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Basic Logic Gates in Two Dimensional Photonic Crystals for All Optical Device Design

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***Abstract*—The research carried out in the field of optics and photonics with an idea to design and develop the all optical logic devices in the fascinating material known as photonic crystals (PhCs). The structural investigation reveals that the two dimensional (2-D) PhCs is more suitable for fabrication of optoelectronic components. In this article we have designed basic logic gates in 2-D PhCs as they are the building blocks for the construction of optical devices and in these, refractive index is periodically modulated with the wavelength. The understanding of light behaviour in complex PhCs helps in creating photonic band gap (PBG) that can prevent light of certain wavelength propagating in crystal lattice structure. For the selected geometry structure, three PBG bands will exists out of which two of them are transverse electric (TE) and one is transverse magnetic (TM) mode. The PBG bands in the TE mode ranges from 0.31($\frac{a}{\lambda}$) to 0.46($\frac{a}{\lambda}$), 0.61($\frac{a}{\lambda}$) to 0.63($\frac{a}{\lambda}$) and TM mode ranges from 0.86($\frac{a}{\lambda}$) to 0.93($\frac{a}{\lambda}$). The free space wavelength of 1550 nm is set for the finite difference time domain (FDTD) simulation of the structure. The response time and computational overhead required for the proposed OR gate is 0.128ps and 4.4MB is obtained. Also we calculated the extinction ratio for AND gate and NOT gate as 6.19 dB and 10.21 dB respectively.**

***Keywords*—Basic gates, Photonic crystals, Finite difference time domain, Plane wave expansion, Photonic band gap**

I. Introduction

THE semiconductor technology applied for optical domain to design and fabrication of all optical devices is the challenging task for an optoelectronics researcher. The variation of dielectric material, geometry of lattice structure effects the field propagation inside the structure. The electric and magnetic field analysis in semiconductor is based on electron movement and same analogy is brought into new kind of material based on photons [1]. A new kind of material called PhCs is fascinating to build all optical devices. The major problems dealing with such material is to compute the energy band diagram known as PBG which measures the band of frequencies in which no light is propagated inside the crystal waveguides and cavities. As electromagnetic waves will be propagated inside the lattice structure of PhCs the time domain analysis becomes a herculean task. The complex analysis will be performed using computational electromagnetic methods such as FDTD, PWE etc. Modeling methods should be very powerful to indicate how the light propagates inside the lattice structure [2].

The above discussed problems will be thoroughly investigated in all types of photonic crystal lattice configurations. The geometry, dielectric variation and PBG of one, two and three dimensional PhCs in TE and TM mode are studied [3]. The 2-D PhCs is the best platform for the design and fabrication of optoelectronic components. The basic requirements such as waveguides, cavities, resonators and coupler can be designed in 2-D PhCs. Waveguides and cavities are the building blocks for all optical device designing. Our current research focused on design and optimization of these waveguides and cavities in developing all optical gates and adders and which intern helps to build logic all optical memory which is the ever demanding requirement of semiconductor industry.

II. Literature of Related Work

The literature carried out in the field of optics and photonics by referring the previous work done by various authors from past decade of years. E. Yablonovitch [1] has discussed about various parameters related to spontaneous emission in solid state physical structures in 1987. Also he presented the existence of electromagnetic bandgap in semiconductor devices due to spontaneous emission of photons. S. John [2] has demonstrated photon localization in crystal lattice structure. Younis et al. [4] investigated all optical AND gate and OR gate in 2-D PhCs using FDTD computational method. The basic building block for any combinational logic circuit is designed using line defect crystal waveguides and ring resonator concept. Pirzadi et al. [5] have proposed a new strategy in building all optical OR gate in 2-D PhCs. The unique characteristics of this crystal lattice structure is both input and output are on one side, so this feature enables the cascading with the other structure. The hexagonal ring resonators are created near the centre cavity of the structure to connect the optical power to the output. The computation of PBG using PWE method indicates the two TE modes exist in the crystal lattice structure. FDTD method is used to calculate transmission efficiency of single cavity all optical OR gate.

Shaik et al. [6] have proposed all optical logic gates such as XOR, OR and NOT gate in 2-D PhCs can be constructed using the concepts of constructive and destructive interference,

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T-waveguide and cavities and phase difference input stimulus. Glushko et al. [7], [8] have investigated the photonic lattice structural behaviour with changing intensity consisting of a periodically layered structure covered with nonlinear optical material. Goudarzi et al. [9] have investigated 2-D PhCs by inserting point and line defects into the lattice structure. The all optical gates constructed in 2-D PhCs square lattice structure with first Brillion zone in ΓX and ΓM directions. The output of two logic function is obtained based on the principle of constructive and destructive inferences with input phase difference of $\frac{\pi}{2}$. They have demonstrated the existence of TE modes of the structure before and after defects insertion.

Alipour-Banaei et al. [10] have discussed optical AND gate and NOT gate in 2-D PhCs and cascading of these two structures NAND gate constructed in 2-D PhCs by taking into considerations of optical nonlinear Kerr effect. Macker et al. [11] have proposed AND logic gate in 2-D PhCs and simulations are performed using OptiFDTD tool. The computational modeling supports both FDTD and PWE to analyze the time domain behaviour of complex nature of light in crystal lattice structure. The AND logic function created in 2-D PhCs is mainly by waveguides and point defects at the intersection will connect the light at the output monitor as logic high and low based on input configurations. The inputs A and B are applied and they intersect at the centre of lattice structure and defect cavity will pushes the light towards output. The crystal defects are introduced such that the constructive energy will pass from that and other low light signal will be destructed due to the interference phenomenon.

Gupta et al. [12] have investigated nonlinear Kerr type MachZehnder interferometer component for optical device designing. They proposed the structure using same operating wavelength to avoid losses occurred in cascading and maintained the inout propagation of light and called it as pure signals. The square lattice structure in 2-D PhCs has two input and two output waveguides to produce AND gate and NOT gate output without mixing of input and output signals. These structures can be used to cascade with one another to form a NAND gate structure from which one can obtain the structure of any Boolean expression.

Rahmani et al. [13] have proposed and designed an all optical OR/NOR gate in a single 2-D PhCs lattice structure. The proposed structure consists of nonlinear Kerr effect with PhC ring resonator cavity to provide output to the OR and NOR gate. The structure consists of two inputs and two outputs and one bias signal as an input. Also they analyzed the behaviour of PhC ring resonator with nonlinear Kerr effect and variation of refractive index of dielectric rods. Shaik et al. [14] have proposed the XOR and NOT gate using T-waveguides in 2-D PhCs. The structure if fed with out of phase input so that due to constructive and destructive interference the output of XOR and NOT gate will be obtained. The logic gates such as NOT [15], [16], AND [17]–[21], OR [22]–[24] in 2-D PhCs becomes very popular platform for the design of all optical logic gates [25]–[32].

III. Results and Discussion

All optical logic gates can be accomplished with 2-D PhCs through the use of PhCs waveguides and cavities. The various defects can be created in 2-D PhCs waveguides to guide electromagnetic radiation with small losses and high efficiency. The use of wave optics theory, the constructive and destructive interference we can measure the logic states as high and low at the output.

The important design constraint for the design of PhCs systems is the operating wavelength must fall under 1.33μm to 1.55μm because of low attenuation reported for this wavelength is around 0.2dB/km. Also, Raleigh scattering and infrared absorption make a valley region indicating minimum absorption. It is necessary to obtain band gap by selecting appropriate PhCs rod radius (r), lattice constant (a) using electromagnetic computational modelling methods. The FDTD method is used as an animated FullWAVE simulation technique for time domain analysis of all optical devices designed in 2-D PhCs. The PBG will be computed as shown in Fig. 1 with the help of BandSOLVE tool using PWE method.

The following equations will be used to determine the extinction ratio and response time of proposed logic gates in 2-D PhCs.

$$Extinction\ ratio = 10\ log_{10}\left(\frac{P_1}{P_0}\right) \tag{1}$$

$$Response\ time = 4 \times (T_2 - T_1) \tag{2}$$

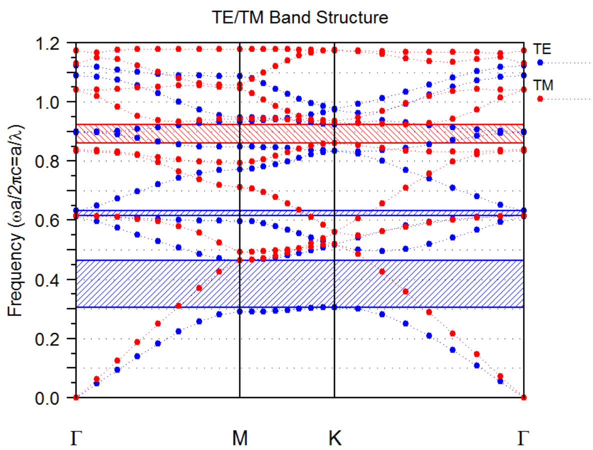


Fig. 1. PBG of proposed 2-D PhCs lattice structure

A. 2-D PhCs AND gate

The 2-D PhCs lattice with hexagonal cell structure of length 16m and width 19m is selected for creating AND logic gate as shown in Fig. 2. The parameters are chosen in such a way that the entire light wave can propagate within the waveguide created in 2-D PhCs lattice structure. The pitch, diameter and operating wavelength for the 2-D PhCs lattice geometry of AND gate are 0.6μm, 0.24μm and 1.55μm. The two waveguides are created for input A, B and one output waveguide Y_P to get the combined power of A, B inputs.

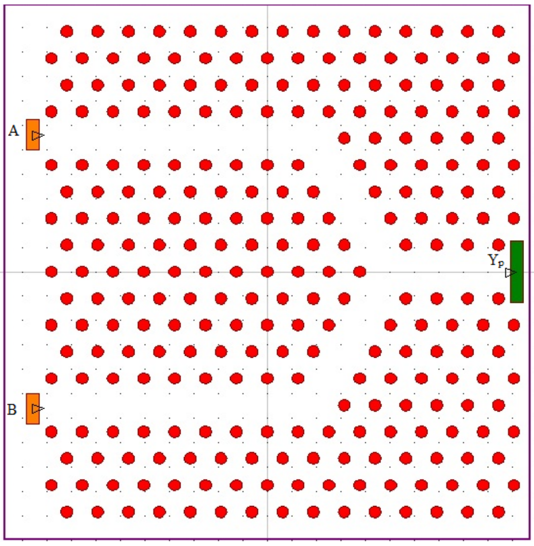


Fig. 2. PhCs lattice structure of 2-D PhCs AND gate

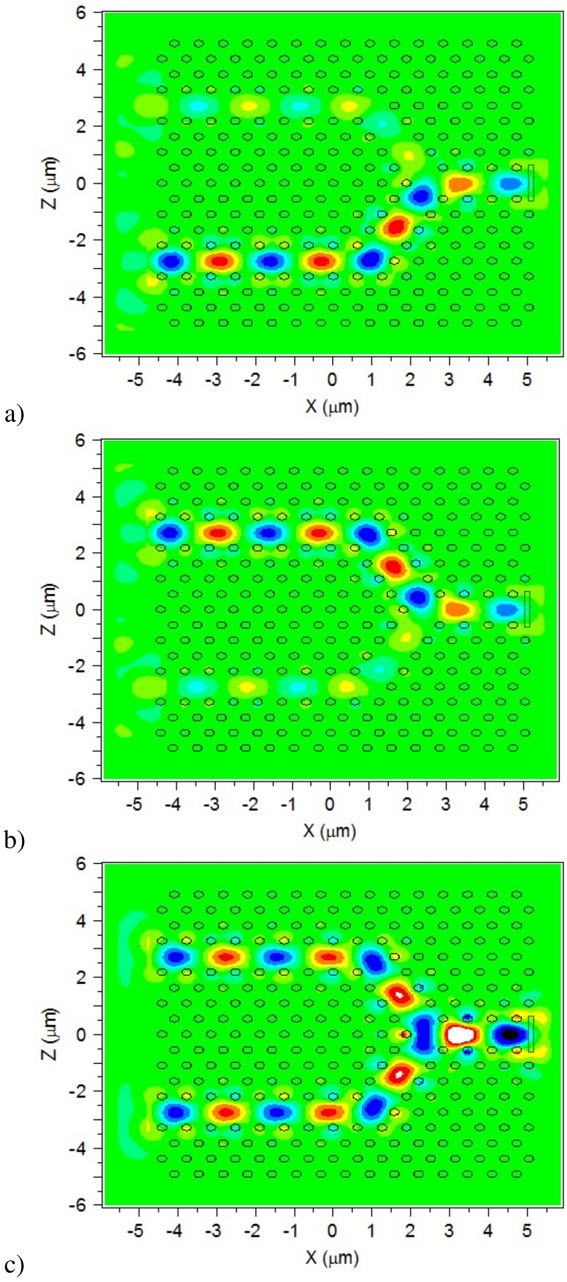


Fig. 3. Power flow indicator diagram of 2-D PhCs AND gate

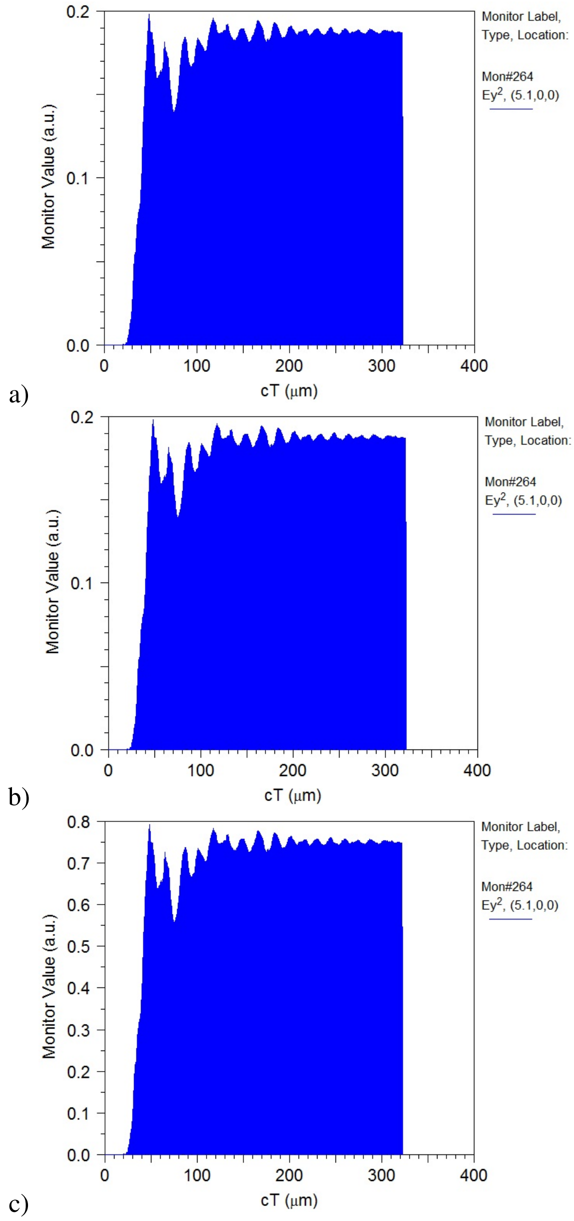


Fig. 4. FullWAVE simulation results of 2-D PhCs AND gate

The 20% power output will be considered as threshold factor for determining the HIGH or LOW logic level of the proposed basic gates. In the proposed AND gate we achieved an average HIGH power of 75% at the output waveguide when both inputs applied and average LOW power of 18% when single input applied. The Fig. 3 and Fig. 4 shows the simulation results of 2-D PhCs AND logic gate. Table I provides the extinction ratio and practical power output for various input combinations. From the FDTD simulation results we can calculate the response time and extinction ratio as follows.

For 10% of output CT= 29μm

T_1=$\left(\frac{29\mu}{3\times10^8}\right)$= 0.096$ps$

For 90% of output CT= 47μm

T_2=$\left(\frac{47\mu}{3\times10^8}\right)$= 0.156$ps$

Response time= 4$\times(T_2 - T_1)$= 0.24ps

Extinction ratio= 10 $log_{10}\left(\frac{P_1}{P_0}\right)$
10 $log_{10}\left(\frac{0.75}{0.18}\right)$= 10 $log_{10}(4.16)$ = $6.19dB$

TABLE I
FULLWAVE SIMULATION RESULT OF 2-D PHCS AND GATE

Input		Logic Output	Power Output $(a.u.)$	Extinction Ratio (dB)
A	B	Y_t	Y_p	r_e
0	0	0	0	6.19
0	1	0	0.18	
1	0	0	0.18	
1	1	1	0.75	

B. 2-D PhCs OR gate

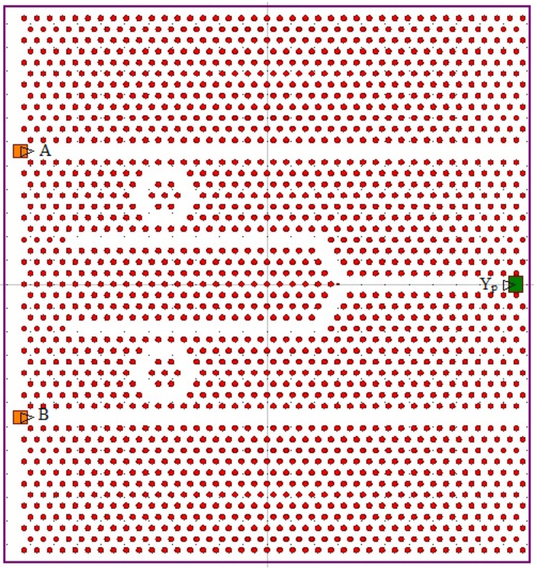


Fig. 5. PhCs lattice structure of all optical OR gate

TABLE II
FULLWAVE SIMULATION RESULT OF 2-D PHCS OR GATE

Input		Logic Output	Power Output (a.u.)
A	B	Y_t	Y_p
0	0	0	0
0	1	1	0.70
1	0	1	0.70
1	1	1	0.89

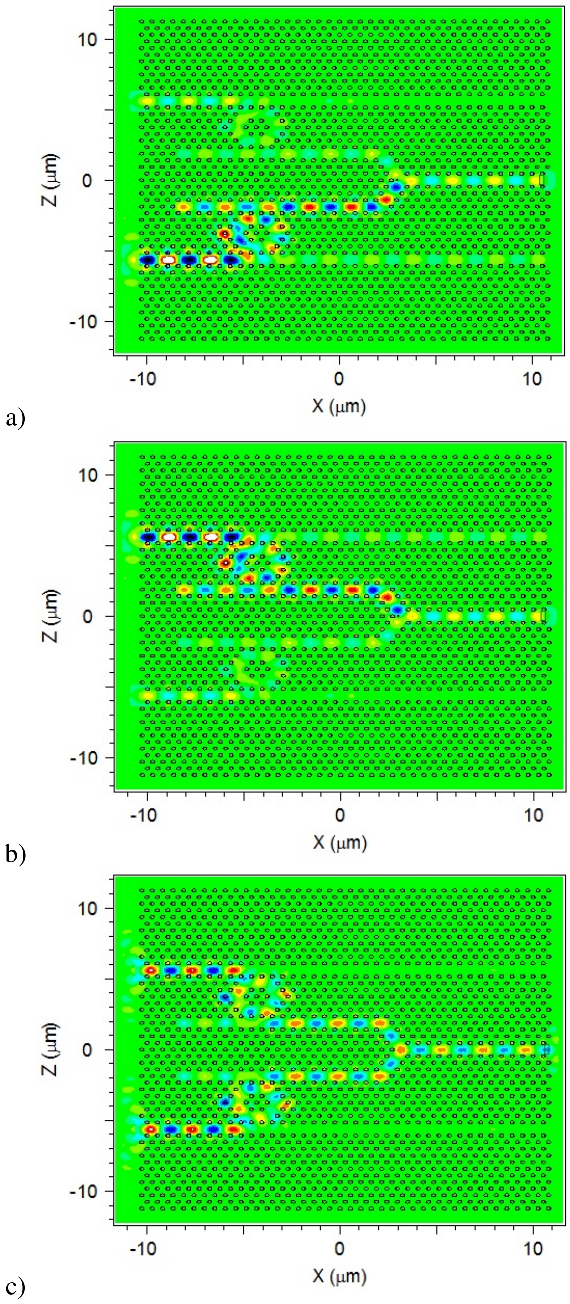
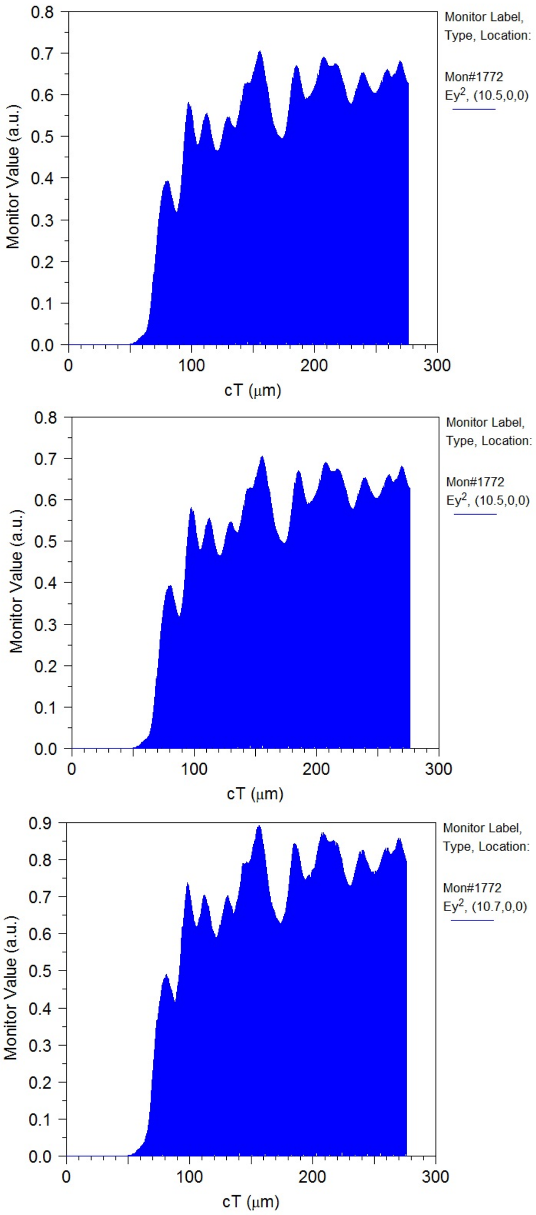


Fig. 6. Power flow indicator diagram of all optical OR gate

The 2-D PhCs lattice with hexagonal cell structure of length 40m and width 49m is selected for creating OR logic gate as shown in Fig. 5. The pitch, diameter and operating wavelength for the 2-D PhCs lattice geometry of OR gate are 0.6μm, 0.24μm and 1.55μm. Five planar waveguides and 2 hexagonal ring structure are created in 2-D PhCs for OR gate logic. The input power flowing through port A and B waveguide will undergo the resonance for coupling the power to the two hexagonal waveguides created within two planar input waveguides. The output power achieved at Y_p either single or both input port having an input power with 1 a.u. will be 70% to 89%.The Fig. 6 and Fig. 7 shows the simulation results of 2-D PhCs OR logic gate. Table II provides the practical power output for various input combinations. From the FDTD simulation results we can calculate the response time as follows.

For 10% of output CT= 62.5μm
T_1=$\left(\frac{62.5\mu}{3\times10^8}\right)$= $0.208ps$
For 90% of output CT= 73μm
T_2=$\left(\frac{73\mu}{3\times10^8}\right)$= $0.24ps$
Response time= $4\times(T_2 - T_1)$= $0.128ps$



a)

b)

c)

Fig. 7. FDTD simulation results of 2-D PhCs OR gate

C. 2-D PhCs NOT gate

The 2-D PhCs lattice with hexagonal cell structure of length 31μm and width 31μm is selected for creating NOT logic gate as shown in Fig. 8. The pitch, diameter and operating wavelength for the 2-D PhCs lattice geometry of NOT gate are 0.6μm, 0.24μm and 1.55μm. Three planar waveguides and 2 square ring type waveguide structure are created in 2-D PhCs for NOT gate logic. The bias or reference input (Ref) is required apart from input (A) in order to get the output Yp power when no input is applied. The weak low output obtained when input power is applied to A and Ref input with opposite phase power is applied. The destruction interference will nullify the output power so we obtained only 6% output power when input is 1 $a.u.$ and 65% of output power when input is zero.

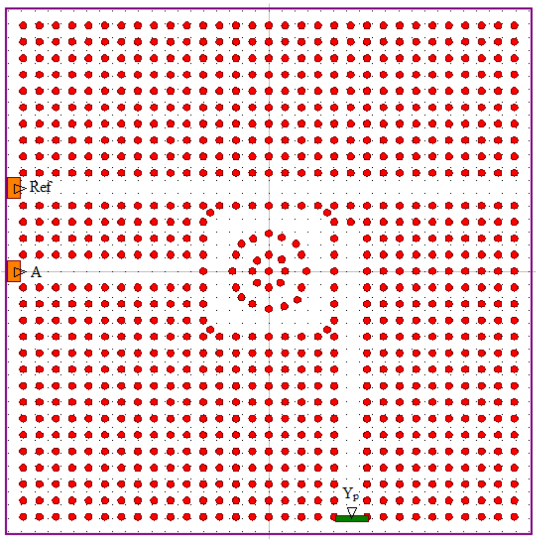
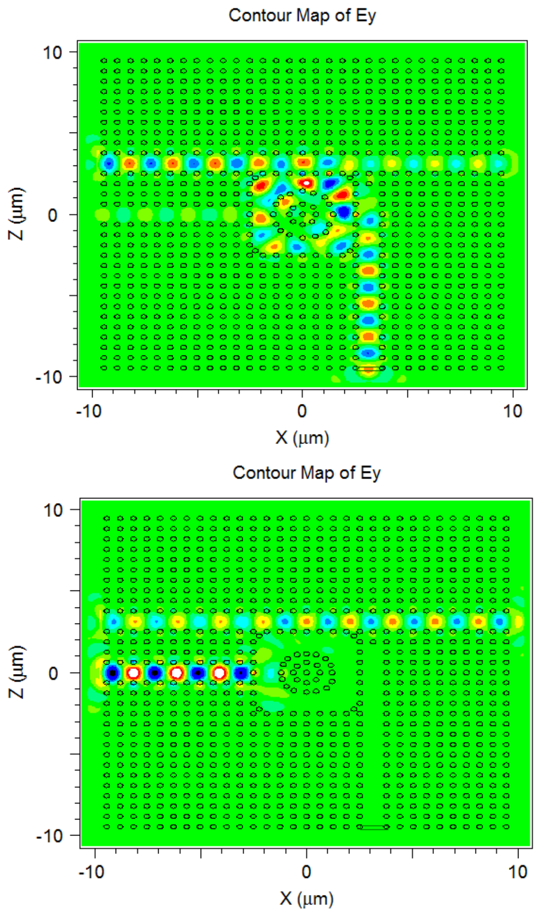


Fig. 8. PhCs lattice structure of all optical NOT gate

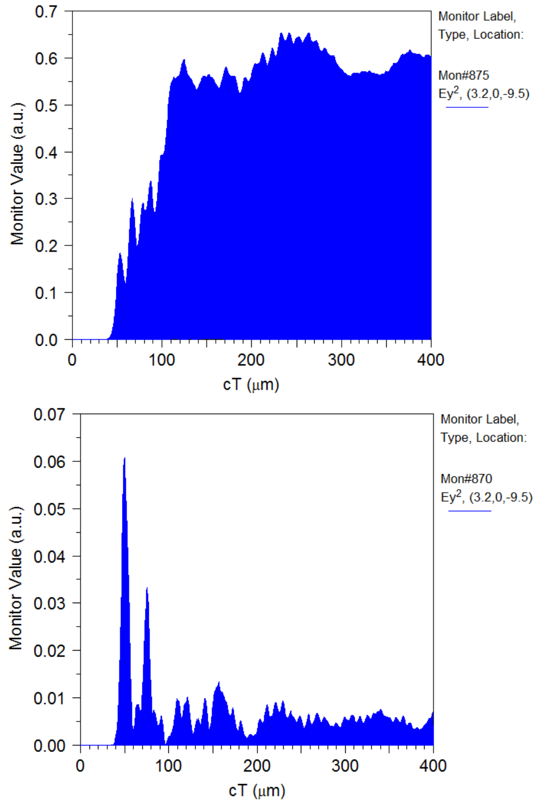


a)

b)

Fig. 9. Power flow indicator diagram of all optical NOT gate

The Fig. 9 and Fig. 10 shows the simulation results of 2-D PhCs AND logic gate. Table III provides the extinction ratio and practical power output for various input combinations. From the FDTD simulation results we can calculate the response time and extinction ratio as follows.



a) b)

Fig. 10. FDTD simulation results of all optical NOT gate

For 10% of output CT= 60μm
T_1=$\left(\frac{60\mu}{3\times10^8}\right)$= 0.303$ps$
For 90% of output CT= 91μm
T_2=$\left(\frac{91\mu}{3\times10^8}\right)$= 0.20$ps$
Response time= 4$\times$($T_2 - T_1$)= 0.416ps
Extinction ratio= 10 $log_{10}\left(\frac{P_1}{P_0}\right)$
10 $log_{10}\left(\frac{0.65}{0.062}\right)$= 10 $log_{10.48}\left(\right)$ = 10.21dB

TABLE III
FULLWAVE SIMULATION RESULT OF 2-D PHCS NOT GATE

Input		Logic Output	Power Output (a.u.)	Extinction Ratio (dB)
Ref	A	Y_t	Y_p	r_e
1	0	1	0.65	10.21
1	1	0	0.062	

IV. CONCLUSION

The research focused on design and analysis of all optical waveguides and cavities in 2-D PhCs to build logic gates. The proposed basic logic gates design with response time of OR gate 0.129 ps and the extinction ratio of 6.19 dB and 10.21 dB achieved for AND gate and NOT gate respectively. The Table IV shows the comparative result analysis of the proposed design with the published works in the literature. The designed structure can be used to develop Optical system using photonic integration techniques. Investigation of 2-D PhCs carried out using electromagnetic computational modeling methods such as PWE and FDTD method provides the existence of bandgap in the structure and animated flow of light insides the structure. The logic gates based on the 2-D PhCs are designed in such a way that, a/λ for a modeled device will operate in 1450 nm to 2150 nm, which is more suitable for most of the telecommunication applications. The designed optical logic devices can be used for cascading to build the optical memory in future.

TABLE IV
COMPARISON WITH THE EXISTING DEVICE DESIGN

Literature	Logic devices	Area $(\mu m)^2$	Efficiency (%)	Extinction ratio (dB)	Response time (ps)
[30]	AND	225	0.58	4.9	1.204
[4]	AND	571.53	0.67	6.3	4.8
	OR	570.24	0.5	6	0.35
[27]	AND	225	0.46	4.32	1.024
	OR	225	0.46		1.024
	NOT	225	0.54	5.01	1.024
	XOR	225	0.44	6.8	1.024
[5]	AND	567	0.75	5.74	3.9
Proposed work	AND	304	**0.75**	6.19	0.24
	OR	1960	**0.89**	- -	**0.128**
	NOT	961	**0.655**	**10.21**	0.416

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