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Research Paper

An All-Optical NOR Gate based on Two-Dimensional Photonic Crystals

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Abstract:
A new configuration of an all optical (2 input) NOR gate based on two-dimensional photonic crystals is proposed. The structure is based on 20*20 rods of silicon in the background of air. The square-ring resonator shaped structure contains three inputs and one output port. Three input ports (Ctrl, A and B) are introduced in to the structure for achieving the appropriate application. In order to investigate the functionality of the structure (functioning as a logic NOR gate), photonic band gap (PBG), field distribution and transmitted power spectrum are considered. PBG and field distribution are obtained considering the plane wave expansion and finite-difference-time-domain methods, respectively. All the states of a NOR gate (truth table or logical values) are considered by applying related inputs to the input ports (incident field with the wavelength in the PBG region). The bit rate, normalized intensity and rise time of 2.5Tbit/s, 99% and 2ps, are azlso obtained for the gate. The obtained logic NOR gate can be an appropriate candidate for utilization in optical integrated circuits.

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1. INTRODUCTION

Recently, optical structures have attracted great attentions of various researchers due to their incredible specifications. They mainly attain higher efficiency and precision, designation flexibility, lower costs and integration ability. They can be utilized for configuring photonic integrated circuits (PICs). As a result, like electronic circuits, all circuit sections (transmitter, receiver, filter, sensor, logic gates and etc.) are needed to be optically or (photonic-based) designed. Photonic crystals (PhCs) are One the most known and efficient structures used for designing photonic devices which are made of periodic rods. These periodic structures are based on the combination of various dielectric layers (mostly two or more) and are positioned in a regulated and definite format (cubic, rectangle, …). Different rods can be considered based on various dielectric materials in the air background. The material used for configuring the PhC are mostly defined by their refractive indices (the index indicating the behavior of the material when the light wave is applied) [1]. Another important parameter in the periodic PhCs is the lattice constant (indicating the periodicity or distance between two adjacent rods in the structure) [1, 2, 3, 4]. Photonic bandgaps (PBG) in the photonic crystal indicate the guided or non-guided wavelengths. Considering this very important diagram (PBG spectrum), the functionality of the designed structure can be engineered. The guided mode's wavelengths allow the transmission of the light through the rods which mainly results in diverse and unappropriated transmission spectrum. In another case, if the defects (point, line, …) can be considered in the structure to format a specific shape, by considering the unguided wavelengths, the light can benefit from the total internal reflection (TIR) behavior and propagates in an appropriate way [5]. As a result, light wave at some wavelengths in the PBG diagram can be propagated according to the TIR behaviors, while in other wavelengths would be dispersed in the structure [5, 6, 7]. Considering this important specification, many optical photonic crystal-based deceives have been designed as filters [2, 5], logic gates [1, 8, 9, 10], sensors [11-13] and etc. In a research [8], a half-subtractor based on photonic crystal arrays was proposed and investigated. In another research [9], a 2*1 optical multiplexer based on photonic crystals was suggested and investigated. Also in [10], a 4*2 encoder was proposed by considering a periodic photonic crystal structure. In [14], all optical NOR and AND gates were proposed considering 2-D photonic crystals. Photonic crystals have also been utilized for designing refractive index biosensors [15]. Interestingly, by utilizing opto-fluidic materials in the photonic crystal structure, a tunable optical filter was obtained [16].

In this paper, a novel NOR gate based on 2D-PhCs with square-ring resonator shaped defects is proposed and investigated. The photonic bandgap, field distributions and transmission's power spectrum are considered for different conditions (inputs) and are presented in the following parts.

2. METHODOLOGY AND DESIGN

In the photonic crystal based structures, photonic bandgap diagram, transmission spectrum and field distribution spectrum are of great interests. All these diagrams can be achieved by considering the Maxwell equations (as basic optical equations). As many graphical user interface (GUI) software like RSOFT Photonic Device Tools or COMSOL Multiphysics and etc. are available, we can utilize them (in this work RSOFT) instead of writing the related codes. As known, different numerical methods can be considered for obtaining the mentioned spectra. In order to analyze the structure, firstly, the photonic bandgap diagram should be obtained. It can be fulfilled by considering plane wave expansion (PWE) method which is based on the frequency analysis. PWE is utilized for calculating modal solutions of Maxwell's equations over a periodic geometry [9, 17]. For obtaining the field distribution and transmission spectra, finite difference time domain (FDTD) method should be considered. The following Maxwell's equations should be considered:

$$\frac{\partial B}{\partial t} = -\nabla * E - J \tag{1}$$

$$\frac{\partial B}{\partial t} = \nabla * H - J \tag{2}$$

Where *E, H, D, B* and *J* stand for the electric field, magnetic field, electric displacement, magnetic induction fields and electric-charge current density, respectively.

Like the PWE method, the numerical FDTD method is utilized instead of the coding approach, which describes electromagnetic fields in finite areas by field approximation with the Taylor series [17].

The proposed structure is consisted of 20a*20a arrays of 2-D PhCs rods (arrays of Si rods in the "air" background) as shown in Fig. 1.

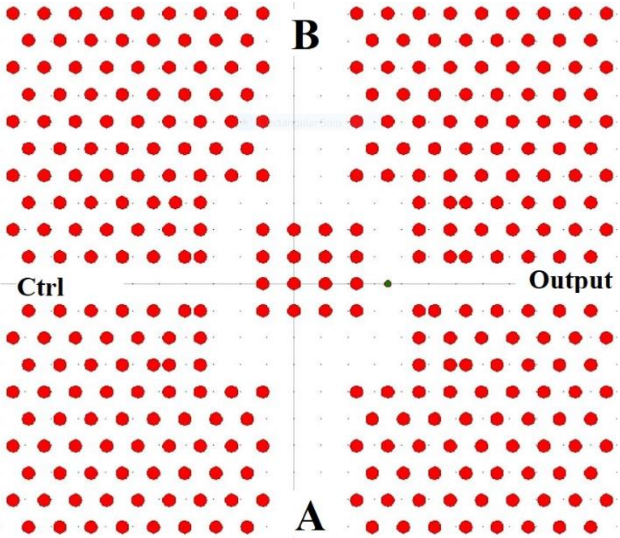


Fig. 1. The proposed NOR gate based on 2-D PhCs

For the proposed structure shown in Fig. 1, a (lattice constant), n (refractive index of Si rods) and r (rod's radius except the green one) are 0.5µm, 3.5 and 0.1µm, respectively. The green rod (with the radius and refractive index of 0.075µm and 2.5, respectively) functions as a phase shifter and helps the structure to act as a NOR gate at specific wavelengths. As indicated in Fig. 1, the structure is designed by considering various line and point defects. Three ports (Ctrl, A and B) are considered as the input ports and one port (Output) is considered as the desired output port. The logical values (truth table) of a 2-input NOR gate are tabulated in Table I.

TABLE I
LOGICAL VALUES OF A NOR GATE

Ctrl	A	B	Output
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

In the first step of investigating the functionality of the proposed structure, the PBG diagram should be obtained. Other steps include achieving the field distribution and transmitted power spectrum for different conditions (inputs). For the photonic crystal structures, PBG and transmission spectrum are obtained considering the plane-wave expansion (PWE) and finite-difference-time-domain

(FDTD) methods [7, 9]. Considering the PWE method, the PBG of the proposed structure can be shown in Fig. 2.

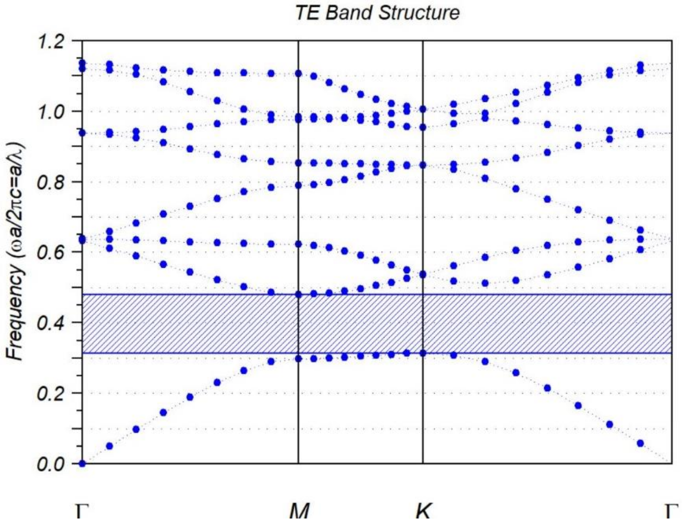


Fig. 2. Schematic of the PBG of the proposed structure.

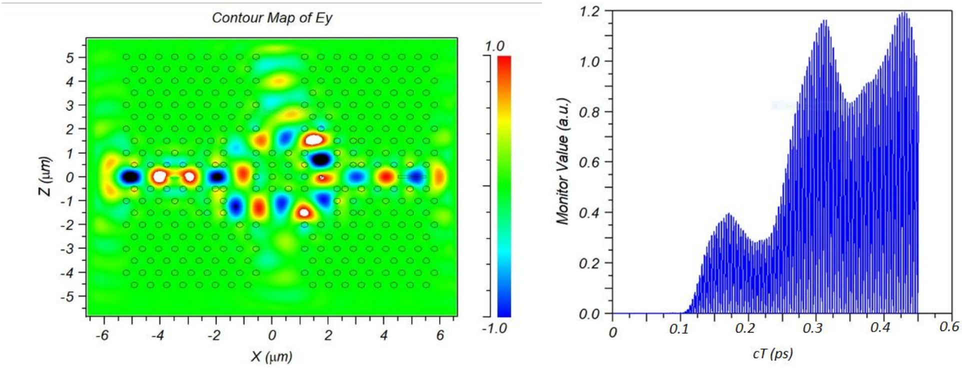
As can be seen for the TE mode, PBG in the wavelength range of 1.04µm<λ<1.6µm is obtained. In this wavelength range, total internal reflection (TIR) effect can occur in the structure. For investigating the functionality of the proposed structure as a NOR gate, the wavelengths positioned in the PBG range should be considered as the input wavelength (for having the TIR effect). In the following parts, different conditions (considering Table. I) would be investigated and the field distribution and transmission spectrum (for output port) would be evaluated.

3. SIMULATIONS AND RESULTS

In this part, different conditions of a NOR gate (stated in Table. I) would be considered by applying the incident field to the defined ports. For each condition, a field distribution and transmitted power spectrum would be obtained.

A. Ctrl=1, A=0, B=0

In this case, an incident light wave (with the power and wavelength of 1W and 1.5µm) is applied to Ctrl port. The field distribution and transmitted power spectrum are depicted in Fig. 3.



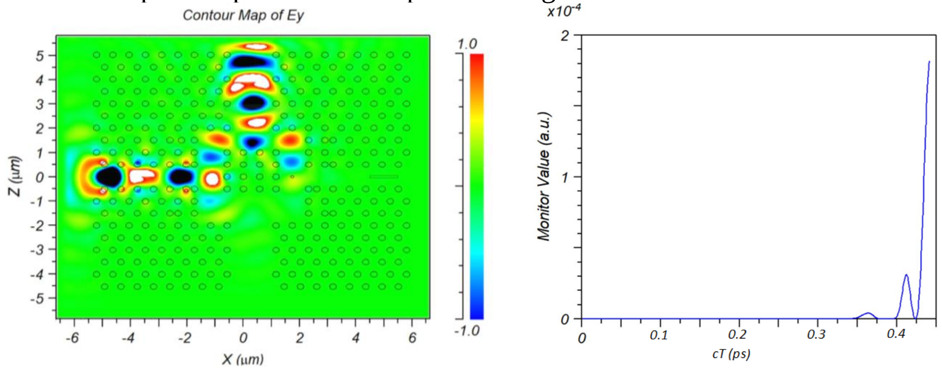
(a) (b)

Fig. 3. a) Field distribution, b) transmitted power spectrum for Ctrl=1, A=0, B=0

As can be seen in Fig.3, for this condition, the transmitted power reaches high values (1.2 equals to “1” logic). The obtained result is similar to the logical values presented in Table. I. Therefore, when no signals are applied to the “A” and “b” ports, the high intensity output would be obtained at the output port, which indicates the “NOR” gate application. As can be seen, the response period of the output power is about 0.*4ps* and the bit rate for the proposed optical gates is about *2.5Tbit/s.*

B. Ctrl=1, A=0, B=1

In the second case, incident light waves (with the power and wavelength of 1W and 1.5µm) are applied to Ctrl and B ports. The field distribution and transmitted power spectrum are depicted in Fig. 4.



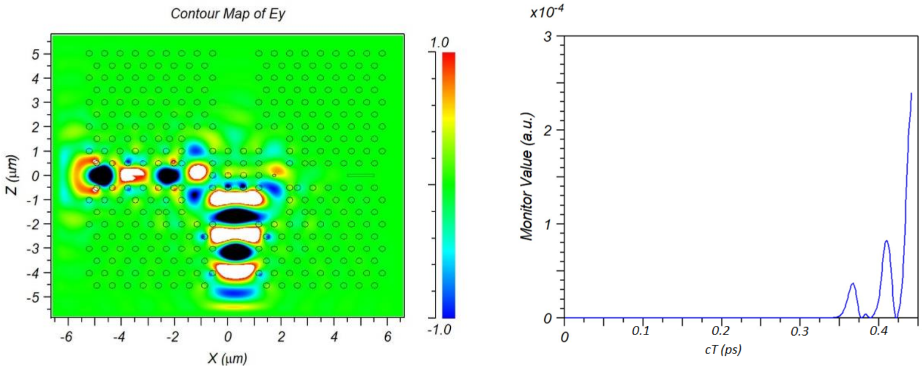
(a) (b)

Fig. 4. a) Field distribution, b) transmitted power spectrum for Ctrl=1, A=0, B=1

In this case as shown in Fig.4, the transmitted power reaches low values (2e-4 which equals “0” logic). As a result, when an incident signal is applied to each input port (here “B” port), no signal would be transmitted to the output port. Therefore, the output is “0” logic which is in accordance with the logical values presented in Table. I.

C. Ctrl=1, A=1, B=0

In another case, incident light waves (with the power and wavelength of 1W and 1.5µm) are applied to Ctrl and A ports. The field distribution and transmitted power spectrum are depicted in Fig. 5.



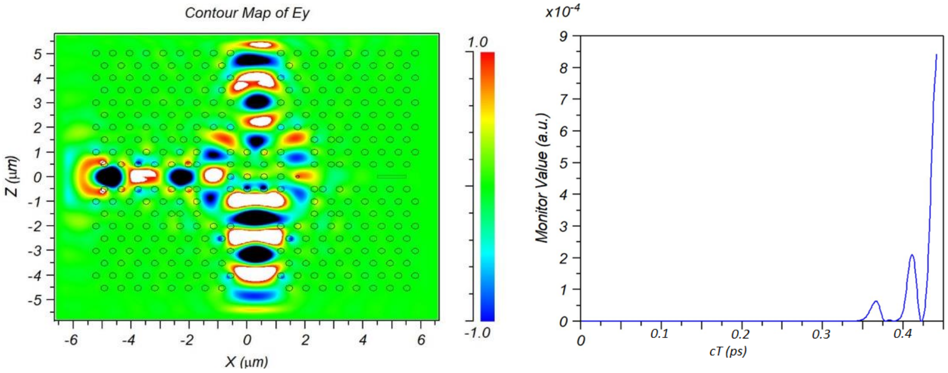
(a) (b)

Fig. 5. a) Field distribution, b) transmitted power spectrum for Ctrl=1, A=1, B=0

In this case, the transmitted power reaches low values (3e-4 which equals “0” logic). Like the previous case, when an incident signal is applied to each input port (here “A” port), no signal would be transmitted to the output port. Therefore, the output is “0” logic which is in accordance with the logical values presented in Table. I.

D. Ctrl=1, A=1, B=1

In the final case, incident light waves (with the power and wavelength of 1W and 1.5µm) are applied to Ctrl, A and B ports. The field distribution and transmitted power spectrum are depicted in Fig. 6.



(a) (b)

Fig. 6. a) Field distribution, b) transmitted power spectrum for Ctrl=1, A=1, B=1

In the final case as seen in Fig. 6, the transmitted power reaches low values (9e-4 which equals "0" logic). Therefore, the output equals "0" logic which is similar to the logical values presented in Table I. As a result, after considering the four states of Table I, and achieving the similar results, the NOR gate's application can be verified. The following table compares the obtained bit rate (for the Ctrl=1, A=0, B=0 case) with previously published works.

TABLE II
COMARISON OF OUR PROPOSED GATE WITH PREVIOUS WORKS

References	Bit rate (*Tbit/s*)	Normalized Intensity (%)	Rise Time (*ps*)
[14]	*1.54*		
[18]	*2*		
[17]		*94.5*	
[19]		*90*	
[20]		*60*	*2.5*
[9]		*95*	*2*
Our proposed gate	*2.5*	*99*	*2*

4. CONCLUSION

In this paper, a new structure for logic NOR gate was proposed and considered. The structure was based on Si rods in the "air" background. Line and point defects formatted a square-ring resonator shaped structure which contained three input ports (Ctrl, A and B) and one output port. In order to verify the functionality of the structure as a NOR gate, PBG, field distribution and transmitted power spectrum for all logical values (truth table) conditions were considered. After evaluating the functionality of the proposed structure as a NOR gate, it can be considered as a logic gate in optical integrated circuits with acceptable bit rate, normalized intensity and rise time of 2.5Tbit/s, 99% and 2ps, respectively.

REFERENCES

[1] E. Rafiee, F. Emami, *Design of a novel all-optical ring shaped demultiplexer based on two-dimensional photonic crystals*, Optik. 140 (2017) 873–877. Available: https://doi.org/10.1016/j.ijleo.2017.05.010.

[2] E. Rafiee, F, Emami, *Realization of tunable optical channel drop filter based on photonic crystal octagonal shaped structure*, Optik. 171 (2018) 798–802. Available: https://doi.org/10.1016/j.ijleo.2018.06.146.

[3] M. Mehrabi, J. Barvestani, *Localized photonic modes in photonic crystal heterostructures*, Opt. Commun. 284 (2011) 5444–5447. Available: https://doi.org/10.1016/j.optcom.2011.07.061.

[4] G. Palai, *Theoretical approach to 3D photonic crystal structure for realization of optical mirror using bandgap analysis: a future application*, Optik. 126 (2015) 5100–5101. Available: https://doi.org/10.1016/j.ijleo.2015.09.164.

[5] E. Rafiee, F. Emami, *Design and Analysis of a Novel Hexagonal Shaped Channel Drop Filter Based on Two-Dimensional Photonic Crystals*, JOPN. 1 (2) (2016) 39-46. Available: https://journals.marvdasht.iau.ir/article_2047.html.

[6] J. Liu, Z. Fan, *Comparison of photonic bandgaps of two-dimensional periodic and quasi-periodic photonic crystals with different relative permittivitydielectric*, Optik. 125 (2014) 6566–6569. Available: https://doi.org/10.1016/j.ijleo.2014.06.165.

[7] A. Taflove, S.C. Hegnese, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, Artech House, Boston, MA, 1998.

[8] F. Pakrai, et al., *Designing of All-Optical Subtractor via PC-Based Resonators*, JOPN. 7 (2) (2022) 21- 36. Available: 10.30495/jopn.2022.29545.1246.

[9] B. Elyasi, S. Javahernia, *All optical digital multiplexer using nonlinear photonic crystal ring resonators*, JOPN. 7 (1) (2022) 97- 106. Available: 10.30495/jopn.2022.29174.1242.

[10] F. khatib, M. Shahi, *Ultra-Fast All-Optical Symmetry 4×2 Encoder Based on Interface Effect in 2D Photonic Crystal*, JOPN. 5 (3) (2020) 103- 114. Available: 20.1001.1.24237361.2020.5.3.7.6.

[11] C. Qi, et al., *Refractive index sensor based on photonic crystal nanocavity,* Opt. Commun 464 (2020) 125393. Available: https://doi.org/10.1016/j.optcom.2020.125393.

[12] L. Zhao, et al., *Photonic crystal all-fiber Mach-Zehnder Interferometer sensor based on phase demodulation*, Opt. Fiber Technol. 53 (2019) 102059. Available: https://doi.org/10.1016/j.yofte.2019.102059.

[13] B. K. Paul, et al., *Investigation of gas sensor based on differential optical absorption spectroscopy using photonic crystal fiber*, Alex. Eng. J., 59 (6), (2020) 5045-5052. Available: https://doi.org/10.1016/j.aej.2020.09.030.

[14] F. Parandin, et al., *Terahertz all-optical NOR and AND logic gates based on 2D photonic crystals*, Superlattices. Microstruct. 101 (2017) 253-260. Available: https://doi.org/10.1016/j.spmi.2016.11.038.

[15] M. Momeni, et al., *Design of High Sensitivity and high FoM Refractive Index Biosensor Based on 2D-Photonic Crystal*, JOPN. 6 (1) (2021) 33- 58. Available: 10.30495/jopn.2022.27033.1217.

[16] M. Bazargani, et al., *Investigating the Design and Simulation of a Tunable Optical Filter Based on Photonic Crystal Using Selective Optofluidic Infiltration*, JOPN. 7 (4) (2022) 67- 79. Available: 10.30495/jopn.2022.29582.1248.

[17] V. Fallahi, M. Seifouri, *Novel Four-Channel All Optical Demultiplexer Based on Square PhCRR for Using WDM Applications*, JOPN. 3 (4) (2018) 59- 70. Available: 20.1001.1.24237361.2018.3.4.5.2.

[18] F. Parandin, et al., *Reconfigurable ALL-OPTICAL NOT, XOR, AND NOR LOGIC GATES BASED ON TWO DIMENSIONAL PHOTONIC CRYSTALS,* Superlattices. Microstruct. 113 (2018) 737-744. Available: https://doi.org/10.1016/j.spmi.2017.12.005.

[19] M. Heidary Orojloo, et al., *Design and Modeling of Photonic Crystal Absorber by Using Gold and Graphene Films*, JOPN. 7 (2) (2022) 1- 10. Available: 10.30495/jopn.2022.28915.1235.

[20] F. Pakrai, et al., *Designing of All-Optical Subtractor via PC-Based Resonators*, JOPN. 7 (2) (2022) 21- 36. Available: 10.30495/jopn.2022.29545.1246.