNOR output are of equal amplitude.

3. Experimental setup and results

The experimental setup is shown in Fig. 4. Two lasers at ~1550nm and ~1549nm respectively, are modulated with 5 Gb/s, 100 ps FWHM RZ data pulses. They are amplified and injected into the SOA as pump signals along with a lower power probe signal at ~1546nm, which is modulated by a 5 GHz clock to generate a pulse stream. The pulses on all three wavelengths are synchronized in time using tunable delay lines before entering the SOA.

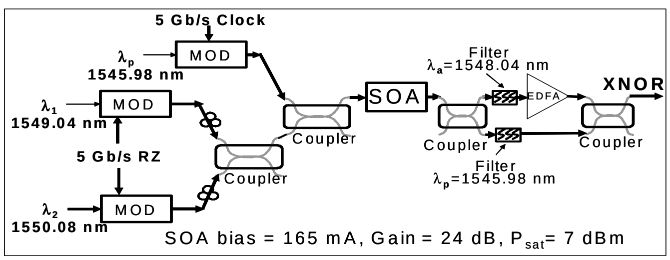


Fig. 4. Experimental setup for the all-optical XNOR gate.

An Alcatel 1901 SOA biased at 165mA is used. The saturated output power (P_{sat}) for the SOA is 7 dBm. The spectrum of the SOA inputs is shown in Fig. 5(a). The two pumps undergo FWM in the SOA giving rise to two products at ~1548nm and ~1551nm. Since FWM is a highly polarization sensitive process the polarizations of the input signals have to be optimized using the polarization controllers to maximize the FWM efficiency. The spectrum for this interaction is shown in Fig. 5(b). The output spectrum is shown in Fig. 5(c).

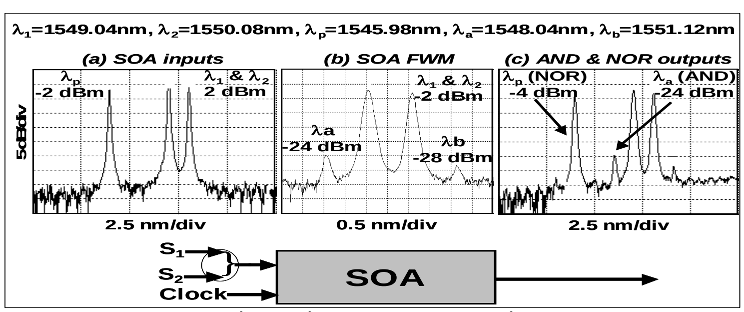


Fig. 5.(a) Inputs to the SOA. λ1 and λ2 are the signals and λp is the pulse train, (b) FWM spectrum for the SOA, (c) Output of the SOA: NOR output on λp and AND output on λa

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The AND output at ~1548nm and NOR output at ~1546nm are filtered separately using bandpass filters with 0.6 nm bandwidths. As shown in Fig. 5(c), the AND output has lesser power compared to the NOR output due to low FWM efficiency. Therefore, the AND output needs to be amplified before being re-combined with the NOR output to provide the final XNOR output. Power levels of all the inputs are adjusted to optimize the performance of the module. A sequence of bits demonstrating the XNOR function is shown in Fig. 6.

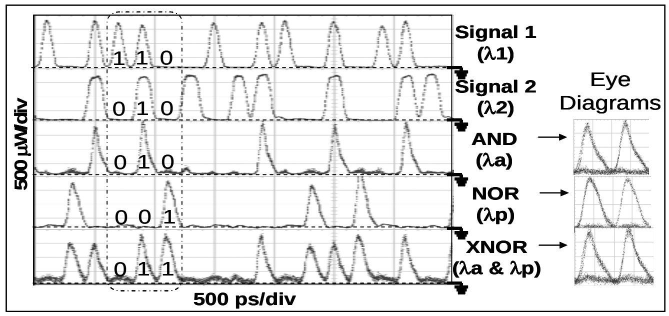

Fig. 6. Bit patterns showing the XNOR gate's performance. The AND output is 'on' only when both the input signals are 'on' while the NOR output is 'on' only when both the inputs are 'off'. The XNOR output is obtained by combining the NOR and AND outputs.

The AND output is 'on' only when both the inputs are 'on', while the NOR output is 'on' only when both the inputs are 'off'. These two outputs are combined to provide the XNOR output. Error free operation was achieved for 2^7-1 random bits at 5 Gb/s. Since the module modifies the data from input to output, BER measurements require manual entry of the output data pattern into the error detector. Thus, only 2^7-1 word-length has been used for BER measurements. However, eye diagrams have been observed to show an open eye for word lengths of 2^{15}-1 also, and error-free operation is expected. Eye diagrams for the individual outputs and the combined XNOR output are shown in Fig. 6. The NOR output from the XGM process exhibits an extinction ratio of ~10 dB. The extinction ratio of the AND output generated through the FWM process is lower and measured to be ~8 dB. The low efficiency of the FWM process leads to a degraded extinction ratio since the ASE noise from the SOA limits the obtained OSNR. Also, the pulses from the AND output need to be amplified to make their amplitudes equal to those from the NOR output. The additional ASE noise from the EDFA used further degrades the AND output. Bit-error rate (BER) curves obtained for the various outputs (Fig. 7.) show less than 2 dB power-penalty at 1e-9 BER. The primary source of this penalty is the ASE noise introduced by the SOA and the low efficiency of the FWM process that degrades the output OSNR.

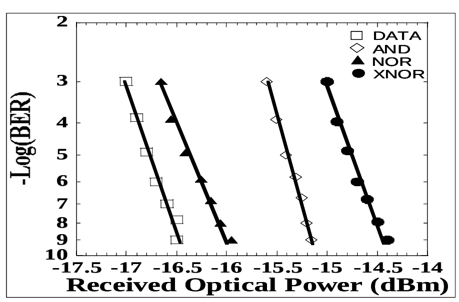

Fig. 7. BER curves for the XNOR gate. The NOR output suffers a power penalty of 0.5 dB for BER=1e-9, and an additional 1 dB penalty is incurred by the AND output. The final XNOR signal exhibits a power penalty of 2 dB. The primary source of penalty is the ASE noise introduced by the SOA and the low efficiency of the FWM process.

Some discrepancies between input and output pulse shapes and pulse widths have been observed due to timing mismatch between the input signals and the probe pulses. Also the pulse shapes of the two input signals are not identical because different modulators have been used, leading to small variation in the output pulse shapes, too. To quantify the performance of the module with respect to timing mismatch between the input signals, switching window measurements were performed for the AND component of the XNOR output. As shown in Fig. 8, the peak power in the FWM product's pulses is maintained above 90% of its maximum for a +/- 8 ps time offset (8% of the FWHM of the input pulses) between the two input signals. For the NOR output, timing mismatch between the probe pulses and the input signal pulses is also significant and the corresponding switching window was observed to be +/- 25 ps. Such a mismatch also leads to variation in the output (NOR) pulse shape. The more stringent timing mismatch between input signals is expected to dominate the overall behavior.

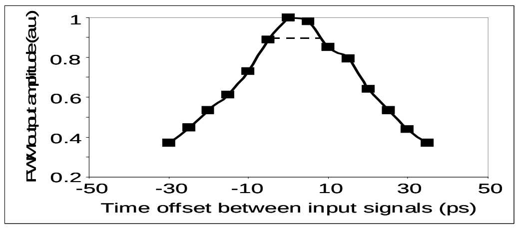

Fig. 8. Switching window measurements for the AND component of the XNOR output. The peak power in the FWM product's pulses is maintained above 90% of its maximum for a +/- 8 ps time offset between the two input signals.

In this demonstration, since FWM is dominated by ultra-fast carrier dynamics, the speed of the module is limited by the slow carrier recovery in the XGM process. The bandwidth of the XGM process is determined by the gain recovery time in the SOA, (few 10's to low 100's of ps). Several operational parameters can be adjusted to reduce the carrier recovery time. These include increasing the bias-current [14], increasing the optical powers used and using assist light [15] in the form of a CW reservoir channel coupled into the SOA. The net result of all these techniques is to keep the SOA close to saturation. However, if the saturation levels of the SOA are high, the efficiency of the XGM process also reduces. A balance has to be struck between XGM efficiency and modulation bandwidth by fine-tuning the operational parameters. Recently, there have been reports on filtering assisted cross-gain modulation, wherein the effective recovery time of the SOA-based switch is dramatically shortened by exploiting the chirp induced in the SOA. Wavelength conversion has been demonstrated up to 320 Gb/s using this technique [16]. If the NOR gate is implemented using filtering assisted XGM, the XNOR design reported may potentially scale to significantly higher bit-rates.

It should also be noted that since the module provides an XNOR output and an AND output (at the second FWM product) it behaves like an all-optical half adder where the AND output represents the CARRY signal and the XNOR output represents an inverted SUM signal. Most of the components used in the module can be readily integrated, and if filters can be fabricated on the same optical chip, integration of the entire module may be realized.

4. Conclusion

We report on an all-optical XNOR gate using a single SOA. The module operates on two serial data streams. FWM in the SOA is used to perform the AND operation on the two inputs while XGM is used to generate the corresponding NOR output. The XNOR output is obtained by combining the NOR and AND signals using a coupler. Error free operation has been observed for RZ data with <2 dB power penalty.

Acknowledgments

The authors would like to acknowledge DARPA's University Photonics Program through the University of New Mexico.