Optical half-adder and half-subtracter employing the Pockels effect

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Abstract: The Pockels effect in periodically poled lithium niobate made it possible to switch optical signals between two orthogonal optical linear polarizations of the vertical and horizontal polarization states. Based on this effect, we demonstrated polarization-based binary optical logic gates: AND, and OR gates. By combining these basic gates with other polarization-based optical logic gates such as XOR gate accomplished in our previous researches, half-adder and half-subtracter of digital signals with a high extinction ratio of about 10dB have been demonstrated in our experiment, which made it possible to run more complex logical calculus.

OCIS codes: (230.2090) Electro-optical devices; (230.3750) Optical logic devices; (130.3730) Lithium niobate.

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1. Introduction

The Moore's law tells us that the calculative ability of computers doubled every 18 months in the past. However, it is believed that in the near future the traditional electrical computer will meet the bottleneck, because of its physical mechanism. In order to overcome the bottleneck of current information systems, ultrafast high-speed, large-capacity, all-optical networks are really necessary [1, 2]. Therefore, all-optical logic gates become more and more important as crucial functions for all-optical signal processing. In the past decades, optical logic using different schemes, including dual semiconductor optical amplifier (SOA) [3], Mach-Zehnder interferometer(MZI) [4, 5], semiconductor laser amplifier (SLA) loop mirror [6], ultrafast nonlinear interferometer (UNI) [7], four-wave mixing (FWM) in SOA [8], photonic solitons [9], cross phase modulation(XPM) in nonlinear devices [10], micro/nano plasmonic structures [11–13] and a triangular triple-core photonic crystal fiber [14]have been demonstrated one by one. In addition, all-optical logic gates based on different schemes in periodically poled lithium niobate (PPLN) [15, 16] have also been presented recently owing to its attractive property.

Most of optical logic gates demonstrated before are encoded based on the intensity of optical waves. However, the intensity is always depleted rapidly along with the computation. It is known that the polarization information of light can be maintained as long as the intensity is above zero. What is more, with the depletion, the polarization information can be distinguished more easily from the opposite information than the intensity information. As a result, to avoid this high intensity depletion and accomplish some more complex signal processing, optical polarization-based binary logic gates have been proposed and demonstrated [17]. In this scheme, two orthogonal states of polarization were used to represent logic one and logic zero.

In our previous work, the capability to change polarization state of optical wave with high precision and rate in PPLN has been researched and verified [18]. By utilizing the linear polarization-state generator in PPLN, polarization-based optical logic controlled-NOT, XOR, and XNOR gates have been demonstrated in our previous work [16]. In this letter, we study the polarization-based optical logic controlled-NOT, AND and OR gates, which are accomplished by employing polarization beam splitter (PBS) and optimizing the external electric field on 5 mol% MgO-doped periodically poled lithium niobate (MgO:PPLN). Additionally, we generate digital signals by using a polarization rotator, and a series of output digital signals have been demonstrated in our experiment. Finally, based on these basic logic gates, digital optical half-adder and half-subtracter are also designed and demonstrated.

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2. Pockels effect

The electro-optic (EO) effect in PPLN has already been theoretically and experimentally studied [16, 18]. With a transverse external electric field applied on PPLN, the optical axis of positive domains can be rotate by angles of + θ, while the negative domains by angles of –θ with respect to the plane of polarization of the input light:

$$\theta = \frac{\gamma_{51} E_y}{(1/n_e)^2 - (1/n_o)^2}. \tag{1}$$

Ey is the field intensity, γ_{51} is the electro-optic coefficient, n_o and n_e represent the refractive indices of the ordinary and extraordinary waves, respectively. The difference of phase velocities between the ordinary wave (OW) and the extraordinary wave (EW) makes each domain of PPLN serving as a half-wave plate at a certain wavelength. After passing through the stack of half-wave plates, the optical plane of polarization will rotate continually and finally create a total rotation angle of 2Nθ, where N is the number of periods of PPLN. As a result, polarization of light can be totally rotated by 90° in the presence of the proper external applied electric field after propagating through PPLN. In our experiment, we used one polarizer to generate a linear polarization state of the input light, and another polarizer as an analyzer to check the output polarization state.

In order to switch these two orthogonal linear polarization states of input signals, we set the polarizer along the Y direction and the analyzer along the Z direction, and then the OW can be switched to the EW after applying the external filed. While the polarizer is set along the Z direction and the analyzer along the Y direction, the EW can be switched to the OW contrarily.

To evaluate this switch, we measured the transmission T, which denotes the depletion of input optical signal after EO modulation. The quantities $T_{\parallel}$ and $T_{\perp}$ corresponding to the horizontal and vertical polarization state of input signal are defined as, $T_{//} = I_{\text{out},\perp} / I_{\text{in},//}$ and $T_{\perp} = I_{\text{out},//} / I_{\text{in},\perp}$, respectively. $I_{\text{in},//}$ and $I_{\text{in},\perp}$ are the intensities of horizontal and vertical polarization state of input optical signal. $I_{\text{out},//}$ and $I_{\text{out},\perp}$ are the intensities of horizontal and vertical polarization state of output optical signal respectively.

In our experiment, The horizontal state could be switched to vertical one at the applied electric field of 3.15 kV/cm where the transmission $T_{//}$ reaches maximum, while the vertical state could be completely switch to the horizontal state, where the applied electric field is about 3.37 kV/cm.

We set a polarizer to generate a state of polarization and the analyzer to check the transmission of the output at the end of the MgO:PPLN crystal. Using this kind of experimental setup, the overall transmission for this optical rotation was measured, and the results are shown in Table 1. Here we used PBS as polarizer and analyzer.

Table 1. The polarization and intensity of input and output lights with different applied electric fields

Input intensity (μW)	Input polarization	Applied electric field (kV/cm)	Output polarization	Output intensity (μW)	Transmission
360	→	0	→	355.2	98.7%
360	→	3.26	↑	322.6	89.6%
280	↑	0	↑	272.6	97.3%
280	↑	3.26	→	272.6	88%

3. Polarization-based optical AND and OR gates

In our work, the experimental schematics of optical logic XOR, XNOR, AND and OR gates are shown in Figs. 1 (a) and 1(b). The corresponding poling grating period of MgO:PPLN

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was 19.9 μm. At a given experimental temperature of 23.5 °C, the device performed the switch between two orthogonal states of polarization at 1552.9 nm.

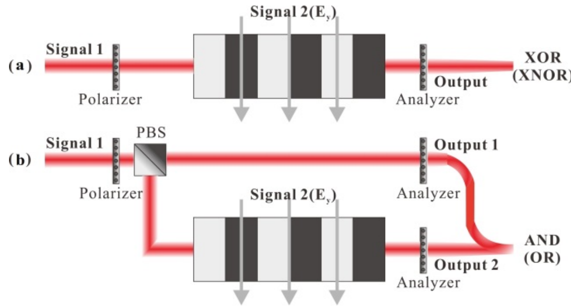

Fig. 1. Experimental schematics for optical polarization-based (a) XOR and XNOR, (b) AND and OR gates. The PBS and polarizer are used to generate and distinguish two orthogonal polarization states, where one state is horizontal, and the other is vertical.

Considering the results obtained in Table 1 and the definitions of different logic gates shown in Table 2, XOR, XNOR, AND and OR logic gates can be achieved respectively. By defining the optical signal with vertical and horizontal polarization state as logic 0 and logic 1 and considering the applied electric field of 0 and 3.26 kV/cm as logic 1 and logic 0 respectively, we can obtain all the basic logic gates shown in Table 3, corresponding to the results in Table 1. It is convenient to switch the logic function between AND (XNOR) gates and OR (XOR) gates by changing the definitions of optical signals in Table 2.

Table 2. Presentation of signals for XOR, XNOR, AND and OR gates

	AND/XNOR		OR/XOR	
	Logic 0	Logic 1	Logic 0	Logic 1
Signal 1	↑	→	→	↑
Signal 2	E	0	0	E
Output	↑	→	→	↑

Table 3. Experimental results and truth table for XOR, XNOR, AND and OR

	Experiment				AND				OR				Experiment				XOR				XNOR			
Signal 1	→	→	↑	↑	1	1	0	0	0	0	1	1	→	→	↑	↑	0	0	1	1	1	1	0	0
Signal 2	0	E	0	E	1	0	1	0	0	1	0	1	0	E	0	E	0	1	0	1	1	0	1	0
Output	→	↑	↑	↑	1	0	0	0	0	1	1	1	→	↑	↑	→	0	1	1	0	1	0	0	1

4. Optical digital half-adder and half-subtracter

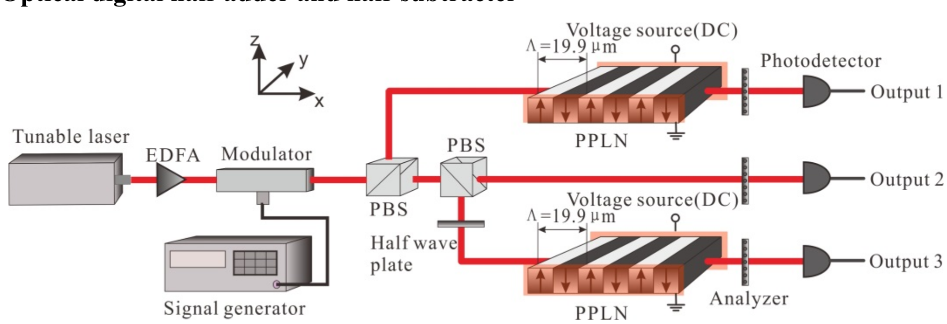

Fig. 2. The experimental setup of the half-adder and half-subtracter based on the AND and XOR gates realized in PPLN with an incident modulated light as signal 1, and an external electronic field Ey as signal 2.

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To achieve the polarization-based optical half-adder and half-subtracter, firstly we need to have the basic logic gates of XOR and AND which have been showned in Fig. 1(a), 1(b) and Table 2 above. Figure 2 shows our experimental setup for achieving the half-adder and half-subtracter.

A continuous wave(CW) with a wavelength of 1552.9 nm was launched from a tunable laser, and amplified to tens of mw through an EDFA. Consequently the CW was modulated as signal 1 by employing an optical rotation modulator (Photline: PS-LN-10) driven by a signal generator with 40 MHZ. The signal 1 passed through a collimator and launched into the PPLN samples with different linear polarizations. An electric field E_y along to Y direction provided by a voltage source was defined as the signal 2. By combining output 2 and 3 in Fig. 2, we constructed an AND logic gate which was shown in Fig. 2(b). Similarly a XOR logic gate could be obtained from output 1, which has been shown in Fig. 2(a). Through combining the above XOR and AND gates, a half-adder could be achieved as shown in Fig. 2. If we want to demonstrate a half-substracter, we just need to detect the output 3 as the BORROW and combine the XOR gate from the output 1. Table 4 shows us the truth tables of SUM, DIFF, CARRY and BORROW for half-adder and half-subtracter.

Table 4. Truth tables of SUM, DIFF, CARRY and BORROW for the half-adder and half-subtracter

	Definition				SUM/DIFF				CARRY				BORROW			
Signal 1	→	→	↑	↑	0	0	1	1	0	0	1	1	0	0	1	1
Signal 2	0	E	0	E	0	1	0	1	0	1	0	1	0	1	0	1
Output 1	→	↑	↑	→	0	1	1	0								
Output 2	→	→	0	0					0	0	0	1				
Output 3	0	0	→	↑									0	0	1	0

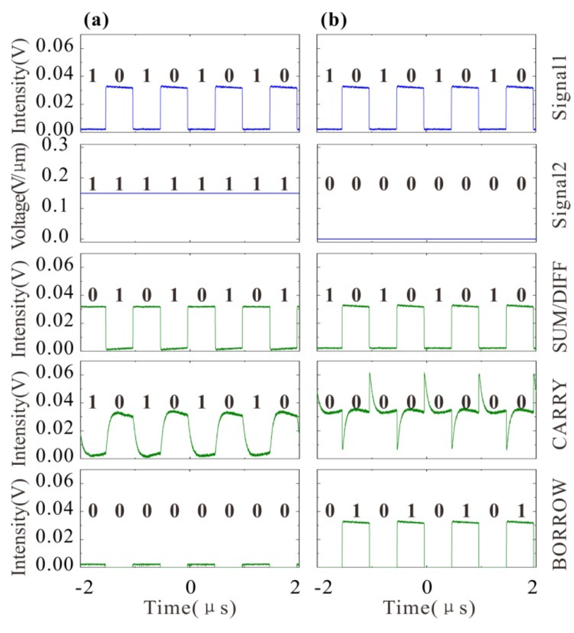

Fig. 3. Experimental results for the half-adder and half-subtracter. (a) Transverse external electric field is on. (b) Transverse external electric field is off. For Signal 1, the horizontal and vertical polarizations are defined as logic 0 and 1. For Signal 2, the logic 0 and 1 are achieved when the external electric field are 0 and E. The definition of SUM/DIFF and CARRY is the same with the definition of Signal 1, while the definition of BORROW is contrary to the definition of Signal 1.

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In our experiment, signal 1 is a bunch of digital optical signals which is polarization modulated, while signal 2 is an alterable external electric field. Then we have a series of digital optical output signals as shown in Fig. 3, where we get a high extinction ratio of about 10dB. For signal 1, we define signal with the horizontal and vertical polarizations as logic 0 and 1 respectively, and for signal 2, we have the logic 0 and 1 when the external electric field are 0 and E.

And as shown in Fig. 3, we can achieve the experimental results of column (a) and (b) when the external electric fields (signal 2) are on and off, in which we demonstrated SUM/DIFF(Output 1) and CARRY(combining Output 2 and Output 3) by using the similar logic definitions as signal 1. Consequently the half-adder has been realized by combining SUM and CARRY. While we can achieve the half-subtracter by employing DIFF and BORROW, in which we have to change the definition of BORROW (Output 3) which is contrary to the definition of signal 1.

Moreover, based on the experimental demonstration in this paper, a potential on-chip quantum computer will be expected by employing different structures with waveguides as shown in Fig. 4 when combining its nonlinearity and electro-optic effects. Thus recently it is necessary to develop an integrated on-chip system in lithium niobate, which attracts more research interesting in fabricating on-chip devices due to its distinguished nonlinear optical [19–21], electro-optical [16, 18] and mechanical properties [22].

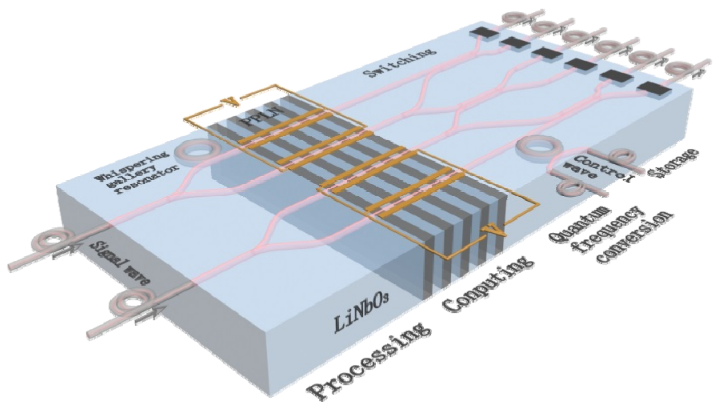

Fig. 4. An on-chip computing system based on $LiNbO_3$, which integrates all necessary signal processing and different structures such as interferometer and whispering gallery resonator etc.

5. Conclusion

By employing Pockels effect in MgO:PPLN, we experimentally demonstrate polarization-based binary optical logic gates using AND and OR gates and the XOR gate completed in our previous work. When choosing the proper electric field, these logic gates can present excellent performance, in which the optical signals are encoded in polarizations, and might not suffer from the possible intensity attenuations for cascading operations. In our future work, the electric field of high intense optical waves will take place of the electric field provided by the applied electrical signal directly. Then a real all-optical logic calculation will be expected. Moreover, by changing these functional structures in PPLN, more complex computing such as full-adder and full-subtracter can also be achieved, which will offer a new solution for the on-chip all-optical signal processing in lithium niobate.

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