Islamic Azad niversity

Journal of
Optoelectronical Nanostructures

Autumn 2021 / Vol. 6, No. 4

Research Paper

PhC-based Majority Gate using a nonlinear directional coupler

Reyhaneh Rigi [1], **Keivan Navi*** [,2], **Hojjat Sharifi** [3]

[1] Department of Computer Engineering, Kerman Branch, Islamic Azad University, Kerman, Iran
[2] Department of Computer Science and Engineering, Shahid Beheshti University, Tehran, Iran
[3] Department of Computer Engineering, Vali-e-Asr University of Rafsanjan, Rafsanjan, Iran

Received: **24 Sep. 2021**
Revised: **12 Oct. 2021**
Accepted: **16 Nov. 2021**
Published: **15 Dec. 2021**

Use your device to scan and read the article online

Keywords:
Photonic Crystal, All-optical Majority Gate, Nonlinear Directional Coupler

Abstract
Wide bandwidth and high data transfer rates are essential advantages of optical telecommunication networks. Full exploitation of the benefits of optical communications requires a fully optical network. All-optical circuits are one of the main alternatives to eliminate the limits of electronic circuits and provide high-speed processing systems. This study aims to design an Majority Gate based on the Nonlinear Kerr Effect. The proposed structure includes a directional coupler with nonlinear rods. In the proposed structure, a nonlinear directional coupler is used to transmit the phase of the input signal. Also, input connections are optimized to prevent the return of light along the structure. To evaluate the operation of the proposed structures, PWE and FDTD methods are used. The effect of some parameters variation on the output power has been investigated, proving the robustness of this designed structure of Majority gate against process variation. In this simulation, the proposed structures' switching power is 3 W and the bit rate is Tbits/s.

Citation: Rigi R, Navi K, Sharifi H. PhC-based Majority Gate using a Nonlinear Directional Coupler. **Journal of Optoelectronical Nanostructures, 2021; 6 (4): 21-32. DOI:** 10.30495/JOPN.2022.28130.1225

***Corresponding author:** Keivan Navi
Address: Department of Computer Science and Engineering, Shahid Beheshti University, Tehran, Iran. **Tell:** 00982129904195 **Email:** navi@sbu.ac.ir

1. INTRODUCTION

Due to the slowdown in processors' speed growth in this years, interest in replacing processors with optical processors has become more[1]. Optical circuits are one of the main alternatives to eliminate the limits of electronic circuits[2]. Wide bandwidth and high data transfer rates are among the essential advantages of optical telecommunication networks. The full exploitation of optical communication benefits requires a network that fully processes the sending, receiving and processing of information fully optical and without interference with electronic devices[3].

A wide range of structures has been proposed to realize photonic crystal-based logic functions. Among the proposed techniques can be referred to "self-collimated beam", "multi-mode interference", "interference-based defect method", and "nonlinear Kerr materials-based gates" [4]. Light is propagated without any refraction along various directions through a structure in the self-collimation method. The phenomenon of Total Internal Reflection plays an essential role in creating logical structures using self-collimated beams [5]. The MMI gates are based on the "self-imaging effect" and support many modes. In MMI-based structures, the signal phase is used to determine the input logic and the signal amplitude is used to determine the output logic[6]. In the interference-based defects gates interact with the input signals can make constructive or destructive interference and provide good performance for each gate. In these gates, the input signals must be triggered in a specific phase[7]. In the nonlinear Kerr materials, the refractive index is dependent on the intensity of the signals. The ranges of operating frequencies can change by increasing or decreasing the refractive index[8].

In this research, an PhC-based logic device is presented that has the same functionality as the Majority gate. A majority gate is a logic gate that has many applications in complex circuits. The majority function is a function with N input to an output. The value of the operator will be one if fifty percent or more than fifty percent of the arguments are one, otherwise it is zero.

This paper proposes an all-optical structure for designing a Majority gate. In this structure, a directional coupler made of nonlinear materials is used for phase transfer for different input powers. The use of identical inputs in terms of power and phase for all inputs of the proposed structures is one of the advantages of the proposed structure for use in optically cascaded circuits. Also, the significant difference in output power at high and low logic modes, which increases the detection power in both logic modes.

 DOI: 10.30495/JOPN.2022.28130.1225

To evaluate the operation of the proposed structures, PWE and FDTD methods are used. To use the unique properties of phonic crystals, we need computational methods to study how light propagates within a photonic crystal structure[9]. For each alternating structure, we must specify the allowable frequencies for light propagation within the structure and the field distribution at each of these frequencies[10].

In this paper, the design method and proposed structure for the Majority gate are presented in sections 2 and 3, respectively. The simulation results and evaluation of the proposed Majority gate are shown in Section 4. Finally, the conclusion is given in the last.

2. DESIGN METHOD

In the proposed method, Si rods in the air bed in the form of a triangular lattice have been used. The Si refractive index for wavelengths in the range of 1550 nm used in our simulations is 3.6. The lattice constant and the silicon rod diameter is chosen to equal 565nm and 0.2a, that 'a' is considered the lattice constant.

We considered the TM mode and the PWE method used to evaluate the "photonic bandgap of the structure". The structure of the photonic band is presented in Fig. 1. As shown in this figure, there are two frequency gaps. The more significant gap is between 0.28 a/λ and 0.45 a/λ. For the input frequency, a frequency of 0.365 a/λ is used.

Suppose that the polarization is denoted by P(t) and the intensity of the applied electric field is denoted by E(t). In this case, in linear materials, the polarization and the electric field are related as follows:

$$P(t) = x^{(1)} E(t) \tag{1}$$

So that $x^{(1)}$ is the linear acceptance coefficient. In nonlinear materials, the nonlinear polarization is as follows:

$$P(t) = x^{(1)} E(t) + x^{(2)} E(t) + x^{(3)} E(t) + \dots = P^{L} + P^{NL} \tag{2}$$

So that P^{L} and P^{NL} are linear polarization and nonlinear polarization, respectively. The observed nonlinear phenomenon depends on which of the above coefficients of acceptance coefficients are dominant[11].

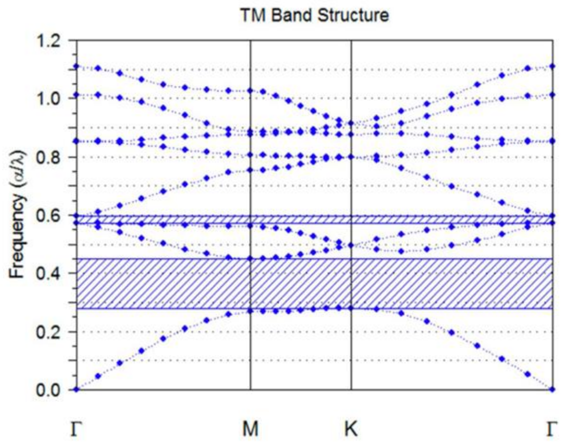

Fig. 1. Photonic band structure of Si rods in the air bed for TM mode.

In the nonlinear Kerr effect, the applied signal intensity can affect the refractive index as

$$n = n_0 + n_2 I \quad (3)$$

Where I is the applied signal intensity, n_0 is the "Linear Refractive Index" and n_2 is the "Nonlinear Kerr Coefficient". Based on the above relationship, with increasing and decreasing the input field strength, the "Refractive Index" increases and decreases. This change in "Refractive Index" in photon crystal defects causes the resonant frequency to change, as a result, the input signal phase changes[12].

In this research, silicon nanocrystals (Si-nc) are used as the nonlinear material. Silicon nanocrystals have a "Linear Refractive Index" of 1.5 and at a wavelength of 1550 nm the "Nonlinear Kerr Coefficient" of 10^{-16} m^2/W.

The directional coupler consists of two rows of removed rods adjacent to a middle row[13]. In a "directional coupler", when light is propagated in one of the waveguides, after crossing the "coupling length", it is coupled with an adjacent waveguide[14]. The "coupling length" is as follows:

$$L_c = \pi/(k_e - k_o) \quad (4)$$

 DOI: 10.30495/JOPN.2022.28130.1225

Where k_o and k_e are odd state propagation constants and even state propagation constants, respectively. When light enters a nonlinear structure, directional couplers can be used as switches[15].

3. PHC-BASED MAJORITY GATE

In the PhC-based Majority gate, the structure presented in Fig. 2 is used to connect the two inputs to prevent the return of light along with the structure. With this structure, the possibility of light return is largely eliminated, which is very effective in increasing the efficiency of the circuit.

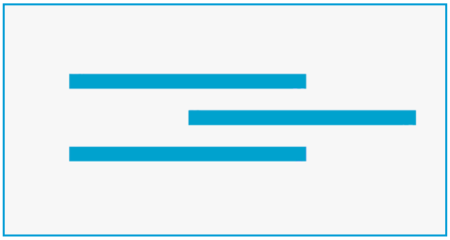

Fig. 2. The proposed structure to prevent the return of light along the structure.

The structure of PhC-based all-optical Majority gate is presented in Fig. 3. The directional coupling can be made by Changing the radius of each rod and using of nonlinear materials in a parallel row of a PC structure at L distance. A directional coupler is used to transfer the phase, and it causes the phase of the input signal to transfer in the size of π. In the proposed structure shown in Fig. 3, I_1 , I_2, and I_3 are input signals, and I_{out} is the output signal. When one of the three input signals is launched, the input signal is divided into two waveguides, A and B. The input signal obtains a phase difference of π as it passes through the B waveguide of the nonlinear direction coupler. So, "destructive interference" occurs at the output of the structure and the I_{out} is at a low logic level. When two or three of the input signals are launched, by increasing the input signal power, a signal phase change of 2π will be created. As a result, "constructive interference" occurs in the output of the proposed structure, the I_{out} is at a high logic level. The simulated structure of PhC-based Majority gate is presented in Fig. 4.

The proposed PhC-based Majority gate simulation has been performed with Rsoft software. The photonic band diagram simulation is performed using the PWE method using the BANDSOLVE tool of Rsoft software. The transmission curves of optical power output are simulated by the FDTD method using the FULLWAVE tool of Rsoft software.

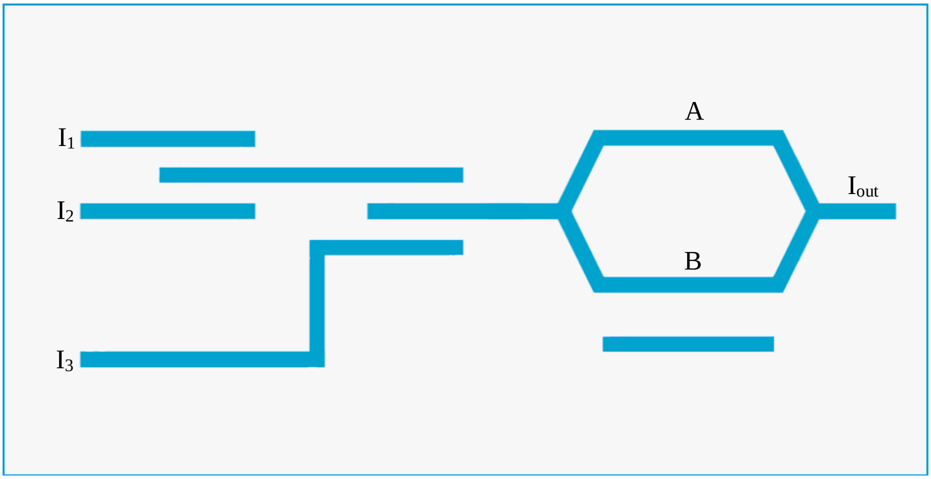

Fig. 3. The proposed structure of all-optical Majority gate.

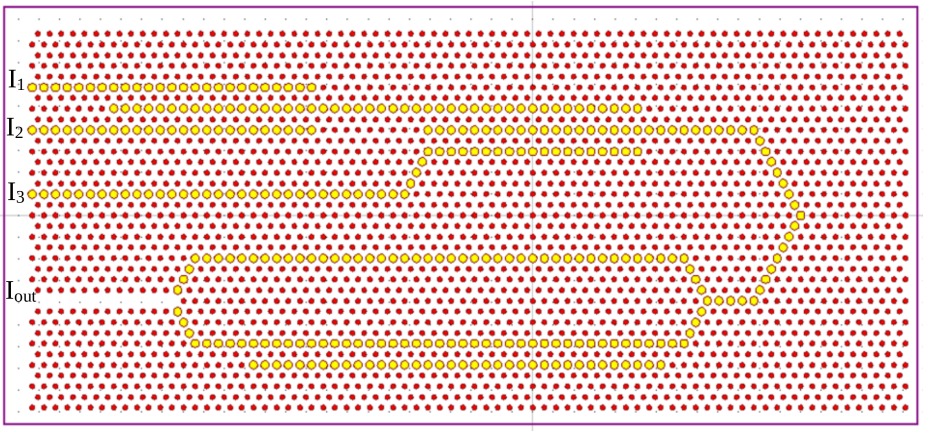

Fig. 4. The proposed all-optical photonic crystal Majority gate.

The domain analysis of the PhC-based Majority gate is presented in Fig.5. When all the input signals are off, the output signal power test is not performed due to the lack of light in the structure.

 DOI: 10.30495/JOPN.2022.28130.1225

In this research, Kerr's nonlinear effect has been used to design the logical gate of the Majority. Applying proper throughput to materials with a nonlinear effect causes changes in the refractive index of materials and changes in light transmission characteristics in nonlinear materials. By using nonlinear materials, the output of the system is affected by the input power, so with increasing input power, the output power also changes with a specific pattern. When the input power increases, the output power also increases slowly, but when the input power reaches a certain value, the output power suddenly increases.

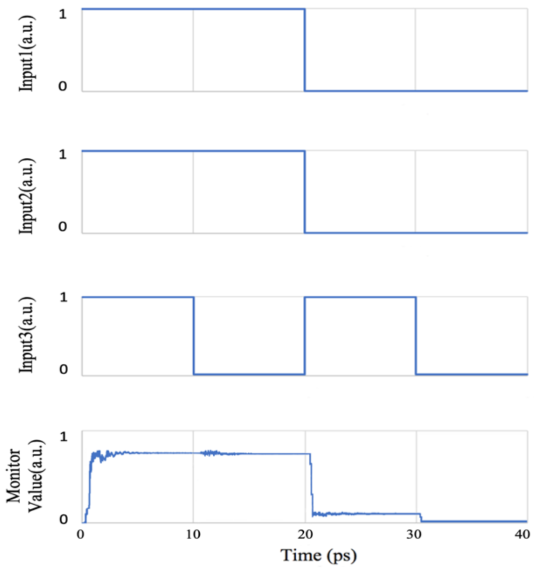

Fig. 5. The normalized domain analysis of the proposed PhC-based Majority gate.

When a square wave is launched as an input signal with power of 3W, the input signal is divided into two waveguides, A and B. The input signal obtains a phase difference of π as it passes through the B section of the "nonlinear directional coupler". So, "destructive interference" occurs in the output of this structure, and the normalized output power is 0.097P0 that P0 is equal to 3W.

When two or three of the input signals are launched, by increasing the input signal power, a signal phase change of 2π will be created. As a result, "constructive interference" occurs in the output of this structure, and the normalized output power is 0.77P0 that P0 is equal to 3 W. Fig. 6 shows the changes in system output power with respect to input power changes.

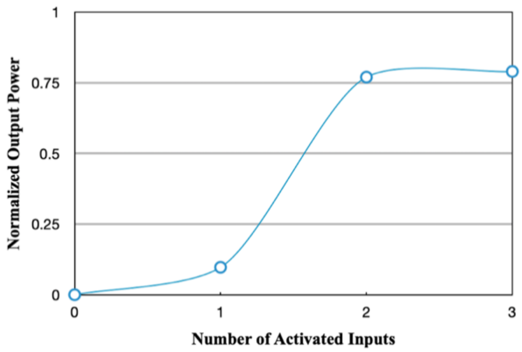

Fig. 6. The range of normalized output power changes compared to input power.

For the case where all the inputs of the majority function are on, the range of normalized output power changes compared to the wavelength changes are examined and the results are reported in Fig. 7. As shown, the range of output power changes is very small compared to the wavelength changes in the proposed structure.

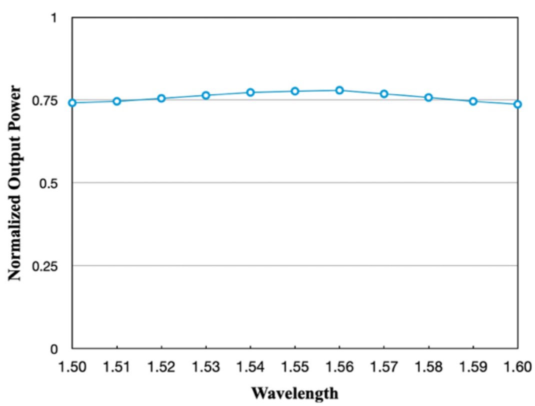

Fig. 7. The range of normalized output power changes compared to the wavelength changes in the proposed structure. (all inputs in the majority function are on).

The range of normalized output power changes compared to the refractive index changes are examined and reported in Fig. 8.

 DOI: 10.30495/JOPN.2022.28130.1225

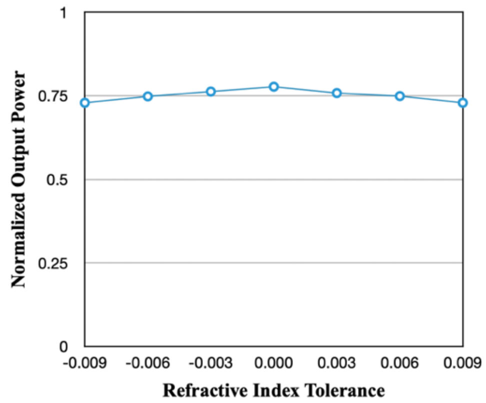

Fig. 8. The range of normalized output power changes compared to the refractive index changes in the proposed structure (all inputs in the majority function are on).

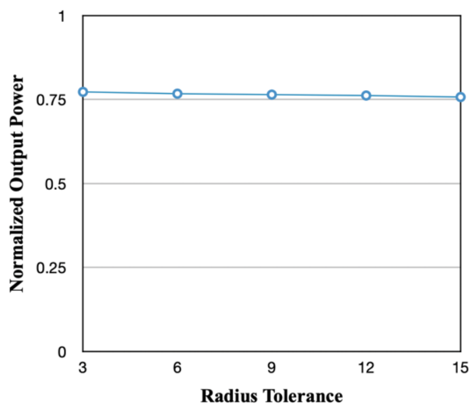

Fig. 9. The range of normalized output power changes compared to the radius changes (all inputs in the majority function are on).

The range of normalized output power changes compared to the radius changes of the rods are examined and the results are reported in Fig. 9 for the case where all the inputs of the majority function are on. As shown in Fig. 9, the range of output power changes is very small compared to the radius changes.

4. CONCLUSION

This study proposes a PhC-based all-optical Majority gate that includes a nonlinear directional coupler. Applying proper throughput to materials with a nonlinear effect causes changes in the refractive index of materials and changes in light transmission characteristics in nonlinear materials. Moreover, the possibility of light return is essentially eliminated by the proposed structure for junctions. The results of the evaluation of this new structure are reported, which confirms the operation of the PhC-based Majority gate. The effect of variations of the output power changes with respect to changes of some parameters was studied and the simulation results was shown the low dependence of this Majority gate on their minor changes.

REFERENCES

[1] A. Goodarzi and M. Ghanaatshoar. *Coherent all-optical transistor based on frustrated total internal reflection*. Sci. Rep. 8(1) (2018) 1-8. Available: https://www.nature.com/articles/s41598-018-23367-6.

[2] T. Matsumoto, K. Komatsu, G. Hosoya, and H. Yashima. *Performance of all-optical AND gate using photonic-crystal QDSOA at 160 Gb/s.* Electron. Lett. 54(9) (2018) 580-582. Available: https://ietresearch.onlinelibrary.wiley.com/doi/pdf/10.1049/el.2018.0371.

[3] S. M. H. Jalali, M. Soroosh, and G. Akbarizadeh. *Ultra-fast 1-bit comparator using nonlinear photonic crystalbased ring resonators*. J. Optoelectron. Nanostructures. 4(3) (2019) 59-72. Available: http://jopn.miau.ac.ir/article_3620.html.

[4] H. M. Hussein, T. A. Ali, and N. H. Rafat. *A review on the techniques for building all-optical photonic crystal logic gates.* Opt. Laser Technol. 106 (2018) 385-397. Available: https://www.sciencedirect.com/science/article/abs/pii/S0030399217318935.

[5] R. Fan, X. Yang, X. Meng, and X. Sun. *2D photonic crystal logic gates based on self-collimated effect.* J. Phys. Appl. Phys. 49(32) (2016) 325104. Available: https://iopscience.iop.org/article/10.1088/0022-3727/49/32/325104/meta.

[6] E. haq Shaik and N. Rangaswamy. *Multi-mode interference-based photonic crystal logic gates with simple structure and improved contrast ratio*. Photonic Netw. Commun. 34(1) (2017) 140-148. Available: https://link.springer.com/article/10.1007/s11107-016-0683-7.

[7] H. M. Hussein, T. A. Ali, and N. H. Rafat. *New designs of a complete set of photonic crystals logic gates.* Opt. Commun. 411 (2018) 175-181. Available: https://www.sciencedirect.com/science/article/abs/pii/S0030401817310611.

[8] T. Jalali, A. Gharaati, M. Rastegar, and M. Ghanaatian. *Enhancement of the magneto-optical Kerr effect in one-dimensional magnetophotonic crystals with adjustable spatial configuration.* J. Optoelectron. Nanostructures. 4(1) (2019) 67-86. Available: http://jopn.miau.ac.ir/article_3386.html.

[9] K. Milanchian. *Analytical Investigation of TM Surface Waves in 1D Photonic Crystals Capped by a Self-Focusing Left-Handed Slab.* J. Optoelectron. Nanostructures. 2(4) (2017) 19-32. Available: http://jopn.miau.ac.ir/article_2571.html.

[10] Z. Rashki. *Novel design for photonic crystal ring resonators based optical channel drop filter*. J. Optoelectron. Nanostructures. 3(3) (2018) 59-78. Available: http://jopn.miau.ac.ir/article_3046.html.

[11] M. Nikoufard and M. Kazemi Alamouti. *Design of Photonic Crystal Polarization Splitter on InP Substrate.* J. Optoelectron. Nanostructures. 1(2) (2016) 69-76. Available: http://jopn.miau.ac.ir/article_2050.html.

[12] F. Mehdizadeh and H. Alipour-Banaei. *All optical 1 to 2 decoder based on photonic crystal ring resonator.* J. Optoelectron. Nanostructures. 2(2) (2017) 1-10. Available: http://jopn.miau.ac.ir/article_2419.html.

[13] Y. Nagpal and R. K. Sinha. *Modeling of photonic band gap waveguide couplers*. Microw. Opt. Technol. Lett. 43(1) (2004) 47-50. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/mop.20371.

[14] N. Yamamoto, T. Ogawa, and K. Komori. *Photonic crystal directional coupler switch with small switching length and wide bandwidth*. Opt. Express. 14(3) (2006) 1223-1229. Available: https://opg.optica.org/oe/fulltext .cfm?uri=oe-14-3-1223&id=87790.

[15] A. Salmanpour, S. Mohammadnejad, and A. Bahrami. *All-optical photonic crystal AND, XOR, and OR logic gates using nonlinear Kerr effect and ring resonators*. J. Mod. Opt. 62(9) (2015) 693-700. Available: https://www.tandfonline.com/doi/abs/10.1080/09500340.2014.1003256.