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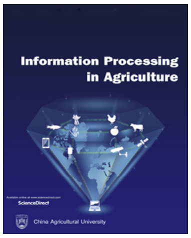

All optical NAND gate based on nonlinear photonic crystal ring resonator

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ABSTRACT

In this paper we proposed a new design for all optical NAND gate. By combining nonlinear Kerr effect with photonic crystal ring resonators, we designed an all optical NAND gate. A typical NAND gate is a logic device with one bias and two logic input and one output ports. It has four different combinations for its logic input ports. The output port of the NAND gate is OFF, when both logic ports are ON, otherwise the output port will be ON. The switching power threshold obtained for this structure equals to 1.5 kW/μm^2. For designing the proposed optical logic gate we employed one resonant ring whose resonant wavelength is at 1554 nm. The functionality of the proposed NAND gate depends on the operation of this resonant ring. When the power intensity of optical waves is less than the switching threshold the ring will couple optical waves into drop waveguide otherwise the optical waves will propagate on the bus waveguide.

1. Introduction

The idea of using photonic crystals (PhC), [1] for designing optical devices had revolutionized the field of integrated optics and photonics. The periodic modulation of refractive index in PhC results in a special characteristic called photonic band gap (PBG). Having PBG makes these periodic structures suitable for confining and controlling the propagation of optical waves with desired wavelength. PBG depends on refractive index, radius of rods and the lattice constant of the structure [2], so by choosing appropriate values for these parameters we can obtain the best PBG region according to our requirements. Optical filters [3–6], optical demultiplexers [7–9], optical switches [10] optical decoders [11,12] and optical logic gates [13,14] are some examples of optical devices proposed based on PhC.

Optical logic gates are essential components required for optical signal processing and optical communication networks. Semiconductor optical amplifiers (SOAs) [15,16] is an example of different mechanisms proposed for realizing optical logic gates. Their performance is limited by spontaneous emission noise and complexity of integration. Fu et al. [17] theoretically discussed the realization of optical logic gates in 2D Si PhC using beam interference effect. They proposed OR, XOR, NOT, XNOR and NAND gates. Saidani et al. [18] proposed a multifunctional logic gate in a 2D PhC waveguide structure using multimode interference concept. By switching optical signal to different input waveguides, different functions such as XOR, OR, NOR and NOT gates have been obtained. An all optical NOR gate have been proposed by Isfahani et al. [19]. First of all they proposed a T-shaped optical switch by using nonlinear photonic crystal micro ring resonators. Then they cascaded two of the proposed switches

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to realize optical NOR gate. They showed that the transmission efficiency of the NOR gate in OFF and ON states are 2% and 81% respectively.

In this paper we are going to propose a new structure for implementing optical NAND gate based on photonic crystal ring resonators (PhCRR). In a PhCRR optical waves propagating in the bus waveguide at a certain wavelength – called resonant wavelength – will drop to the drop waveguide [20]. The resonant wavelength of PhCRR depends on the refractive index, radius and dimensions of the core section of resonant ring [21]. High power optical waves trigger nonlinear effect in dielectric materials, which is called Kerr effect [22]. Therefore 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 [10].

The rest of the paper has been organized as follows: in Section 2 we proposed the basic photonic crystal ring resonator then on Section 3 we discussed the design and results of the simulations for NAND gate. Finally in Section 4 we conclude from our work.

2. Basic filter

As far as we know most of the PhC-based devices like optical switches and optical logic gates are designed by employing an optical filter as the basic structure of the proposed device. Therefore in this paper for designing the proposed NAND gate, first of all we should propose and design a PhC-based optical filter. We used a photonic crystal ring resonator as the wavelength selection part of the filter. The photonic crystal structure used for designing the PhCRR is a 32*18 square array of chalcogenide glass rods with refractive index of 3.1 in air. The radius of the rods is $r = 0.2*a$, where $a = 640$ 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 one photonic band gap region at TM mode at $0.31 < a/\lambda < 0.43$ in TM mode this region is in normalized frequency domain, we have to convert it into wavelength domain by dividing it into $a = 640$ nm, therefore the PBG region in wavelength region will be at 1488 nm $< \lambda <$ 2064 nm. This means that, optical waves at this wavelength region will not scatter inside the fundamental PhC structure.

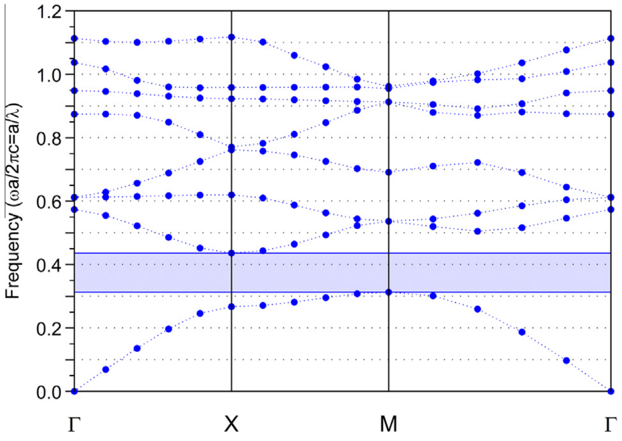
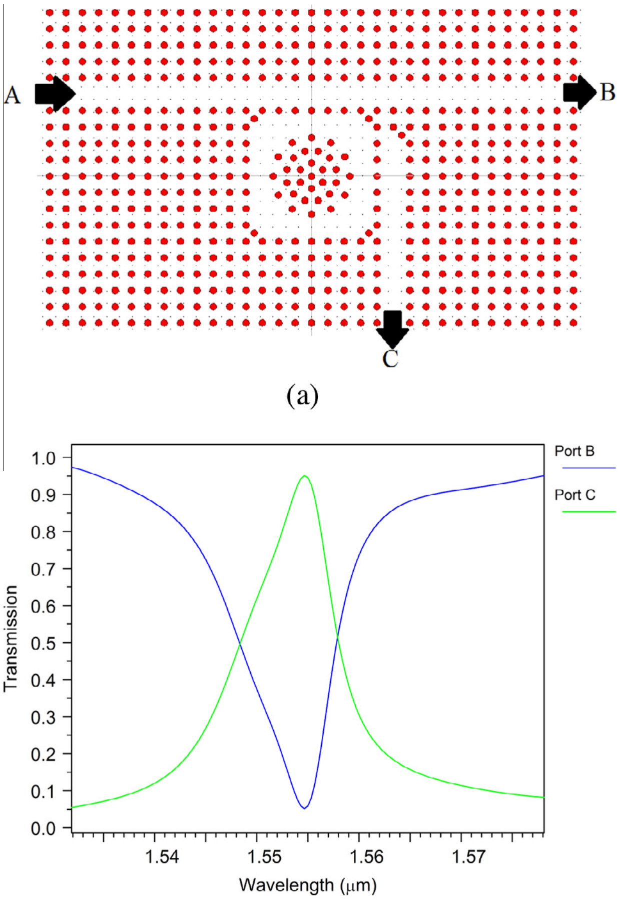


Fig. 1 – The band structure of the fundamental PhC structure.

Our PhCRR structure is composed of a resonant ring sandwiched between two waveguides namely bus and drop waveguides. The bus waveguide was created by removing a complete row of dielectric rods in X direction, also by removing 12 rods in Z direction we created the drop waveguide. For creating the resonant ring, first a 7*7 array of dielectric rods was removed and then a 12-fold quasi crystal was replaced at the center of the structure. The PhCRR structure has three ports; input port (A), forward transmission port (B), and forward drop port (C). 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 $\lambda = 1554$ nm.

The output spectra of the PhCRR for different refractive indices of the rods are shown in Fig. 3. According to Fig. 3 by increasing refractive index, the resonant wavelength of the structure will shift toward higher wavelengths. This proves that by changing the refractive index of the rods one can control the optical properties of the proposed resonator. One way of changing refractive index of dielectric rods is making use of the nonlinear Kerr effect, in which one can change the refractive index by launching high intensity



(a)

(b)

Fig. 2 – (a) The basic PhCRR and (b) its output spectrum.

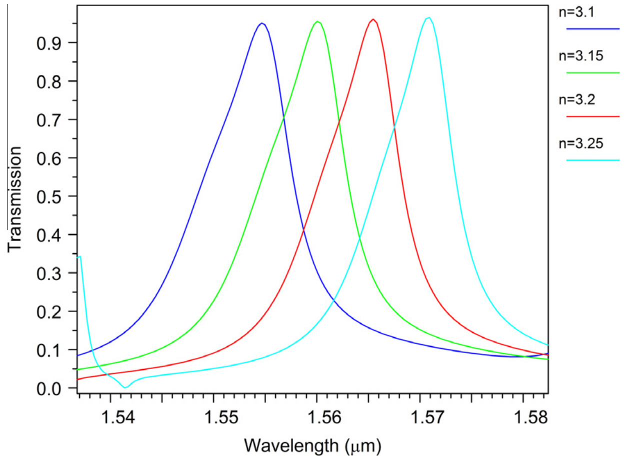


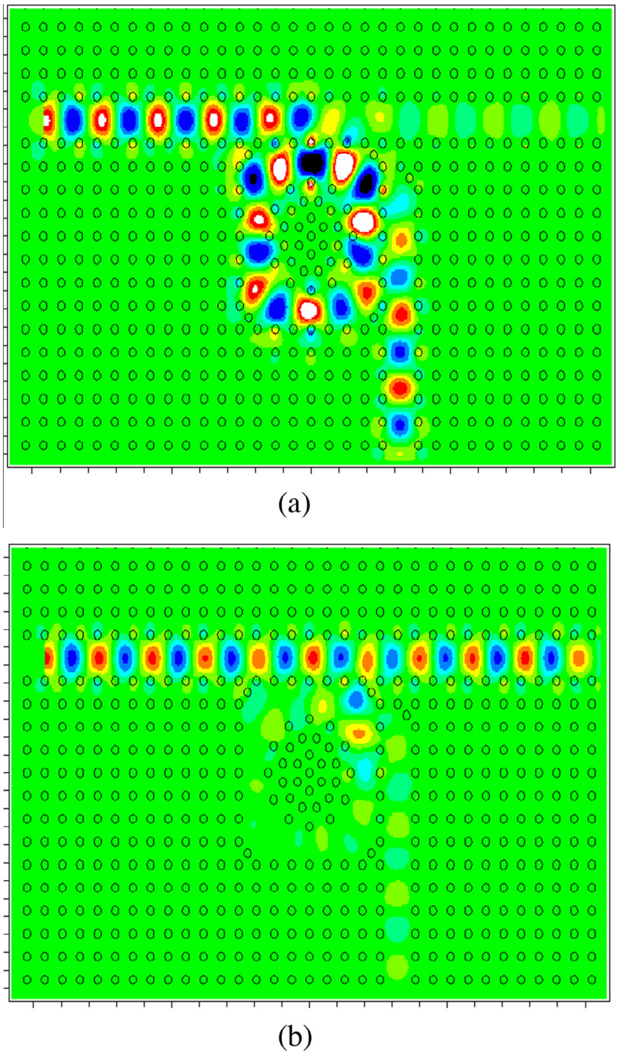
Fig. 3 – Output spectra of the PhCRR for different refractive indices.

optical power into dielectric rods. In our structure the dielectric rods have a high Kerr coefficient equal to $n_2 = 9*10^{-17}\ \mathrm{m^2/W}$. 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 $\lambda = 1554$ nm is shown in Fig. 4. For low intensity input power the PhCRR work at linear region so the input light due to resonant effect of the ring resonator will drop to the drop waveguide and travel toward port C (Fig. 3(a)) but for high intensity input power – equal to $1.5\ \mathrm{kW/\mu m^2}$ – 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 port B. So the structure shows switching behavior. We will use this property for designing the proposed NAND gate.

3. Design and simulation of optical NAND gate

For designing the proposed optical logic NAND gate we employed a 33*26 square array of dielectric rods. The refractive index, radius and lattice constant of the structure are the same as the PhCRR structure. For realizing the proposed NAND gate we need three input waveguides, one output waveguide and one resonant ring. The first waveguide was created by removing a complete row of rods in X direction. This waveguide is used to create an optical path from the bias port toward resonant ring. The other two input waveguides are created by removing 12 rods for each in order to connect the logic input ports to the resonant ring. The output port was created by removing 18 rods in Z direction. Therefore our proposed structure has four ports: A, B and BIAS are the input ports and OUT is the output port. The final schematic of our proposed NAND gate structure is shown in Fig. 5. From Bias port, bias optical waves enter the structure and the output state of the NAND gate will be controlled via A and B ports. Logic NAND gate is OFF when both of its logic inputs – A and B – are ON (A = B = 1), otherwise it turns ON.


(a)

(b)

Fig. 4 – Optical behavior of the proposed PhCRR for (a) low and (b) high incident power.

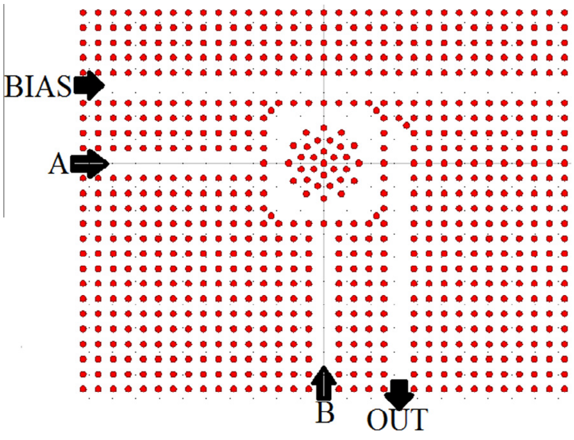


Fig. 5 – Final sketch of the proposed NAND gate.

After finalizing the design procedure of the proposed NAND gate, we are going to test and simulate the proposed structure. For this purposed we used 3 optical source with continuous wave for BIAS, A and B ports. The central wavelength and power density of all sources are $\lambda = 1554$ nm and

0.5 kW/μm^2. The proposed NAND gate has 2 logic input port, so according to the counting principle we have 4 different input states. In all of the 4 states the bias wave should be ON. When both of the logic ports are OFF (A = B = 0) the optical power near the resonant ring is 0.5 kW/μm^2 which is less than the switching threshold of the resonator – 1.5 kW/μm^2 – so the bias wave propagating in the B3 waveguide will drop to output waveguide due to resonant effect of the resonant ring and will travel toward output port and turn on the NAND gate. For this case the gate will be at ON state (OUT = 1) (Fig. 6a).

In the second case in which A is ON and B is OFF (A = 1, B = 0), the optical waves coming from bias and A port will travel toward the resonant ring, the power density is about 1 kW/μm^2 which is less than the switching threshold so the resonant ring will drop the optical waves into output port. As a result optical waves will reach to the output port and the gate will be at ON state (OUT = 1) (Fig. 6b).

In the third case in which A is OFF and B is ON (A = 0, B = 1), the optical waves coming from bias and B port will travel toward the resonant ring, the power density is about 1 kW/μm^2 which is less than the switching threshold so the resonant ring will drop the optical waves into output port. As a result optical waves will reach to the output port and the gate will be at ON state (OUT = 1) (Fig. 6c).

Table 1 – Working states of the logic NAND gate for different states of input ports.

BIAS	A	B	OUT
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	0

Finally when both logic ports are ON (A = B = 1), the optical waves coming from bias, A and B port will travel toward the resonant ring, at this case the overall optical power intensity near the resonant ring reach to the switching threshold –1.5 kW/μm^2 – and will shift the resonant wavelength of the ring so the optical waves in bus waveguide could not drop into output waveguide and will not reach the output port so the gate will turn OFF (OUT = 1) (Fig. 6d). The different working state of the proposed structure are summarized in Table 1. In this table “0” and “1” are representatives of ‘ON” and “OFF” states respectively. Table 1 shows that when both logic input ports are ON, the output port will be OFF, otherwise the output port is ON. All of these states are valid when BIAS port is ON, therefore the BIAS poer in the Table 1 is always “1”.

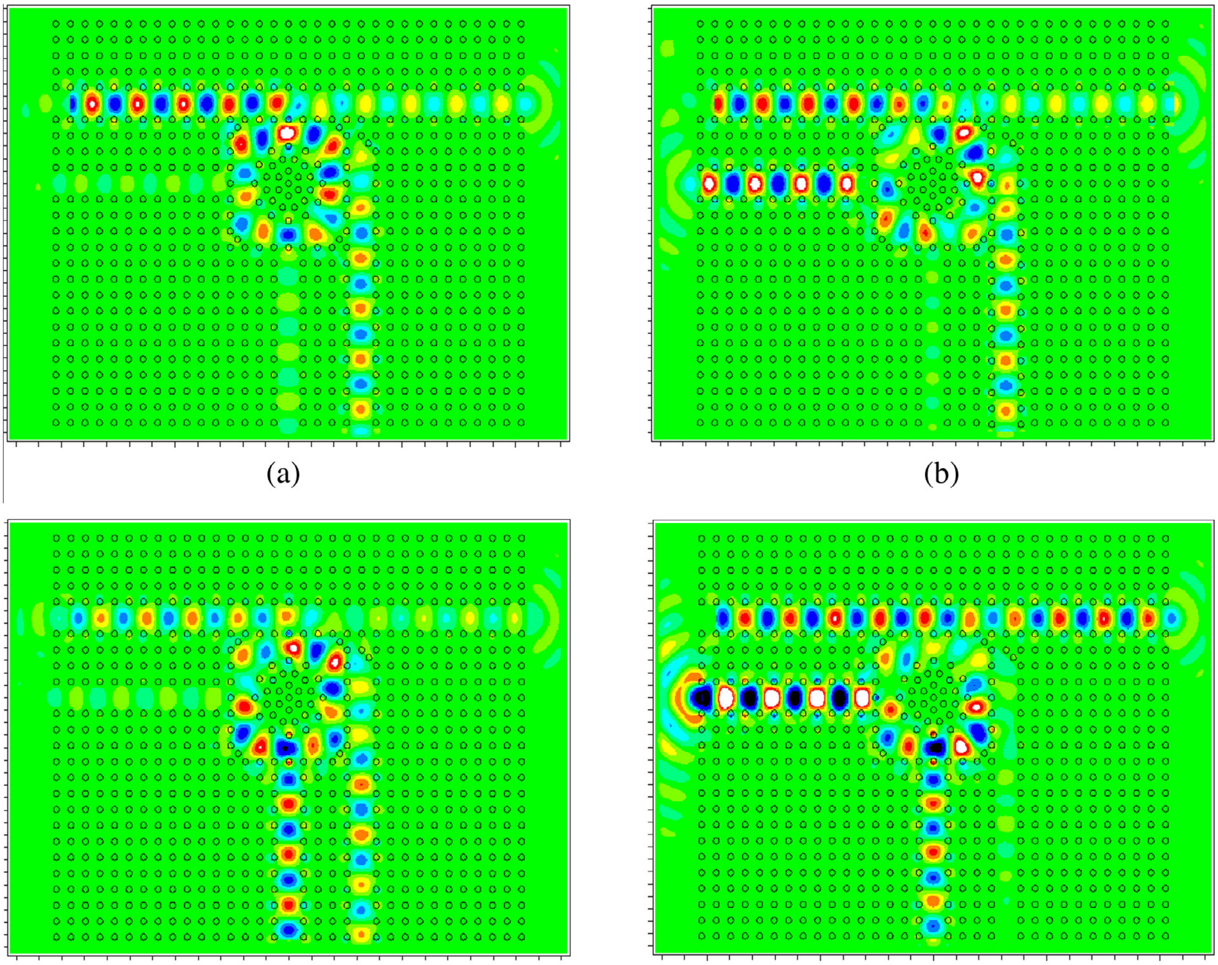


Fig. 6 – Working states of NAND gate (a) A = B = 0, (b) A = 1, B = 0, (c) A = 0, B = 1 and (d) A = B = 1.

Comparing Table 1 with the truth table of NAND gate proves that the proposed structure van be used as an optical logic NAND gate.

4. Conclusion

In this paper by combining the dropping effect of photonic crystal ring resonators via nonlinear Kerr coefficient we proposed optical NAND gate based on photonic crystal ring resonators. In the proposed structure when both logic ports are ON the bias light will not drop to the output 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 output waveguide and the gate will become 1.

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