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Efficient and Compact Optical NOR Gate based on Photonic Crystal Platform

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KEYWORDS:
Photonic crystal, optical T-shaped switch, optical logic gates, photonic integrated circuits (PICs), plan wave expanses (PWE)

***Abstract*—Highly efficient optical NOR gate based photonic crystal (Phc) is proposed and analyzed. The suggested NOR gate has a silicon (Si) dielectric in air arranged in a square lattice. The photonic bandgap of the proposed PhC structure is calculated using plane wave expansion (PWE) technique. Further, the propagation through the PhC NOR structure is studied by using finite element method. COMSOL Multiphysics software tool is used to simulate the propagation through the PhC NOR structure is investigated the finite element method (FEM). A low input power and minimal power loss are achieved using the proposed design. Further, short switching time of few picoseconds is obtained with a response time of 1.2 picoseconds and a switching rate of 133 GHz. Furthermore, a 150-mW input power per port may be employed with a little amount of power loss in the output port. In addition, in this design the out of plane scattering is eliminated from the PhC platform which has direct influence to enhance the efficiency. The reported optical NOR gate has also a small dimension of 21×12 µm2 which makes it a practical design for photonic integrated circuits (PICs)**

I. INTRODUCTION

THe optical NOR gate is a key component of optical signal processing and network architecture. Optical NOR gates based on photonic crystal (PhC) architectures have recently been developed. The PhCs are optical periodic structures that can be used to regulate and manipulate the light flow [1]. For certain frequency ranges, light waves could not pass through the PhC, which is known as a forbidden bandgap. As a result, a flaw is inserted into the periodic structure to allow the forbidden frequencies to propagate. Multiplexer-demultiplexers [2], photonic crystal fiber [3], couplers [4], all-optical liquid PhC router [4], optical PhC AND gate [5], sensors ([6]-[7]), and a nematic liquid PhC layers-based multiple picture encryption scheme [8] are just a few examples of PhC applications. Different types of optical logic gates based on PhCs have been recently presented. In this context, an all-optical AND gate has been designed based on PhCs [9]. Further, nonlinear PhC ring resonator (PhCRR) has been suggested to implement an all-optical NOR gate [10]. In the ON state, the output intensity is more than 70%, but it is only 35% in the OFF state. Another optical NOR gate based on PhCRRs has been proposed a NOR gate by using cascaded two optical switches [11]. In this study, the reported NOR gate transmission is only around 2% in the OFF state, while it is about 81 % in the ON state. PhC structures are also used to create an optical AND gate [12]. Further, an all-optical RS-FF has been

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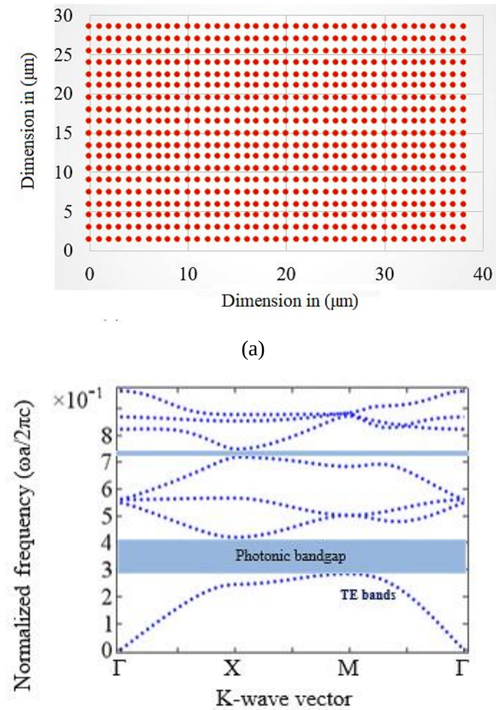
reported [13] two resonant tunneling filters based on a 2D PhC slab with a switching rate of 100 GHz.

In reference [21], a NOR gate with an out power of 68 % of the input power when the state is ON and 7 %, while the state is off, is described. The NOR gate was presented in reference [22] with an out power of 60% at ON and 5% at off states with a switching rate of 3.4 ps. Reference [23] presented a 45.36 μm^2 NOR gate with a reaction time of 1.2 Ps. The stated NOR output power was 58.4 % when turned on and 27 % at off state. Reference [24] presented an XNOR gate with a size of 85.8 μm^2 and output power of 56% at ON and 2% at OFF, with a time response of 8.33 Ps.This device also includes two optical NOR gates and two multimode-interfere structures, all of which are powered by PhC technology and have a response time of 1.2 Ps [14]. In this paper, an efficient compact optical NOR gate based on PhCs is proposed and analyzed. The proposed PhC gate consists of waveguides, optical PhC T-type switches, and PhC ring resonators (PhCRRs). Further, the suggested NOR gate was simulated using the COMSOL Multiphysics software tool and the finite element technique (FEM). The plane wave expansion (PWE) approach is used to compute the bandgap of the required PhC [15-17]. The reported optical NOR gate can only transmit around 2% of the signal in the OFF state, but in the ON state, it transmits 94% from the input signal. Furthermore, a 150-mW input power per port can be employed in the output port with low power loss. The propagation via the PhC NOR gate structure is investigated with a switching frequency of up to 133 GHz where the reported NOR gate has an output time response of 1.2 ps.

Additionally, the proposed compact NOR gate has a smaller size of 21×12 μm^2. Our suggested NOR gate has high Q-factor and tiny size with a modest input power of 150 mW. It has also a short switching time of few picoseconds. This paper aims to provide an optical NOR gate based PhCs suitable for all-photonic integrated circuits (PICs) with ultra-fast data transmissions and low power loss. The remaining paper was arranged as follows, the considered PhCs were explained in Section 2. Finally, The NOR optical gate design was explained in Section 3.

II. II. Design Considerations

The suggested design is based on 2D photonic crystal waveguide as revealed from Fig.1(a). A square lattice of Si rods is used in air in the 2D-PhC. The PhC Si rods with refractive index of 3.39 have a radius (r_a) of 0.2*a*, where *a* is the lattice constant (a = 630 nm). The dispersion diagram of the PhC structure is calculated using the method of plane wave expansion (PWE). The predicted band structure for the analyzed 2D-PhC platform is shown in Fig. 1. (b). The TE mode may be shown to have a bandgap between a/ λ = 0.32 and a/ λ =0.44.



(a)

(b)

Fig. 1 (a) The proposed PhC platform in (μm), and (b) PhC band structure diagram.

III. All-optical mode NOR gate

By introducing line defects into the 2D-PhC structure in the x- and y-directions, two optical T-shaped switches can be formed to introduce the input and output waveguides. Further, photonic crystal ring resonator (PhCRR) is implemented to build the reported NOR gate [18]. In order to eliminate light wave back reflection, four additional Si rods, each having a radius of 0.3a, are placed at the corners of the PhCRRs, as illustrated in blue in Fig. 2. Further, 4 extra Si rods shown in green color are used with a radius of 0.1a as illustrated in Fig. 2. Such green rods are utilized in the PhCRR to increase the optical wave interaction with the material. They're also used to increase the quality factor of the suggested design, which has a direct effect on the stored energy in the PhCRRs.

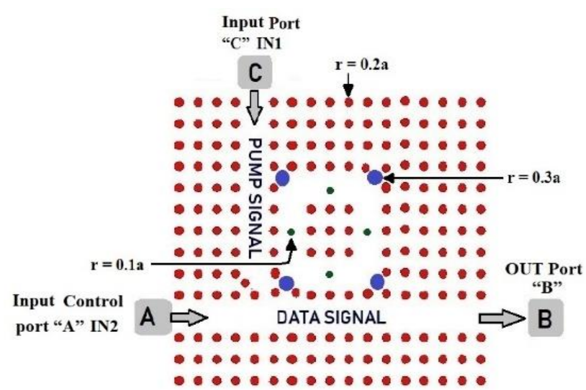


Fig.2 2D optical T-switch based on PhCRR.

In Fig. 2, 'A' is the input control port, 'C' is the input port, and output port is 'B'. These ports are three forward-transmission ports for the proposed switch. Figure 3 in blue shows port B output power when port C is switched off. If an optical signal is sent to port C for whatever reason, certain normalized frequency ranges between $a/\lambda = 0.392$, to $a/\lambda = 0.398$, as demonstrated in Fig. 3 in Green, Port A's optical signal will be unable to reach port B. Fig. 3 shows the calculate output power at Port B as a function of a/λ for two opposite turning states of the control port. Results shown in Fig. 3 have been used to select the best a/λ range with a good performance for the suggested structure. In this context, a/λ range extending from 0.392 to 0.398 has been selected since around the wavelength of 1600 nm ($a/\lambda = 0.393$) the state of output power changes from high to low values with dynamic range of about 51 dB when varying the turning state of the control port from ON to OFF.

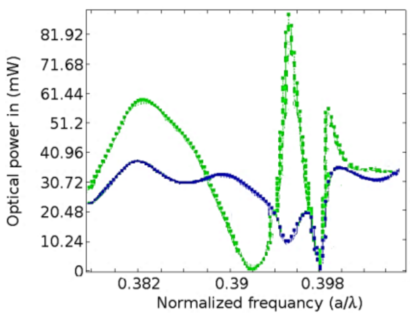


Fig.3 the transmission spectra of the PhC T –switch at port B when port C is turned OFF in Blue and in Green when turned ON.

The proposed 2D photonic NOR gate has a dimension of $21\times12\ \mu m^2$ of Si rod in air. Additionally, two T-shaped optical switches are used using the same material and lattice constant. There are three ports on each of the two optical T-shaped switches. The initial port to direct the data signal is placed between control port 'A' and output port 'B'. To make the data signal port, a whole line of Si rods is removed in the x-direction, as shown in Fig.4. Additionally, 'C' and 'D,' are input ports that are used to connect the logic control port 'A' with the PhCRRs in order to determine the logic state of port B. Moreover, 12 rods are removed in the y-direction in order to achieve this connection. All optical NOR gate has optical light wavelengths 1600 nm based on the simulation as shown in Fig.3. The normalized resonant frequencies of the structure is equal to $a/\lambda_1 = 0.3937$ for ports 'A', 'C', and 'D'.

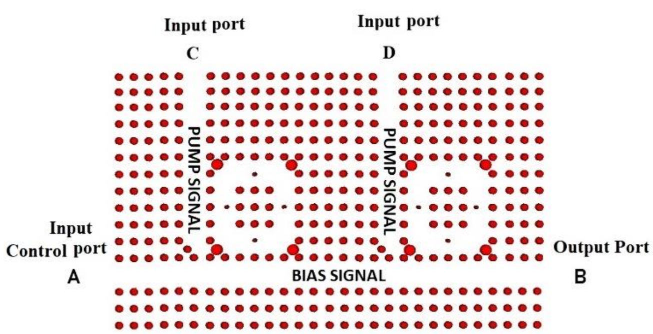


Fig.4 The proposed optical logic NOR gate

TABLE 1
ALL OPTICAL NOR GATE TRUTH TABLE, WHERE BIAS CONTROL PORT **A** IS ON IN ALL CASES.

Input port 'C'	Input port 'D'	Output port 'B'
0	0	1
0	1	0
1	0	0
1	1	0

Additionally, Port A is used to control the operation of the NOR gate. First, the input optical light wave with wavelength of 1600 nm enter the suggested structure through control port A. If input ports C and/or port D have “1” state, the output port B will have off state of “0” with no output signal as shown in Fig. 5 (a, b, c). Furthermore, the output power at port B is 160 mW when logic inputs C and D have “0” state as shown in blue in Fig. 6. Figure 6 shows the optical output power in Blue at port ‘B’ when logic inputs C and D are off. When one or both logic inputs C and D are in the ON state, the output is plotted in green. The truth table of the optical NOR gate is summarized in Table 1.

A comparison between the suggested structures with the previously known structures is shown in Table 2. From the table, it can be shown that in reference [10], the NOR gate has been implemented with an out power of 70% from input power signal at ON state and 35% at off state. In reference [11], the NOR gate has been suggested with an out power of 81% from the input power at ON state and 2% at off state. Further, NOR gate has been proposed with an out power of 90% from the input power at ON state and less than 5% when the state is off [19]. In reference [21] a NOR gate with an out power of 68% of the input power while the state is ON and 7% when the state is off. The NOR gate has been proposed in reference [22] with an out power of 60% at ON state and 5% at off states with a switching rate of 3.4 ps. Reference [23] proposed NOR gate with dimension of $45.36\ \mu m^2$ and response time 1.2 Ps. The reported NOR output power of 58.4% at ON state and 27% at OFF state. Reference [24] proposed XNOR gate with dimension of $85.8\ \mu m^2$ while the output power of 56% at ON state and 2% at OFF state with time response of 8.33 Ps.

However, the suggested NOR gate has an out power of 94% from the input power at ON state and less than 2% when the state is off. Additionally, our reported NOR gate has very little power loss and has also a small dimension of $21\times12\ \mu m^2$ which makes it a practical design for photonic integrated circuits (PICs). Two PhCRRs were employed in the proposed NOR gate, which have a switching rate of 133 GHz. Further, the disclosed optical NOR has just a few picoseconds of switching time.

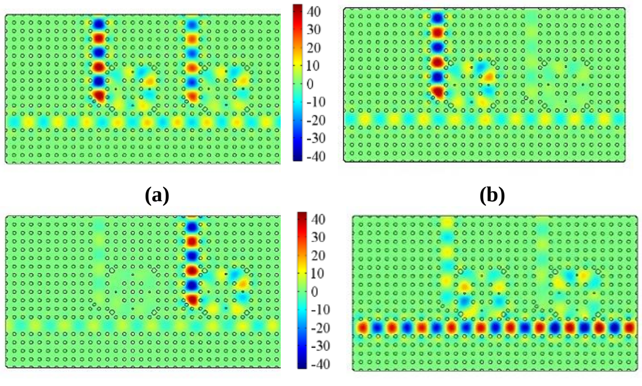


Fig.5 NOR gate electric field pattern when the normalized frequency is equal to a/λ=0.3937, (a), (b), and (c) when logic inputs **C** and/or **D** are ON, and (d) when logic inputs **C** and **D** are off.

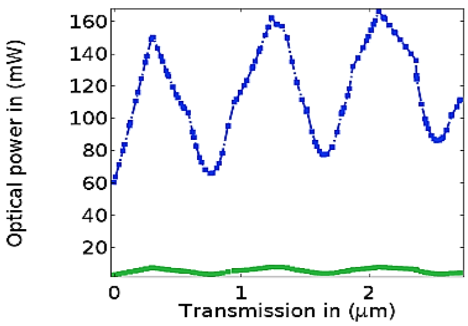


Fig.6 The optical output power in Blue at port '**B**' when logic inputs **C** and **D** are off, when one or both logic inputs **C** and **D** are in the ON state, the indicator becomes Green.

The compact dimensions of the suggested design allow low power input with negligible power loss and improved transmission efficiency. The suggested NOR gate can be made of low refractive index of Si of 3.39 and polymers, as introduced in references [25, 26]. The suggested NOR gate may be made by utilizing a substrate, core Si rods, and two layers of reduced refractive index (SiO_2), as illustrated in Fig. 8 [25, 26]. The metalorganic vapor phase epitaxy (MOVPE), and plasma-enhanced chemical vapor deposition (PECVD) [25, 26] can be used to add a Si substrate with a thickness of 500 nm, a guiding layer SiO_2 with a thickness of 340 nm, and core Si rods with a thickness of 220 nm, as shown in Fig. 7. The waveguides of the NOR gate are used in the air to maximize the vertical confinement and symmetry [18]. In order to minimize the out of plane scattering from the PhC and boost the achieved efficiency, a polymer layer pile can be inserted between the Si rods. This will reduce the index contrast in the suggested PhC where the polymer refractive index is greater than the air.

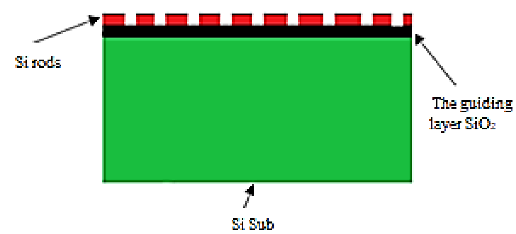


Fig.7 The suggested fabrication of all optical NOR gate.

TABLE 2
COMPARISON BETWEEN THE PROPOSED STRUCTURE AND THE PREVIOUSLY REPORTED NOR GATES

Design	**Out Power on State**	**Out Power off State**	**Device Dimensions in Mm²**	**Power Loss**	**Switching Rate**	**Improvement Percentage**
[10]	70%	35%	306.5 μm²	30%	3.42 ps	10%
[11]	81%	2%	410.13 μm²	19%	3.61 ps	15%
[24]	56%	2%	85.8 μm²	44%	8.33 Ps	18%
[19]	90%	5%	43.84 μm²	10%	2.3 ps	25%
[20]	92%	3%	46.32 μm²	8%	3.83 ps	30%
[23]	58.4%	27%	45.36 μm²	41.6%	1.2 ps	31%
[22]	60%	5%	950.33 μm²	40%	3.4 ps	36%
[21]	68%	7%	90.31 μm²	32%	1.73 ps	33%
Suggested NOR gate	94%	Less than 2%	252 μm²	6%	1.2 ps	40%

IV. CONCLUSION

In this work, an optical NOR is suggested and analyzed using square lattice of dielectric rods with a diameter of 21×12 μm² and lattice constant of 630 nm. The suggested NOR gate may be placed in photonic integrated circuits due to its modest size 252 μm² by compare with references [10, 11, 22]. The suggested all optical NOR gate is characterized by improvements up to 40% which makes it a practical design for photonic integrated circuits (PICs). To enhance the quality factor and decrease the scattered wave, the proposed NOR gate employs two PhC ring resonators and T-type waveguides. The PBG of the recommended design is calculated using the plan wave expansion method (PWE). In addition, the FEM is used in conjunction with the COMSOL software tool to investigate the propagation of the suggested design. The suggested NOR gate may be placed in photonic integrated circuits due to its compact size of 252 μm² compared to those reported in [10, 11, 22]. The suggested all optical NOR gate has an improvement of 40% which makes it a practical design for photonic integrated circuits (PICs). Further, a rapid temporal response of 1.2 PS is achieved with a switching rate of 133GHz which is slower than those introduced in [10, 11, 19, 20, 21, 22]. Finally, the suggested NOR gate can be used to boast the optical computing and signal processing. Additionally, the data will remain in the optical mode without the need for OEO conversions. This would aid in increasing the efficiency of the optical -mode gadget.

AUTHORS CONTRIBUTION

Nihal F. F. Areed and Amr Sherif H. Ahmed:conceived the presented idea.

Amr Sherif H. Ahmed developed the theory and performed the computations.

Nihal F. F. Areed verified the analytical methods and supervised the findings of this work.

Amr Sherif H. Ahmed, Nihal F. F. Areed, Hamdi El Mikati and S. S. A. Obayya **discussed the results and contributed to the final manuscript.**

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TITLE IN ARABIC:

بوابة NOR الضوئية الفعالة والمضغوطة المبنية على الكريستالات الضوئية

ABSTRACT IN ARABIC:

تم اقتراح وتحليل بوابة NOR المنطقية الضوئية الفعالة والمضغوطة. تعتمد بوابة NORالمقترحة على بلورة ضوئية ثنائية الأبعاد) 2 (PhC) (Dمع شبكة مربعة من قضبان السيليكون (Si) العازلة في الهواء. يتم استخدام طريقة تمدد الموجة المستوية (PWE)لحساب فجوة النطاق الضوئية لهيكل PhC المقترح. علاوة على ذلك، تتم دراسة الانتشار من خلال بنية PhC NOR باستخدام حزمة برامج COMSOL Multiphysicsبناءً على طريقة العناصر المحدودة .(FEM) يتم تحقيق وقت تبديل لا يتجاوز بضع بيكو ثانية مع طاقة إدخال منخفضة وفقدان طاقة منخفض. بالإضافة إلى ذلك، فإن بوابة NOR المقترحة لها استجابة وقت إخراج تبلغ Ps 1.2 مع معدل تحويل يصل إلى 133 جيجاهرتز. علاوة على ذلك، يمكن استخدام طاقة إدخال تبلغ 150 ميجاوات لكل منفذ مع فقد طاقة محدود للغاية في منفذ الإخراج. تتميز بوابة NOR الضوئية المبلغ عنها أيضًا بأبعاد صغيرة تبلغ 21 × 12 ميكرومتر 2 مما يجعلها تصميمًا عمليًا للدوائر المتكاملة الضوئية.(PICs).