40 Gbit/s all-optical logic NOR gate based on a semiconductor optical amplifier and a filter

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Abstract. A novel all-optical logic NOR gate is presented that is composed of a semiconductor optical amplifier (SOA) and an optical bandpass filter. The NOR gate is successfully experimentally demonstrated at 40 Gbit/s. The experiment result shows good extinction ratio of larger than 12.0 dB with clear and open eye. The NOR gate has a simple configuration and allows photonic integration.
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Subject terms: optical communication; semiconductor optical amplifier; all-optical logic function; all-optical NOR gate.

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1 Introduction

It is well known that an optical mechanism instead of an electronic mechanism for signal processing and computing will be required to achieve high-speed performance.[1] All-optical signal processing and computing operation fundamentally rely on material nonlinearities.[2–4] All-optical logic devices based on nonlinearities in semiconductor optical amplifiers (SOAs) have recently attracted considerable research interest. Boolean logic gates, including NOR and OR, are the essential logic devices and are capable of forming parts of more complex all-optical functional blocks, modules, or subsystems as in a full-adder, half-adder, counter, or parity checker. The OR function may be a NOR with an inverter of delayed interferometer at the output.[5] Several schemes for logic NOR gates based on SOAs have been demonstrated.[4,6–8] Each scheme has its own advantages and disadvantages. For example, NOR gates,[6] which are based on cross-gain modulation in SOAs, have a simple configuration, but the output signals have relatively large chirp and their operation speed is limited by the carrier's recovery time. NOR logic gates at 10 Gbit/s using solely cross-phase modulation are capable of having a good contrast ratio but require complex interferometer configurations.[7] In Ref. 8, a NOR gate based on cross-polarization modulation was demonstrated at 2.5 Gbit/s. It required neither interferometric configuration nor input logic signals producing a strong saturation of the amplifier gain. Recently, an attention-getting scheme based on an SOA followed by a filter was used to realize some functions such as wavelength conversion[5,9,10] and logic gates including AND, OR, and XOR at 10 Gbit/s (Ref. 11). However, its application to a logic NOR gate has not been reported to date.

This letter presents a novel all-optical logic NOR gate that is based on an SOA and a bandpass filter that is detuned to the blue-shifted sideband of the probe wavelength and selects the blue-shifted sideband of the output signal. The logic gate is experimentally demonstrated at 40 Gbit/s. The experimental results show a good extinction ratio (ER) of larger than 12.0 dB with clear and open eye.

2 Experimental Setup and Principle

Figure 1 shows the schematic diagram of the experimental setup to implement our all-optical NOR logic gate at 40 Gbit/s. The optical logic gate is composed of an SOA, a bandpass filter with 3 dB bandwidth 0.40 nm. The SOA bias current is set to 280 mA. The pulses from a 10-GHz tunable mode-locked laser (TMLL) are modulated by a $LiNbO_3$ modulator at 10 Gbit/s with a 2^7-1 return to zero (RZ) pseudorandom binary sequence (PRBS). After passing through an erbium-diped Fiber amplifier (EDFA) and a 1.2-nm (3-dB bandwidth) optical bandpass filter BPF1 centered at the data source wavelength of 1545.12 nm, the 10-Gbit/s data stream is multiplexed to 40 Gbit/s by an optical multiplexer. Then the data stream is split into two data streams by a 3-dB optical coupler. The two data streams are used as two input logic signals. A variable optical delay line (ODL) is inserted in upper arm to synchronize the two signals to each other. Furthermore, the data signal in the lower arm is delayed sufficiently compared to upper data signal by using standard single-mode (SM) fiber to ensure that the two data signals are decorrelated with respect to each other while being mixed together in next 3-dB coupler. Two polarization controllers PC2 and PC3 are used to adjust polarization states of the two data signals, respectively. Both input logic signals are injected into the SOA in the opposite direction to a probe wave via the optical circulator. The continuous-wave probe signal from a tunable laser source at 1562.50 nm is coupled into the SOA after passing through a polarization controller PC1 and an optical isolator. In the SOA, the probe is cross-gain modulated, and cross-phase modulated by the injected two logic signals, resulting in a chirped converted signal, i.e., the leading edge of the (inverted) modulated probe is shifted toward lower frequencies (red-shifted), whereas the trailing edge is shifted toward higher frequencies[10] (blue-shifted).

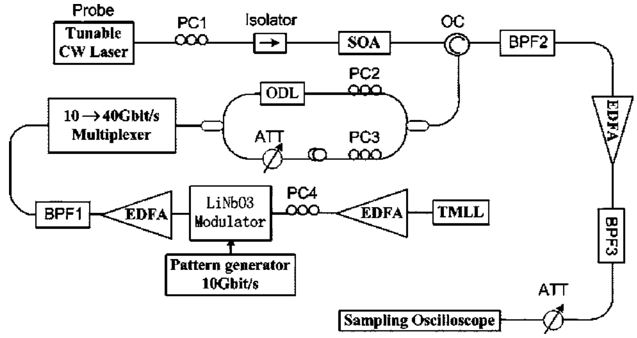

Fig. 1 Schematic diagram of experimental setup: ODL, optical delay line; BPF, optical bandpass filter.

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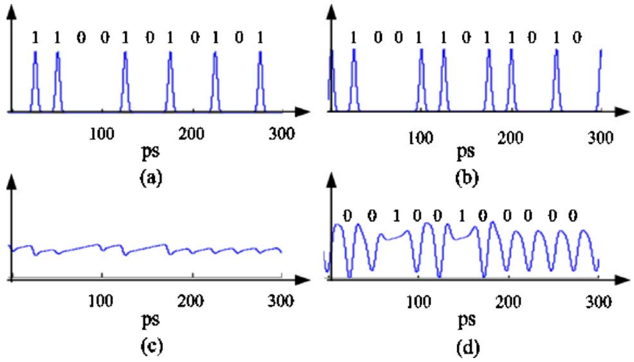

Fig. 2 Simulation realization of logic NOR gate at 40 Gbit/s: (a) input data signal 1, (b) input data signal 2, (c) at SOA output, and (d) output NOR signal.

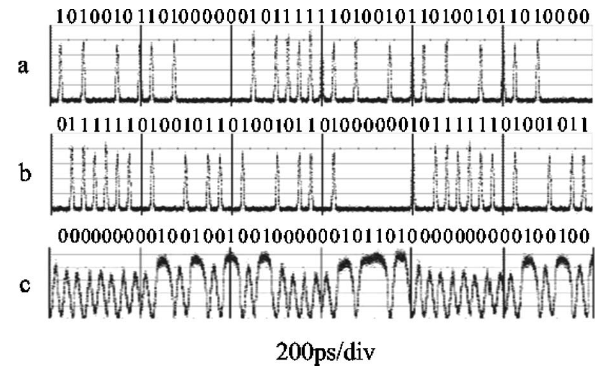

Fig. 4 Waveforms for 40-Gbit/s NOR measurements: (a) input data stream 1, (b) input data stream 2, and (c) output NOR signal.

At the output of SOA, a bandpass filter BPF2 (3 dB bandwidth of 0.4 nm) is used to achieve the blue-shifted filtering effect; the central wavelength for the BPF is at 1562.09 nm, i.e., detuned 0.41 nm to the blue side of the probe wavelength. Filter BPF2 selects the blue-shifted side-band of the probe from the SOA. The magnitude of the induced blue-shift can be controlled by the individual powers of the input signals. By controlling the power levels and the filter detuning between the center wavelength of the filter BPF2 and the cw probe wavelength, the logic NOR function can be realized. An inverted pulse will be generated as long as an input data 1 appears, that is to say, there is one logic 0 output from the filter. On the other hand, no inverted pulse is generated when two input logic signals are 0, that is to say, there is one logic 1 output from the filter. The simulation realization of logic NOR operating at 40 Gbit/s is shown in Fig. 2. Here, the model used and main physical parameters are based on Ref. 12. The filter for simulation is a Gaussian filter. In the simulation, we consider the carrier heating effect and the length effect of the SOA. The simulation shows the bandwidth of the Gaussian filter and the phase modulation coefficients of the SOA are very important to the shape and width of the output pulse. The simulation also shows that the difference in the amplitude of the blue chirp in the SOA, which is induced by two simultaneous control pulses or a single control pulse, may be very small. Thus, good logic NOR output signals can be achieved. After the filter, the output signal is amplified by an EDFA and then passed through a tunable bandwidth filter BPF3 (3 dB bandwidth of 1.2 nm) to suppress the noise of the EDFA before being monitored by an oscilloscope.

Note that, in the experiment, we tuned the wavelength of the probe to change the relative position of the filter with respect to the probe without adjusting the BPF2 center wavelength.

3 Experimental Results

The mean power for the probe is −1.2 dBm, and the mean power for two input data signals are 3.15 dBm before the SOA. Figure 3 lines a and b show the spectra of probe light at SOA output and at the filter BPF2 output, respectively. We can see that the spectrum of probe light at SOA output is broadened. Figure 3 (line c) shows the filter shape for measurement. Figure 4 shows the two input data signals and the NOR output signal at 40 Gbit/s. We can see that all of the input signal shows correct output logic, verifying the NOR functionality at 40 Gbit/s. The corresponding eye diagram, as shown in Fig. 5(a), is clear and open. In this eye diagram, the extinction ratio is defined as the ratio of the mean value of the "one" level and the mean value of the "zero" level. The ER is larger than 12.0 dB. However, we can see that some pattern dependency and amplitude noise

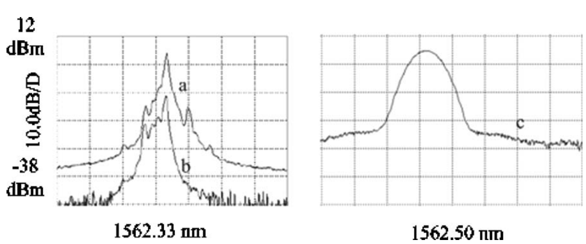

Fig. 3 Output optical spectra and filter shape with a resolution of 0.05 nm and a division of 0.5 nm: (line a) optical spectrum at SOA output, (line b) optical spectrum at the BPF2 output, and (line c) filter shape for measurement.

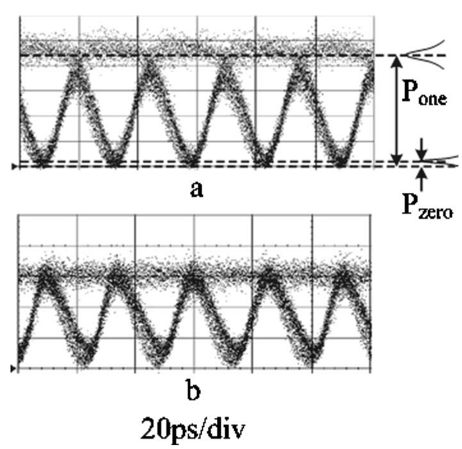

Fig. 5 Eye diagrams for 40 Gbit/s NOR measurements: (a) at BPF2 output corresponding to the waveform in Fig. 3 (line c) and (b) NOR output with a tunable BPF (3-dB bandwidth 1.2 nm) in place instead of BPF2.

exist. This could be improved by optimizing the filter. A filter with a steeper slope and higher out-of-band suppression is beneficial to improve pattern dependency. We also exploit a tunable bandwidth filter with smaller slope and larger 3-dB bandwidth of 1.2 nm to replace BPF2, and complete the NOR function. As seen in Fig. 5(b), this even shows severe pattern dependency and a decreased ER of less than 8 dB. Here, the central wavelength of this BPF is optimized at 1561.42 nm, i.e., detuned 1.08 nm to the blue side of the probe wavelength. The two eye diagrams in Figs. 5(a) and 5(b) have same power.

4 Conclusions

A novel all-optical logic NOR gate, composed of an SOA and a bandpass filter, was presented and experimentally demonstrated with RZ 2^7-1 pseudorandom data pattern at 40 Gbit/s. The logic NOR gate shows a good ER of larger than 12.0 dB with a clear and open eye at 40 Gbit/s, and has a simple structure and enables photonic integration. On the other hand, simultaneous wavelength conversion is also realized and low input powers are required. This work may help to improve the high-speed all-optical logic and arithmetic operations. For instance, with the help of a delayed interferometer as an inverter, an OR gate operating at 40 Gbit/s can be easy to achieve.

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