Polarization-based all-optical logic controlled-NOT, XOR, and XNOR gates employing electro-optic effect in periodically poled lithium niobate

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Based on electro-optic Pockels effect of periodically poled lithium niobate, different polarization-based binary all-optical logic functions: controlled-NOT, XOR, and XNOR gates were demonstrated by altering the linear polarization state of input optical signal about 90° on the polarization plant. Because the depletion of signal intensity in polarization-based logic gates is smaller than that of digital logic signal in intensity-based logic gates and almost negligible, this scheme has potential application in realizing complex logic functions by cascading several basic gates. © *2011 American Institute of Physics*. [doi:10.1063/1.3656000]

The emergence of complex digital optical systems demands high-speed and parallel signal processing devices. But present electronic signal processing speeds have fallen far behind the capabilities of both optical time-division and wavelength division multiplexed (WDM) systems. Meanwhile, the speed of photonic networks is also highly limited by electrical-to-optical and optical-to-electrical conversions. Therefore, all-optical logic devices are becoming key elements in future all-optical communication networks. In the past decades, most of the all-optical logic gates were intensity-based and realized in Semiconductor Optical Amplifier (SOA).[1,2] At the same time, periodically poled lithium niobate (PPLN), a sort of artificial nonlinear material, received more and more attention owing to its outstanding nonlinear optical properties and its transparent format conversion as all-optical devices in communication band.[3–5]

As a result of the periodic domain inversion in PPLN, its nonlinear optical coefficient, the electro-optic (EO) coefficient, the acousto-optic coefficient,[6] and the piezoelectric coefficient[7] are modulated periodically. Based on the nonlinear frequency conversion processes in PPLN, some intensity-based all-optical logic gates have been demonstrated already.[8,9]

Most of these applications have been focused on the change of intensities on certain wavelengths, in which signals are encoded in the intensity of optical waves. And the depletion of optical signal is great induced by insertion loss. To avoid high intensity depletion of signal in intensity-based all-optical logic gates, a basic idea is introduced from the previous research work,[10] where an all-optical polarization-based representation and implementation of binary logic gates have been proposed. They employed two orthogonal linear polarization states of a beam to represent logic 0 and logic 1. Because the polarization change of optical waves was utilized, the depletion of signal intensity is smaller than that of intensity-based all-optical logic gates. On the other hand, the capability to change polarization state of optical wave by PPLN has been researched and verified recently, which has demonstrated a linear polarization-state generator with high precision in PPLN.[11]

By combining these two above works and utilizing similar configuration in Ref. 11, in this paper, we demonstrate experimentally three polarization-based all-optical logic gates: controlled-NOT, XOR, and XNOR gates, which are based on the variety of the polarization states modulated by the electro-optic effect in PPLN.

Resent researches[12,13] on electro-optic effect of PPLN show that with transverse electric field along PPLN, the optical axis of each domain can be alternately aligned at the angles of $+\theta$ and $-\theta$ with respect to the polarization plane of the input light, the rocking angle θ, which is given by $\theta \approx \gamma_{51}E/[(1/n_e)^2 - (1/n_o)^2]$, and the optical axis of each domain will rotate continually with the increment of the electric field.

In this case, the coupled-wave equations of the ordinary and extraordinary waves are

$$\begin{cases} dA_1/dx = -i\kappa A_2 e^{i\Delta\beta x} \\ dA_2/dx = -i\kappa^* A_1 e^{-i\Delta\beta x} \end{cases}, \quad (1)$$

with $\Delta\beta = k_1 - k_2 - m\left(\frac{2\pi}{\Lambda}\right)$, and $\kappa = -\frac{\omega}{2c}\frac{n_o^2 n_e^2 \gamma_{51} E}{\sqrt{n_o n_e}}\frac{i(1-\cos m\pi)}{m\pi}$ $(m = 1, 3, 5\ldots)$, where A_1 is the normalized complex amplitude of ordinary wave, and A_2 is the normalized complex amplitude of extraordinary wave. n_o and n_e are refractive indices of the ordinary wave and the extraordinary wave, respectively. Λ is the period of the PPLN; γ_{51} is the electro-optical coefficient of PPLN. E is the transverse external

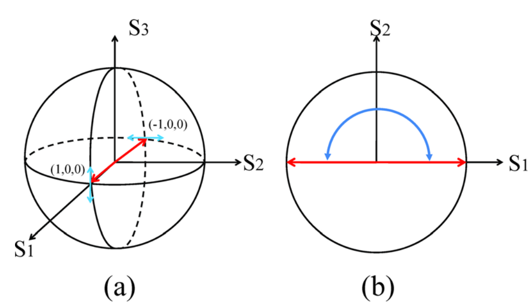

FIG. 1. (Color online) (a) Two orthogonal polarization states of input optical signal on a Poincare sphere for logic representation: vertical polarization state (point(1,0,0)) and horizontal polarization state (point(−1,0,0)). (b) Switching between the two orthogonal polarization states.

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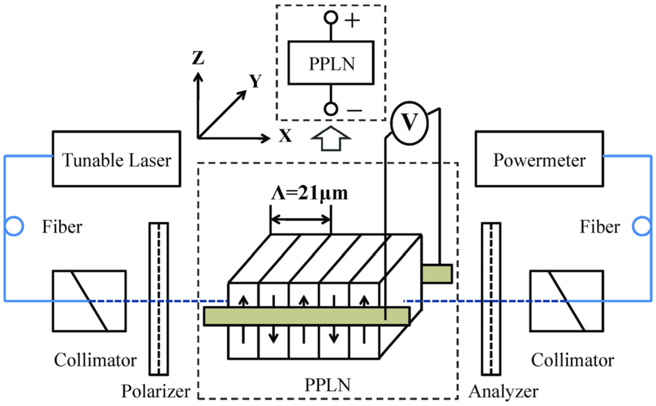


FIG. 2. (Color online) Experimental setup for all-optical polarization-based logic gates. The 3.5 cm PPLN crystal is Z cut and consists of 2588 domains with the period of 21μm. The input optical signal propagates along the X axis, and a uniform electric field is applied along the Y axis on the PPLN.

applied electric field. For the Quasi-Phase-Matched (QPM) wavelength ($\Delta\beta = 0$), solutions of the coupled-wave equations are given by[14]

$$\begin{cases} A_1(L) = \cos(|\kappa|L)A_1(0) - \sin(|\kappa|L)A_2(0), \\ A_2(L) = \cos(|\kappa|L)A_2(0) + \sin(|\kappa|L)A_1(0). \end{cases} \quad (2)$$

From the solution, the output normalized complex amplitudes of the ordinary and extraordinary waves are totally determined by the transverse external electric field E, which reveals that the output polarization state will periodically changes with $|\kappa|L$. When input light has passed through a stack of domains, each serves as a half-wave plate, and its optical plane of polarization will rotate continually and finally create a total rotation angle of 2Nθ, where N is the number of domains of PPLN. Finally, PPLN can act as a role in rotating linear polarization state of input light.

In our approach, we choose the linear horizontal polarization state of the optical signal and its orthogonal state, the linear vertical polarization state to be logic 1 or 0, as is shown on the equatorial plane of Poincare sphere in Fig. 1(a). With the electro-optic effect of PPLN, the polarization state of input

TABLE I. The relationship between the polarization and intensity of input and output lights with different external electric field. The sign → and ↑ denotes horizontal and vertical polarization states, respectively. If input optical signal is horizontal polarization state, then T = $T_\parallel$, otherwise T = $T_\perp$.

Eletric field E (kV/cm)	Input polarization	Input intensity (μW)	Output polarization	Output intensity (μW)	T (%)
3.14	→	120	↑	106	88.4
2.71	↑	500	→	480	96.0

optical signal can be switched between the two orthogonal states, as is shown in Fig. 1(b). To evaluate the accuracy of the switching, that is, an angle 90° rotation between each other, we measured the transmission T, which denotes the depletion of input optical signal after EO modulation. The quantities $T_\parallel$ and $T_\perp$ for the horizontal and vertical polarization state of input signal are defined, respectively, by

$$T_\parallel = \frac{I_{out,\perp}}{I_{in,\parallel}}, \quad \text{and} \quad T_\perp = \frac{I_{out,\parallel}}{I_{in,\perp}}, \quad (3)$$

where $I_{\text{in},\parallel}$ and $I_{\text{in},\perp}$ are the intensity of horizontal and vertical polarization state of input optical signal, respectively; $I_{\text{out},\parallel}$ and $I_{\text{out},\perp}$ are the intensity of horizontal and vertical polarization state of output optical signal, respectively.

The experiment setup is shown in Fig. 2. We selected the QPM wavelength 1540.8 nm as operating wavelength, where $\Delta\beta = 0$ at a given experimental temperature about 26 °C. In the experiment, we set polarizer parallel to Y axis, so the input optical signal is of a horizontal polarization state and the analyzer parallel to Z axis, as shown in Fig. 3(a). In Fig. 3(c), similarly, we set polarizer parallel to Z axis, so the input optical signal is of a vertical polarization state and the analyzer parallel to Y axis. At last, we measured the change of $T_\parallel$ and $T_\perp$ with the increment of transverse external electric field E from 0 to 4.5 kV/cm as shown in Figs. 3(b) and 3(d). The experimental results have shown that the polarization state of output optical signal could be switched between horizontal and vertical polarization state when the transmission $T_\parallel$ and

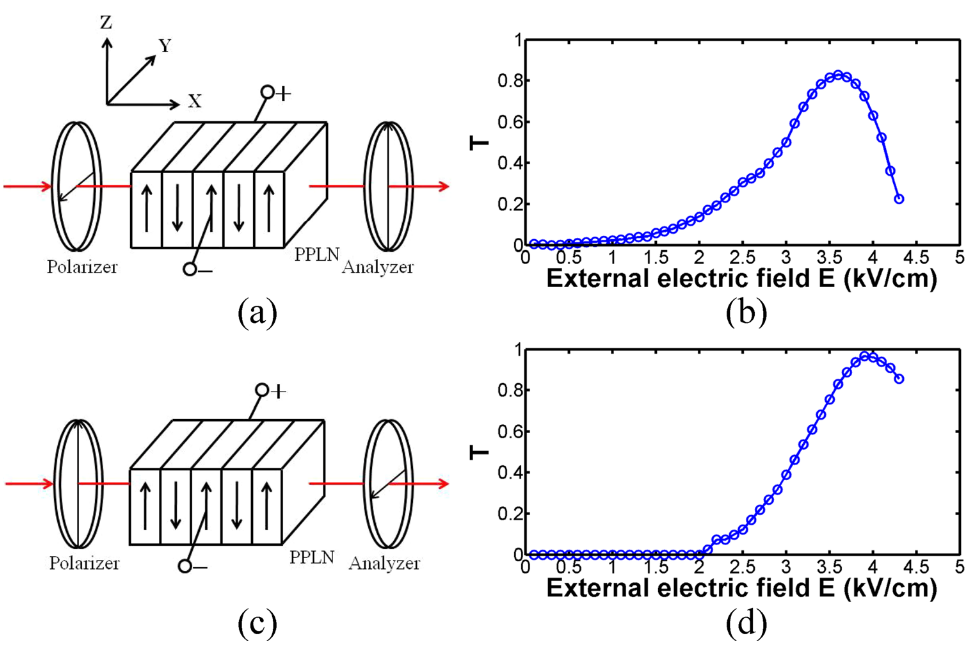
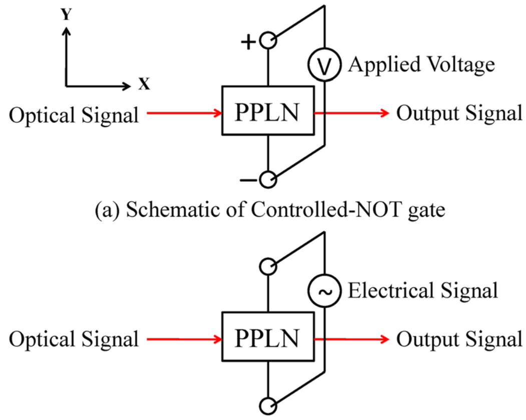


FIG. 3. (Color online) Two schematic configurations with different polarization in Figs. 3(a) and 3(c), which have the similar performances in Figs. 3(b) and 3(d): the output transmissions $T_\parallel$ and $T_\perp$ are changed from 0 to their maximum by rotating the input polarization states about 90°.



(a) Schematic of Controlled-NOT gate

(b) Schematic of XOR/XNOR gate

FIG. 4. (Color online) Schematic diagram of logic gates: (a) controlled-NOT gate and (b) XOR/XNOR gate.

$T_\perp$ got their maximum at the applied electric fields, of 3.6 and 3.9 kV/cm, respectively. In our experiment, there was a difference of the intensity between input optical signals with different polarization states in Figs. 3(a) and 3(c). Then the variation of the transmission T in Fig. 3(d) was not evident when the external electric field is small, because of the limitation by the sensitivity of measurement instrument.

By optimizing the experimental conditions, we got the maximum transmission $T_\parallel$ and $T_\perp$ about 88.4% and 96.0% as shown in Table I. The maximum transmission T was relative large, which means that the depletion of polarization encoded signal induced by coupling and propagating process was very small and could be neglected. Because of the insertion loss and propagation loss of optical signal in bulk device of PPLN, and also due to the reflection on the incidence planes of used optical devices, the measured transmission T in our experiment was smaller than theoretical results.

According to above experimental results, we can realize controlled-NOT gate by representing two orthogonal linear polarization states of optical signal as logic 0 and logic 1, as is shown in Fig. 4(a). When the applied electric field is on, the input optical signal can be switched between the two orthogonal linear polarization states; otherwise, it can keep its polarization state. Because the logic NOT function can be obtained by switching on or off the applied electric field, it is called controlled-NOT gate.

In order to obtain XOR and XNOR gate as shown in Fig. 4(b), we give the definition of the input and output signals for XOR and XNOR. Above all, we choose the input optical signal and the applied voltage as two binary logic signals, with the presentation shown in Table II. For XOR gate, the input optical signal with horizontal polarization state as signal 1 is logic 0; and that with vertical polarization state is logic 1. At the same time, we suppose the applied voltage as signal 2,

TABLE II. Presentation of signals for XOR and XNOR gates.

	XOR		XNOR	
	Logic 0	Logic 1	Logic 0	Logic 1
Signal 1	→	↑	↑	→
Signal 2	0	V	V	0
Output	→	↑	↑	→

TABLE III. Experimental results and truth table for XOR and XNOR.

	Experiment				XOR				XNOR			
Signal 1	→	→	↑	↑	0	0	1	1	1	1	0	0
Signal 2	0	V	0	V	0	1	0	1	1	0	1	0
Output	→	↑	↑	→	0	1	1	0	1	0	0	1

with logic 0 and logic 1, which corresponds to the electric voltage 0 and V (i.e., E is not equal to 0), respectively; while for XNOR logic gate, the definition of logic 0 and logic 1 is contrary to that for XOR gate. Accordingly, based on the experimental results in Table III and the definition in Table II, we obtain the truth tables of our XOR and XNOR gates as shown in Table III. The presentation of output optical logic signals are the same as that of the input optical logic signals, and the output logic signals are totally identical with the truth table of XOR and XNOR gates. By cascading the controlled-NOT gate above, it is convenient to switch the function between XOR gate and XNOR gate by switching the presentations of input optical signal in Table II.

In summary, by utilizing electro-optic modulation of polarization in PPLN, we propose an approach to demonstrate binary all-optical polarization-based logic gates, including controlled-NOT, XOR, and XNOR. By applying these gates in different structures,[15] they will realize more logic functions conveniently, such as AND gate and OR gate. Through processing optical signal encoded in the polarization state, where the intensity of the optical signal itself carries no information, this system is more suitable for cascading gates infinitely to implement some complex Boolean functions. Additionally, the realization of all-optical logic gates in PPLN enriches its unique advantage, which can be as a compact one-chip integrating multiple optical processing functions such as optical routing[16] and optical convertor,[17] etc.

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