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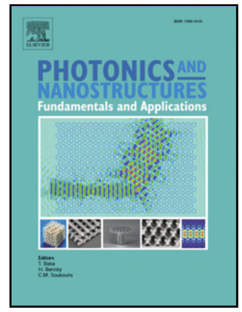

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Authors: Hojjat Sharifi, Seyedeh Mehri Hamidi, Keivan Navi

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All-optical photonic crystal logic gates using nonlinear directional coupler

Hojjat Sharifi[1], Seyedeh Mehri Hamidi[2,*] and KeivanNavi[1,*]

[1]Faculty of Computer Science and Engineering, Shahid Beheshti University, GC, Tehran, Iran

[2] Laser and Plasma Research Institute, Shahid Beheshti University, GC, Tehran, Iran

***m_hamidi@sbu.ac.ir and k_navi@sbu.ac.ir**

Highlights

1. Nonlinear directional coupler and junctions is proposed to design all-optical logic gates.
2. New topologies for all-optical XNOR, NOR and AND logic gates is proposed.
3. Silicon nano-crystal has been used as nonlinear efficient material.

Abstract

In this paper, a nonlinear photonic crystal structure consisting of a nonlinear directional coupler and junctions for the design of all-optical logic gates is proposed. A bi-functional photonic crystal structure is initially designed which provides different two XOR or OR logic operations. Thereafter, by applying some modifications in the basic structure, new topologies for all-optical XNOR, NOR and AND logic gates are proposed. Nonlinear rods of the proposed structure are made of silicon nanocrystal to create required phase shift. The finite difference time domain and plane wave expansion methods are used to evaluate the proposed structures. Our simulation results show that the proposed gates can operate with a bit rate of more than 1 Tbits/s and also, inputs and output of the proposed logic gates are homogeneous with the required power of 3W for switching operation.

Keywords: All-optical logic gate, Photonic crystal, Kerr effect, Directional coupler.

1. Introduction

All-optical integrated circuits have become one of the most promising alternatives to face the problem of speed limit of conventional electronic technology in computation and communication systems. All-optical logic gates and switches are fundamental elements of optical signal processors and next generation optical networks. Recently more research attention has been directed towards photonic crystals (PCs) [1-4] and plasma photonic crystals structures [5-7] in order to design optical devices.

PCs are periodic structures that introduce photonic band gap (PBG), i.e., the range of frequencies within which a propagating electromagnetic wave does not exist. PBG provides the ability of engineering the flow of light [8, 9]. The possibility of creating integrated circuits and high switching speed make these structures promising candidates for implementation of fast devices such as waveguides, couplers, logic gates and switches [10-14].These new generation waveguides, couplers [15, 16] and logic gates [17-22] can be created by many techniques such as introducing defects in PC lattice or use of nonlinear materials.

Until now, scientists have reported many researches on all-optical logic gates based on nonlinear materials in PCs, such as AND gate based on an interference between a bent waveguide with embedded nonlinear rods and a T-branch [17]. In [16], Andalib et al. proposed an all-optical NOR gate based on nonlinear PC ring resonators in which inputs and output of the logic gate had different frequencies. In the same year, kabilan et al. designed XNOR and NAND logic gates based on self-collimation phenomena [18]. Later, an all-optical AND gate based on nonlinear cavity has been proposed in [19]. Also, in [22] a design procedure has been proposed for all-optical logic gates and functions based on threshold logic and nonlinear PC resonators. The nonlinear Kerr effect of the Si nanocrystals is used in the proposed devices. The demands for Si-nc have been increased due to the technological significance. Moreover, Si-nc introduces high nonlinearity and compatibility with Si technology [16, 23-25].

In this paper, firstly we have proposed a bi-functional (XOR/OR) logic gate using nonlinear Kerr effect and directional coupler. We have designed the structure by a triangular lattice of Si rods in air with Si nanocrystal (Si-nc) used as nonlinear material. The proposed structure provides two different logic operations by means of a control signal that empowers circuit designers to have more flexibility in design procedure. Optical logic gates based on nonlinear PC structures suffer from high power values to correctly perform switching operation, however, the proposed device does not need high power values with high intensity only required for control signal of the proposed logic gate to determine preferred logic operation in output port. Although the proposed structure can operate with low input power, we have considered the input power the same as control power in order to have homogenous input signals. XNOR, NOR and AND logic gates have been designed by applying some modifications in the basic proposed structure. Plane wave expansion (PWE) and 2D finite difference time domain (FDTD) methods are used to simulate and investigate the operation of proposed logic gates [20].

This paper is organized as follows: description of the proposed structure is presented in section2. In section 3, we explain the structure design of the proposed bi-functional OR/XOR logic gate. Sections 4, 5 and 6 describe the proposed structures of XNOR, NOR and AND logic gates respectively and finally we present the conclusions in section 7.

2. Design procedure

The proposed structure has been designed by 2D PC triangular lattice of Si rods in air substrate. The refractive index of Si in our simulations is 3.4 for wavelengths of around 1550 nm that offers a considerable bandgap. The radius of rods is selected to be 0.2a, where 'a' is the lattice constant. In order to operate the proposed PC lattice in the third telecommunication window, the lattice constant 'a' is determined to be equal to 565 nm. The plane wave expansion (PWE) method is used to calculate the photonic bandgap of the structure (Fig. 1). As can be seen in Fig. 1 the lattice structure has two frequency gaps for TM light in which the larger one is between 0.279 (a/λ) and 0.450 (a/λ).

The basic component of the proposed structure is a nonlinear directional coupler. The switching operation of the proposed structures is controlled by the nonlinear directional coupler as a passive phase shifter. The nonlinear directional coupler includes two nonlinear PC waveguides adjacent to a central row. As discussed in [21], when two PC waveguides are placed close to each other, light propagating in one of the waveguides can be coupled to the neighbouring waveguide after passing a certain distance referred to as a full coupling length (L_C).The coupling length of a directional coupler is related to the propagation constants of the odd and even modes as follows [26]:

$$L_C = \frac{\pi}{\left|\beta_{odd} - \beta_{even}\right|} \tag{1}$$

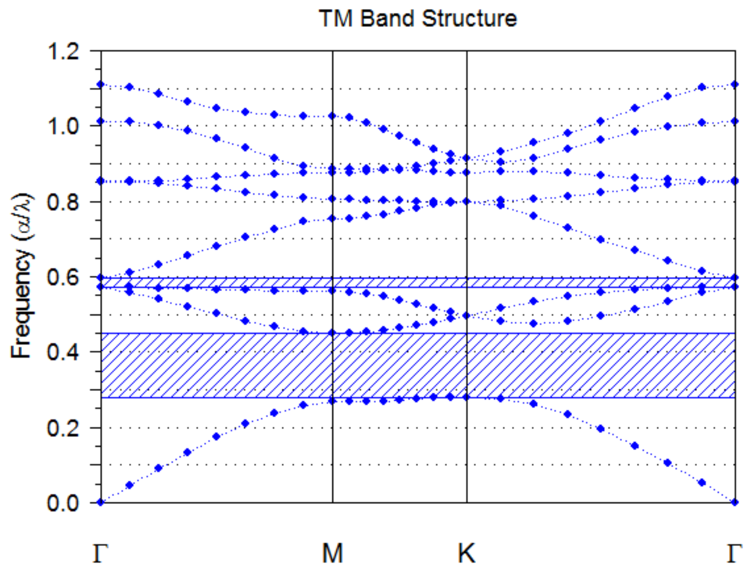


Fig1. Band structure of a PC triangular lattice of Si rods in air for TM polarisation

Where, β_{odd} and β_{even} are the odd and even mode propagation constants, respectively. Also, the relative phase difference between waveguides in coupling length L_C is equal to $\Delta\beta \cdot L_C$ [27] with $\Delta\beta = |\beta_{odd} - \beta_{even}|/2$.

Furthermore, by applying two identical signals to the inputs of a two input junction, the output transmission is about 1.76P0 due to the constructive interference in the junction. Also, the output transmission of the junction when a directional coupler with a length of $2L_C$ is formed in one of the inputs of the junction is calculated to be about 0.0029P0. The very low transmission is based on the destructive interference in the junction that shows π phase difference between inputs of the junction in this condition.

The block diagram of the proposed photonic crystal logic gates is depicted in Fig. 2. The nonlinear directional coupler with a length equal to $2L_C$ is the essential part of the proposed structure. I_1 and I_2 are input signals, $I_{control}$ is control signal which determines the output function of the structure and OUT is the output that can provide XOR or OR logic operations based on the value of control signal. The inputs and output of the structure are connected by a junction. Since length of the coupler is $2L_C$, the input signal I_2 couples to the lower waveguide and then returns back to the higher waveguide again in the end of the coupler. The input signal I_2 passes through the coupler and π phase shift would take place in this procedure so a phase difference of π exisits between two inputs I_1 and I_2.

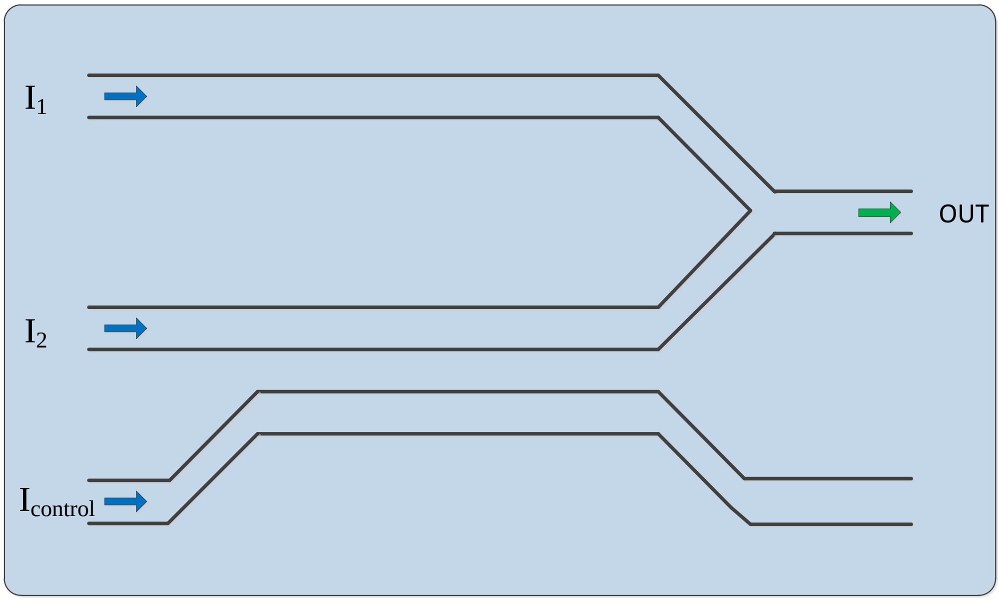


Fig2. Proposed basic block diagram for the counstruction of logic gates

Furthermore, applying an intense control signal to the nonlinear coupler will change the refractive index of the nonlinear waveguides and introduces additional phase shift.

The simulation results prove the possibility of π phase shift by increasing the intensity of the control signal. In order to examine this behaviour, we applied the same signals to the input ports of the proposed structure and as could be seen in Fig. 4, normalized transmission from output port is near to zero with low control signal power values. However, as the intensity of the control signal increases, the refractive index of the nonlinear coupler changes and a phase shift appears in the coupler. As the intensity of the control signal increases, the amount of phase shift rises and this increases the output transmission of the junction that proves the possibility of phase shift of about 2π . However, in this paper the amount of phase shift required for a normalized output transmission around 1 is sufficient. The operation of the proposed structure could be analysed based on the state of the control signal.

First, the proposed device acts as a XOR logic gate when the control signal is OFF. In this state, the I_2 signal propagates through the directional coupler and introduces phase difference of π between inputs I_1 and I_2 reaching the junction. Therefore, when both the inputs are ON, destructive interference occurs between the inputs in the output of the junction. So, output OUT would have low value (logic 0) and on the other hand, when only one of the inputs I_1 or I_2 is ON, the input signal reaches the output through the junction and output OUT would have high value (logic 1). Thus, the structure implements XOR logic operation. It should be noted that low and high amount of signal's power is defined as logic "0" and "1", respectively.

Second, the proposed structure performs OR logic operation when the control signal is ON. In this condition, the control signal $I_{control}$ increases the refractive index of the nonlinear waveguides of the directional coupler. Thus, the output phase of the coupler changes from π to 2π and this leads to constructive interference between two inputs in the output of the junction, when both the inputs are ON. So, output OUT would have high value (logic 1) and when only one of the inputs I_1 or I_2 is ON, it will go towards the output OUT . Hence, the output would have high value (logic 1) and creates OR logic gate.

Fig.3 shows the dispersion curve of the even and odd modes in the directional coupler. It could be seen from Fig. 3 that different frequencies for the input signal introduce different coupling length of the coupler. So, in the design procedure it should be noted that the length of the directional coupler in the proposed structure should be altered by changing the frequency of the input signal. On the other hand, the transmission of the output junction is another important factor that changes by altering the input frequency. Therefore, this factor should be considered in the structure design in order to provide appropriate value for the logic "1" in the output of the logic gates.

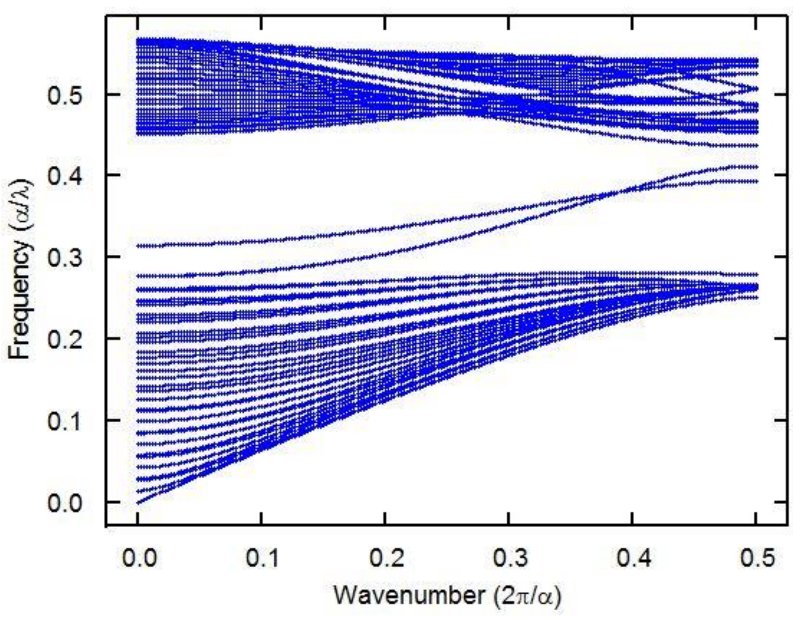


Fig 3.Dispersion curve of even and odd modes in the directional coupler

After the design of bi-functional (OR/XOR) logic gates in the structure, NOR , XNOR and AND logic gates are implemented by applying some modifications in the structure. In order to introduce an appropriate amount of phase shift for implementing our proposed logic gates, the silicon nanocrystals (Si-nc) with high Kerr effect are used as nonlinear material. The Si-nc has linear refractive index of 1.5 and nonlinear Kerr coefficient of 10^{-16} m^2/W at wavelength of 1550 nm [24, 25]. In materials with Kerr-type nonlinear effect, the refractive index can be linearly changed proportional to the optical signal intensity as follows:

$$n = n_0 + n_2 I \tag{2}$$

Where, n_0 is the linear refractive index, n_2 is the nonlinear Kerr coefficient and I is the optical field intensity.

3. All-optical Bi-functional (OR/XOR) logic gate structure

The proposed bi-functional structure is shown in Fig.5 which consists of a PC nonlinear directional coupler and waveguides which are connected by a PC Y-junction. Three input waveguides are created by introducing line defects by changing rods in the structure. The radii of rods in the waveguides are equal to $0.35a$ with refractive index of 1.5. The junction is used to direct input signals to the output port and we expect the most amount of input power goes to the output, rather than leaking to another input. For this purpose, three rods in the junction are removed to provide better transmission of the input signal to the output port.

The proposed structure provides two different logic operations (OR or XOR) by means of control signal $I_{control}$. As previously explained, when two inputs signals of I_1 and I_2 are activated, they would interfere destructively or constructively, reaching the junction as the control signal is OFF or ON, respectively. So, this configuration would implement two different logic operations in one structure.

By performing the FDTD simulations, field distributions and time-domain response of the logic gate structure, when control signal is OFF (XOR logic gate) or ON (OR logic gate), are shown in Fig 6 and Fig 7 respectively. Four different permutations of two input values of I_1 and I_2 including ‘00’, ‘01’, ‘10’ and ‘11’ should be investigated to verify the operation of the logic gates. Since, there is no reference signal in the junction when the permutation of input values is ‘00’, it is not required to test its operation. For exploring ‘10’ case, a CW signal with power 3 W has been applied to the input port I_1 and the achieved power from output port OUT is 0.71P0 or 0.68P0 when control signal $I_{control}$ is OFF or ON, respectively. To check ‘01’ combination, a CW signal with power 3 W is lunched from input port I_2 with the received 0.7P0 or 0.62P0 power from output port OUT for different values of control signal $I_{control}$ for OFF or ON, respectively.

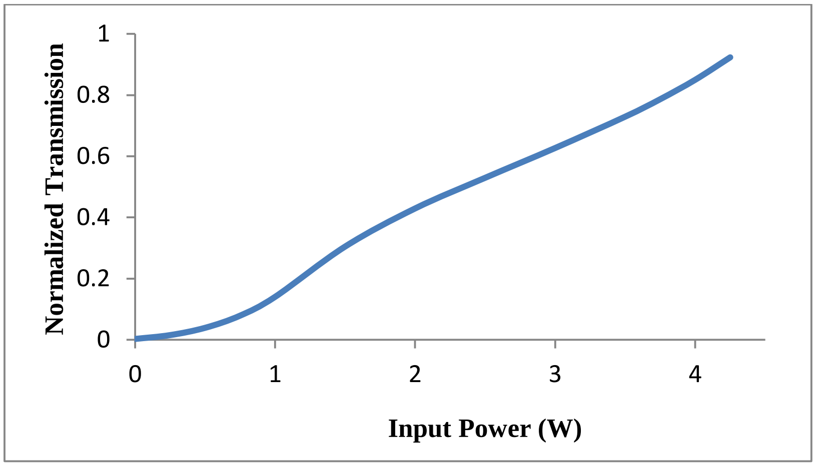


Fig.4. Normalized transmission vs. inputs power for the structure

To investigate '11' case, two CW signals with equal power of 3 W were applied to the input ports I_1 and I_2 simultaneously with the power value of the output port OUT of 0.003P0 or 0.63P0 when control signal $I_{control}$ is OFF or ON, respectively. Therefore, the proposed structure operates as all-optical XOR or OR logic gates when the control signal is OFF or ON, respectively. The time the logic gate takes to respond to the changes in the input signals is the response time and could be seen from the time-domain response of the proposed gates that is less than 1ps.

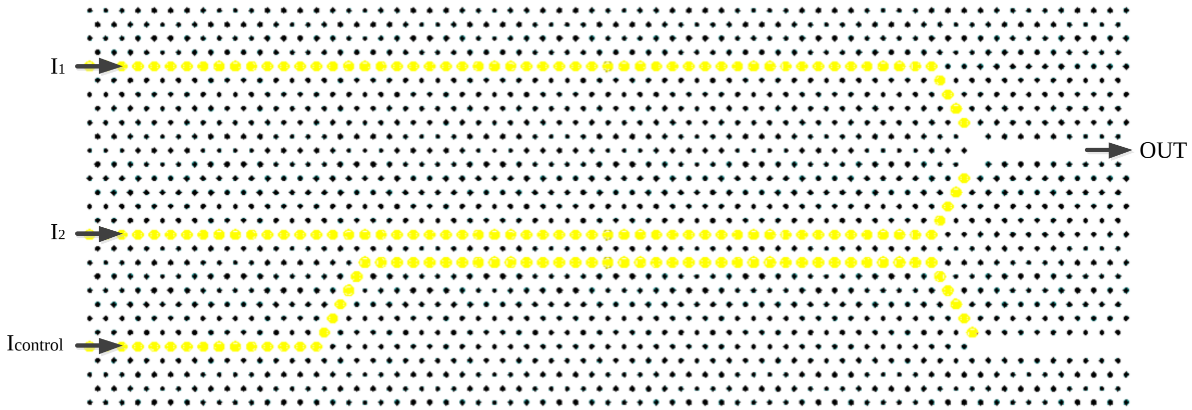


Fig5. Proposed structure for the bi-functional (OR/XOR) logic gate

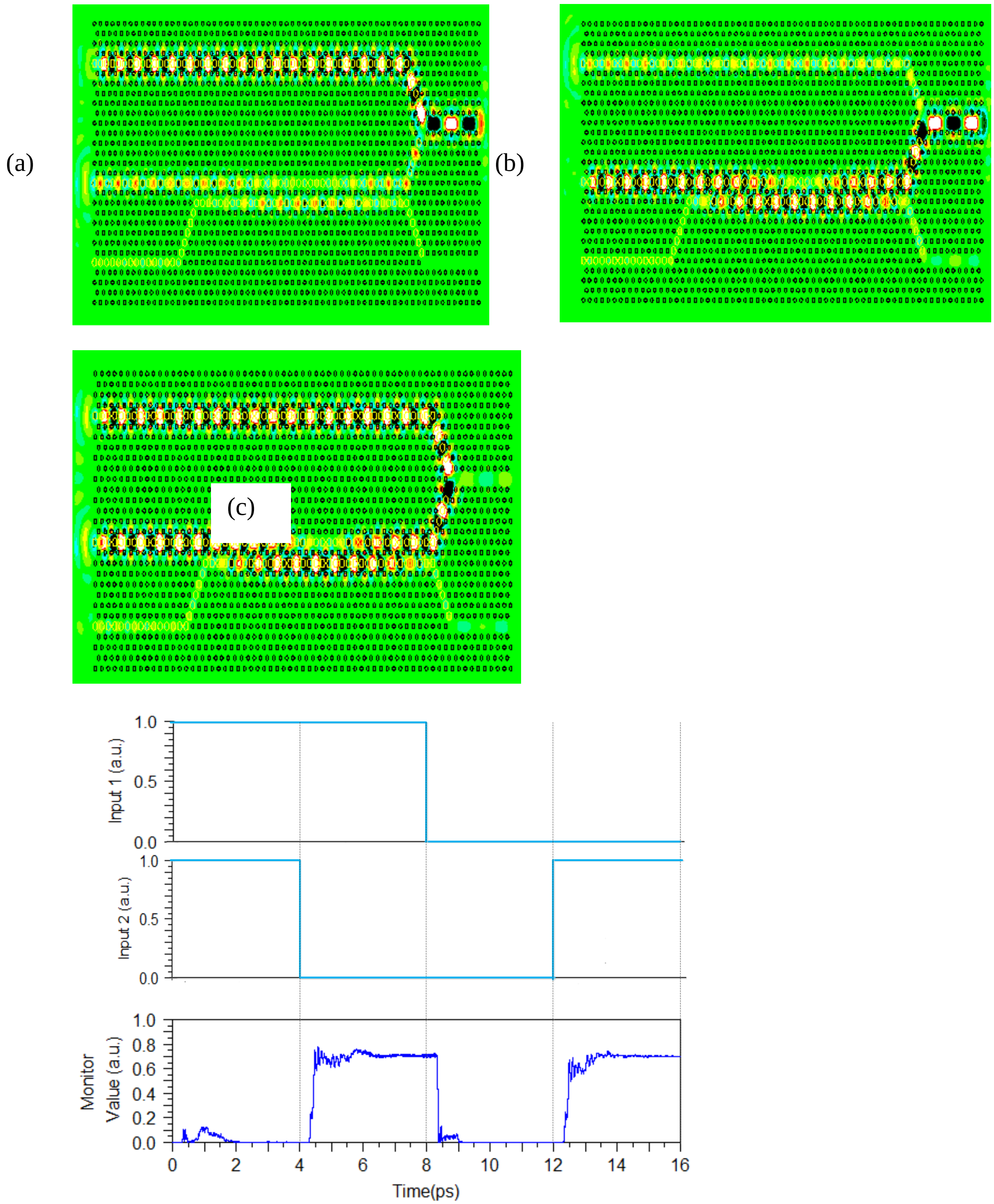


Fig.6. The field distribution and the time-domain response of the proposed all-optical bi-functional logic gate when control signal is OFF (XOR operation). (a) input I_1 is ON (b) input I_2 is ON (c) both the inputs are ON.

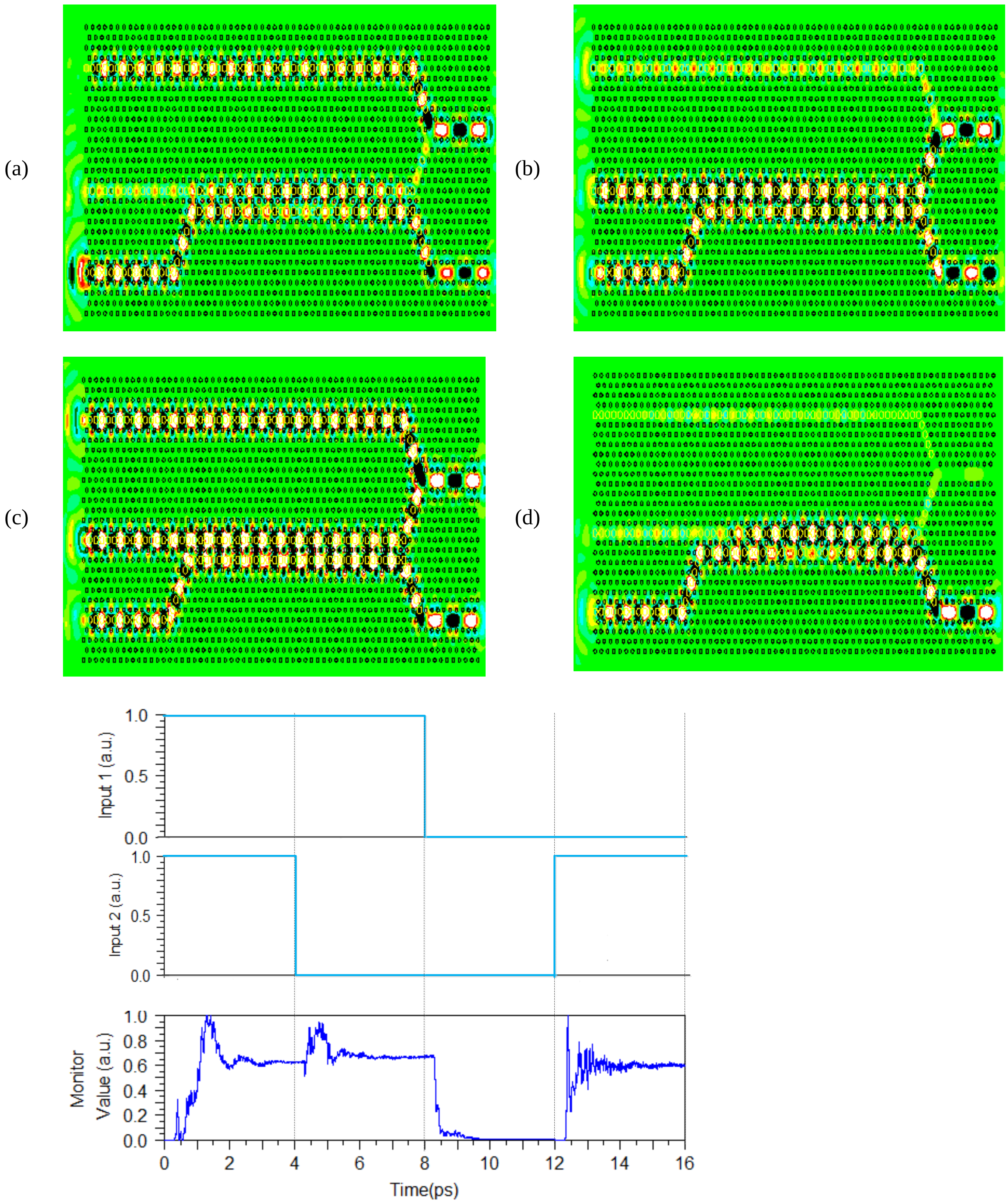


Fig. 7. The field distribution and the time-domain response of the proposed all-optical bi-functional logic gate when control signal is ON (OR operation). (a) input I_1 is ON (b) input I_2 is ON (c) both the inputs are ON (d) both the inputs are OFF.

4. All-optical XNOR logic gate

The proposed structure to implement an all-optical XNOR logic gate has been designed and depicted in Fig. 8. A Y-junction in the input of this structure is used to obtain the summation of two input signals. Also, a nonlinear directional coupler has been utilized to accomplish the switching operation of the proposed logic gate. As it is shown in Fig.8, I_{ref} is a reference signal that always exists and I_1 , I_2 and OUT are two inputs and output ports of the proposed XNOR logic gate, respectively.

As previously discussed, when one of the inputs of the logic gate is ON, the input signal encounters π phase shift passing through the coupler. But, when both the inputs are ON, the summation of the input signals provides the required power to increase the refractive index of the nonlinear coupler. Thus, the propagating signal from the coupler meets 2π phase shift.

To verify the operation of the proposed XNOR logic gate, different combinations of two input values have been investigated and their field distributions and time-domain response have been displayed in Fig.9. It could be seen when both of the inputs are OFF, the power achieved from the output OUT is 0.61P0. When one of the inputs of I_1 or I_2 is ON, the phase difference between the input signal and the reference signal is about π resulting in a destructive interference in the output of the output junction, and the power obtained from the output is about 0.08P0. In the case that both the inputs are ON, the phase difference between the input signal and the reference signal is about 2π and therefore a constructive interference occurs in the output of the output junction and the power reaching the output port is 0.57P0. Thus, the proposed structure implements an all-optical XNOR logic gate.

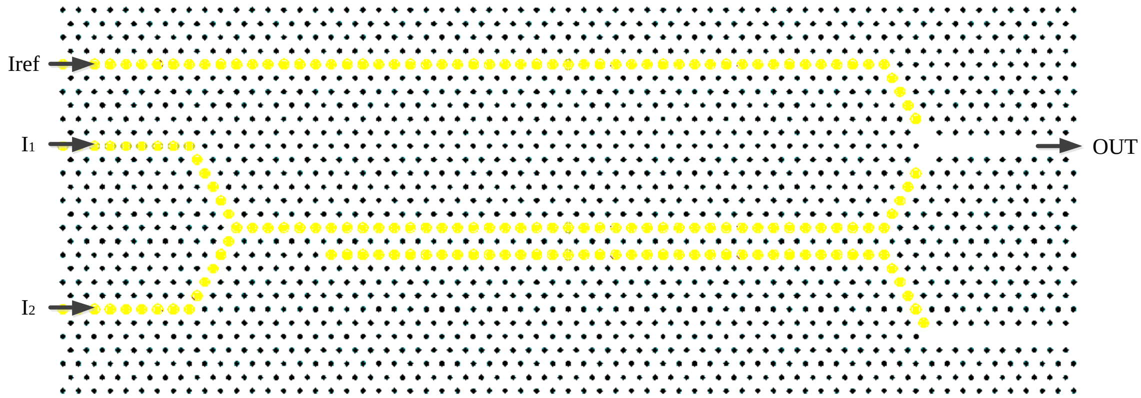


Fig. 8. Proposed structure for XNOR logic gate

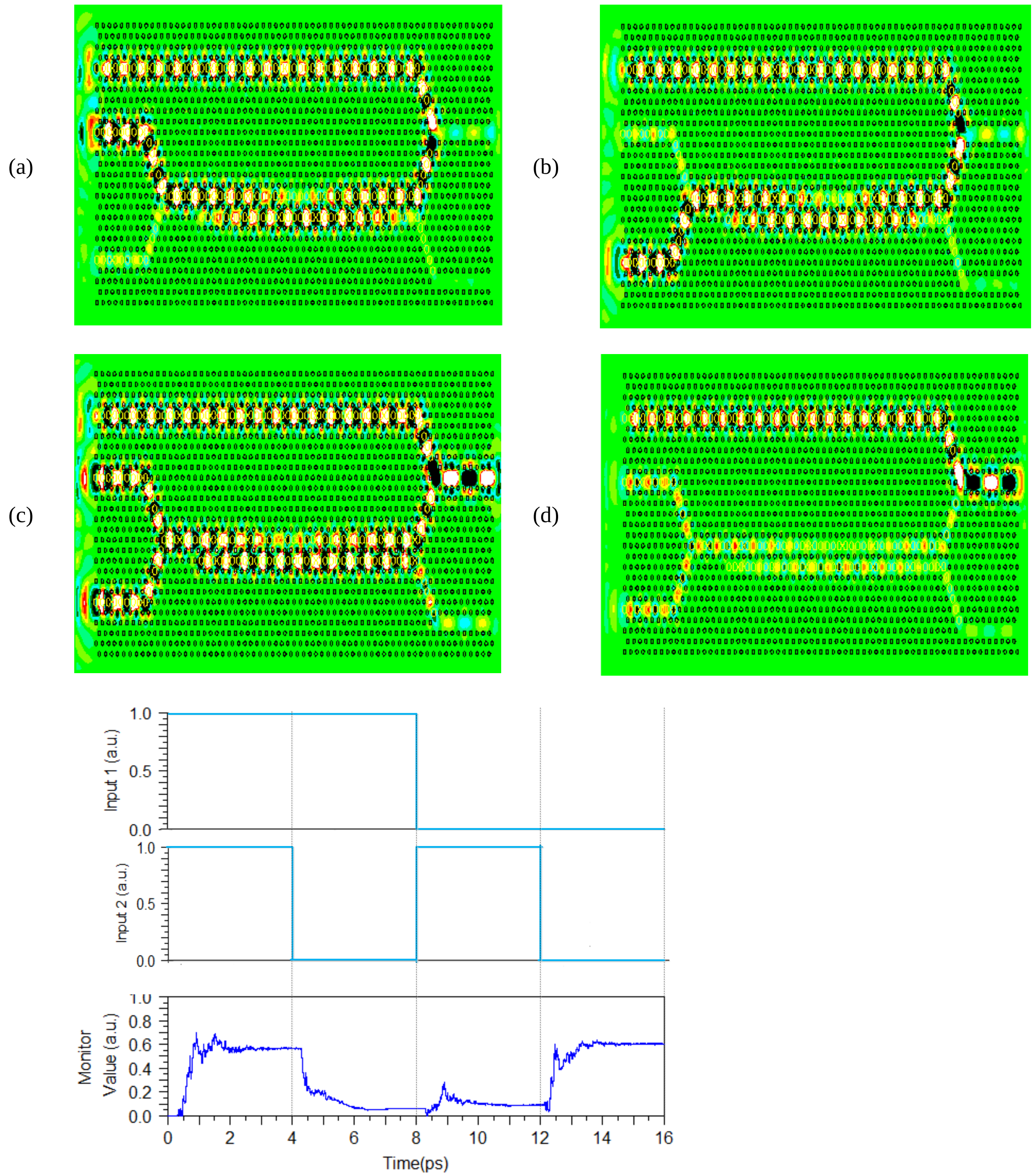


Fig. 9. The field distribution and the time-domain response of the proposed all-optical XNOR logic gate. (a) input I_1 is ON (b) input I_2 is ON (c) both the inputs are ON (d) both the inputs are OFF.

5. All-optical NOR logic gate

An all-optical NOR logic gate has been designed by utilizing a directional coupler, Y-junctions and waveguides as depicted in Fig. 10. As explained previously, I_{ref} is a reference signal which is always activated and , I_1, I_2 and OUT are inputs and output ports of the proposed Logic gate.

To describe switching mechanism of the proposed all-optical NOR logic gate, it should be noted that a reference signal with fixed power value is activated in the input of the coupler. So the mentioned reference signal sees π phase shift passing through the coupler. In this condition when one or both of the inputs are ON, destructive interference occurs between reference and input signals in the output junction (Fig. 11). Therefore, the power value reaching the output is about $0.1P_0$ (both the inputs are ON) and $0.08P_0$ (one of the inputs is ON). On the other hand, the power value at the output from the reference signal is about $0.73P_0$, when none of the inputs are activated. The simulation results (Fig. 11) show operation of the proposed NOR gate.

6. All-optical AND logic gate

The proposed structure for all-optical AND gate which is designed using a directional coupler and Y-junctions is displayed in Fig. 12 . In order to describe the operation of the proposed logic gate, the nonlinear behaviour of the coupler should be considered. The summation of the input signals is obtained by the input junction and then directed towards upper and lower waveguides equally.

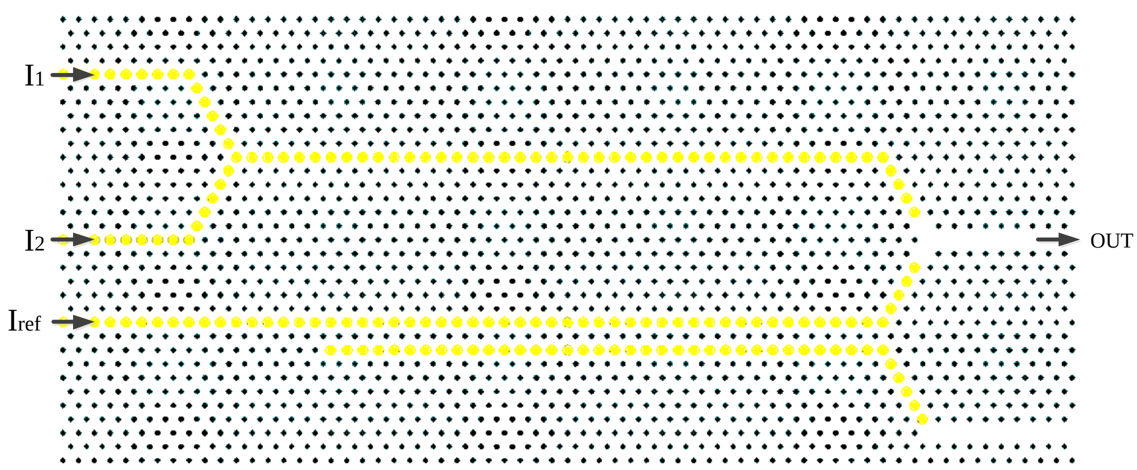


Fig. 10. Proposed structure for NOR logic gate.

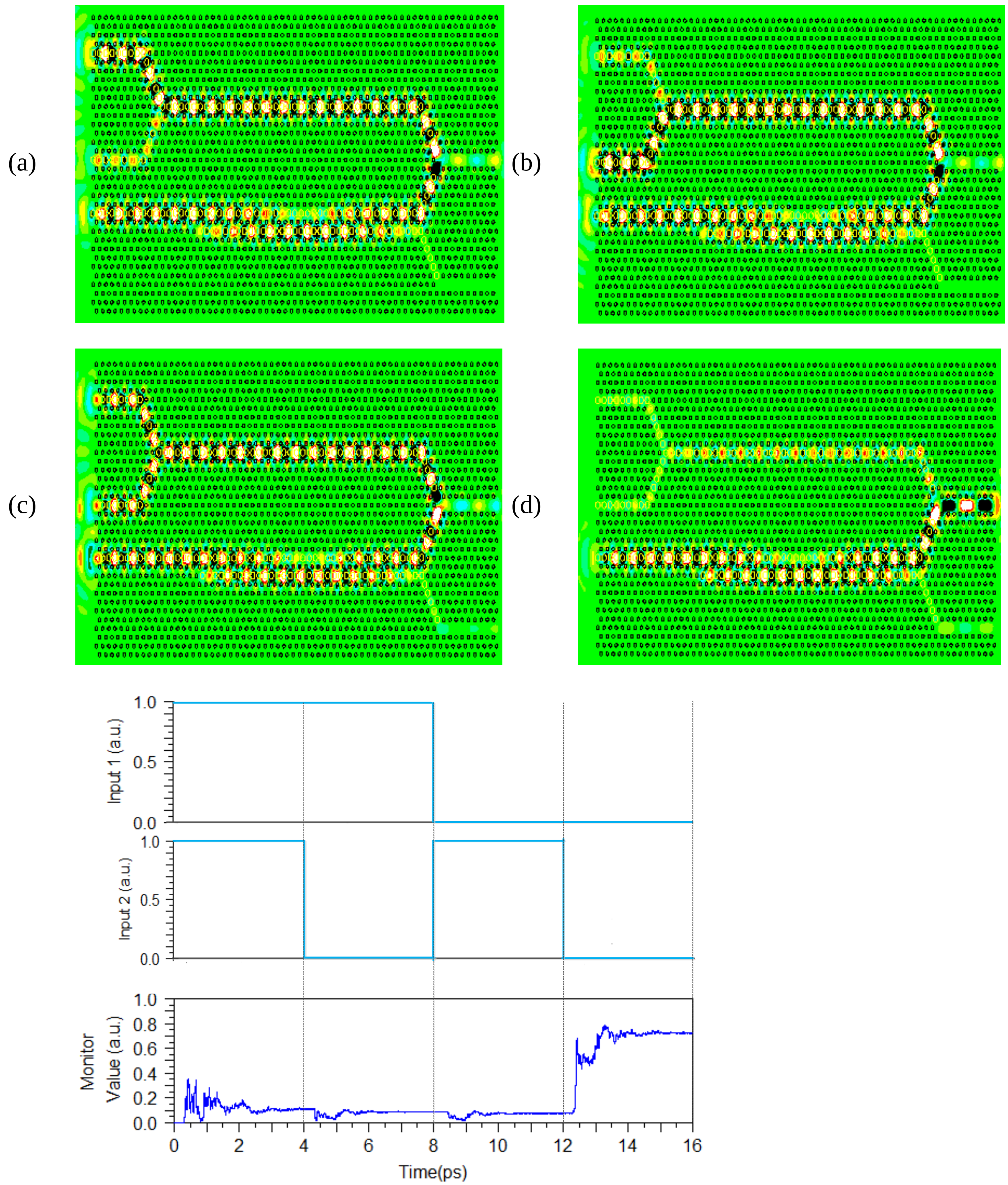


Fig 11. The field distribution and the time-domain response of the proposed all-optical NOR logic gate. (a) input I_1 is ON (b) input I_2 is ON (c) both the inputs are ON (d) both the inputs are OFF.

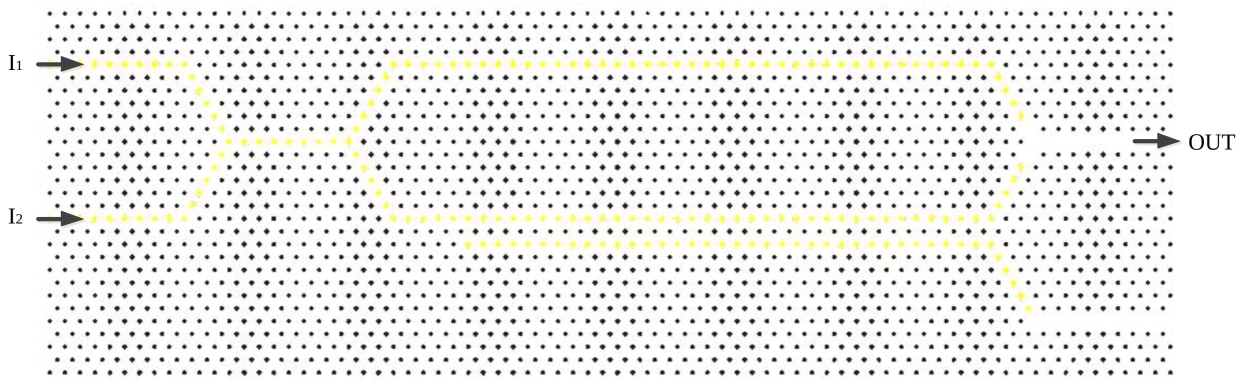


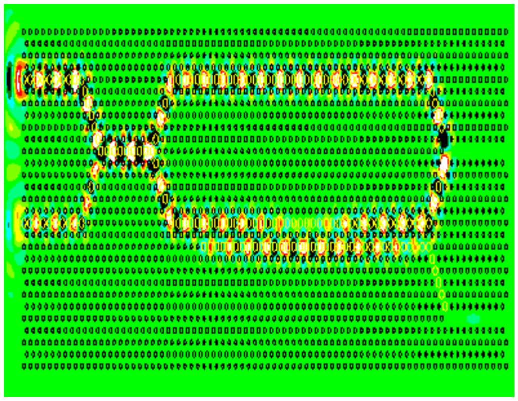
Fig. 12. Proposed structure for AND logic gate.

When one of the input signals is activated, the directional coupler causes a phase shift equal to π for the signal entering lower waveguide. So, a destructive interference occurs in the output junction resulting in a low value output. On the other hand, activating both the inputs provides higher amounts of power passing through the nonlinear coupler that increases the refractive index of nonlinear material. Therefore, the signal passing the coupler sees phase shift of about 2π leading to a constructive interference in the output junction resulting in a high value output. The simulation results are displayed in Fig. 13 which verify operation of the proposed AND logic gate. This current version of the proposed bi-functional gate is not applicable for reversible logic designs in [28- 29]. But, a revised version of the proposed logic gate could be useful to create a system with minimum amount of reversible or quantum hardware resources that execute basic operations.

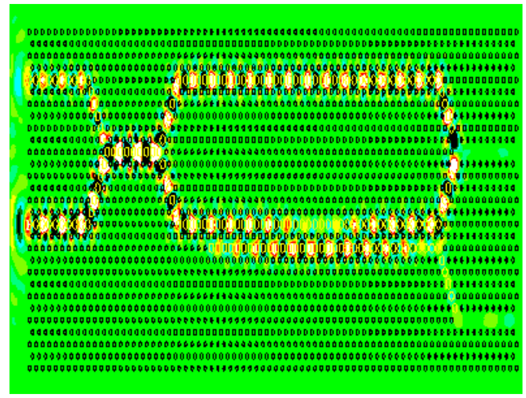
7. Conclusion

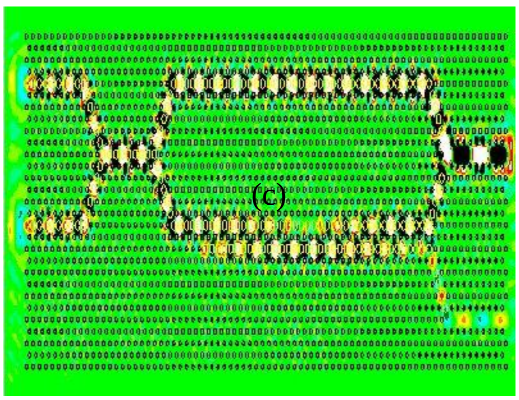
A novel photonic crystal structure based on nonlinear directional coupler has been proposed in this paper for designing all-optical logic gates. A bi-functional structure which implements two different logic operations (XOR/OR) in one structure by means of a control signal is designed. We designed XNOR, NOR and AND logic gates, using a junction in order to obtain summation of the input signals. A nonlinear material, Si-nc, is used because of its proper nonlinear characteristics. In order to analyse the performance of the structure, time domain simulations were performed. The calculated response time for the proposed devices is less than 1ps.

(a)



(b)





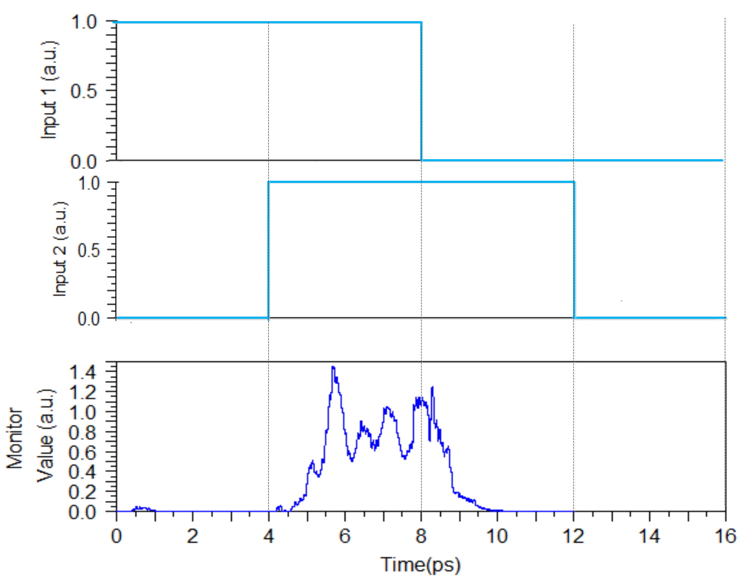


Fig 13. The field distribution and the time-domain response of the proposed all-optical AND logic gate. (a) input I_1 is ON (b) input I_2 is ON (c) both the inputs are ON.

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References

[1] E.-H. Lee, "Micro/nano-scale optical network: A new challenge toward next generation," in *Transparent Optical Networks, 2008. ICTON 2008. 10th Anniversary International Conference on*, 2008, pp. 118-119.

[2] S. Robinson and R. Nakkeeran, "A bandpass filter based on 2D circular photonic crystal ring resonator," in *Wireless And Optical Communications Networks (WOCN), 2010 Seventh International Conference On*, 2010, pp. 1-3.

[3] R. Bchir, A. Bardaoui, and H. Ezzaouia, "Design of silicon-based two-dimensional photonic integrated circuits: XOR gate," *IET Optoelectronics,* vol. 7, pp. 25-29, 2013.

[4] Y.-P. Yang, I.-C. Yang, C.-H. Chang, Y.-T. Tsai, K.-Y. Lee, Y.-R. Tsai*, et al.*, "Binary operating in all-optical logic gates based on photonic crystals," in *Computer, Consumer and Control (IS3C), 2012 International Symposium on*, 2012, pp. 302-304.

[5] H.-F. Zhang and Y.-Q. Chen, "The properties of two-dimensional fractal plasma photonic crystals with Thue-Morse sequence," *Physics of Plasmas,* vol. 24, p. 042116, 2017.

[6] H.-F. Zhang and S.-B. Liu, "Analyzing the photonic band gaps in two-dimensional plasma photonic crystals with fractal Sierpinski gasket structure based on the Monte Carlo method," *AIP Advances,* vol. 6, p. 085116, 2016.

[7] H.-F. Zhang and S.-B. Liu, "Enhanced the tunable omnidirectional photonic band gaps in the two-dimensional plasma photonic crystals," *Optical and Quantum Electronics,* vol. 48, p. 508, 2016.

[8] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic crystals: molding the flow of light*: Princeton university press, 2011.

[9] S. Noda and T. Baba, *Roadmap on photonic crystals*: Springer Science & Business Media, 2013.

[10] F. Cuesta-Soto, A. Martinez, J. Garcia, F. Ramos, P. Sanchis, J. Blasco*, et al.*, "All-optical switching structure based on a photonic crystal directional coupler," *Optics Express,* vol. 12, pp. 161-167, 2004.

[11] X.-q. Li and Y. Xu, "Optical sensing by using photonic crystal based Mach–Zehnder interferometer," *Optics Communications,* vol. 301, pp. 7-11, 2013.

[12] K. Fasihi and S. Mohammadnejad, "Highly efficient channel-drop filter with a coupled cavity-based wavelength-selective reflection feedback," *Optics express,* vol. 17, pp. 8983-8997, 2009.

[13] A. Shinya, S. Mitsugi, T. Tanabe, M. Notomi, I. Yokohama, H. Takara*, et al.*, "All-optical flip-flop circuit composed of coupled two-port resonant tunneling filter in two-dimensional photonic crystal slab," *Optics Express,* vol. 14, pp. 1230-1235, 2006.

[14] J. Bao, J. Xiao, L. Fan, X. Li, Y. Hai, T. Zhang*, et al.*, "All-optical NOR and NAND gates based on photonic crystal ring resonator," *Optics communications,* vol. 329, pp. 109-112, 2014.

[15] I. A. Sukhoivanov and I. V. Guryev, *Photonic crystals: physics and practical modeling* vol. 152: Springer, 2009.

[16] P. Andalib and N. Granpayeh, "All-optical ultra-compact photonic crystal NOR gate based on nonlinear ring resonators," *Journal of Optics A: Pure and Applied Optics,* vol. 11, p. 085203, 2009.

[17] Z.-H. Zhu, W.-M. Ye, J.-R. Ji, X.-D. Yuan, and C. Zen, "High-contrast light-by-light switching and AND gate based on nonlinear photonic crystals," *Optics Express,* vol. 14, pp. 1783-1788, 2006.

[18] A. Kabilan, X. S. Christina, and P. E. Caroline, "Realization of optical logic gates using photonic crystal," in *International Conference on Optic Photonics*, 2009, pp. 3-6.

[19] M. Danaie and H. Kaatuzian, "Design and simulation of an all-optical photonic crystal AND gate using nonlinear Kerr effect," *Optical and Quantum Electronics,* vol. 44, pp. 27-34, 2012.

[20] J. H. Greene and A. Taflove, "General vector auxiliary differential equation finite-difference time-domain method for nonlinear optics," *Optics express,* vol. 14, pp. 8305-8310, 2006.

[21] Y. Nagpal and R. Sinha, "Modeling of photonic band gap waveguide couplers," *Microwave and optical technology letters,* vol. 43, pp. 47-49, 2004.

[22] H. Sharifi, S. M. Hamidi, and K. Navi, "A new design procedure for all-optical photonic crystal logic gates and functions based on threshold logic," *Optics Communications*, vol. 370, pp. 231-238, 2016.

[23] S. Hernández, P. Pellegrino, A. Martínez, Y. Lebour, B. Garrido, R. Spano, *et al.*, "Linear and nonlinear optical properties of Si nanocrystals in Si O 2 deposited by plasma-enhanced chemical-vapor deposition," *Journal of Applied Physics*, vol. 103, p. 064309, 2008.

[24] G. V. Prakash, M. Cazzanelli, Z. Gaburro, L. Pavesi, F. Iacona, G. Franzo, *et al.*, "Nonlinear optical properties of silicon nanocrystals grown by plasma-enhanced chemical vapor deposition," *Journal of applied physics*, vol. 91, pp. 4607-4610, 2002.

[25] C. Koos, L. Jacome, C. Poulton, J. Leuthold, and W. Freude, "Nonlinear silicon-on-insulator waveguides for all-optical signal processing," *Optics Express*, vol. 15, pp. 5976-5990, 2007.

[26] J. Zimmermann, M. Kamp, A. Forchel, and R. März, "Photonic crystal waveguide directional couplers as wavelength selective optical filters," *Optics communications*, vol. 230, pp. 387-392, 2004.

[27] Z. F. Chaykandi, A. Bahrami, and S. Mohammadnejad, "MMI-based all-optical multi-input XOR and XNOR logic gates using nonlinear directional coupler," *Optical and Quantum Electronics*, vol. 47, pp. 3477-3489, 2015.

[28] R. Cuykendall, "Three-port reversible logic", *Appl.Opt.* Vol. 27, 9, pp. 1772-1779 (1988).

[29] N. Kostinski, M. P. Fok, and P. R. Prucnalet, "Experimental demonstration of an all-optical fiber-basedFredkin gate", *Opt. Lett.*, Vol. 34(18), pp. 2766-2768 (2009).