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Design, simulation and optimization of all-optical NOT/XOR logic gates for use in the new photonic crystal 4×2 encoder

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Abstract

In this paper, in a unique work, the structure of NOT / XOR multifunctional all-optical logic gates is provided using interference effects in 2D photonic crystal structures for use in photonic integrated circuits of next generation. The applicability of the structure has been analyzed by modifying the output waveguide to optimize it and finally examining its performance by placing several structures together for using in optical integrated circuits. In both basic and optimized structures, the contrast ratio, response time, and data transfer rate were measured 36 dB, 0.176 ps and 5.68 Tbit/s, respectively. Appropriate output results along the very small size of about 75.78 µm2, these circuits make the logic very proper for use in optical integrated circuits. For this purpose, in a more complete work, an all-optimal 4×2 Encoder has been designed using optimized structure. In this structure, the contrast ratio is about 13.2 dB, the response time is 0.168 ps and the data transfer rate is 6 Tbit/s. The results of this NOT/XOR basic and optimized all-optical logic gate structure as well as 4×2 Encoder indicate the high flexibility and applicability of these designs for use in structures in this field for use in optical integrated circuits. In this paper, the Plane Wave Expansion method is used to obtain and analyze the photonic band gap range and the Finite-difference time-domain is used to analyze and simulate the designed structures.

Keywords: Photonic crystal, Optical logic gate, Photonic band gap, Optical integrated circuit

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1. Introduction

In general, photonic crystals (PC) are structures of alternating dielectrics that act as a mirror for a specific range of optical waves with specific wavelengths, which are common to the photonic band gap (PBG) and prevent the emission of light within the structure [6, 7]. In these structures, the optical waves transmitted into the structure alternately face with different refractive indexes in their path, so that the motion of the photon in such structures is similar to the motion of electrons within the semiconductor. In the semiconductor, the electron in the path of its motion in the semiconductor observes the alternating potential well generated by the order of the semiconductor PC lattice and it is affected by the nucleus effect of the lattice atoms. In this case, it is needed to solve the Schrödinger equations to investigate the behavior of the electron motion. The very similarity of the differential equations describing the behaviors of electron and photon in these two states will cause to achieve their behavior in a similarity way. For this reason, PCs are sometimes referred as dual electronic circuits that by changing the dielectric refractive index of a material, an artificial atom can be created, although its properties can be changed, manipulated and improved by the designer [19].

After discovering the phenomenon of PBG in these alternating PC structures, the researchers thought to use PCs in the design of photonic integrated circuits (PIC) [2]. Shortly after introducing the properties and features of PC structures, the idea of using them in the designing and manufacturing of optical waveguides, optical lenses, optical filters, optical multi/demultiplexers, optical lasers, optical sensors are proposed and much welcomed [3, 4]. Meanwhile, the debate over the use of optical switches and all-optical logic gates and next-generation optical memories is being seriously discussed among researchers. Compatible with the technology of manufacturing PC with the technology of semiconductor devices and electronic integrated circuits causes to easily integrate them with an electronic chip [18].

As it was mentioned, logic gates are one of the important optical devices in the design of next generation integrated circuits [14]. One of the solutions for using and designing these devices will be the use of PC structures. In general, in the design of all-optical logic gates based on PCs, several parameters are involved in their evaluation, comparison and efficiency. Among them, it can be referred to the contrast ratio, signal and input response time, implementing capability, output power and bit rate [17, 16]. However, three main mechanisms are used to implement these structures in order to meet these parameters and obtain the best performance, including:

- Kerr nonlinear effect in PCs
- Self-collimation effect in PCs
- Interference effect in PCs

Among the three cases, the use of the Kerr nonlinear effect has been widely used by designers and researchers, but the use of this mechanism will cause lack of proper implementing capability and complex and difficult design, high response time and low contrast ratio compared to two other mechanisms [15, 11]. Using the self-balancing effect, in turn, has a high scattering of light within the structure along with the difficult design. But in the meantime, the use of the interference effect is relatively better [22]. Because its use due to its nature causes simplicity in terms of designing and manufacturing, as well as a relatively smaller structure with a higher contrast ratio than the other two mechanisms [9, 13, 1].

The main purpose of this paper is to use the interference effects to the design of the PC all-optical logic gate. The way of the performance of structure by using this method is that if the light waves during the interference have a phase difference of about $2n\pi$ and $(n = 1, 2, 3, \dots)$, the interference is constitutive and in this case, the output of the logic gate will have the mode π or on. Now if the phase difference between the waves during the interference is about $(2n+1)\pi$ and $(n=1,2,3,...)$, then the interference would be destructive and the logic gate output will have mode 0 or off. Therefore, according to this expression in PC logic gate structures, it can use the phase difference between the waves to control the output waves and finally designing the considered structure [12, 10].

In this paper, NOT and XOR all-optical logic gates are designed and simulated using 2D PC structures. To investigate the applicability of these structures, we investigate the effects of changes in optical waveguides in the simulation results. For this purpose, the vertical waveguide was first used in the design of the logic gates and then, by the changes made, the curved waveguide to design the considered structure is used. After this operation, the structure is applied to various applications such as optical integrated circuits. For this purpose, several structures of these devices are placed together and the results are studied. Finally, by investigating the results and its satisfactory, the all-optical encoder logic gate is designed.

2. Theoretical aspects of all optical logic gates based on PC

The theoretical modeling of the behavior of in-device light based on the optical properties of the material should be considered for manufacturing optical devices, including pre-design PC based optical devices. For this purpose, there are various techniques for theoretical studying of light scattering and wave interference in these devices. The analytical approaches used to study these cases are based on defining and simulating magnetic fields in the structure [19],[20, 5, 8]. These common approaches include:

- Transfer matrix techniques
- Finite-difference-Time-Domain (FDTD) and Finite-Difference-Frequency-Domain (FDFD)
- PBG calculation based on Plane Wave Expansion (PWE)

In these theoretical approaches, if their limitations are considered due to the nature of their application and the results are properly analyzed, it will become a powerful tool in the hand of designers.

In this paper, one of the objectives is to model alternating PC structure using PWE and FDTD methods. As mentioned in this paper, the main objective is to design the structure using interference effects, which using the above mentioned methods, this structure can be modeled in the best possible way and provide accurate and complete solutions for the considered calculations.

In FDTD method, the matrix inversion is not used, and due to its computational nature, it does not have linear algebra problems and it is a very accurate and stable method. In this way, errors are identified as best as possible and allow for a more accurate answer by reducing them. In this method due to its time domain, it is also possible to generalize and present a model based on nonlinear problems. Structural analysis in this way is reduced to a networking problem and does not need to rewrite complex integral equations, which will increase the computational speed and thus reduce the memory occupied by the computer [20].

The computational method of determining how light is scattered, diffused, and transmitted within these structures is crucial and essential for using the unique properties of PCs to design the optical devices based on them. Specifically, the frequency range for the light emitted within these structures in all directions of the PC must be specified, and the range of distribution in the PC for each frequency must be correctly calculated. One of the approaches used in this field is the use of PWE method that this method is simple and efficient to calculate frequency eigenvalues and to solve the band structure (scattering ratio) in PC structures. This method is possible using the Helmholtz method in plane wave and Maxwell equation analysis. One of the unique features of this method is the separation of Transverse Electric (TE) and Transverse Magnetic (TM) modes in addition to the aforementioned cases, which enables the design and manufacturing of different devices in different modes and different efficiencies [8, 21].

The amount of articles and research published annually using both methods to analyze and model PC based structure is a testament to the claim of expanding and importance of these methods. The expansion will continue with the attention of engineers and scientists in various fields including nanoelectronics, optics and photonics as well as integrated optical circuits.

3. Design and simulation results

3.1. Design of all optical logic NOT & XOR gate

In order to design optical devices based on PCs, first, it should be achieved the PBG to determine the scattering range of optical waves and the emission of light within the structure. For this purpose, in order to design the considered logic gate structures at first, 14×20 dielectric rods of silicon PC with refractive index of $n = 3.14$ and rod radius and lattice constant equal to $R = 100nm$ and $a = 519nm$ are used, respectively. According to the values of the structure parameters in this mode, the overall structure size will be $75.78\ \mu m^2$ with the PBG range shown in Fig. 1. According to the considered figure, the structure has two wavelength ranges in TM mode. The values of these photonic band gaps are $0.291 \leq \dfrac{a}{\lambda} \leq 0.427$ and $0.730 \leq \dfrac{a}{\lambda} \leq 0.750$, respectively, which will be equal to the wavelength range of $1215\ nm \leq \lambda \leq 1783$ nm and $692nm \leq \dfrac{a}{\lambda} \leq 720nm$, respectively. According to the coverage range of the wavelength, the PBG of the very suitable structure for designing the considered structures is evaluated applied.

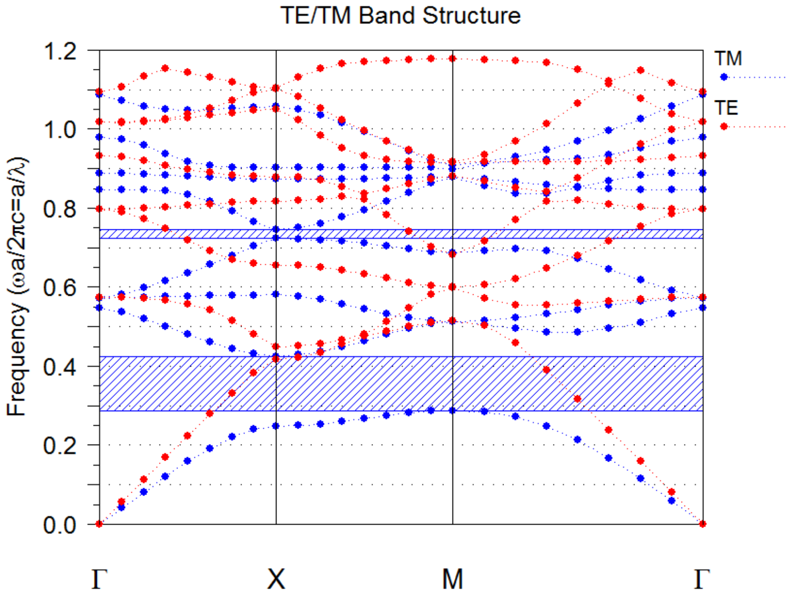


Figure 1: The band gap structure of the fundamental PC

Three optical waveguides with two input ports and one output port connected to each other as T-shaped connection are used to design the all-optical logic gate structure. Each of the input waveguides (W1, W2) is removed by removing a row of dielectric rods to create a 180° phase difference. The way of T-shape connection of the input waveguides, the outputs are optimally selected, in which the defect in the radius of the dielectric rods at the connection of the optical waveguides is used to reduce the power loss and backlighting that is clearly shown in Figure 2.

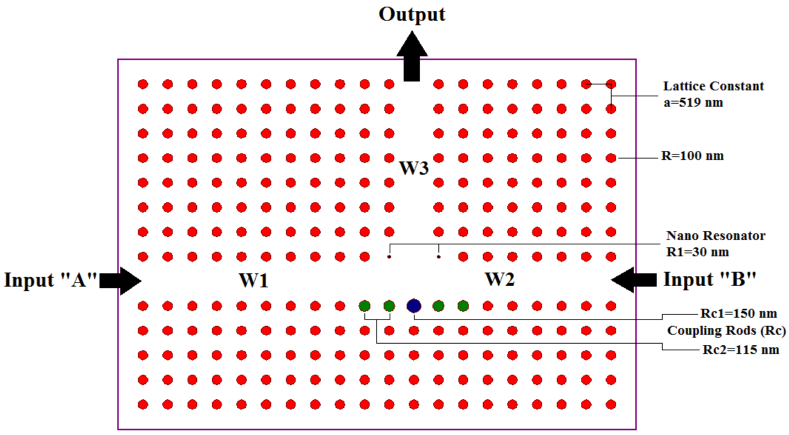


Figure 2: Schematic of the proposed all optical NOT/XOR logic gate

The way of designing structure has been to take advantage of the interference effects of the waves. All simulations were performed at the applied wavelength of 1550 nm. As it can be seen in Fig. 3a, to implement the NOT logic gate, port B is the associate of bias in the structure. If port A is switched on, in this case, the input signal with the bias port is destructively interfered due to the lack of the same distances at the connection point and the 180 degree phase difference and the logic state 0 will be at the output port. In this case, the input power at the output port is 0.0002 Pin.

However, if the input port is off, since the bias port is switched on at the T point, no destructive interference will occur, mode 1 will be created at the output, which is visible in Fig. 3b. In this case, the input power is estimated at output port 0.854 Pin.

One of the unique features of this structure is its high flexibility to create an all-logical XOR structure in addition to the NOT mode, so ports A and B are considered as input. All modes of this logic gate are fully illustrated in figure 3 after the simulation. In this structure, in addition to the two previous port modes, the switching on mode of port A and switching off mode of port B will be occurred, in this case, the input power is 0.846 Pin in output (Fig. 3c). According to the results, the structure contrast ratio in both NOT and XOR logic gates is 36 dB, the response time is $0.184ps$ and the data transfer rate is about $43.5Tbit/s$.

3.2. Design of optimization all optical logic NOT & XOR gate

Following the process of designing to optimize the structure for use in other PICs, the changes are made to arrange the output waveguide. For this purpose, the output waveguide has been changed from the vertical mode to the curve mode shown in Figure 4. As it can be seen, scattering rods have been used in the waveguide curve to better direct the light inside the waveguide as well as to prevent the reflection of light within the structure. The results of the optimized structure simulation are presented in the two modes of NOT and XOR logical gates. The amount of power received in the output does not change significantly than the original structure. The contrast ratio, response time as well as data transfer rate in the considered structure is 39 dB and $0.176ps$ and $68.5Tbit/s$, respectively.

As it is shown in the simulations of both the initial and the optimized structures, the results show the high flexibility and applicability of these structures in the applied designs for next generation

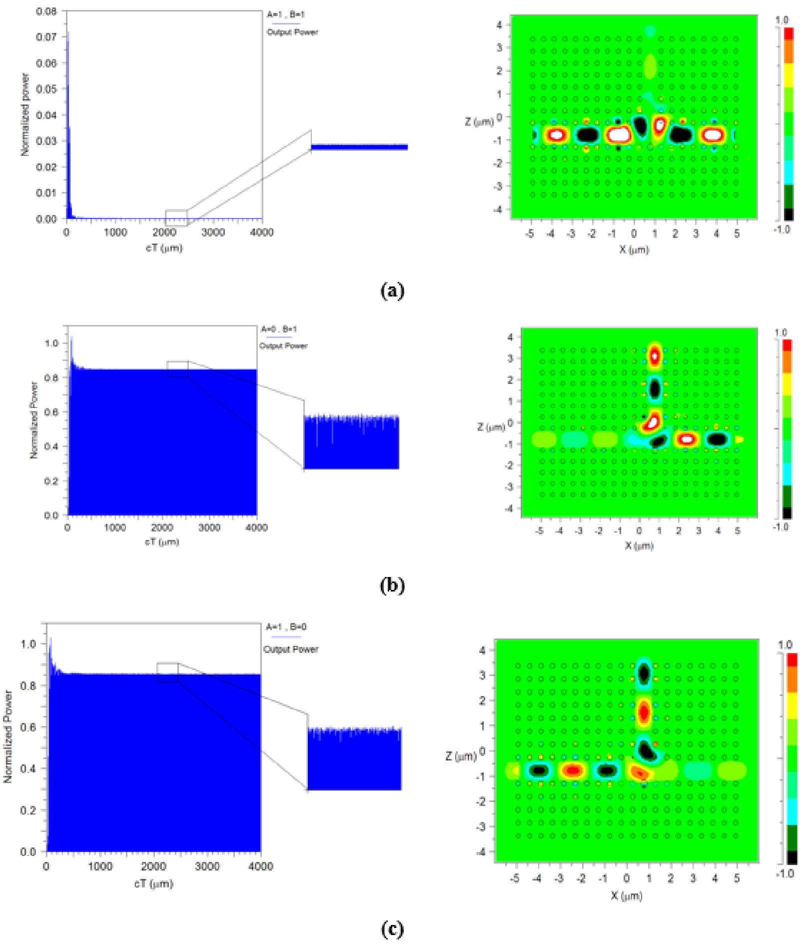


Figure 3: The power transfer diagram and the electromagnetic field pattern of all optical NOT/XOR logic gate. (a) NOT: 1 & XOR: 1 1. (b) NOT: 0 & XOR: 0 1. (c) XOR: 1 0.

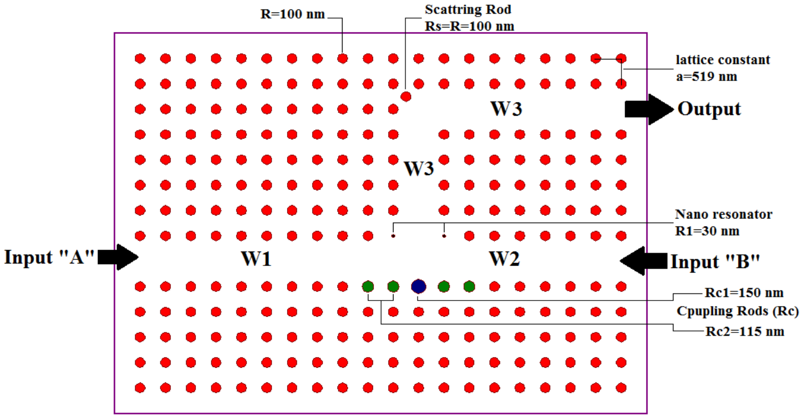
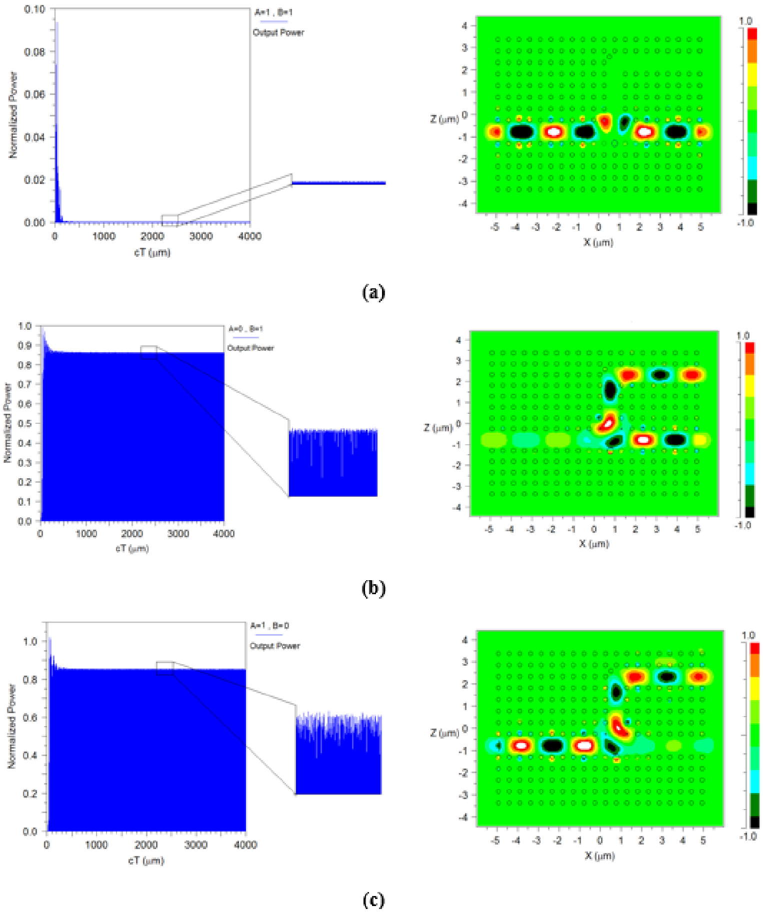


Figure 4: Schematic of the optimization all optical NOT/XOR logic gate

integrated circuits compared to other structures in this field. Table 1 is presented for a better comparison between the structures considered and the other structures presented so far.



(a)

(b)

(c)

Figure 5: The power transfer diagram and the electromagnetic field pattern of optimization all optical NOT/XOR logic gate. (a) NOT: 1 & XOR: 1 1. (b) NOT: 0 & XOR: 0 1. (c) XOR: 1 0.

Table 1: Comparison of the proposed NOT/XOR logic gates with previous designs

REF	Logic gate	Lattice constant	Size (μm^2)	Response Time (ps)	Contrast ratio (dB)
This paper	NOT/XOR	Square	78.75	0.184	36.3
This paper (Optimization)	NOT/XOR	Square	78.75	0.176	39.3
[10]	NOT/XOR	Triangular	252	0.466	20
[12]	NOT/XOR	Square	85	0.317	43
[1]	NOT/XOR	Square	465	***	20
[14]	NOT	Triangular	122	***	5
[16]	XOR	Square	105.7	0.136	55.2

3.3. Investigation of optimized structure performance for use in PICs

One of the most important methods for designing and manufacturing all-optical logic gates is the integrated capability of these structures to use in larger, higher-level logic circuits. For this purpose, in the following of this article, the optimized logic gates by focusing on several structures and their functionality have been investigated. As it is shown in Figure 6, the two optimized logic gate structures are designed in parallel by creating a 360 degree difference. In this structure, 22 × 20 dielectric rods were used to design the structure. According to the figure, the structure has 4 input ports and 2 output ports.

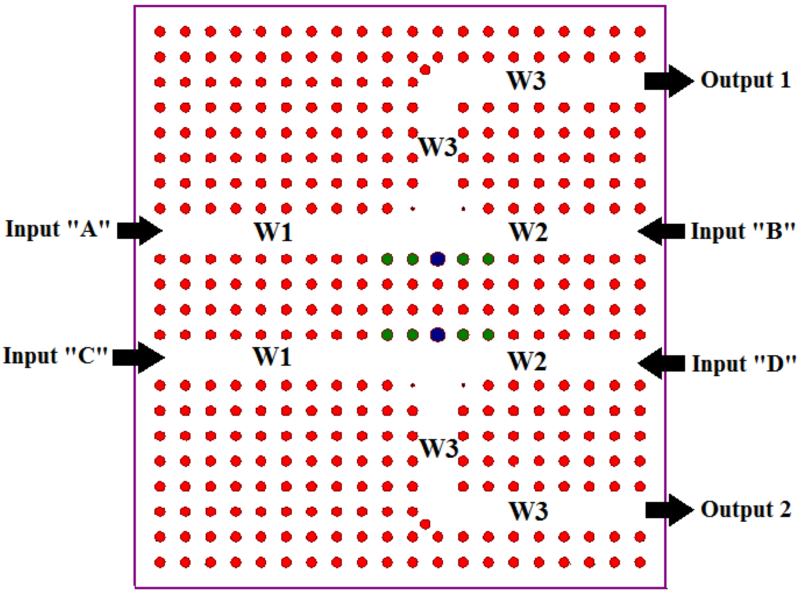


Figure 6: Putting two optimization all optical logic gate on each other in an PICs

After designing the structure, the structure has been stimulated for investigating its performance, in Fig. 7, a number of possible modes with different inputs are shown that in Table 2, the amount of power received in each output and logic modes is fully presented. They are fully brought. In this structure, the contrast ratio is $39dB$ and the response time is $0.165ps$, which shows the proper performance of the structure along with the high flexibility of the structure optimized for various applications of all-optical logic devices.

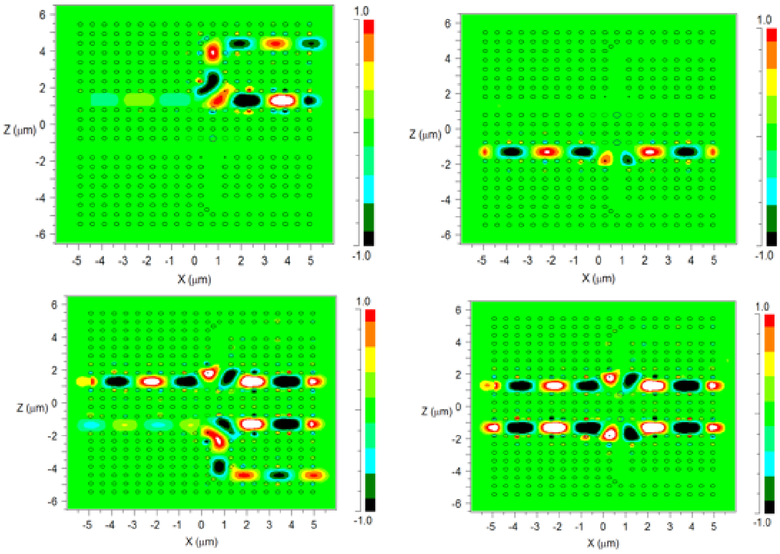


Figure 7: The electromagnetic fields pattern for some possible modes.

Table 2: The amount of outputs power and truth table for the proposed structure

Upper Input	0/1	Bottom Input	0/1	Upper Output	0/1	Bottom Output	0/1
0	0	***		$0.86P_{in}$	1	***	
P_{in}	1	***		$0.0001P_{in}$	0	***	
***		0	0	***		$0.858P_{in}$	1
***		P_{in}	1	***		$0.0001P_{in}$	0
0	0	0	0	$0.851P_{in}$	1	$0.85P_{in}$	1
0	0	P_{in}	1	$0.851P_{in}$	1	$0.0001P_{in}$	0
P_{in}	1	0	0	$0.0001P_{in}$	0	$0.852P_{in}$	0
P_{in}	1	P_{in}	1	$0.0001P_{in}$	0	$0.0001P_{in}$	0

*3.4. Design of all optical 4*2 encoder for Use in PICs*

Following the design process to evaluate the usefulness of the structure and its use for higher level designs for use in optical integrated circuits using the previous structure, a 4×2 encoder structure has been designed. The final outline of this structure is shown in Figure 8. As it can be seen in this structure, there is a slight difference in the input ports to create logical modes. Generally, an encoder has n output port and 2n input lines, which produce binary code outputs related to binary value.

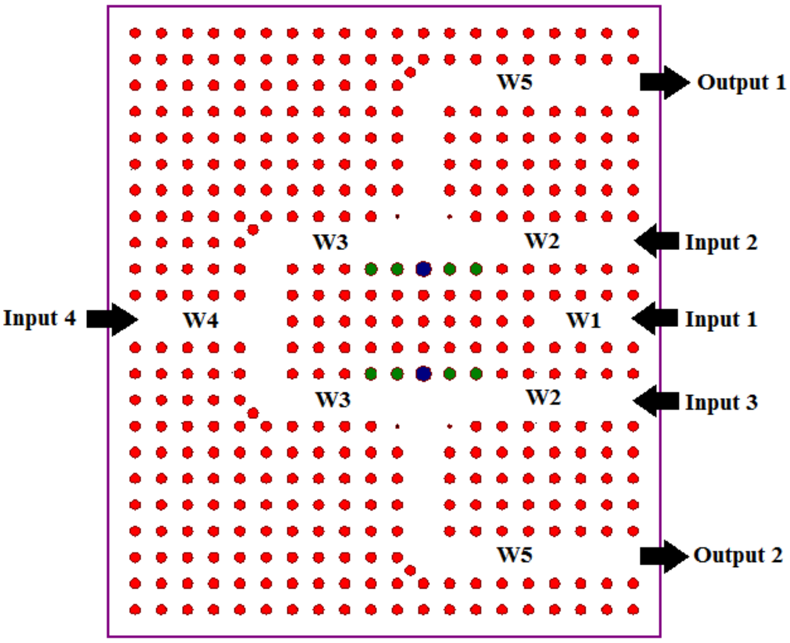


Figure 8: Schematic of the all-optical 4 × 2 Encoder.

The results of the simulation of these different modes are shown in Figure 9. Table 3 shows the input power of each output in its logical modes. As it can be seen from the results, the same power distribution in each of the outputs in different situations will also show the high symmetry and flexibility of the structure for use as other optical devices. The contrast ratio, response time and bit rate in this structure will be 13.2 dB, 0.168ps and 6$Tbit/s$ respectively, which is very suitable and competitive with other structures in this domain.

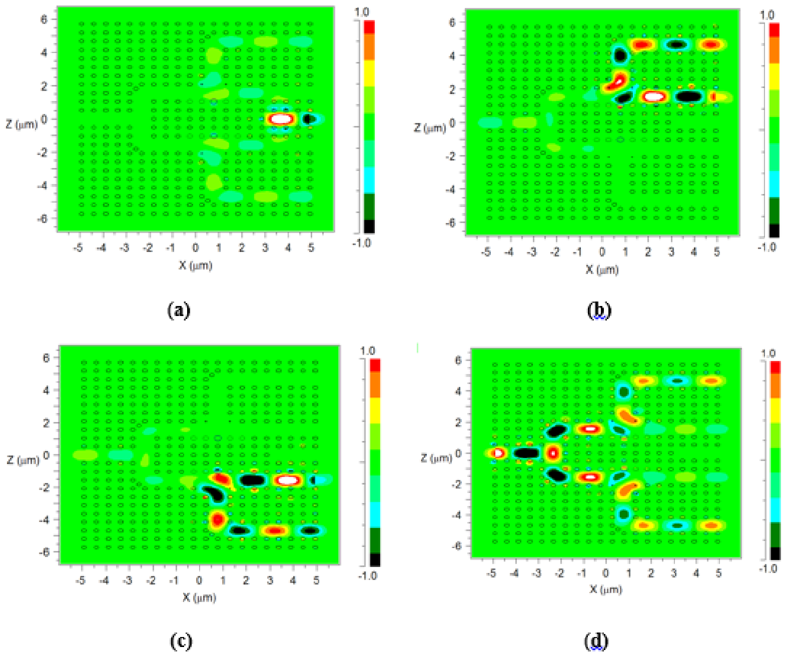

(a) (b) (c) (d)

Figure 9: The electromagnetic field pattern for the all-optical 4×2 Encoder, (a) Input 1: 1. (b) Input 2: 1. (c) Input 3: 1 & (d) Input 4: 1.

Table 3: Truth table and optical power in output for all optical 4×2 Encoder

I1	0/1	I2	0/1	I3	0/1	I4	0/1	O1	0/1	O2	0/1
P_{in}	1	0	0	0	0	0	0	$0.021p_{in}$	0	$0.021p_{in}$	0
0	0	P_{in}	1	0	0	0	0	$0.76P_{in}$	1	$0.004P_{in}$	0
0	0	0	0	P_{in}	1	0	0	$0.004P_{in}$	0	$0.76P_{in}$	1
0	0	0	0	0	0	P_{in}	1	$0.44P_{in}$	1	$0.44P_{in}$	1

4. Conclusion

This paper was conducted to design and simulate new all-optical logic gates despite the use in PICs. For this purpose, an all-optical NOT / XOR logic gate based on 2D PC using wave interference effects were presented. In order to apply this structure and make changes in the output waveguide of the structure, it has been optimized and finally investigated in the multiple structures. The basic and optimized structure has a contrast ratio of 36 dB, a response time of 0.178 ps and a data transfer rate of $5.68Tbit/s$, which is much more suitable and applicable than structures in this field. According to the results obtained, the high flexibility of the structure along with the optimization of the primary structure for use in PICs, a 4×2 encoder has been designed and stimulated that has good results in this field. High flexibility, functionality, simplicity of design, small size, convenient optimization, good results for structures in this field along with the use of interfering effects of waves instead of Kerr nonlinear effects make this structure very suitable for designing other devices in this field and use in optical integrated circuits of new generation.

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