Optik 125 (2014) 5701–5704

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

All optical NOR and NAND gate based on nonlinear photonic crystal ring resonators

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ARTICLE INFO

Article history:
Received 1 October 2013
Accepted 27 May 2014

Keywords:
Photonic crystal
NAND gate
NOR gate
Band gap

ABSTRACT

In this paper we proposed optical NOR and NAND gates. By combining nonlinear Kerr effect with photonic crystal ring resonators first we designed a structure, whose optical behavior can be controlled via input power intensity. The switching power threshold obtained for this structure equal to 2 kW/μm^2. For designing the proposed optical logic gates we employed two resonant rings with the same structures, both rings at the logic gates were designed such that their resonant wavelength be at λ = 1550 nm. Every proposed logic gate has one bias and two logic input ports. We used plane wave expansion and finite difference time domain methods for analyzing the proposed structures.

1. Introduction

The advent of photonic crystals (PhCs) [1] had revolutionized the optical and photonic device designing field. PhCs are periodic structures, mostly composed of 2 different materials with high and low refractive indices [2]. According to the refractive index distribution function of these structures, they are divided into 3 categories: one, two and three dimensional PhCs. The periodic nature of PhCs gives them the ability to prohibit the propagation of optical waves in certain frequency ranges called photonic band gap (PBG). Due to this PBG property PhCs can confine and guide optical waves inside ultra-small spaces and waveguides. 2D PhCs due to their complete PBG and ease of design and fabrication attract more attention than 1D and 3D structures do. Obtaining suitable PBG region is very important in designing optical PhC-based devices. PBG region in 2D PhCs depends on the refractive index of the dielectric materials, the shape of the rods, the crystal structure, and the radius of the rods and the lattice constant of the structure [3–5].

All optical logic gates play a crucial role in all optical signal processing and optical communication networks. Low loss transmission, immunity to electromagnetic interference, high bandwidth and high data transmission and processing speed are the main advantages of optical networks. Optical devices such as optical filters, demultiplexers, switches and logic gates are the fundamental structures for realizing all optical networks, which can work completely in optical domain without employing electronics. One mechanism proposed for designing optical gates is based on waveguide interferometers [6], but due to their dimensions they are not suitable for integrated optical circuits [7]. Semiconductor optical amplifiers (SOAs) [8] are another mechanism used for creating optical logic gates, whose performance is limited by spontaneous emission noise and complexity of integration [9,10]. PhC ring resonators (PhCRRs) are basic structures used for designing opticl devices such as optical filters [11–14], optical demultiplexers [15–17], and optical switches [18]. A PhCRR simply is an optical device composed of a resonant ring sandwiched between two parallel waveguides called bus and drop waveguides. At a certain wavelength – resonant wavelength – optical waves in bus waveguide will drop to drop waveguide through the resonant ring. So PhCRR structure can perform filtering behavior. It has been shown that the resonant wavelength of PhCRRs depends on the refractive index and structural parameters of the ring core structure [19]. This property has been used for designing optical demultiplexers, by employing multiple resonant rings with different structural parameters in a single structure [20]. As far as we know high power optical waves trigger nonlinear effect in dielectric materials, which is called kerr effect [21]. It means that at high powers, the refractive index of dielectric materials depends on the power intensity of incident light. So we can control the optical behavior of the PhCRR structure via input intensity, and realize switching task.

Different kinds of optical logic gates have been proposed based on PhCs recently. An optical AND gate has been designed using nonlinear ring resonators by andalib and Granpaye [22]. Bai et al. [23] proposed optical NOT and optical NOR gates based on PhCRRS.

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http://dx.doi.org/10.1016/j.ijleo.2014.06.013
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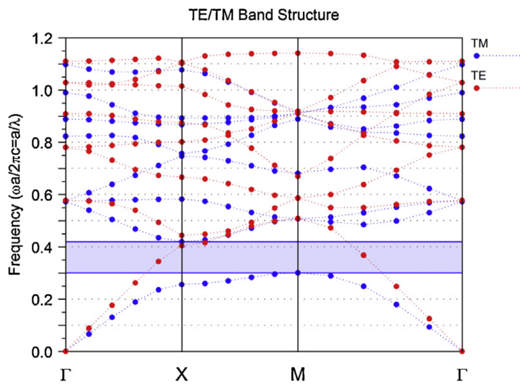

Fig. 1. The band structure of the fundamental structure.

Another optical NOR gate based on PhCRRs has been proposed by Isfahani et al. [24]. Danaie and Kaatuzian [25] proposed an optical AND gate based on PhC structures. In this paper we used nonlinear PhCRRs for designing two optical logic gates. An optical NOR and an optical NAND gate are proposed in this paper. To the best of or knowledge our structure is the first optical NAND gate proposed based on photonic crystals. We used plane wave expansion [26] and finite difference time domain [27] methods for analyzing the proposed structures.

The rest of the paper has been organized as follows: in Section 2 we proposed the basic nonlinear PhCRR structure then in Section 3 we discussed the design and results of the NAND and NOR gates. Finally in Section 4 we conclude from our work.

2. PhC ring resonator

As we mentioned the basic structure used for designing the optical logic gates in this paper is a photonic crystal ring resonator. The photonic crystal structure used for designing the PhCRR is a 31 × 21 square array of chalcogenid glass rods with refractive index of 3.1 in air. The radius of the rods is $r = 0.215 \times a$, where $a = 630$ nm is the lattice constant of the structure. For this structure the band structure diagram has been calculated and obtained like Fig. 1. This PhC structure has BPG region at $0.3 < a/\lambda < 0.42$ in TM mode which is equal to $1500\,\text{nm} < \lambda < 2100\,\text{nm}$. Our PhCRR structure is composed of a resonant ring sandwiched between two waveguides namely bus and drop waveguides. The core section of the resonant ring is a 12 fold quasi crystal. The PhCRR structure has four ports; input port (A), forward transmission port (B), backward drop port (C) and forward drop port (D). Optical waves enter the structure through port A and exit it from port B, however at the desired wavelength the optical wavelengths drop to drop waveguide through the resonant ring and travel toward port C. The schematic diagram of the PhCRR along with its output spectrum is shown in Fig. 2. This PhCRR has resonant wavelength at $\lambda = 1550$ nm. It has been shown that the resonant wavelength of PhCRRs depends on the refractive index of the structure and slightly changing the refractive index will shift the resonant wavelength of the structure. In our structure the dielectric rods have a high kerr coefficient equal to $n_2 = 9 \times 10^{-17}\,\text{m}^2/\text{W}$. So by launching high power light into the structure we can control the optical behavior of the PhCRR. The optical behavior of the proposed structure at $\lambda = 1550$ nm is shown in Fig. 3. For low intensity input power the PhCRR work at linear region so the input light due to resonant effect of the ting resonator will drop to the drop waveguide and travel toward port C (Fig. 3(a)) but for high intensity input power – equal to $2\,\text{kW}/\mu\text{m}^2$ – the refractive index of the structure will increase due to the kerr coefficient of the dielectric rods, this in turn shifts the resonant wavelength of the PhCRR, therefore the input light will not drop to drop waveguide and will travel toward

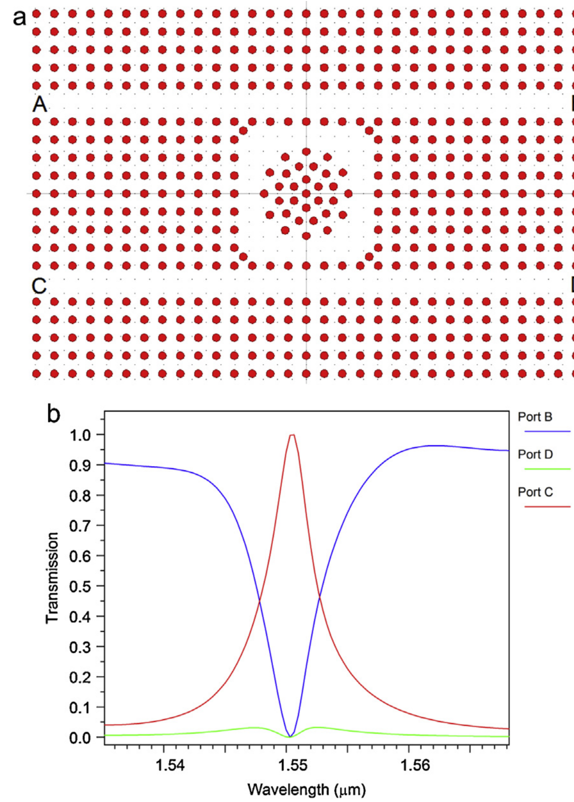

Fig. 2. The (a) schematic and (b) output spectrum of the PhCRR.

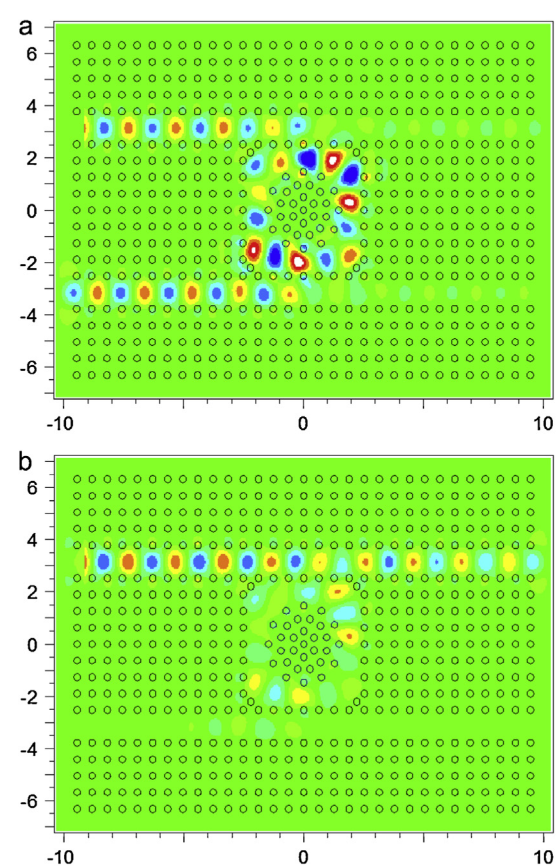

Fig. 3. Distribution of optical waves inside the structure for different power intensities (a) $1\,\text{kW}/\text{mm}^2$ and (b) $2\,\text{kW}/\text{mm}^2$.

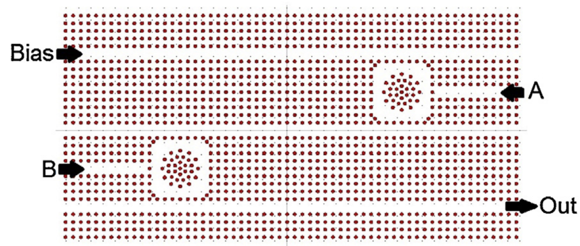

Fig. 4. The schematic diagram of the proposed NOR gate.

Table 1
Working states of the logic NOR gate for different states of input ports.

A	B	OUTPUT
0	0	1
0	1	0
1	0	0
1	1	0

port B. So the structure shows switching behavior. At the following we will employ this structure for designing NOR and NAND gates.

3. Optical logic gates

3.1. NOR gate

The proposed structure for optical logic NOR gate is shown in Fig. 4. It consists of two nonlinear resonant rings and five waveguides. Our structure has four ports. The logic ports are shown via A and B letters. Each logic port is connected to the corresponding resonant ring with a one waveguide. The resonant rings have been designed such that their resonant wavelength at input intensities lower than the switching threshold – 2 kW/μm^2 – to be at λ = 1550 nm. The bias pulse enters the structure through port BIAS. As far as we know 2 input logic gates have 4 different cases according to their logic input states. Logic NOR gate is at ON state only when both of its logic inputs are OFF, and if one or both of its logic inputs turn(s) ON the gate will turn OFF. The working states of the logic NOR gate for different states of input ports (A and B) are listed in Table 1.

Working states of the proposed logic NOR gate for different states of A and B ports are shown in Fig. 5. Fig. 5(a) shows the case in which A and B both are OFF (A = B = 0), at this case both rings are at linear state, bias pulse entering the structure, will drop to the middle waveguide through the upper ring and then through lower ring will drop into the lower waveguide and travel toward OUPPUT port in this case the gate is at ON state (OUTPUT = 1). Fig. 5(b) shows the case in which A is on (A = 1) and B is OFF (B = 0). At this case the overall intensity of optical waves – pulse intensity plus the port A intensity – near the upper ring reach to the switching threshold – 2 kW/μm^2 – and will shift the resonant wavelength of the upper ring so the bias pulse could not drop into middle waveguide, so there will be no optical pulse in the output port. Therefore the gate is at OFF state. Fig. 5(c) shows the case in which A is OFF (A = 0) and B is ON (B = 1). At this case the overall intensity of optical waves near the upper ring is less than the switching threshold – 2 kW/μm^2 – so the bias pulse will drop to the middle waveguide through upper ring and travel toward lower ring. But the overall intensity of optical waves – pulse intensity plus the port B intensity – near the lower ring reach to the switching threshold – 2 kW/μm^2 – and will shift the resonant wavelength of the lower ring so the bias pulse could not drop into lower waveguide and will not travel toward output port so similar to previous case the logic gate is at OFF state. Finally Fig. 5(d) shows the case in which A and B both are ON (A = B = 1). At this case the overall optical intensity near both rings reaches the switching threshold and will shift the resonant wavelength of the rings so the bias pulse will not be dropped into middle and lower waveguide and the gate will be at OFF state. The states are valid only if the bias port is ON, and if bias port turns OFF the gate always will be at OFF state. We have to mention that the power intensity of bias and logic inputs is 1 kW/μm^2.

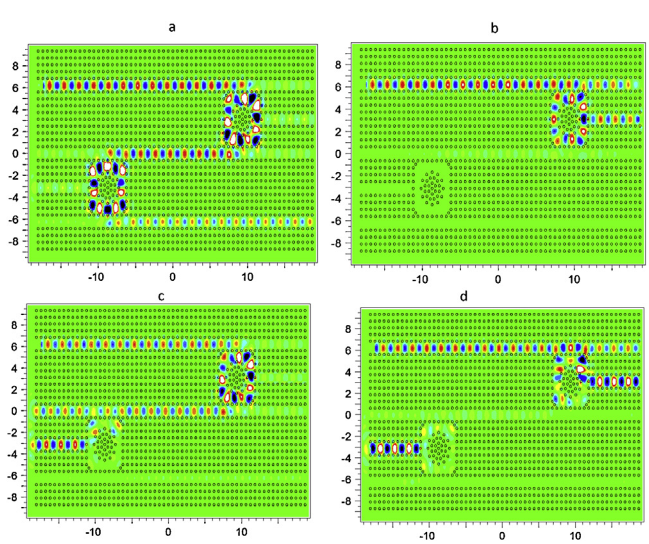

Fig. 5. The working states of the NOR gate.

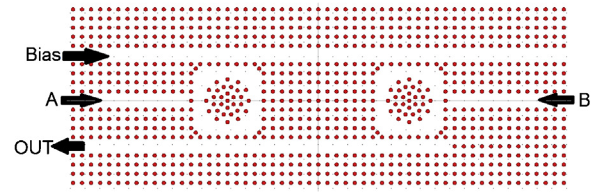

Fig. 6. The schematic diagram of the proposed NAND gate.

3.2. NAND gate

The proposed structure for optical logic NAND gate is shown in Fig. 6. It consists of four waveguides and two resonant rings place between bus waveguide and drop waveguide. Similar to NOR gate this structure has 4 ports Bias port, A and B as logic input ports and output port. The resonant rings have been designed such that their resonant wavelength at input intensities lower than the switching threshold – 2 kW/μm^2 – to be at λ = 1550 nm. The bias pulse enters the structure through port BIAS. As far as we know logic NAND gate is ON when one or both of its logic inputs (A and B) are OFF, and it is OFF when both inputs are ON. The working states of the logic NAND gate for different states of input ports (A and B) are listed in Table 2.

Working states of the proposed logic NAND gate for different states of A and B ports are shown in Fig. 5. Fig. 5(a) shows the case in which A and B both are OFF (A = B = 0), at this case both rings are at linear state, bias pulse entering the structure, will drop to the drop waveguide through the resonant rings and travel toward OUPPUT

Table 2
Working states of the logic NAND gate for different states of input ports.

A	B	OUTPUT
0	0	1
0	1	1
1	0	1
1	1	0

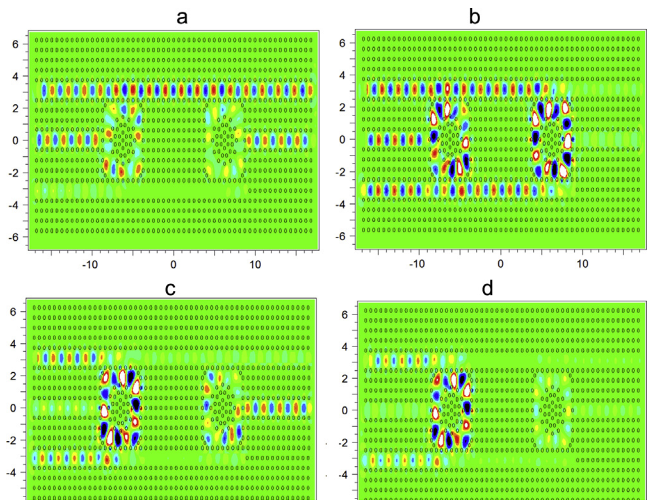

Fig. 7. The working states of the NOR gate.

port in this case the gate is at ON state (OUTPUT = 1). Fig. 5(b) shows the case in which A is on (A = 1) and B is OFF (B = 0). At this case the overall intensity of optical waves – pulse intensity plus the port A intensity – near the left side ring reach to the switching threshold – 2 kW/μm^2 – and will shift the resonant wavelength of the left side ring so the bias pulse could not drop into drop waveguide through this ring, but the right side ring is still at linear region and will drop the bias light to drop waveguide, so there will be optical pulse in the output port. And the gate is at ON state. Fig. 5 (c) shows the case in which A is OFF (A = 0) and B is ON (B = 1). At this case the overall intensity of optical waves near the left side ring is less than the switching threshold – 2 kW/μm^2 – so the bias pulse will drop to the drop waveguide through right side ring and travel toward output port. Therefore we have optical waves at the output port and the gate is ON. Finally Fig. 5(d) shows the case in which A and B both are ON (A = B = 1). At this case the overall optical intensity near both rings reaches the switching threshold and will shift the resonant wavelength of the rings so the bias pulse will not be dropped into drop waveguide and the gate will be at OFF state. The states are valid only if the bias port is ON, and if bias port turns OFF the gate always will be at OFF state. We have to mention that the power intensity of bias and logic inputs is 1 kW/μm^2 (Fig. 7).

4. Conclusion

In this paper we first we proposed a PhCRR structure, whose optical behavior was controllable via intensity of input power. The PhCRR was designed such that its resonant wavelength at power intensities lower than the switching threshold – 2 kW/μm^2 – to be at λ = 1550 nm. The resonant wavelength of the proposed structure depends on the refractive index of ring core rods, so by increasing the intensity of input power due to the nonlinear Kerr coefficient the refractive index of the structure will change and consequently will shift the resonant wavelength of the PhCRR. Then we used this PhCRR for designing all optical logic NAND and NOR gates. In the NOR gate when both logic inputs are OFF the bias light will drop to the output waveguide and the output become 1, but when one or both of the logic input ports turn ON the bias light could not drop to the output waveguide so the NOR gate would become 0. In the NAND gate when both logic ports are ON the bias light will not drop to the drop waveguide and will not go toward output port and the gate will be 0, but when one or both of the logic ports turns OFF the bias light will drop to the drop waveguide and the gate will become 1.

References

[1] S. John, Strong localization of photons in certain disordered dielectric superlattices, Phys. Rev. Lett. 58 (23) (1987) 2486–2489.
[2] K. Sakoda, Optical Properties of Photonic Crystals, Springer-Verlag, Berlin, 2001.
[3] Z. Wu, K. Xie, H. Yang, Band gap properties of two dimensional photonic crystals with rhombic lattice, Optik 123 (2012) 534–536.
[4] F. Mehdizadeh, H. Alipour-Banaei, Band gap management in two dimensional photonic crystal thue-morse structures, J. Opt. Commun. 34 (2013) 61–65.
[5] B. Rezaei, M. Kalafi, Engineering absolute band gap in anisotropic hexagonal photonic crystals, Opt. Commun. 266 (2006) 159–163.
[6] Z.J. Li, Z.W. Chen, B.J. Li, Optical pulse controlled all optical logic gates in SiGe/Si multimode interference, Opt. Express 13 (1033–1038) (2005).
[7] H. Azuma, Quantum computation with kerr nonlinear photonic crystals, J. Phys. D 41 (025102) (2008).
[8] X. Zhang, Y. Wang, J. Sun, D. Liu, D. Huang, All-optical AND gate at 10 Gbit/s based on cascaded single-port-coupled SOAs, Opt. Express 12 (361–366) (2004).
[9] J. Wang, J. Sun, Q. Sun, Experimental observation of a 1.5 μm band wavelength conversion and logic NOT gate at 40 Gbit/s based on sum-frequency generation, Opt. Lett. 31 (1711–1713) (2006).
[10] J. Wang, J. Sun, Q. Sun, Proposal for all-optical switchable OR/XOR logic gates using sum-frequency generation, IEEE Photon. Technol. Lett. 19 (541–543) (2007).
[11] A. Taalbi, G. Bassou, M.Y. Mahmoud, New design of channel drop filters based on photonic crystal ring resonators, Optik (2012), http://dx.doi.org/10.1016/j.ijleo.2012.01.045.
[12] M. Djavid, A. Ghaffari, F. Monifi, M.S. Abrishamian, T-shaped channel-drop filters using photonic crystal ring resonators, Phys. E 40 (2008) 3151–3154.
[13] M. Djavid, M.S. Abrishamian, Multi-channel drop filters using photonic crystal ring resonators, Optik 123 (2011) 167–170.
[14] M.Y. Mahmoud, G. Bassou, A. Taalbi, Z.M. Chekroun, Optical channel drop filter based on photonic crystal ring resonators, Opt. Commun. 285 (2012) 368–372.
[15] M.R. Rakhshani, M.A.M. Birjandi, Design and simulation of wavelength demultiplexer based on heterostructure photonic crystals ring resonators, Phys. E 50 (2013) 97–101.
[16] H. Alipour-Banaei, F. Mehdizadeh, S. Serajmohammadi, A novel 4-channel demultiplexer based on photonic crystal ring resonators, Optik (2013), http://dx.doi.org/10.1016/j.ijleo.2013.04.117.
[17] M. Djavid, F. Monifi, A. Ghaffari, M.S. Abrishamian, Heterostructure wavelength division multiplexers using photonic crystal ring resonators, Opt. Commun. 281 (2008) 4028–4032.
[18] T. Ahmadi-Tame, B.M. Isfahani, N. Granpayeh, A.M. Javan, Improving the performance of all optical switching based on nonlinear photonic crystal micro ring resonator, Int. J. Electron. Commun. (AEU) 65 (2011) 281–287.
[19] F. Mehdizadeh, H. Alipour-Banaei, S. Serajmohammadi, Channel-drop filter based on a photonic crystal ring resonator, J. Opt. 15 (2013), 075401 (7 pp.).
[20] M.A.M. Birjandi, M.R. Rakhshani, Anew design of tunable four-port wavelength demultiplexer by photonic crystal ring resonators, Optik (2013), http://dx.doi.org/10.1016/j.ijleo.2013.04.128.
[21] G. Vijaya Prakash, M. Cazzanelli, Z. Gaburro, L. Pavesi, F. Iacona, G. Franzò, F. Priolo, Linear and nonlinear optical properties of plasma-enhanced chemical-vapour deposition grown silicon nanocrystals, J. Mod. Opt. 49 (719–730) (2002).
[22] P. Andalib, N. Granpayeh, All optical ultracompact photonic crystal AND gate based on nonlinear ring resonators, J. Opt. Soc. Am. B 26 (2009) 10–16.
[23] J. Bai, J. Wang, J. Jiang, Z. Chen, H. Li, Y. Qin, Z. Qiang, Photonic NOT and NOR gates based on photonic crystal ring resonator, Appl. Opt. 48 (6923–6927) (2009).
[24] B.M. Isfahani, T. Ahamdi Tameh, N. Granpayeh, A.M. Javan, All-optical NOR gate based on nonlinear photonic crystal microring resonators, J. Opt. Soc. Am. B 26 (2009) 1097–1102.
[25] M. Danaei, H. Kaatuzian, Design and simulation of an all optical photonic crystal AND gate using nonlinear Kerr effect, Opt. Quant. Electron. 44 (2012) 27–34.
[26] S.G. Johnson, J.D. Joannopoulos, Block-iterative frequency-domain methods for Maxwell's equations in a plane wave basis, Opt. Express 8 (2001) 173–190.
[27] S.D. Gedney, Introduction to Finite-Difference Time-Domain (FDTD) Method for Electromagnetics, Morgan & Claypool, Lexington, KY, 2010.