Design of all-optical basic logic gates using periodically poled lithium niobate

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Electro-optic effect on periodically poled lithium niobate are used to develop different binary all-optical logic functions, such as NOT, buffer, OR, AND, NOR, NAND, XOR and XNOR circuits by varying the polarization state of the input optical signal around 90° on the plane of polarization using external electric field. Different performance parameters are estimated. Circuit parameters that are optimized have been chosen in order to construct the circuit practically. This approach has potential applicability in creating complicated logic functions by cascading many basic gates together.

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1. Introduction

High-speed, parallel signal processing technology is required for digital optical systems that are emerging at a rapid pace. Photonic networks are severely limited in their speed by electrical-to-optical conversions and vice-versa. Consequently, the future of all-optical communication networks will rely significantly on all-optical logic hardware. Realizing logical gates in the optical domain is a crucial aspect of current research to leverage the advantages of light speed in future demands [1-4]. The fundamental concept of all-optical basic logic gates is the utilization of magneto-optic, electro-optic, and linear interference of light propagation. As a result, a wide range of different structures have been used in their design, such as all-optical logic gates based on plasmonic waveguides [5-7], highly nonlinear fibre (HNLF) [8], waveguide-based structures [9-11], photonic crystals (PhC) [12-14], and semiconductor optical amplifiers (SOAs) [15-16].

Optical switches have an important part in the communication of optical signals like wavelength conversion, multiplexing and demultiplexing, logic gate design etc. [17-20]. Different technologies like opto-mechanical switches [21], thermo-optical switches [22], liquid crystal [23], micro-electro-mechanical system (MEMS) [24], acousto-optic switches [25], polarization conversion based switches [26], etc. have been already proposed. Periodically poled lithium niobate (PPLN) is a non-linear material that has drawn greater interest due to its exceptional non-linear optical features, extremely high-speed response, and full transparency [27–29]. The optical, acousto-optic, electro-optic (EO) coefficient changes periodically for the ferroelectric domain inversion and these properties are utilized for frequency conversion, polarization conversion and other non-linear optical process by quasi phase matching (QPM) technique. The EO effect of PPLN was studied by Y. Q. Lu et al. in 2001 [30]. Another study shows that adjustable filtering in PPLN may be achieved by the transverse electro-optic effect and the polarization coupling mechanism [31]. PPLN was also applied to temperature-tuned wavelength conversion and temperature-insensitive laser Q-switching [32]. Several studies have also shown how to use cascaded sum and difference frequency generation in a single PPLN different all-optical logic circuit [33–34]. Y. Zhang et al. have already shown how to use the EO effect in a PPLN to illustrate various logic circuits [35].

In this communication, PPLN-based EO switch is explained and developed. Various optical logic circuits are created by manipulating the applied electric field externally. Compared to prior published publications, a significantly lower electric field is needed to create the different logic operations. It can be used to integrate all-optical circuits and realize complex logic functions by cascading several basic circuits.

2. Principles and theoretical analysis

The electro-optic effect causes the optical axis in a Z-cut PPLN to alternately align at angles of $+\theta$ and $-\theta$ with respect to the polarization plane of incident light in every domain when a transverse electric field is applied. The deformation of index ellipsoid happens in the lithium niobate crystal when the y-axis is subjected to an applied field, and the y and z axes rotate by an angle θ with respect to the X axis [30]. This can be stated as,

$$\theta \approx \frac{r_{51}E_y}{\left(\frac{1}{n_e^2}\right)-\left(\frac{1}{n_o^2}\right)} \quad (1)$$

where E_y denotes the applied field, r_{51} denotes the electro-optic coefficient, n_o and n_e resembles the ordinary as well as extraordinary refractive indices respectively.

Change of refractive index due to applied electric field along X, Y and Z axis are represented by n'_x, n'_y, and n'_zrespectively and can be written as,

$$n'_x = n_o\left(1+\frac{n_o^2}{2}r_{22}E_y\right),\ n'_y = n_o\left(1-\frac{n_o^2}{2}r_{22}E_y\right)$$

and $n'_z = n_e$

Values of electro optic coefficients r_{22} is 6.8 pm/V and r_{51} is 32 pm/V [36-37].

The dielectric constant with an electric field may thus be expressed as follows while taking into account the periodic electro-optic coefficients [30]:

$$\epsilon = \epsilon(0) + \Delta\epsilon f(x) \quad (2)$$

where, $\epsilon(0)$ is the original dielectric tensor, and $\Delta\epsilon$ is the dielectric tensor change and can be written as,

$$\epsilon(0) = \epsilon_0\begin{bmatrix} n_o^2 & 0 & 0 \\ 0 & n_o^2 & 0 \\ 0 & 0 & n_e^2 \end{bmatrix} \text{ and}$$

$$\Delta\epsilon = -\epsilon_0\gamma_{51}En_o^2n_e^2\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Value of f(x) is denoted as +1 and -1 for positive and negative domains respectively.

Periodically-poled lithium niobate (PPLN) is a domain-engineered lithium niobate crystal. The ferroelectric domains point alternatively to the clockwise and anticlockwise direction in a PPLN with a constant period and the period typically varies between 5 and 35 µm.

A 2×2 matrix technique called a Jones matrix is used to monitor the polarization state of light as it travels over the PPLN [38]. The Jones matrices for positive and negative orientation of the domain for alternate directions are represented as M+ and M-, where,

$$M_+ = R(\theta)W_0\,R(-\theta) \qquad \text{(+ve orientation)} \quad (3)$$

$$M_- = R(-\theta)W_0\,R(\theta) \qquad \text{(-ve orientation)} \quad (4)$$

where, $R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$ is the rotation matrix and $W_0 = \begin{bmatrix} e^{-i\tau/2} & 0 \\ 0 & e^{i\tau/2} \end{bmatrix}$ is a Jones matrix for phase retardation of the block.

where, $$\tau = \frac{2\pi d}{\lambda}\left(n'_y - n'_z\right) \quad (5)$$

d represents the domain thickness, n'_y, n'_z are the refractive indices along y and z axes due to electro-optic effect and λ is the operating wavelength.

The overall Jones matrix for N number of domains is given by

$$M = [R(\theta)W0\ R(-\theta)R(-\theta)W0\ R(\theta)]^m = \prod_{i=1}^{m} M_i = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^m \quad (6)$$

where it is assumed that total number of domains is an even number and N = 2m

Four matrix elements A, B, C and D can be represented as,

$$A = \left(\cos\frac{\tau}{2} - i\sin\frac{\tau}{2\cos 2\theta}\right)^2 + \sin^2 2\theta\sin^2\frac{\tau}{2}, B = \sin 4\theta\sin^2\frac{\tau}{2}, C = -B \text{ and}$$

$$D = \left(\cos\frac{\tau}{2} + i\sin\frac{\tau}{2\cos 2\theta}\right)^2 + \sin^2 2\theta\sin^2\frac{\tau}{2}.$$

As, this is an unimodular matrix (AD - BC = 1), therefore, Eq. 6 can be simplified using Chebyshev's identity.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}^m = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \text{ where,}$$

$$M_{11} = \frac{A\sin(mk\Lambda) - \sin(m-1)k\Lambda}{\sin(k\Lambda)},\quad M_{12} = \frac{B\sin(mk\Lambda)}{\sin(k\Lambda)} = -M_{21},\ M_{22} = \frac{D\sin(mk\Lambda) - \sin(m-1)k\Lambda}{\sin(k\Lambda)} \text{ and}$$

$$k\Lambda = \cos^{-1}(A+D) = \cos^{-1}\left(\cos^2\frac{\tau}{2} - \sin^2\tau/2\cos 4\theta\right)$$

If the Jones vector of the incident light is written as $\begin{bmatrix} E_z \\ E_y \end{bmatrix}$ then the Jones vector of the emerging light from the PPLN can be written as

$$\begin{bmatrix} E'_z \\ E'_y \end{bmatrix} = M\begin{bmatrix} E_z \\ E_y \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}\begin{bmatrix} E_z \\ E_y \end{bmatrix} \quad (7)$$

The transmissivity of the emergent light from the PPLN can be determined as [30]

$$T = \frac{|E'_z|^2 + |E'_y|^2}{|E_z|^2 + |E_y|^2} \quad (8)$$

3. PPLN based optical switch

The schematic setup of PPLN to realize an optical switch is shown in Fig. 1. A transverse electric field is applied in the Y axis and a Z polarized light is incident on PPLN. A polarization beam splitter (PBS) is employed at the output to split the emergent light into two channels. Every domain in the PPLN behaves as a half wave plate when quasi phase matching (QPM) condition is satisfied. For satisfying QPM condition, domain thickness is taken as equal or multiple of the coherence length L_c. Where, $L_c = \lambda/2(n_o-n_e)$. λ is the operating wavelength. With the increase in domain thickness the transmission graph shifts towards a higher wavelength and does not have any significant change in FWHM of the transmission graph.

When the input signal is passed through the PPLN, the polarization plane of the output light will rotate and the output light will emerge at an angle 2Nθ, N denotes the total amount of domains in the PPLN. Thus the thickness of each domain and total number of domains is optimized accordingly.

At the output when 2Nθ is zero, for port 1, the switch is in the ON state and for port 2 light is prohibited. When 2Nθ is $\pi/2$ light is prohibited for port 1 and the switch is in the OFF state and for port 2, the light will be transmitted and the switch is in the ON state.

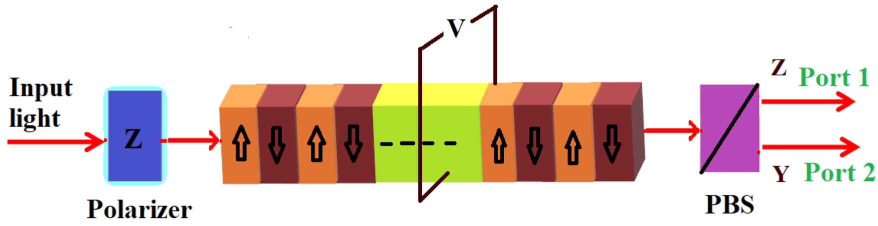
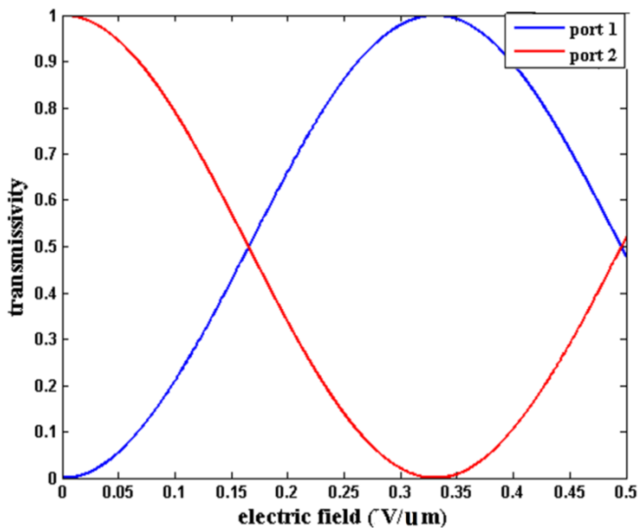


Fig. 1. Schematic representation of PPLN based optical switch (color online)

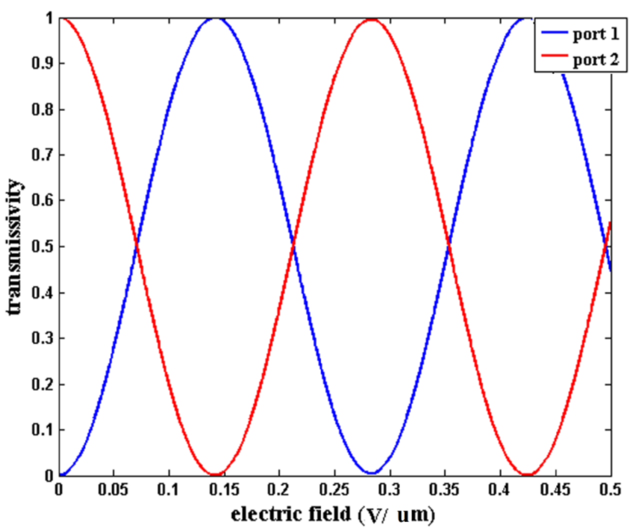
4. Optimization of parameters

The transmission of light at port 1 (Z polarized) and port 2 (Y polarized) changes when the applied field varies for varying numbers of domains, as shown in Figs. 2(a) and 2(b). According to the graph, for a total of 1200 domains, a field of 3.3 kV/cm causes the transmissivity at ports 1 and 2 to reverse, and for a total of 2800 domains, a field of roughly 1.5 kV/cm is needed to change the transmissivity from low level (0) to high level (1) or vice versa. It is noteworthy that the field needed to alter the transmissivity for a given domain thickness will decrease as the number of domains in the PPLN increases.

From Fig. 3 it is observed that the operating wavelength is changed due to the change in domain thickness. For satisfying QPM condition, domain thickness is taken as equal or multiple of the coherence length L_c. Where, $L_c = \lambda/2(n_o-n_e)$. λ is the operating wavelength. For domain thickness of 10.4 µm operating wavelength is 1515 nm and by choosing domain thickness of 10.657 µm the operating wavelength is changed to 1549.3 nm. Both of the domain thickness is taken after verifying the QPM condition. List of controlling parameters and their optimized values is given in Table 1.



(a)



(b)

Fig. 2. Transmissivity of light at port 1 and port 2 with the variation of applied electricfield for (a) N = 1200 and (b) N = 2800 (color online)

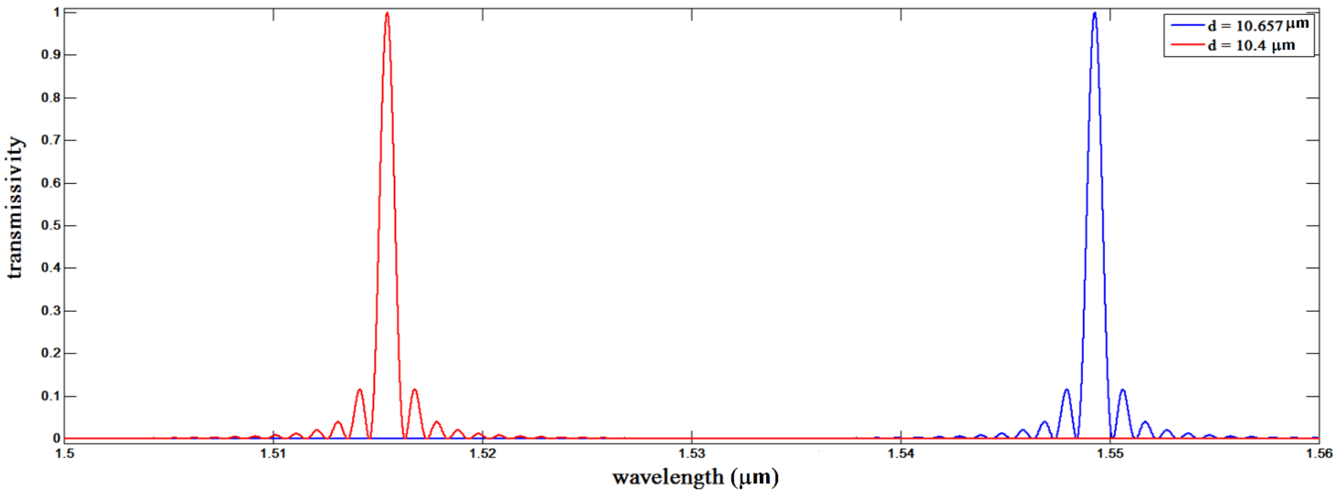


Fig. 3. Change of operating wavelength with the change in domain thickness (color online)

Table 1. List of controlling parameters

Sl. No.	List of parameters	Optimized value
1	Operating wavelength	1549.3 nm
2	Domain thickness	10.657 μm
3	Total number of domains in PPLN	2800
4	Applied electric field	0 kV/cm and 1.5 kV/cm

5. Design of NOT and Buffer circuit using PPLN based electro-optic switch

When the input signal is passed through the PPLN, the polarization plane of the output light will rotate and the output light will emerge at an angle 2Nθ, N denotes the total amount of domains in the PPLN. So, when number of domains is increased, then for the same applied electric field the rotation angle of the light will be higher and less electric field is required to change the polarization state.

It is assumed that, the PPLN have 2800 domains with the domain thickness of 10.657 μm and the operating wavelength is 1549.3 nm. Fig. 4(a) and Fig. 4(b) show the transmissivity graph at the port 1 and port 2 for the fields of 0 kV/cm and 1.5 kV/cm with the incident Z polarized light.

With no field applied to the PPLN, transmissivity is zero at port 1 and at port 2 transmissivity is one at the operating wavelength of 1549.3 nm. When applied field is 1.5 kV/cm the transmissivity attends the maximum value at port 1 at that particular wavelength and at port 2 the transmissivity drops to zero. For Z polarized incident light, with no field applied we will get Y polarized output light and with the application of the field of 1.5 kV/cm we will get Z polarized light at the output. Also, for the Y polarized incident light, the output light will be Z polarized without the field and with the application of field 1.5 kV/cm the polarization state will be Y-polarized light. In the Fig. 4(a) and Fig. 4(b) the transmissivity graphs at the port 1 and port 2 are shown for the fields of 0 kV/cm and 1.5 kV/cm with the incident Z polarized light.

For the field of 0 kV/cm the PPLN switch will act as a NOT gate and for the field of 1.5 kV/cm the PPLN switch will act as a buffer circuit. Polarization nature of the input and output light with different applied electric field is shown in Table 2.

Table 2. Change of polarization with the applied field

Electric Field	Input light (polarized nature)	Output light (polarized nature)
0 kV/cm	Z	Y (port 2)
1.5 kV/cm	Z	Z(port 1)
0 kV/cm	Y	Z(port 1)
1.5 kV/cm	Y	Y(port 2)

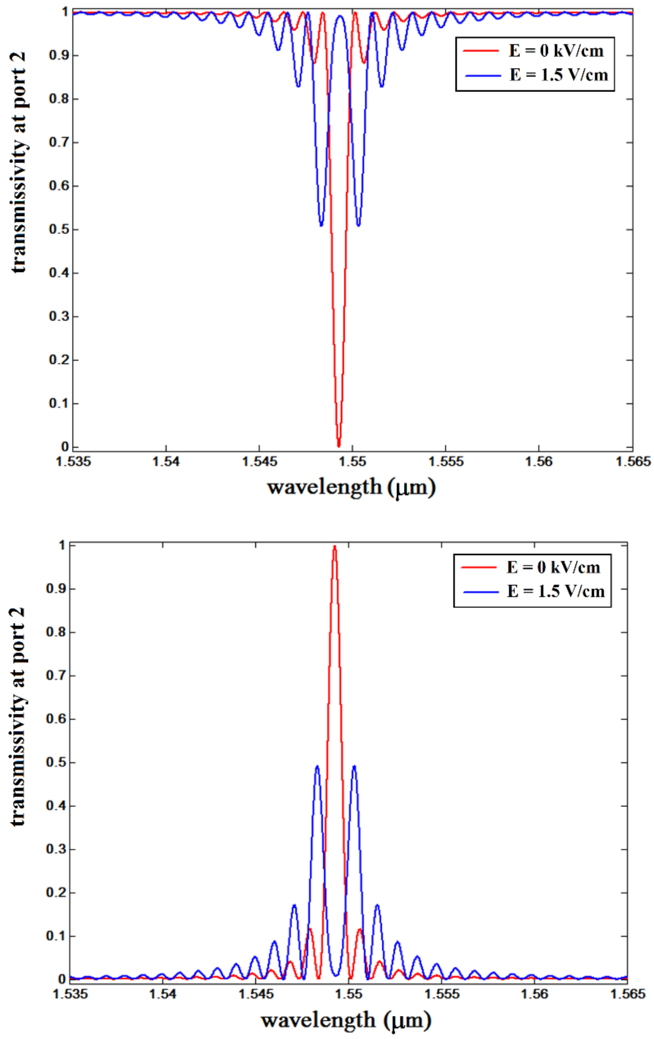


Fig. 4. Transmissivity of light with the field of 0 kV/cm and 1.5 kV/cm for N = 2800 and domain thickness of 10.657 μm (a) at port 1 and (b) at port 2 (color online)

6. Cascaded arrangement of PPLN to design different logic gates

The schematic diagram of cascaded arrangement of PPLN to design different logic gates is represented in Fig. 5. The circuit consists of five PPLN and four Beam Combiner (BC). When a Z-polarized light is incident on PPLN 1, based on the applied field (A) to the PPLN, the output light will emerge either from the port 1(P1) or port 2(P2). The light from port 1 is fed to PPLN 2 and the light from port 2 is fed to PPLN 3. Depending on the field (B), applied to the PPLN 2 and PPLN 3, the output light will emerge from one of the four ports port 3 (P3), port 4 (P4), port 5 (P5) and port 6 (P6).

The Z-polarized emergent light from P3 is taken as output from port 7 (P7), which gives the result of the AND gate. The Z-polarized emergent light from P3 is fed to PPLN-4 and no field is applied to this PPLN. As a result, the polarization state of light from PPLN-5 will change to Y-polarization state. The emergent light from PPLN-4 is combined with P4 and P6 by a BC and the emergent light is taken from port 8 (P8). P8 gives the result of the OR gate. P4 and P6 are combined together by a BC and the output light is taken from port 9 (P9), that resembles the XOR gate. P3 and P5 are combined by a BC and the combined port is labeled as port 10 (P10). The result of XNOR gate is taken from P10.P5 gives the result of the NOR gate. The Z-polarized light from P5 is passed through PPLN-5 to change its polarization state. The emergent light from PPLN-5 is combined with P4 and P6 by a BC and the resultant light from port 11 (P11) gives the output of the NAND gate.

Case 1: When A=B=0, No field is applied to the PPLN1, for Z-polarized incident light, the Y-polarized light will emerge from P2 that will incident on PPLN 3. As B is also 0, the Y-polarized incident light to the PPLN 3 will emerge as Z-polarized light from P5. On the other side, as the output from P1 is zero, so PPLN2 and PPLN3 will be deactivate and P3=0 and P4=0. So, P7=0, P8=0, P9=0, P10=1, P11=1, and P12=1. All the possible output states are shown in 1st row of Table 3.

Case 2: When A=0, B=1, the input light will emerge from P2 as Y polarized light and will activate the PPLN 3 and output from P1 as well as P3 and P4 will be zero. As B=1 that is field is applied to the PPLN 3, the output light will be Y-polarized emerging from P6 and output from P5 will be zero. So, P7=0, P8=1, P9=1, P10=0, P11=0, and P12=1. All the possible output states are shown in 2nd row of Table 3.

Case 3: When A=1, B=0, the emergent light from PPLN 1will be Z-polarized and will emerge from P1 and no light will emerge from P2 and so output at P5 and P6 will be zero. Z-polarized light from P1 is fed to PPLN 2. As no field is applied to the PPLN 2, the output light will be Y-polarized that will activate the P4 and output at P3 will be zero. So, P7=0, P8=1, P9=1, P10=0, P11=0, and P12=1. All the possible output states are shown in 3rd row of Table 3.

Case 4: When A=B=1, the Z-polarized incident light to the PPLN 1 will emerge from P1 as Z-polarized light and no light will emerge from P2. So, P5 and P6 will be zero. Z-polarized light from P1 will activate the PPLN 2. As field is also applied to PPLN 2, so the Z-polarized output light will emerge from P3 and output at P4 will be zero. So, P7=1, P8=1, P9=0, P10=1, P11=0, and P12=0. All the possible output states are shown in 4th row of Table 3.

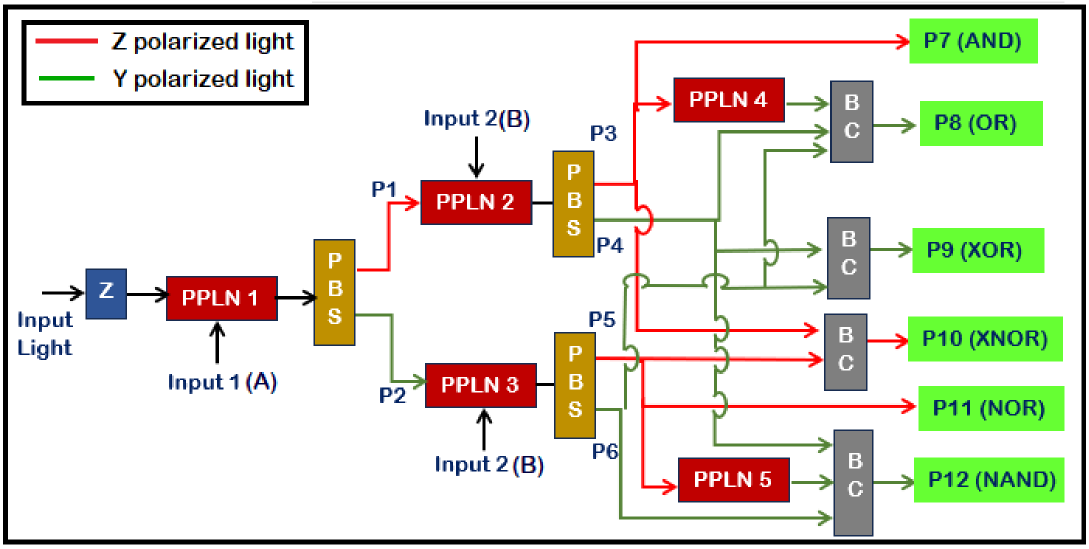


Fig. 5. Design of different logic gates using cascaded arrangement of PPLN (color online)

7. Simulation result

The two electric fields applied to the PPLNs are denoted by two input variables A and B. The field of 0 kV/cm is treated as logic 0 and the field of 1.5 kV/cm is treated as logic 1. Getting an optical signal in any output port or in other words getting unit transmissivity in any output port is treated as logic 1 and getting zero transmissivity is treated as logic zero.

For four different combinations of two input signals A (MSB) and B(LSB) and six different output ports (P7, P8, P9, P10, P11 and P12) are used to design different logic gates (AND, OR, XOR, XNOR, NOR, and NAND).

Fig. 6 shows the simulation result of different logic gates. Table 3 represents all the possible combinations of the input electrical signals and the output optical signals at the different output ports.

Table 3. Truth table of the PPLN based logic gates

Input signals (electric field)		Output signals at different output ports					
A	B	Port 7 (AND)	Port 8 (OR)	Port 9 (XOR)	Port 10 (XNOR)	Port 11 (NOR)	Port 12 (NAND)
0	0	0	0	0	1	1	1
0	1	0	1	1	0	0	1
1	0	0	1	1	0	0	1
1	1	1	1	0	1	0	0

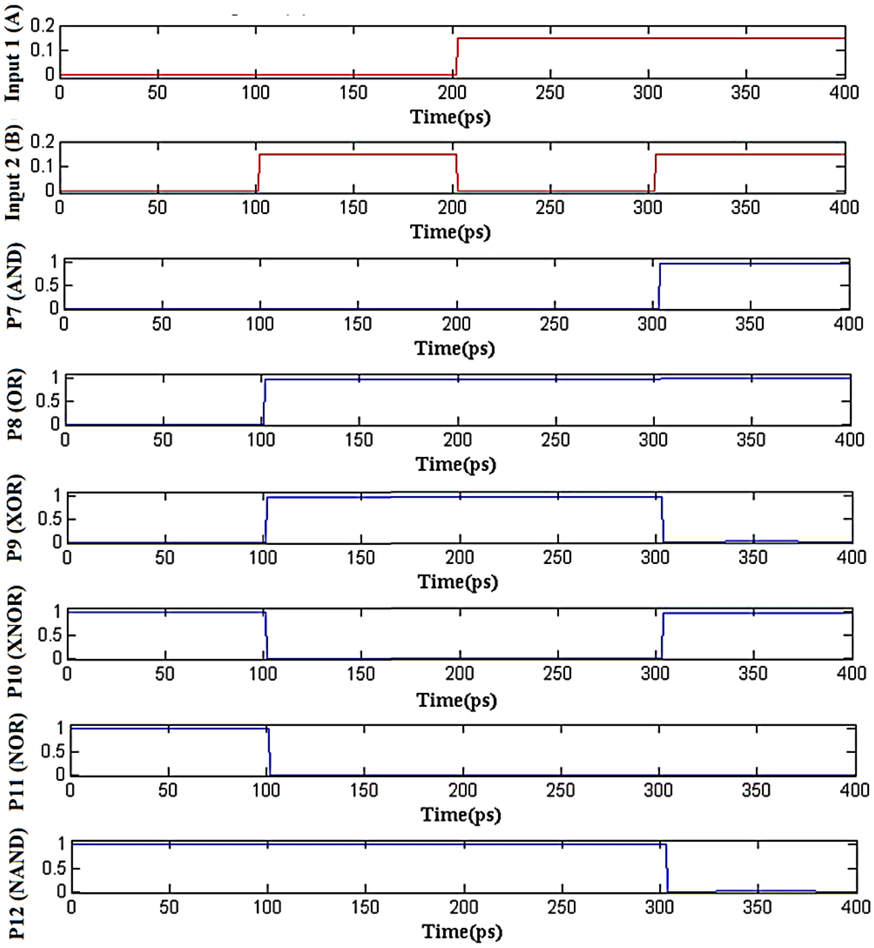


Fig. 6. Simulation result of different logic gates (color online)

8. Discussion

The proposed model has the following design parameters.

Transit time (TT) – The Transit Time is the travelling time of light from the input port to the output port in an optical switch. The transit time can be defined as, TT = L/v

Where, L is the propagation length of the light in the optical switch, v is the speed of light in the optical medium.

Transit time can also be written as, TT = nL/c.

The proposed optical switch has the transit time of 22 ns.

Extinction Ratio (ER) – The ER can be defined as, ER (dB) =10 log $\left(\frac{P^1_{Min}}{P^0_{Max}}\right)$

where P^1_{Min} and P^0_{Max} represents the minimum and maximum values of the peak power ON and OFF state respectively. The proposed model has the ER of 20.93 dB.

Contrast Ratio (CR) –The CR can be defined as, CR (dB) =10 log $\left(\frac{P^1_{Mean}}{P^0_{Mean}}\right)$

where P^1_{Mean} and P^0_{Mean} are the mean values of the peak power of ON and OFF state respectively. The proposed model has the CR of 23.95 dB.

9. Conclusion

In conclusion, a method is suggested to show binary all-optical polarization-based logic gates via electro-optic modulation of polarization state of light in PPLN crystal like NOT and buffer circuit and OR, AND, XOR, XNOR, NOR and NAND respectively. Very small electric field is required to change the polarization state of light. The proposed model is simulated using MATLAB and some important parameters like transit time, ER and the CR of the proposed electro-optic switch are calculated as 22 ns, 20.93 dB and 23.95 dB respectively. The proposed scheme is useful for cascading gates to perform some complex Boolean functions since it analyzes optical signals stored in the polarization state. Moreover, PPLN's unique advantage is increased by the emergence of all-optical logic gates, which may combine several optical processing functions onto a small one-chip.

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 and also the flip-flops, multiplexers and demultiplexers. Additionally, the realization of all-optical logic gates in PPLN can be used for optical routing, optical convertor etc. Also, multivalued logic circuits (e.g: ternary and quaternary) can be designed by using this polarization conversion properties of PPLN with the applied field.

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Authors' Contributions:

U. B.– Methodology, Implementation, Simulation and Writing original draft preparation.
J. K. R.- Conceptualization, Supervision, Reviewing and editing the draft manuscript.
B. Y., V. N., K. M. and M. H. – Conceptualization, Reviewing and editing the draft manuscript.

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