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A novel proposal based on 2D linear resonant cavity photonic crystals for all-optical NOT, XOR and XNOR logic gates

<https://doi.org/10.1515/joc-2020-0184>

Received May 14, 2020; accepted September 7, 2020;

published online November 5, 2020

Abstract: In this paper, we are going to propose a novel structure of all-optical NOT, XOR and XNOR logic gates are presented using a two-dimensional photonic crystal (2D-PhC). This structure is optimized by varying the radius of the cavity, to obtain a quality factor $Q = 1192$, and also has several ports of entry and one port of output. The size of each structure is equal to $85.8 \mu\text{m}^2$. The contrast ratios for the structures proposed all-optical NOT, XOR and XNOR logic gates between levels “0” and “1” are, respectively, 25.08, 25.03, and 14.47 dB. The response time for the three logical gates is 8.33 ps, and the bit rate is calculated at about 0.12 Tbit/s, all simulations are based on both numerical methods such as finite difference time domain (FDTD) and plane wave expansion (PWE). Designed logic gates are characterized by low power consumption, compactness and easy integration.

Keywords: all-optical XNOR and NOT XOR logic gate; contrast ratio; interference effect; photonic crystal; optical integrated circuits (OIC); resonant cavities.

1 Introduction

In the world of communication, the speed of data transfer and bandwidth are essential parameters of modern telecommunications networks [1]. Optical communications networks have high bandwidth and acceptable speed, which can receive and send a large volume of data since they use light for information transfer [2]. On the other

hand, the issue of converting an electrical signal into an optical signal and vice versa in optical telecommunications networks creates a loss of energy and time. The efficiency of these systems is greatly decreased. Therefore, the tendency to replace processors with all-optical processors has increased [3]. Logic gates are the main components of the processing unit and a lot of attention has been paid to the design of optical logic gates [4].

All-optical logic gates based on photonic crystals (PhCs) have attracted worldwide attention due to the low switching power and high speed of data transfer [5]. Photonic crystals are periodic structures that provide a photonic bandgap (PBG) specifying a frequency region where no propagating electromagnetic wave exists. Band gap-based PCs have a wide range of applications that can revolutionize the technology and industry [6–8].

Due to its specific features in controlling the propagation of optical signals, PhCs received considerable attention from researchers [9, 10]. Among the methods suggested, we can divide into four categories: self-collimated beam, nonlinear Kerr material-based gates, multi-mode interference, and interference-based defect method [11]. So far, a lot of effort has been made to design all-optical logic gates [12–21], while few studies focused on the development of multifunctional structures. These structures offer considerable flexibility in the design of digital systems. In the study by Hussein et al. [22], photonic crystal based on the interference effects for NOT and XOR logic gates. The structure made up of germanium dielectric rods in the air substrate, a ring resonator with two waveguide inputs and one output. To create destructive interference, the method of changing the lengths of the input waveguides was used. The dimensions of the structure are $14 \mu\text{m}$ in $11.1 \mu\text{m}$, and the overall area is $155.4 \mu\text{m}^2$, and the contrast ratio for the XOR logic gate is 11.64 dB, and for the NOT logic gate, contrast ration is 12.15 dB. Also, Hussein et al. [22] proposed a new design for the XNOR gate, with a surface area of $240.1 \mu\text{m}^2$, and the contrast ratio equal to 9.38 dB. In the studies by Rani et al. [23, 24], multifunctional PhC structures were designed using a triangular lattice of air holes in a Si substrate, The waveguide interference in the proposed structures has been used to create logic operations. Different logic functions are realized in

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different input permutations based on the phase change of the inputs. A multi-functional PC structure is designed in the study by haq Shaik and Rangaswamy [25], based on a square lattice of Si rods in the air background. This structure was designed using a T-shaped waveguide, which creates different logic functions by changing the phase of the inputs in different inputs permutations. However, the most crucial problem with these works, studies by Rani et al. and haq Shaik and Rangaswamy [23–25], is the requirement to change the phase of the inputs at different input permutations, which makes it practically impossible to use those structures in optical integrated circuits.

In this paper, we have proposed a new structure for the implementation logic gates of all-optical NOT, XOR and XNOR, based on a resonant cavity and the interference effect. The fundamental structure used to design these proposed gates is ultra-compact with a surface area of $(7.8 \times 11 \mu\text{m}^2)$ and simple to fabricate with low power consumption. The results obtained are compared to the results published previously to validate the performance of our proposed structure. The simplification of the design and the very high contrast ratio (CR) are the advantages of our structure compared to the logic gates previously provided.

2 Simulation methods

In this paper, we have used the Bandsolve simulation tool of Rsoft Photonic CAD software to simulate the efficiency of logic circuits based on the plane wave method which is adapted for the calculation of frequency bands and the FullWave simulation tool based on the 2D-FDTD method, for modeling the electromagnetic behavior of excitation in an all-optical component [26].

The most important parameter to examine the efficiency of all-optical logic gates is the contrast ratio. The contrast ratio is defined as follows [27]:

$$CR(\text{dB}) = 10 \log \frac{P_1}{P_0} \quad (1)$$

where P_1 is the output power for logic “1” and P_0 is the output power for logic “0.”

Another parameter for examining the efficiency of the logic circuits is the response time, which is a factor of the speed of data transmission through the logic circuits. Depending on the type of resonance used for the design, the response time will be different. Shorter response time will result in very high data transmission speeds [28].

3 Description of the initial structure

The initial structure used for the design of the proposed all-optical logic gates is (20×14) the square lattice of silicon rods with a refractive index of 3.43 in the air (Figure 1). The radius of the dielectric rods is $r/a = 0.2$, where $a = 52 \text{ nm}$ is the PhC lattice constant. TE band diagram for selected parameters includes the band structure of the initial structure shows two photonic band gaps (PBGs) situated between the normalized frequencies for TE/TM mode $0.28 < a/\lambda < 0.42$ and $0.73 < a/\lambda < 0.74$, or in other words $1.23 \mu\text{m} < \lambda < 1.85 \mu\text{m}$ and $0.70 \mu\text{m} < \lambda < 0.71 \mu\text{m}$, respectively, (Figure 2). The results show that the design proposed may be used in the third communication window ($\lambda = 1550 \text{ nm}$) and is useful for all-optical communications.

Figure 1: The initial structure (dielectric rods made up of silicon in air substrate).

Figure 2: TE band diagram for selected parameters ($r/a = 0.2$).

Figure 3: Schematic block diagram of the proposed structure for the NOT logic gate.

The initial design of the all-optical logic gate consists of three ports that are coupled between them by a resonant cavity by a waveguide, which is presented in Figure 4. This structure is optimized by varying the cavity radius, to obtain a quality factor $Q = 1192$, the resonant cavity rod radius has been modified to achieve high performance. The output spectrum, presented in Figure 5, of the proposed linear logical gate is 87% around the central wavelength of $\lambda = 1550$ nm where (Bias = 1, Input = 0).

4 Results and discussion

4.1 Results of the simulation of “NOT”

A schematic block diagram of the structure proposed for the NOT logic gate is shown in Figure 3. For the all-optical NOT gate, the two input ports are labeled “Bias” and “Input,” and the output port is labeled “Output,” each port is connected to the resonant cavity by a waveguide.

Figure 4: The final design of our proposed all-optical NOT logic gate.

Figure 5: The resonant spectrum of the resonant cavity.

The proposed operating states of the logic gate “NOT” are summarized in Table 1. According to Figure 3 and Table 1, the “bias” is permanently placed at logic “1” and plays the role of signal control. If the normalized output signal intensity is higher than or equal to 50%, the logic level is considered to be “1” and if it is less than or equal 5%, it is “0,” as shown in Figure 6.

Case 1: When “Bias” = 1, “Input” = 0. The optical signal “ P_{in} ” at the input of “Bias” couples to the resonant cavity using light-trapping phenomenon and transmitted to the output port “Output = 1” with an efficiency of 87% at a wavelength of $\lambda = 1550$ nm, as shown in Figures 7(a) and 8(a).

Table 1: Truth table and optical power in output for all-optical NOT logic gate.

Bias	Input	Output logic	Contrast ratio (CR)	Response period	BIT rate
Power	Power	Power normalized	25.08 dB	8.33 ps	0.12 Tbit/s
1 (P_{in})	0	1 ($0.87 P_{in}$)			
1 (P_{in})	1 (P_{in})	0 ($0.0027 P_{in}$)

Figure 6: Transmission level ranges.

Figure 7: Optical field distribution for different states for proposed NOT gate for: (a) Bias = 1, Input = 0. (b) Bias = 1, Input = 1.

Figure 8: Time-evolving curve of proposed "NOT gate" for: (a) Bias = 1, Input = 0. (b) Bias = 1, Input = 1.

Table 2: Comparison table "NOT gate."

	The operating wavelength, nm	Size of structure, μm^2	CR	Response time, ps
Our work	1550	85.8	25.08	8.33
Bahabady-Olyaei [20]	1550	252	20.53	0.466
Singh and Rawal [29]	1550	122	5	—
Ghadrdan and Mansouri-Birjandi [30]	1550	144	10.79	0.84
Fu et al. [31]	1550	558	20	—
Jianga et al. [32]		729	9.33	—

Case 2: At "Bias" = 1, "Input" = 1. If the two inputs "Bias" and "Input" are equal to "1," the signal inputs have a destructive interference which gives an output signal "Output = 0." In this case, the output monitor receives a very low power up to 0.0027% of the " P_{in} " signal input power, as shown in Figures 7(b) and 8(b).

This "NOT" gate is compared by several logic gates as presented in previous studies [20, 29–32]. Table 2 shows that the proposed "NOT" logic gate is smaller in size than the other motioned gates and has a very high contrast ratio.

4.2 Results of the simulation of "XOR"

One of the interests of all-optical logic gates based on photonic crystals is to be able to use one structure for multiple gates. Not only does the proposed structure serve as an all-optical logic gate "NOT," but it can also be used as an all-optical logic gate "XOR." A schematic block diagram

of the proposed structure for the XOR logic gate is shown in Figure 9. According to Figure 10 and Table 3, this "XOR" gate is made up of two inputs (Input 1 and Input 2) and the output (Output). To test and simulate the operation of the proposed structure, the following cases can be examined:

Figure 9: Schematic block diagram of the proposed structure for the XOR logic gate.

Figure 10: The final design of our proposed all-optical XOR logic gate.

Case 1: “Input 1” = “Input 2” = 0. When both inputs are equal to “0,” there is no transmission within the structure, so the output port is equal to “0,” as shown in Figures 11(a) and 12(a).

Cases 2 and 3: When “Input 1” = 0, “Input 2” = 1, and “Input 1” = 1, “Input 2” = 0, respectively, one of the “Input 1” or “Input 2” inputs is equal to “1” and the other is equal to “0,” the signal passes from the resonant cavity and reaches the output. In both cases (cases 2 and 3), the monitor receives up to 86% and 87% of the “ P_{in} ” input intensity at a wavelength of $\lambda = 1550$ nm. As shown in Figures 11(b–c) and 12(b–c).

Case 4: At “Input 1” = “Input 2” = 1. If the two inputs “Input 1” and “Input 2” are equal to “1,” the signal inputs have destructive interference which in this case gives an output signal “Output = 0,” and the output monitor receives up to 0.0027% of the input power of the P_{in} signal, as shown in Figures 11(d) and 12(d). The truth table for this optical XOR logic gate is shown in Table 3, and the contrast ratio is equal to 25.03 dB.

Our “XOR” structure is compared by several structures as presented in previous studies [20, 31–33]. Table 4 shows that the proposed “XOR” logic gate has a very high contrast ratio and a smaller size than other structures.

Table 3: Truth table and optical power in output for all-optical XOR logic gate.

Bias	Input	Output logic	Contrast ratio	Response time, ps	BIT rate
Power ($W/\mu m^2$)	Power ($W/\mu m^2$)	Power normalized			
0	0	0			
0	1 (P_{in})	1 ($0.86 P_{in}$)	25.03 dB	8.33 ps	0.12 Tbit/s
1 (P_{in})	0	1 ($0.87 P_{in}$)			
1 (P_{in})	1 (P_{in})	0 ($0.0027 P_{in}$)

Figure 11: Optical field distribution for different states for proposed “XOR” gate for: (a) Input 1 = Input 2 = 0. (b) Input 1 = 0, Input 2 = 1. (c) Input 1 = 1, Input 2 = 0. (d) Input 1 = Input 2 = 1.

Figure 12: Time evolving curve of proposed “XOR gate” for:
 (a) Input 1 = Input 2 = 0. (b) Input 1 = 0, Input 2 = 1. (c) Input 1 = 1, Input 2 = 0. (d) Input 1 = Input 2 = 1.

Table 4: Comparison table “XOR gate.”

	The operating wavelength, nm	Size of structure, μm^2	CR	Response time, ps
Our work	1550	85.8	25.03	8.33
Ghadrdan and Mansouri-Birjandi [33]	1550	265	5.67	0.85
Fu et al. [31]	1550	558	20.48	–
Bahabady and Olyaei [20]	1550	252	19.95	0.466
Jianga et al. [32]	–	729	9.33	–

4.3 Results of the simulation of “XNOR”

This part describes the results obtained and the optical performance for the XNOR structure proposed. This optical gate is a very important gate for designing logic

comparators, full adders, optical half adders, lattice parity checks and other logic circuits based on two-dimensional photonic crystals. The basic idea of operation for optical XNOR is based on the use of the resonant cavity with photonic crystals with a resonant wavelength of 1550 nm. This

Figure 13: Schematic block diagram of the proposed structure for the XNOR logic gate.

Figure 14: The final design of our proposed all-optical XNOR logic gate.

“XNOR” gate is composed of three inputs (Bias, Input 1 and Input 2) and the output (Output), as shown in the schematic block diagram of the structure proposed for the XNOR logical gate in Figures 13 and 14. To describe and realize the operation of this gate, the following scenarios can be examined:

Case 1: When “Bias” = 1, “Input 1” = “Input 2” = 0. The optical signal “ P_{in} ” at the input of “Bias” couples to the resonant cavity and flows directly to the output port

“Output = 1” with an efficiency of 56% at a wavelength of $\lambda = 1550$ nm. As shown in Figures 15(a) and 16(a).

Case 2: At “Bias” = 1, “Input 1” = 0, “Input 2” = 1. If the two inputs “Bias” and “Input 2” are equal to “1,” the signal inputs have destructive interference resulting in an output signal “Output = 0.” In this case, the output monitor receives up to 0.003% of the signal input power, as shown in Figures 15(b) and 16(b).

Figure 15: Optical field distribution for different states for the proposed “XNOR” gate for:

(a) Bias = 1, Input 1 = Input 2 = 0. (b) Bias = 1, Input 1 = 0, Input 2 = 1. (c) Bias = 1, Input 1 = 1, Input 2 = 0. (d) Bias = 1, Input 1 = Input 2 = 1.

Figure 16: Time-evolving curve of proposed “XNOR” gate for:

(a) Bias = 1, Input 1 = Input 2 = 0. (b) Bias = 1, Input 1 = 0, Input 2 = 1. (c) Bias = 1, Input 1 = 1, Input 2 = 0. (d) Bias = 1, Input 1 = Input 2 = 1.

Table 5: Truth table and optical power in output for all-optical “XNOR” logic gate.

Bias	Input 1	Input 2	Output logic	Contrast ratio (CR)	Response period	BIT rate
Power ($\text{W}/\mu\text{m}^2$)	Power ($\text{W}/\mu\text{m}^2$)	Power ($\text{W}/\mu\text{m}^2$)	Power normalized			
1 (P_{in})	0	0	1 ($0.56 P_{\text{in}}$)	14.47 dB	8.33 ps	0.12 Tbit/s
1 (P_{in})	0	1 (P_{in})	0 ($0.02 P_{\text{in}}$)			
1 (P_{in})	1 (P_{in})	0	0 ($0.003 P_{\text{in}}$)			
1 (P_{in})	1 (P_{in})	1 (P_{in})	1 ($0.71 P_{\text{in}}$)			

Table 6: Comparison table “XNOR gate.”

	The operating wavelength, nm	Size of structure, μm^2	CR	Response time, ps
Our work	1550	85.8	14.47	8.33
Tamer-Moniem [34]	1550	735	–	–
Sun Xiao-Wen et al. [35]	1550	625	–	–

Case 3: When “Bias” = 1, “Input 1” = 1, “Input 2” = 0. The signal inputs have a destructive interference, which gives an output signal “Output = 0.” In this case, the output of the gate “Output = 0” with almost zero efficiency is about 0.002%, as shown in Figures 15(c) and 16(c).

Case 4: At “Bias” = 1, “Input 1” = “Input 2” = 1. As shown in Figures 15(d) and 16(d), the two inputs “Input 1” and “Input 2” are coupled together and flow directly to the output by coupling with the resonant cavity with 71% efficiency and prevent destructive interference with the signal input of “Bias” (Table 5).

As shown in Table 6, this structure is compared by several logic gates, as presented in the studies by Moniem and Sun et al. [34, 35]. The logic gate proposed is smaller in size than the other gates and has a very high contrast ratio.

5 Conclusions

In this paper, a novel all-optical NOT, XOR and XNOR gates based on the interference effect was proposed and demonstrated by simulation in the telecom wavelength range.

The proposed structure is ultra-compact with a surface area of $85.8 \mu\text{m}^2$, characterized by low energy consumption, ease of design and simplicity of operation compared with other logic gates with complex structures and suitable for integrated all-optical circuits. For the proposed all-optical NOT, XOR and XNOR logic gates the contrast ratios

are 25.08, 25.03 and 14.47 dB, respectively. The logic gates have a response time and a bit rate of, respectively, 8.33 ps and 0.12 Tbit/s. The two-dimensional finite difference time domain (2D-FDTD) method demonstrates the optical behavior of the intended structure and the dispersion diagram is extracted using the PWE method.

Acknowledgment: This work was supported by the Directorate General for Scientific Research and Technological Development (DGRSDT).

Author contribution: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: This work was supported by the Directorate General for Scientific Research and Technological Development (DGRSDT)

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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