Low Size All Optical XOR and NOT Logic Gates Based on Two-Dimensional Photonic Crystals

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ABSTRACT:
This paper presents a square lattice of two-dimensional photonic crystal in the design of NOT and XOR logic gates. The important characteristic of this method is that the one structure allows implementation of two types of logic gate. The structure consists of two inputs and one output; thus, whenever it is used as a NOT gate, one of the entrances acts as a controller for the input. The Plane Wave Expansion (PWE) method is used to calculate the frequency band structure of the proposed lattice. The Finite Difference Time Domain (FDTD) method is used to calculate the optical power distribution in waveguide paths. The smaller size and simple structure of the design are advantages which make the proposed structure suitable for using in optical integrated circuits. In addition, the optical power transmitted to the output in "0" logic state is very close to zero.

KEYWORDS: Photonic Crystals, Photonic Band Gap, Waveguide, Defect.

1. INTRODUCTION

Photonic crystals are periodic structures in which the refractive index varies periodically. The refractive index can be changed to one, two or three dimensions, which present one-dimensional, two-dimensional or three-dimensional photonic crystals, respectively [1]. Due to the flexibility of photonic crystals for controlling light by changing the structure's physical properties, this method has recently received much research attention [2]. In recent years, a lot of research has been done on optical devices based on photonic crystals, the most notable of which are waveguides, optical resonators, filters, de-multiplexers, couplers, lasers and delay lines [3-6].

Many studies have focused on photonic crystal structures because of their particular properties such as low size, low power consumption and good restriction. These special properties mean that photonic crystal structures have promising application in photonic integrated circuits. The reason behind this recently increased interest is that optical instruments operate at great speed compared with their electronic counterparts. According to these studies, it is expected that future research will be done to develop these types of optical integrated circuits.

Light propagation in photonic crystals depends on the specific wavelength of the light. The range of light wavelength that cannot pass through the photonic crystal is termed the Photonic Band Gap (PBG). The PBG is created by frequency of the refractive index [7].

PBG makes it possible to have control of the light. By controlling and guiding light wavelengths in the PBG in a specified direction, it is possible to make changes to the routes and this is called defect. Defects can be formed by changes in the refractive index, change in measurements, removing rods, by displacing some of the rods or any other change to the photonic crystal [8].

In addition to using photonic crystals as analog circuits, they can also be used instead of digital circuits. For example, they can be applied for designing logic gates. Low loss transmission, high speed and high bandwidth are the main advantages of them. As photonic crystal forms the basis of integrated circuits, recent studies have been done to design logic gates and circuits using photonic crystals [9-17].

In this paper, two types of gate; NOT and XOR were designed and simulated by applying two-dimensional photonic crystal using a square lattice. For the implementation of these gates, a photonic crystal was used with two inputs and one output related to each other using a linear defect. In order to make use of this structure as a NOT gate, only one of the entrances is used as the entrance gate and the other is used as the controller of the input light source. If it is applied as an XOR gate, it will have two inputs and one output. The PWE method was applied to simulate this structure for calculating band structure and the FDTD method was used to calculate optical power distribution.

The simplicity of the proposed structure and thus its fabrication process are its advantages. Another advantage is in symmetrical structure. Also, two gates can be used from one structure. The symmetrical structure may be used as XOR gates, in this case, the outputs will be equal for unequal inputs (A=0, B=1 and A=1, B=0).

The logic of "0" and "1" is defined according to the distribution of the optical power of the input signal. This means that if the optical power is close to zero, it is defined as logic "0" and if its value is close to the optical power created by the source, it is defined as logic "1".

This paper is organized as follows: following the introduction, field equations are presented. Subsequently, the suggested design is introduced and the simulation results for the optical NOT and XOR gates are shown in sections 3 and 4, respectively. Afterwards, the conclusion of this study is presented in section 5.

2. THE FIELD EQUATIONS

To study the behavior of light in photonic crystals, it is necessary to solve Maxwell's equations. Maxwell's equations consist of two main equations, those of TE and TM polarization [18].

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (1)$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} \quad (2)$$

$$\nabla . \vec{D} = 0 \ , \ \nabla . B = 0 \quad (3)$$

Which in the above relationships $D(r,t) = \epsilon_0 \epsilon_r \vec{E}(r,t)$ and $\vec{B}(r,t) = \mu_0 \vec{H}(r,t)$. In the given relations, ϵ_r is relative electric permittivity, ϵ_0 is the air permittivity and μ_0 is the magnetic permittivity. For the purpose of this study, we were most interested in analyzing this type of mode, considering that the forbidden band gap was apparently created for TM polarization.

Using the Maxwell's equations, it is possible to find the time-independent equation for the wave equation [18].

$$\nabla \times \frac{1}{\varepsilon} \nabla \times H(r) = \frac{\omega^2}{c^2} H(r) \quad (4)$$

Using the acquired equation and solving it, it is possible to calculate the optical power distribution and special frequencies in a lattice.

3. DESIGN AND ANALYSIS

The proposed model for the desired gate is that of a two-dimensional photonic crystal with a square lattice including dielectric rods in the air. The refractive index of air is equal to 1 and the refractive index of the rods is 3.4. Lattice constant (a) is 540nm and radius of rods is 0.2a, which is equal to 108nm. Inputs A and B are chosen in such a way that they had phase difference of π in relation to each other. Simulation for this mode is done according to the created band gap for optical waves. Fig. 1 shows that the proposed structure included 12 × 15 rods in the air.

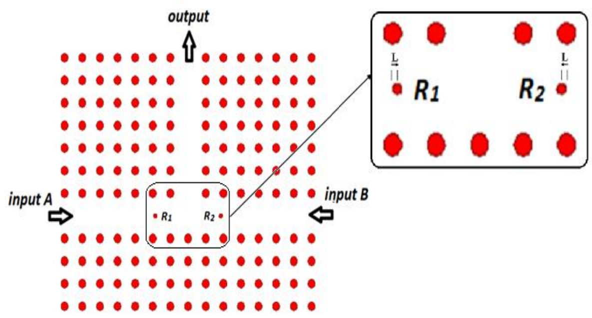

Fig. 1. The proposed structure for NOT and XOR logic gates.

Radiuses of rods of the input paths are R1 and R2 such that they would be considered as half the radius of each of the other rods. These rods prevented the entry of another source wave when the input value in the path is zero. Fig. 2 shows the band structure for the proposed photonic crystal lattice. PWE is used to calculate band structure.

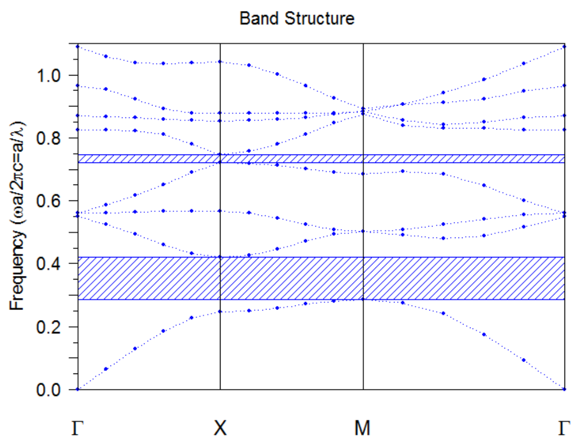

Fig. 2. The obtained band structure for the given photonic crystal lattice.

According to the obtained band structure, it can be seen that a photonic band gap is created in the normalized frequency interval of 0.29-0.42, which equals to the wavelength of 1285-1862nm. In the following, simulation of wavelength input is considered as 1550nm, which is located within the band gap.

4. SIMULATION RESULTS

The boundary condition of Perfectly Matched Layer (PML) was used to make simulations to calculate the optical power. The FDTD method was used to simulate and calculate the optical power distribution. RSOFT software was used in this paper.

To use the proposed structure as the NOT gate; source A is considered as the input, and source B is applied as the controller of the input, which had π phase difference with the input and its value is always equal to " 1". Distance between the two sources of output is similar, so this phase difference is made when the input is "1 ", the input waves cancel each other's effect at the confluence point and the output signal will be close to zero.

When input A is "0", the created wave from source B through its path by rod R_2, is coupled into the cavity and reflected in such a way that rod $R_1$is there and its maximum value is transmitted to the output path that contained no rod. In other word, the source B can be used as a controller input when the input is "0" and may be causing that the output is in logic "1" state. In fact, the distance between the two rods by radiuses R_1 and R_2, acted as a cavity and prevented leakage in the input path A. Fig. 3 shows simulation results for different input values of A.

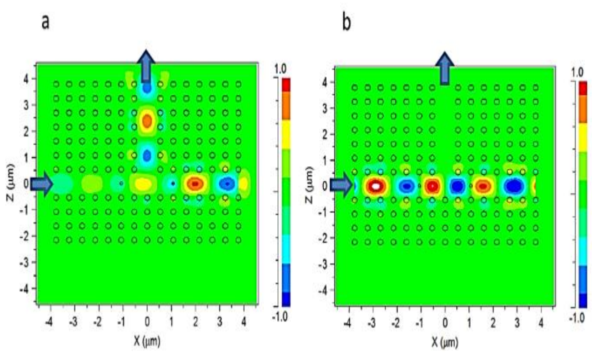

Fig. 3. Using the structure as a NOT gate a) Input A=0 and b) Input A=1.

As shown in Fig. 3(a) for input A=0, the light from the control input is transmitted to the output and the logical value of the output is "1". Fig. 3(b) shows that, if the input A is "1", the light from this source affects the control source light and prohibits it from reaching the light to the output. In this case, the logical value of the output is "0". Table 1 shows the normalized input and output values of optical NOT logic gate and their equivalent logical values.

Table 1. Input and output values for the NOT gate.

Input **A**	Input **A** (Logic)	Output (normalized value)	Output (Logic)
OFF	**0**	**0.82**	**1**
ON	**1**	**0**	**0**

It is possible to simulate the structure for calculation of the transmitted power according to the input wavelength within the distance of the intended wavelengths to find wavelengths at which the gate works properly. Fig. 4 shows the results of this simulation.

Fig. 4 indicates that the proposed structure can be used as a NOT gate in wavelength band between 1540nm to 1585nm. As shown, both states "0" and "1" in the vicinity of a wavelength of 1550nm work well.

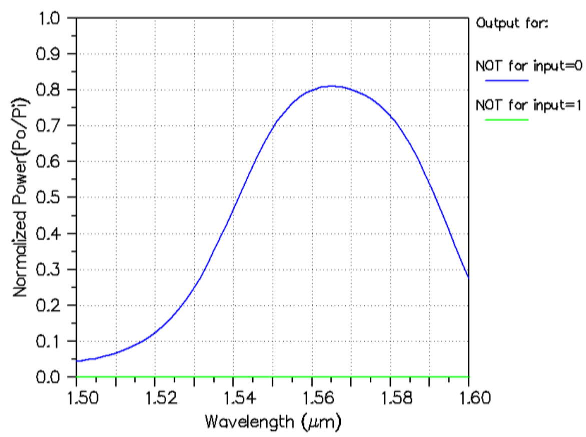

Fig. 4. Transmitted power versus wavelength of input light for NOT gate.

In order to apply the same structure as the XOR gate, A and B inputs are selected in such a way that together they had a phase difference of π. In this case, if both inputs are equal, they had a neutralizing effect on the optical power at the intersection point and the optical power distribution at the output is minimal and this is equivalent to logic "0". If the inputs are not equal, namely one of the inputs is in logic "0" and the other is in logic "1", then the optical power distribution at the output is considerable and this is equivalent to logic "1".

Figs. 5(a) and 5(b) show results of simulations for unequal inputs. As can be seen, much of the optical power distribution related to the input value "1" went to the output and a small amount of that went to input with the value of "0". When inputs are equal to "0", any field distribution at the output is not created. If the inputs are equal to "1", due to phase difference of π to each other, then they neutralize the effects of optical power at the confluence point and the optical power distribution at the output is approximately zero (see Fig. 5(c)).

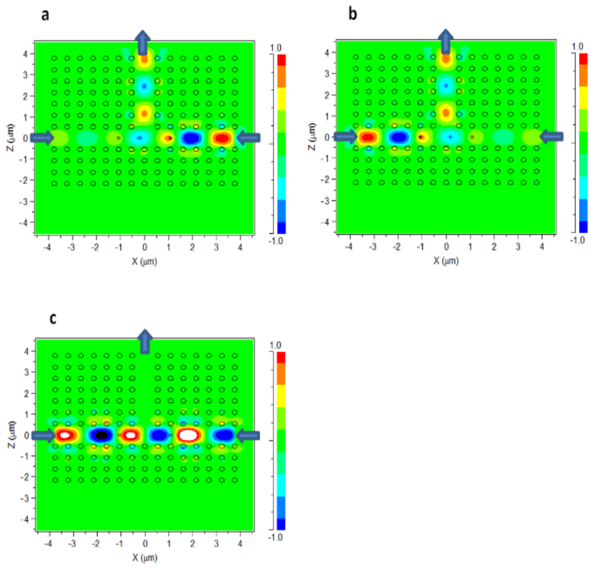

Fig. 5. Using the structure as the XOR gate
a) A=0, B=1, b) A=1, B=0 and c) A=1, B=1.

According to Fig. 5 (a) it can be observed that when one input source is on and the other is off (A=0, B=1), the highest amount of light is transferred to the output and very slight amount of light emitted is conducted to the other input that is off. In this case, the optical power ratio of output to input is 0.82 implying logical "1". The same situation occurs also for A=1, B=0 in Fig. 5 (b). Fig. 5 (c) exhibits that both input sources are on (A=B=1). In this case, the optical power ratio of output to input is very trifle implying logical "0". Table 2 shows the normalized input and output values of the optical XOR logic gate and their equivalent logical values.

Table 2. Input and output values for the XOR gate.

Input A	Input **A**(Logic)	**Input B**	Input **B**(Logic)	Output (normalized value)	Output(Logic)
0	**0**	**0e**	**0**	**0**	**0**
0	**0**	**1**	**1**	**0.82**	**1**
1	**1**	**0**	**0**	**0.82**	**1**
1	**1**	**1**	**1**	**0**	**0**

Variation of optical power distribution with change in radiuses of rods in the defects ($R_1$and R_2) is calculated based on two unequal inputs. Fig. 6 shows the distribution of the transmitted optical power into the output and input A, when A=0 and B=1.

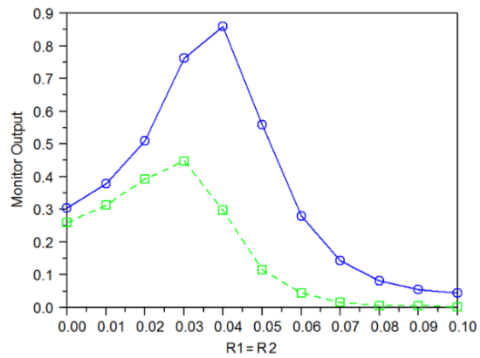

Fig. 6. Variation of optical power ratio with the change in radius of rods in the defects. Transmitted power to the output (solid line) and off input path (dashed line).

Calculation results showed that if $R_1 = R_2 = 0.37R$ (where R is the radius of the other rods), the maximum optical power is transmitted to the output and transmitted power into the input by the "0" value, is not considerable. For larger values of $R_1$and R_2, the leakage power consumptions into the A input will decrease, but the transmitted light power to the output will be decreased too. The transmitted light power to the output will decrease for smaller values of $R_1$and R_2. Also the leakage power consumptions into the A input will decrease.

Another way to optimize power transmission is through changing the position of the rods in the defect. In this step, two rods (size 2L) are close together, whereby each is moved to the other side of L. Fig. 7 shows changes in the distribution of the optical power at the output and input path with the value of zero.

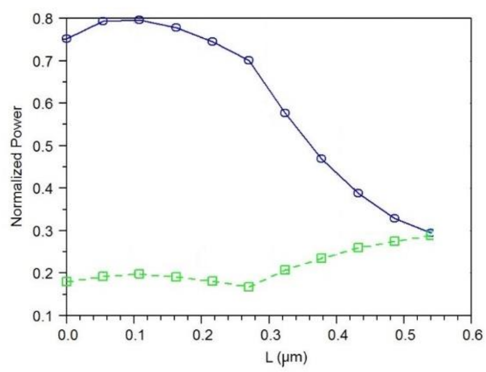

Fig. 7. Variation of optical power ratio with the change in position of rods in the defects. Transmitted power to the output (solid line) and off input path (dashed line).

As seen in Fig. 7, optimal status is achieved when the rods are moved towards each other, with the size of 0.1μm. In this case the transmitted optical power to output is high and the power consumptions into the A input is low.

5. CONCLUSION

In this paper, NOT and XOR gates are designed using a two-dimensional photonic crystal with a square lattice. The FDTD method is used to simulate the proposed photonic crystal lattice. Based on the optical power distribution at the input and output terminals, logic "0" and "1" are defined. This structure has two inputs with a phase difference of π. When the structure is used as a NOT gate, one of its ports served as the input controller. By changing the radiuses of the defect rods and changing distances, it is possible to optimize conditions for transferring the maximum output power and the lowest leakage into the input path with the value of zero.

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