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A novel proposal for all-optical XOR/XNOR gate using a nonlinear photonic crystal based ring resonator

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Optical logic gates are very important structures required for creating all-optical digital signal processing systems. Optical XOR and XNOR gates can be used for designing optical adders and optical comparators, respectively. In this paper we proposed a novel structure which can be used for simultaneous implementation of optical XOR and XNOR logic gates. The proposed structure was designed using a nonlinear photonic crystal ring resonator. The delay time for XOR and XNOR gates are 1.7 and 3 ps, respectively.

Keywords: photonic crystal, optical logics, XOR gate, XNOR gate, Kerr effect.

1. Introduction

Photonic crystals [1] are periodic structures made of two or more dielectric materials with different refractive indices. These structures have great properties which made them very popular for designing optical devices. Photonic band gap [2, 3], self-collimation [4–6], optical wave guiding [7, 8], wavelength selection [9, 10], threshold switching [11–14] are the most significant properties of PhCs. These properties give them the capability to be used in designing optical devices such as filters [9, 15–23], demultiplexers [24–31], logic gates [12, 32–40], data converters [41–44], adders [6, 45–49], decoders [50–54] and encoders [55–59].

Optical logic gates are very important for designing all-optical digital data processing and optical digital networks. Because of their significant role in optical networks and signal processing, so many researches have been done for designing optical logic gates using PhCs. Shaik and Rangaswamy [60] proposed novel structures for optical AND gates using T-shaped waveguides. They proposed two different configurations, one with probe light and the other one without probe light. SALMANPOUR *et al*. [61] proposed NOT/OR gates using nonlinear photonic crystal ring resonators (PhCRRs). RANI *et al*. [62] proposed an optical AND gate using a Y-shaped PhC waveguide. A NAND/NOR gates were proposed by ALIPOUR-BANAEI *et al*. [32]. The authors used two nonlinear PhCRRs combined with parallel optical waveguides for designing the proposed structures. FU *et al*. [63] used an optical beam interference effect for designing OR/XOR/NOT/NAND/XNOR gates. JIANG *et al.* [64] proposed reconfigurable structures for designing different kinds of optical logic gates such as NOR/OR/XNOR/NOT. LIU *et al.* [65] used nonlinear PhC-based resonant cavities for designing all-optical AND/NAND/OR/NOR gates. RANI *et al*. [37] proposed other designs for creating optical logic gates inside hole-type Si-based PhC.

In this paper we present a novel design for realizing a compact structure which can be used as XOR/XNOR logic gates. The proposed structure will be created using a nonlinear PhCRR, which can be obtained by introducing some nonlinear defect rods inside the linear PhCRR. The nonlinear defects are made of doped glass. The linear refractive index and the Kerr coefficient of the doped glass are 1.4 and 10^{-14} m^2/W. Finite difference time domain [66] and plane wave expansion [67] methods were used for analyzing the proposed structure.

2. Design procedure

A 2D PhC structure is composed of a 65 × 45 matrix of dielectric rods with square lattice. The refractive index and radius of dielectric rods are 3.46 and 127 nm, respectively. Also the lattice constant of the PhC structure is 633 nm. The space between the dielectric rods was filled with air whose refractive index is 1. For this structure, the band structure diagram was calculated using a plane wave expansion method and the obtained diagram is shown in Fig. 1, according which the main PBG region is at $0.28 < a/\lambda < 0.42$, which is equal to $1507 \text{ nm} < \lambda < 2260 \text{ nm}$.

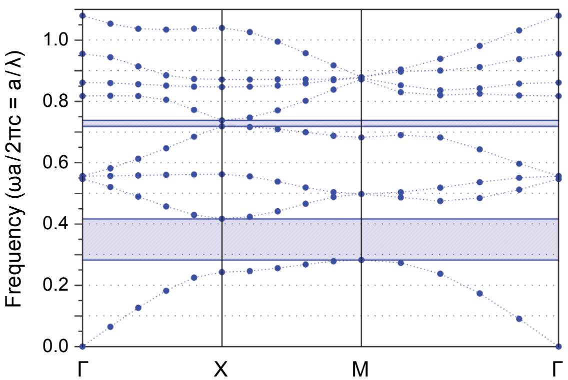

Fig. 1. Band structure diagram of the PhC structure.

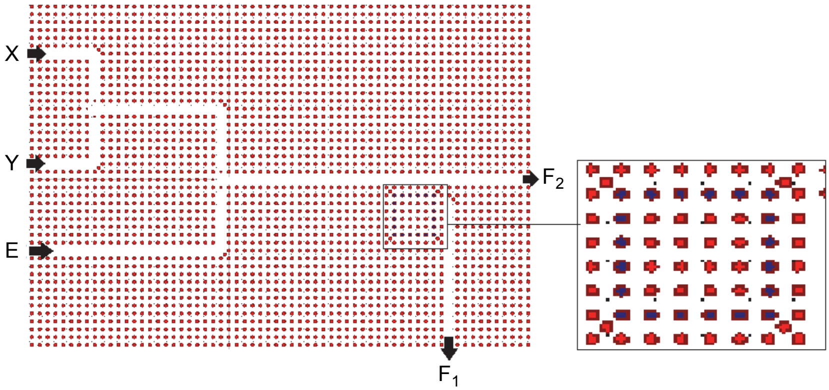

Fig. 2. Final structure of the proposed XOR/XNOR gate.

The first step for designing the proposed structure is creating a nonlinear PhCRR with the suitable functionality for realizing XOR and XNOR operations. For this purpose, a resonant ring was created inside the fundamental PhC, whose core section is a 4 × 4 square shaped structure. Then 16 nonlinear defect rods made of doped glass were place around the core section. The resulted nonlinear resonant ring can drop optical waves with central wavelength and input intensity equal to 1550 nm and 0.02 W/μm^2, respectively. However, when the optical intensity is less than 0.01 W/μm^2 or more than 0.025 W/μm^2, the resonant ring cannot drop the optical waves. In order to complete the proposed structure, suitable waveguides were created inside the PhC structure which connect the resonant ring to the input and output ports. As shown in Fig. 2, the final structure has three input ports labeled as X, Y, E, and it has two output ports labeled as F_1, F_2. In the proposed structure, E serves as an enable port and X, Y serve as the input ports of the logic gate.

3. Simulation and results

The final step after designing the proposed structure is testing its functionality. For this purpose, three Gaussian optical sources with central wavelengths and optical intensities equal to 1550 nm and 0.01 W/μm^2 were used at the input ports of the proposed structure. In the active state of the proposed structure, port E always should be ON. There are four different working states for combination of X and Y states. The description of the simulation results is as follows.

When both input ports are OFF (X = Y = 0), only optical waves coming from E can reach the resonant ring, and it is obvious that in this case the amount of optical intensity is less than 0.01 W/μm^2, therefore the resonant ring cannot drop the optical beams and they will propagate toward port F_2. As a result, at this case F_2 will be ON and F_1 will be OFF. When one of the input ports is ON (X = 1, Y = 0 or X = 0, Y = 1), at this case the amount of optical intensity near the resonant ring is about 0.02 W/μm^2, therefore

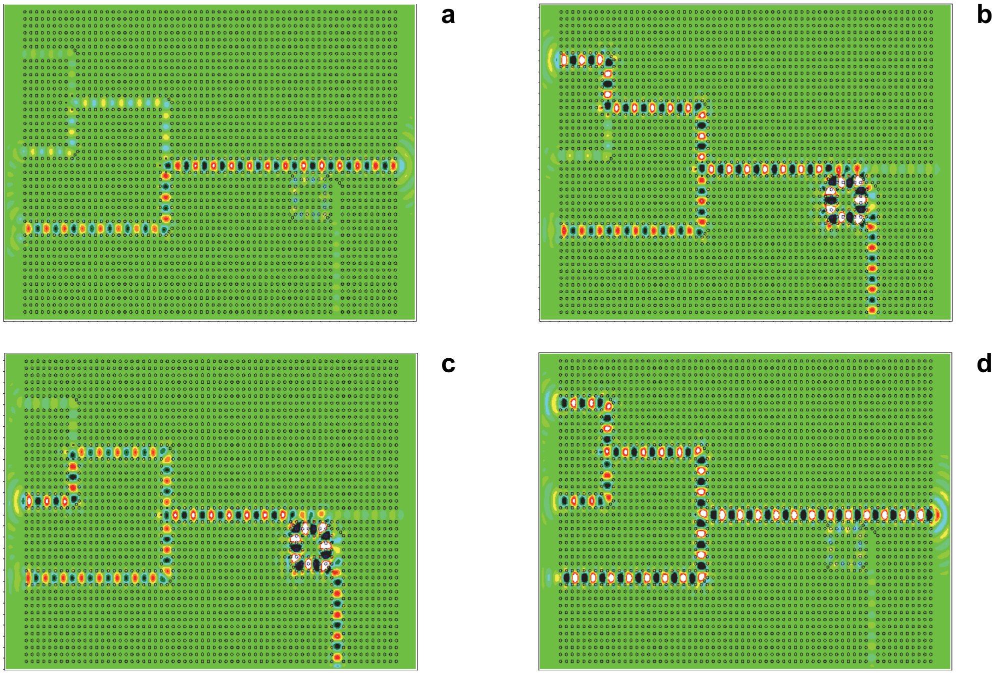

Fig. 3. Optical behavior of the proposed structure when X = Y = 0 (**a**), X = 1, Y = 0 (**b**), X = 0, Y = 1 (**c**), and X = Y = 1 (**d**).

the resonant ring can drop the optical waves and guide them toward port F_1. As a result, at these cases F_2 will be OFF and F_1 will be ON. Finally, when both input ports are ON (X = Y = 1) the amount of optical intensity near the resonant ring will be more than 0.025 W/μm^2, therefore the resonant ring cannot drop the optical waves and they will propagate toward F_2. As a result, at this case F_2 will be ON and F_1 will be OFF. These are shown in Fig. 3.

In order to investigate the time response of the proposed structure, we calculated the output diagrams of the proposed structure as shown in Fig. 4. Figure 4**a** shows the output diagram for the case in which both input ports are OFF, and one can see that in this case the normalized intensity at F_1 and F_2 are 4% and 71%, respectively. Also the time delay for F_2 is about 1.5 ps. Figure 4**b** shows the output diagram for the cases in which one of the input ports is ON, and one can see that in this case the normalized intensities at F_1 and F_2 are 175% and 12%, respectively. Also the time delay for F_1 is about 3 ps. Figure 4**c** shows the output diagram for the case in which both input ports are ON, and one can see that in this case the normalized intensities at F_1 and F_2 are 5% and 280%, respectively. Also the time delay for F_2 is about 1.7 ps.

In summary, in the proposed structure the F_1 is ON when only one of the input ports is ON, and F_2 is ON when both input ports have the same state. The truth table of the

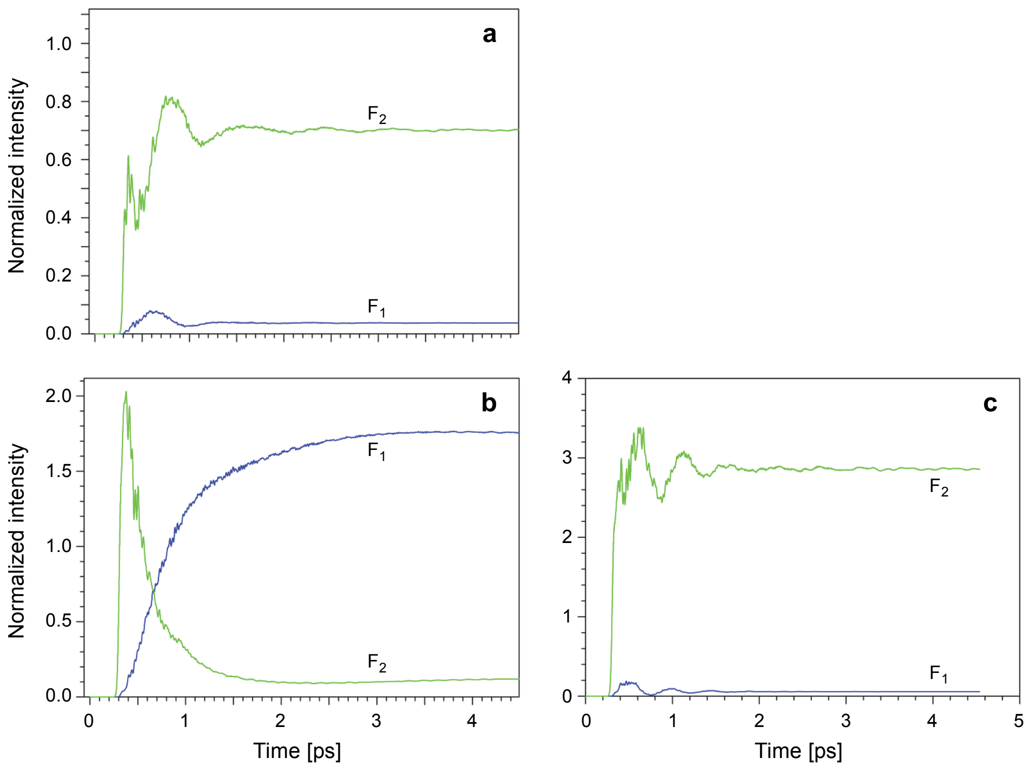

Fig. 4. Output diagram of the proposed structure when none (**a**), one (**b**), and both (**c**) of input ports are ON.

T a b l e. The truth table of the proposed structure.

Inputs		Outputs	
X	Y	F_1 [%]	F_2 [%]
0	0	4	71
0	1	175	12
1	0	175	12
1	1	5	280

proposed structure is listed in the Table. Therefore F_1 serves as an optical XOR gate and the F_2 can serve as an optical XNOR gate. The overall footprint of the structure is about 1200 μm^2.

4. Conclusion

A nonlinear PhCRR was created by adding some nonlinear rods around the core section of the linear PhCRR. The resulted structure can drop optical waves when the central wavelength is 1550 nm and the optical intensity is between 0.01 and 0.025 W/μm^2. Then the final structure was designed with one enable port, two input and two output ports. Port F_1 is ON when only one of the input ports is ON, therefore it serves as XOR gate. Port F_2 is ON when both input ports are in the same sate, therefore it can be used as optical XNOR gate.

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