All-Optical XOR in a Semiconductor Optical Amplifier-Assisted Fiber Sagnac Gate

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***Abstract*—All-optical Boolean XOR is demonstrated on a high-speed serial bit stream with a three-optical input fiber Sagnac interferometer switch, which uses a semiconductor optical amplifier. Full duty cycle bit switching has been demonstrated up to 5 GHz with contrast ratio as high as 14.6 dB.**

***Index Terms*— High-speed logic, optical gates, semiconductor optical amplifiers.**

I. Introduction

THE INTEREST that telecommunications companies have shown in increasing the data transmission capacity in their networks and the recent advances at the photonic device level has spurned intense research effort on ultrafast, nonlinear, all-optical switching devices. The devices that have been mostly studied are based on the Sagnac interferometer [1] and initially used the nonlinear Kerr effect in optical fibers as the switching nonlinearity. With these fiber devices a large number of circuits [2]–[5] have been demonstrated including the XOR operation at up to 10 Gb/s [5]. More recently a low-switching energy and compact device operating on the same principle, but using the nonlinear gain saturation of a semiconductor optical amplifier (SOA) (TOAD/SLALOM) [6]–[8] has been demonstrated. So far efforts on the semiconductor-based device have concentrated on single optical control switching experiments that are pertinent to transmissions applications. Two control beam switching experiments are however very important because they will allow the full complement of Boolean bitwise logic to be performed on ultrafast optical signals. Recently, a single-arm ultrafast nonlinear interferometer (UNI) employing the nonlinearity of a SOA [9] has been used to show extended logic functionality at up to 100 Gb/s [10], but as yet XOR has not been shown. Boolean XOR is particularly important in decision and comparator circuits as well as for the production of pseudorandom patterns and encryption. In this letter, we report on the full duty cycle XOR operation of a SOA-assisted Sagnac interferometer gate at up to 5-GHz signal rate.

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II. Experiment

In this experiment, three optical signals are used as inputs into the gate. A and B are the logical inputs to the gate which control its state while CLK is the clock input on which the outcome of the logic XOR of A, B is imparted. Only a brief description of the operation of the SOA-assisted Sagnac gate is given as a full detailed description can be found elsewhere [6]–[8]. The gate operates by measuring the differential phase change between the two counterpropagating CLK pulses. This phase change is imposed on them by their nonlinear interaction with the temporally synchronized control pulses A, B in the SOA and is due to the rapid carrier depletion in the presence of one or two control pulses. Crucial to the operation of the device is the position of the SOA with respect to the center of the loop. This has to be asymmetrically placed, so that the two counter-propagating CLK pulses can experience a π differential phase change as only one of them interacts with the control pulse in the SOA. In the absence of any control pulses the gate is reflective and the CLK pulses exit through the same port that they enter (port R). When either pulse A or B is present, the gate becomes transmissive (port T) and if both A and B are present it becomes reflective again (port R). Fig. 1 shows the experimental configuration. The SOA-assisted Sagnac interferometer gate was constructed using a 3-dB polarization preserving coupler into the ports of which the optical clock signal (CLK) is injected. The logical inputs A and B are inserted in the loop via two optical fiber polarization beam splitters/combiners PBS1 and PBS2. Polarization preserving passive components have been employed so as to ensure cascadability with a single device. Nonlinear interaction between the CLK and data beam was performed in a fully packaged and pigtailed SOA. The SOA was a 1000 μm, bulk InGaAsP–InP ridge waveguide device which could provide a small-signal gain of 23 dB, with a gain recovery time of 100 ps at 400 mA. The SOA was pigtailed with standard single-mode optical fiber and exhibited a 2-dB gain polarization dependence. This required the use of

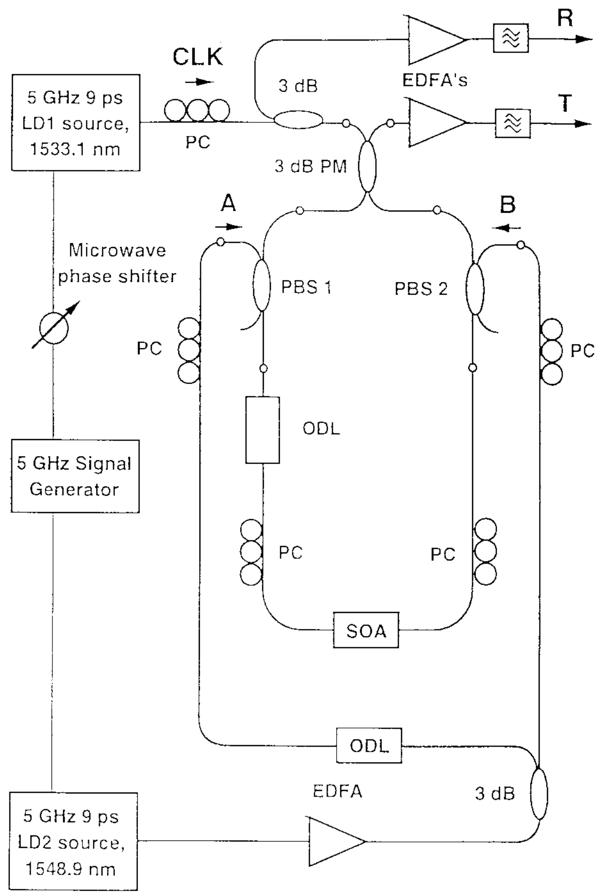

Fig. 1. Experimental setup. A, B, CLK: Inputs into gate. R, T: Outputs. LD: Laser diode. EDFA: Erbium-doped fiber amplifer. SOA: Semiconductor optical amplifier. PC: Polarization controller. 3 dB PM: 3-dB polarization preserving coupler. PBS: Fiber polarization splitter/combiner. ODL: Variable optical delay.

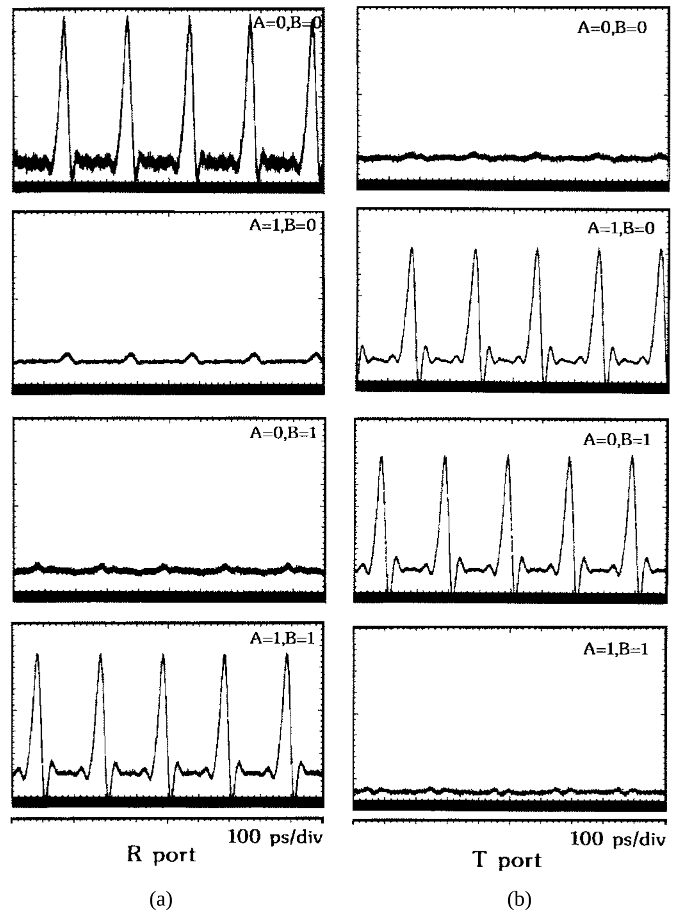

Fig. 2. (a) and (b), outputs at R port and T port of the gate at 5 GHz for $A = B = 0$; $A = 1$, $B = 0$; $A = 0$, $B = 1$, and $A = B = 1$, respectively. The timebase is 100 ps/div.

polarization controllers at its input and output for optimum control. A variable optical delay line was introduced in the loop to adjust the position of the SOA with respect to the center of the loop. For best performance, this was set to about 50 ps from the center during the experiment.

The three optical signals were produced from two packaged, fiber pigtailed, gain switched DFB semiconductor diode lasers, LD1 and LD2, which were driven from a synthesized signal generator with a microwave variable phase shifter inserted to synchronize their signals. At 5 GHz, the diode lasers produced 9-ps pulses after compression in a dispersion compensating fiber. The optical clock signal was provided by LD1 at 1533.1 nm. The two logic inputs A and B were provided by LD2 at 1548.9 nm, whose output was amplified in an EDFA, split in a 3 dB coupler, and fed into the control ports of the Sagnac gate. The polarization state of the signal from LD1 was adjusted before entry into the gate so that no light would couple out of the loop at PBS1 and the polarization states of A and B were adjusted independently for best switching results. For the gate to operate, the three optical signals (input A, input B, CLK) were temporally synchronized into the SOA by adjusting the phase delay at the RF synthesizer to synchronize CLK with A and the optical delay line external to the loop to synchronize CLK with B.

III. Results and Discussion

For successful Boolean XOR between A and B, the clock signal entering into the gate must exit through the same port R of the 3 dB coupler, in the absence of both A and B. If either A or B is present then the clock pulse must exit through port T, and if both A and B are present then it must exit again at R. The switching properties of the gate were observed at the reflection and transmission ports R and T, with a 40-GHz sampling oscilloscope. Fig. 2(a) and (b) show the results obtained at R and T at 5-GHz repetition rate of the signals, respectively. In this case, the contrast ratio for the R and T ports between the ON–OFF states was 13 and 14.6 dB, respectively. The optical power for the CLK signal was 30 μW and the two inputs A and B was 165 and 220 μW, respectively, corresponding to 6-, 33-, and 44-fJ pulse energies. Fig. 2 shows the full duty cycle switching XOR between A and B as the most demanding test on the gate's performance because of the highest average power entering the SOA and its deepest saturation. It has been possible to switch different pulse patterns from CLK using appropriate A and B inputs, with no appreciable data pattern-dependent effect on its output. It is worth noting that despite the simultaneous presence of the two control beams, the switching energy of the gate is very low and the switching contrast ratio of the ON–OFF states is high. This is the first, to our knowledge, demonstration of an

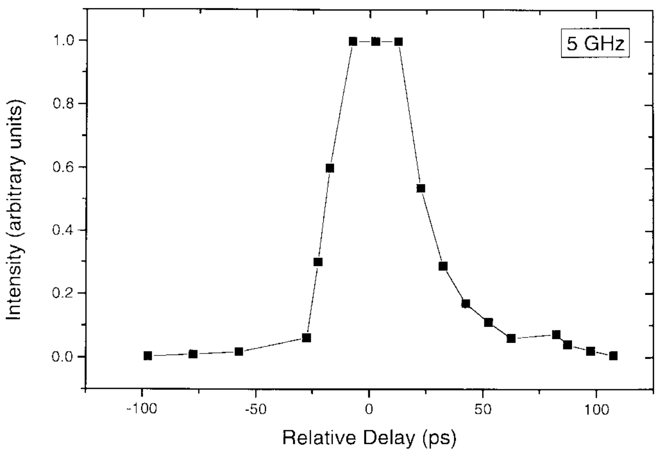

Fig. 3. Dependence of T port output for $A = 1$, $B = 0$ input at 5-GHz optical signal.

XOR operation with a SOA-assisted Sagnac gate and in general of any two-control beam input experiment with the device.

The contrast ratio at the output of a SOA-assisted Sagnac gate depends on parameters as the gain and recovery time of the SOA, the signal and control repetition rates and pulsewidths. Of these parameters, the only one that is easy to alter so as to increase the switching rate of the gate is the width of the clock and input pulses. In order to examine whether the length of the pulses was appropriate for the repetition rate, the local temporal window over which the "on" state of the gate was high has been measured. This has been achieved by introducing a logical 1 at control input A and recording the output at the T port of the gate while changing the relative asymmetry in the position of the SOA in the loop. Fig. 3 shows the resulting switching window for 5 GHz, indicating that the "on" state of the switch is achieved over approximately a 21-ps window which is considerably longer than the 9-ps input pulses, permitting the achievement of good switching results.

IV. Conclusion

We have demonstrated the implementation of Boolean XOR logic using an all-optical, SOA-assisted Sagnac interferometer switch. In particular, we have demonstrated full duty cycle XOR logic at up to 5-GHz clock and data signals with contrast ratio better than 13 dB. Experiments are currently in progress to extend the operation of the device to higher rates. This is a two control input beam experiment performed with the SOA-assisted gate and proves that it is possible for the interferometer to pass to the second interference fringe simply by introducing twice as much energy/pulse as for the first.

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