Physics Letters A 377 (2013) 329–333

Contents lists available at SciVerse ScienceDirect

Physics Letters A

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Silicon photonic crystal all-optical logic gates

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ARTICLE INFO

Article history:
Received 4 July 2012
Received in revised form 30 October 2012
Accepted 14 November 2012
Available online 19 November 2012
Communicated by R. Wu

Keywords:
Photonic crystal
Logic gates
Silicon

ABSTRACT

All-optical logic gates, including OR, XOR, NOT, XNOR, and NAND gates, are realized theoretically in a two-dimensional silicon photonic crystal using the light beam interference effect. The ingenious photonic crystal waveguide component design, the precisely controlled optical path difference, and the elaborate device configuration ensure the simultaneous realization of five types of logic gate with low-power and a contrast ratio between the logic states of "1" and "0" as high as 20 dB. High power is not necessary for operation of these logic gate devices. This offers a simple and effective approach for the realization of integrated all-optical logic devices.

Recently, all-optical logic gates have been attracting wide attention because of their potential applications in the fields of optical computing systems and optical interconnection networks. Many schemes have been proposed to realize all-optical logic gates, including the use of nematic liquid crystals [1], metallic (or dielectric) waveguides [2–4], and silicon optical resonators [5]. Because of their unique ability to control the propagation states of photons, photonic crystals, with their photonic bandgaps, provide a perfect platform for the realization of integrated photonic devices. All-optical logic gates based on photonic crystals are promising for practical on-chip applications. Photonic crystal-based all-optical logic gates can be realized through the third-order nonlinear optical effect [6,7], the self-collimation effect [8], or the multi-mode interference effect [9–11]. Because of the relatively small third-order nonlinear susceptibility of the conventional materials, high operating powers are required to drive the photonic crystal all-optical logic gates [6,7]. It is also difficult to achieve the self-collimation effect because of the difficulty in controlling the dispersion relations of the photonic crystal [8]. No more than two types of logic gate have been reported in photonic crystal structures based on the linear interference effect because it is difficult to precisely control the phase difference for all input light signals [9]. It is also difficult to achieve high intensity contrast between the output signals for the logic states of "1" and "0" [12]. Recently, Zhang et al. reported all-optical logic NOT, XOR, and XNOR gates in periodically poled lithium niobate with an incident light power of the order of hundreds of μW [13]. However, until now, it has proved challenging to realize a number of all-optical logic gates with high contrast ratios and low power in a photonic crystal structure.

Here, we show how to realize five types of all-optical logic gate with high contrast ratios and low power in a single photonic crystal structure simultaneously. We use two-dimensional (2D) silicon photonic crystal optical waveguides to construct the logic gates on the basis of the light beam interference effect. According to wave optics theory, if the phase difference between two light beams is $2k\pi$ (where $k = 0, 1, 2, \ldots$), then constructive interference will occur, and the output light will have high power (corresponding to the logic state of "1") [9–11]. If the phase difference is $(2k+1)\pi$ (where $k = 0, 1, 2, \ldots$), then destructive interference will occur, and the output light will be approximately zero (corresponding to the logic state of "0"). The ingenious photonic crystal waveguide component design, the precisely controlled optical path difference, and the elaborate device configuration ensure the simultaneous realization of five types of logic gates, i.e. all-optical OR, XOR, NOT, XNOR, and NAND gates, without any high power requirements, in a 2D photonic crystal structure. The intensity contrast ratio between the output logic states of "1" and "0" can be as high as 20 dB.

The schematic structure of the 2D silicon photonic crystal is shown in Fig. 1. The photonic crystal structure is composed of triangular lattice arrays of cylindrical silicon rods embedded in a background medium of air. The lattice constant and the diameter of the silicon rods are 875 and 495 nm, respectively. Two symmetrical optical waveguides, AC and BC, were formed along the Γ–M direction by removing two rows of silicon rods, as shown in Fig. 1. The angle at the cross point between the two waveguides, AC and BC, 120°. The distance from both input ports A and B to the cross point is 10.5 μm. The optical waveguides AC and BC can both support a single waveguide mode with a resonant wavelength

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0375-9601/$ – see front matter
http://dx.doi.org/10.1016/j.physleta.2012.11.034

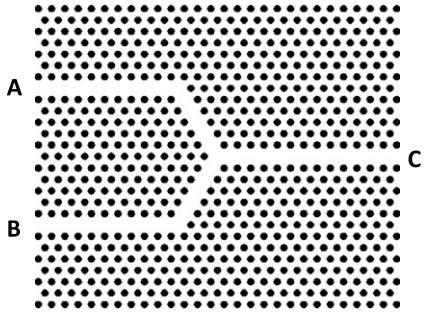

Fig. 1. Schematic structure of a two-dimensional silicon photonic crystal.

of 1550 nm. The finite difference time-domain (FDTD) method (using the MIT software package MEEP) was used to study the electric field distribution of the photonic crystal structure [14]. The dielectric constant of silicon was set at 11.56. A continuous wave (CW) light source at a wavelength of 1550 nm was used in our calculations. The signal light was a transverse-magnetic (TM) polarized wave, with an electric field vector perpendicular to the silicon rods.

To study the all-optical OR logic gate function, we calculated the electric field distribution of the 2D photonic crystal for the 1550-nm signal light, and the calculated results are shown in Fig. 2. If a single beam is injected into input port A, then the signal light can propagate through the optical waveguide AC and be output from port C, as shown in Fig. 2(a). This corresponds to a logic operation of "1 OR 0 = 1". If a single beam is injected into input port B, then the signal light can propagate through the optical waveguide BC and be output from port C, as shown in Fig. 2(b). This corresponds to a logic operation of "0 OR 1 = 1". If two beams are injected into input ports A and B simultaneously, then the signal light can propagate through optical waveguides AC and BC. Because the value of the light path difference is zero for the two signal light beams propagating in optical waveguides AC and BC, the phase difference of these two signal light beams is zero. Constructive interference occurs, and the output signal has high power, as shown in Fig. 2(c). This corresponds to a logic operation of "1 OR 1 = 1". Thus, an all-optical OR logic gate can be achieved very easily.

To study the all-optical XOR logic gate function, we modified the structure of waveguide BC such that the light path length of a 1550-nm signal light beam in waveguide BC is longer than that of waveguide AC by one lattice constant. The calculated electric field distribution of the 2D photonic crystal for the 1550-nm signal light is shown in Fig. 3. If a single beam is injected into input port A, the signal light can then propagate through waveguide AC and be output from port C, as shown in Fig. 3(a). This corresponds to the logic operation of "1 XOR 0 = 1". If a single beam is injected into input port B, then the signal light can propagate through waveguide BC and be output from port C, as shown in Fig. 3(b). This corresponds to the logic operation of "0 XOR 1 = 1". If two beams are injected into input ports A and B simultaneously, then the signal light can propagate through waveguides AC and BC. The light path difference of one lattice constant produces a phase difference between the beams of π. Destructive interference then occurs, and the output signal is approximately zero, as shown in Fig. 3(c). This corresponds to the logic operation of "1 XOR 1 = 0". When we apply a signal light beam with power P_0 at the input port or ports, the output power at port C was calculated to be 0.75 P_0 (logic '1') for singular excitation at port A, 0.86 P_0 (logic '1') for singular excitation at port B, and 0.0067 P_0 (logic '0') for simultaneous excitation at A and B. The intensity contrast ratio between the output logic states of "1" and "0" is as high as 21.1 dB, which is much better than previously reported values [6–12]. An all-optical XOR logic gate with a high intensity contrast ratio is therefore realized. An all-optical NOT logic gate can also be realized using the same photonic crystal structure that was used for the XOR logic gate. We can select the original optical waveguide BC to be the reference waveguide RC. The calculated electric field distribution of the 2D photonic crystal for a 1550-nm signal light beam is shown in Fig. 4. A 1550-nm CW reference light beam is input continuously into the reference waveguide RC. If no signal light is injected into input port A, then the reference light can propagate through waveguide

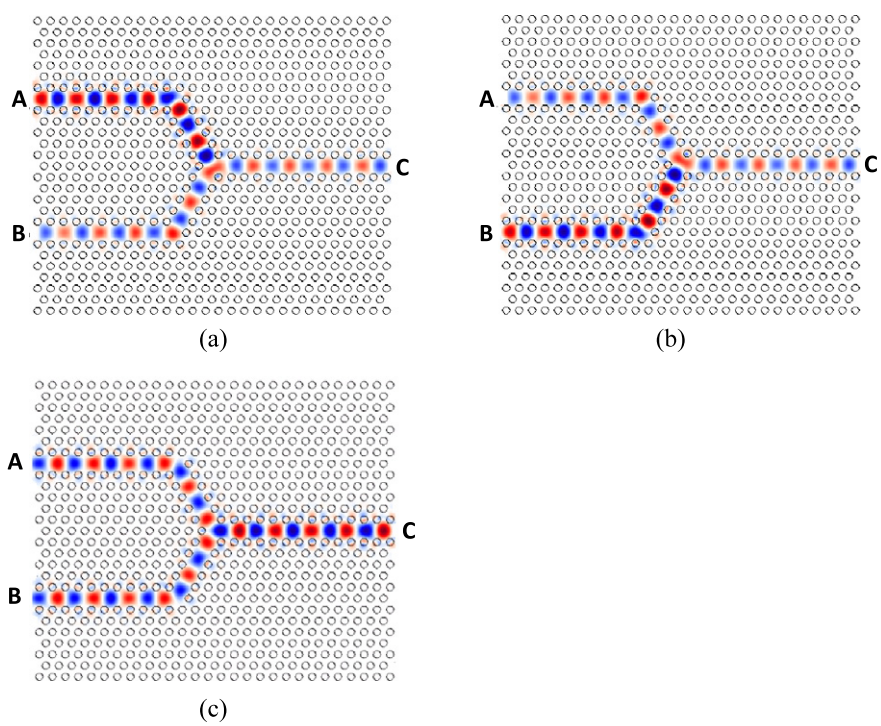

Fig. 2. Calculated steady state electric field distributions of all-optical OR gate. (a) Single signal light beam injected into input port A. (b) Single signal light beam injected into input port B. (c) Two single beams injected into input ports A and B, separately but simultaneously.

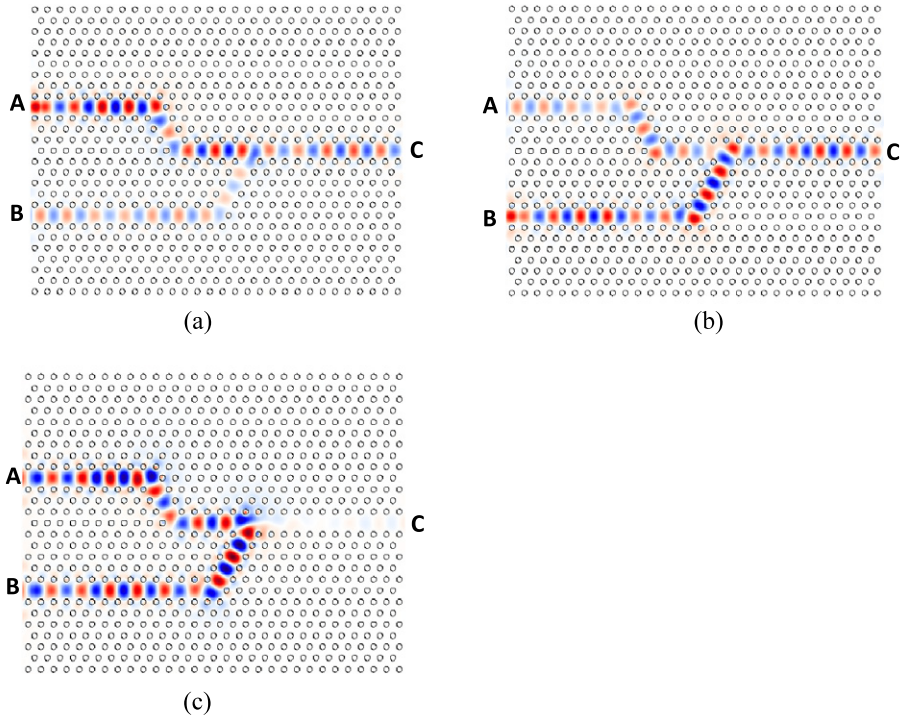

Fig. 3. Calculated steady state electric field distributions of all-optical XOR gate. (a) Single signal light beam injected into input port A. (b) Single signal light beam injected into input port B. (c) Two signal beams injected into input ports A and B, separately but simultaneously.

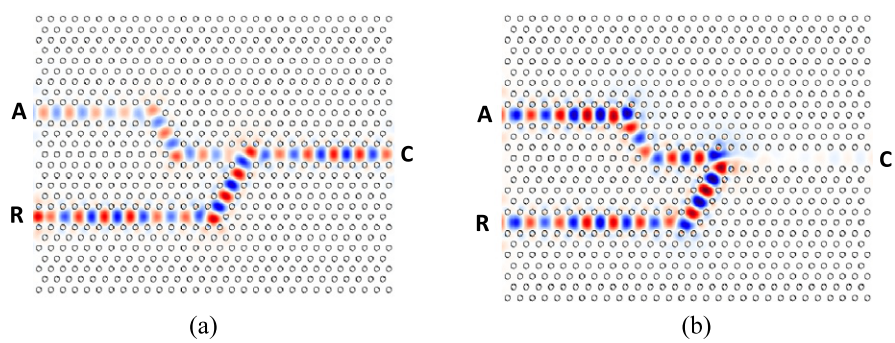

Fig. 4. Calculated steady state electric field distributions of the NOT gate. (a) No signal light injected into input port A. (b) Single signal light beam injected into input port A.

RC and be output from port C, as shown in Fig. 4(a). This corresponds to the logic operation of "0 NOT = 1". If a single signal light beam is injected into input port A, destructive interference will occur between the signal light and the reference light in the output waveguide. The output signal is then approximately zero, as shown in Fig. 4(b). This corresponds to the logic operation of "1 NOT = 0". The intensity contrast ratio between the output logic signals "1" and "0" also reaches 20 dB in this case. An all-optical NOT logic gate with high intensity contrast ratio is therefore realized.

To study the all-optical XNOR logic gate function, we modified the photonic crystal structure for the XOR logic gate, such that the light path length of a 1550-nm signal light beam in waveguide AC is larger than that in waveguide RC by one lattice constant, while the light path length of a 1550-nm signal light beam in waveguide BC is less than that in waveguide RC by one lattice constant. The calculated electric field distribution of the 2D photonic crystal for a 1550-nm signal light beam is shown in Fig. 5. A 1550-nm CW reference light beam is input continuously into the reference waveguide RC. The reference and signal light beams have the same power. If no signal light is injected into input ports A and B, then the reference light can propagate through waveguide RC and be output from port C, as shown in Fig. 5(a). This corresponds to the logic operation of "0 XNOR 0 = 1". If a single signal light beam is injected into input port A, destructive interference will occur between the signal light and reference light beams in the output waveguide. The output signal is then approximately zero, as shown in Fig. 5(b). This corresponds to the logic operation of "1 XNOR 0 = 0". If a single signal light beam is injected into input port B, then destructive interference will also occur between the signal light and reference light beams in the output waveguide. The output signal is also approximately zero in this case, as shown in Fig. 5(c). This corresponds to the logic operation of "0 XNOR 1 = 0". If two signal light beams are injected into input ports A and B simultaneously, then destructive interference again occurs in the output waveguide. Because the power of the reference light beam is only half of the total power of the two signal light beams, there is an output signal with a certain power in port C, as shown in Fig. 5(d). This corresponds to the logic operation of "1 XOR 1 = 1". When we apply CW signal and reference light beams with power P_0 at the input port or ports, the output power at port C was calculated to be $0.85P_0$ (logic '1') for no excitation at ports A and B, $0.0058P_0$ (logic '0') for singular excitation at port A, $0.0061P_0$ (logic '0') for singular excitation at port B, and

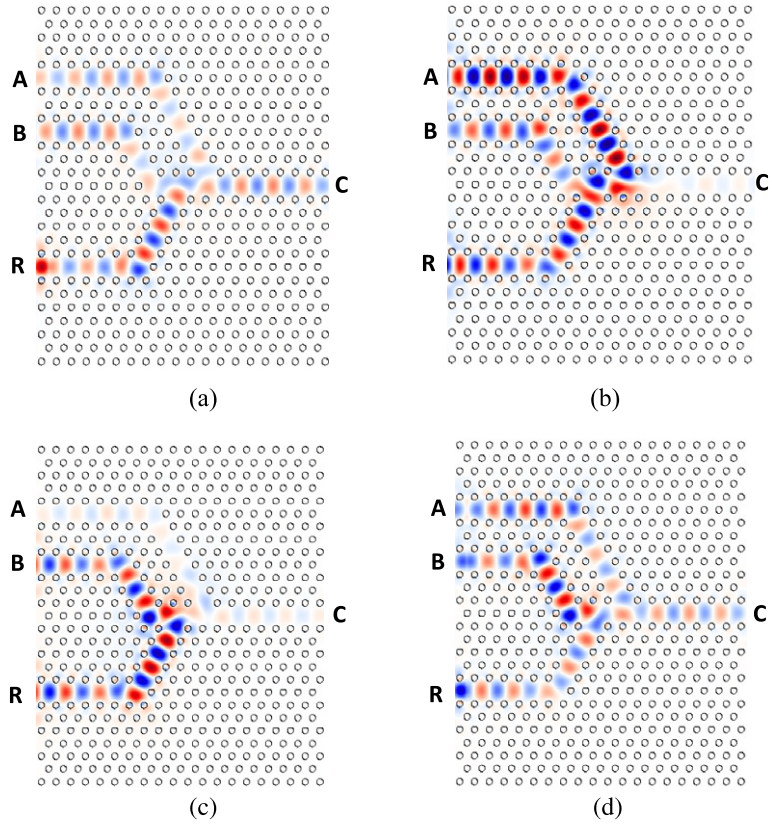

Fig. 5. Calculated steady state electric field distributions of the XNOR gate. (a) No signal light injected into input ports A and B. (b) Single signal light beam injected into input port A. (c) Single signal light beam injected into input port B. (d) Two signal beams injected into input ports A and B, separately but simultaneously.

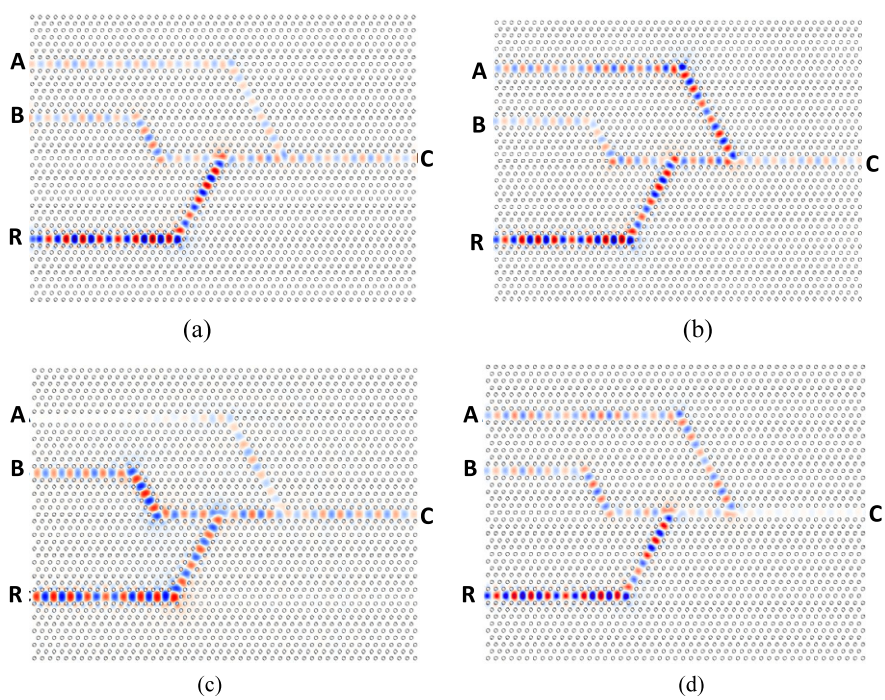

Fig. 6. Calculated steady state electric field distributions of the NAND gate. (a) No signal light injected into input ports A and B. (b) Single signal light beam injected into input port A. (c) Single signal light beam injected into input port B. (d) Two signal beams injected into input ports A and B, separately but simultaneously.

$0.91P_0$ (logic '1') for simultaneous excitation at ports A and B. The intensity contrast ratio between the output logic states of "1" and "0" is as high as 22 dB, which again is much better than previously reported values [6–12]. An all-optical XNOR logic gate with a high intensity contrast ratio is therefore achieved.

To study the all-optical NAND logic gate function, we use the same photonic crystal structure that was used for the XNOR logic gate. The light path length of a 1550-nm signal light beam in waveguide AC is larger than that in waveguide RC by one lattice constant, while the light path length of a 1550-nm signal light

beam in waveguide BC is less than that in waveguide RC by one lattice constant. The calculated electric field distribution of the 2D photonic crystal for a 1550-nm signal light beam is shown in Fig. 6. A 1550-nm CW reference light is input continuously into the reference waveguide RC. The reference light power is double that of the signal light beam. If no signal light is injected into input ports A and B, then the reference light can propagate through waveguide RC and be output from port C, as shown in Fig. 6(a). This corresponds to the logic operation of "0 NAND $0 = 1$". If a single signal light beam is injected into input port A, then destructive interference will occur between the signal light and reference light beams in the output waveguide. Because the reference light power is double of that of the signal light, there is an output signal with a certain power in port C, as shown in Fig. 6(b). This corresponds to the logic operation of "1 NAND $0 = 1$". If a single signal light beam is injected into input port B, then destructive interference will again occur between the signal light and reference light beams in the output waveguide. Because the reference light power is again double of that of the signal light, there is an output signal with a certain power in port C, as shown in Fig. 6(c). This corresponds to the logic operation of "0 NAND $1 = 1$". If two beams are injected simultaneously into input ports A and B, destructive interference again occurs in the output waveguide. However, because the power of the reference light is equal to the total power of the two signal light beams, there is no output signal at port C, as shown in Fig. 6(d). This corresponds to the logic operation of "1 NAND $1 = 0$". The intensity contrast ratio between the output logic signals of "1" and "0" is as high as 20 dB, which is again much better than previously reported values [6–12]. An all-optical NAND logic gate with a high intensity contrast ratio is thus realized.

In our calculations, we used separate light sources operating at the same frequency and phase for each of the input waveguides. The correctness and feasibility of this method have been confirmed by the calculated results of Liu et al. and our group's recent measured results [4,15]. In practice, multiple coherent light signals can be achieved by using a two-dimensional photonic crystal one-to-*n* beam splitter [16]. The 2D photonic crystal structure can be fabricated very easily by using microfabrication technique, such as electron-beam lithography and focused ion-beam etching methods. Also, the operation of these logic gates does not require high power excitation. The proposed photonic crystal all-optical logic gates therefore hold great potential for on-chip integration applications.

In summary, we have theoretically realized all-optical logic gates, including OR, XOR, NOT, XNOR, and NAND logic gates, in a 2D silicon photonic crystal using the light beam interference effect. The intensity contrast ratio between the output signals for the logic states of "1" and "0" is as high as 20 dB. This may be useful reference for the study of integrated photonic devices based on photonic crystals.

Acknowledgements

This work was supported by the National Basic Research Program of China under grant No. 2013CB328704, the National Natural Science Foundation of China under grant Nos. 61077027, 11134001, 11121091, and 90921008, and the Program for New Century Excellent Talents in University.

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