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Designing of all optical NOR gate based on photonic crystal

Farhad Mehdizadeh* & Mohammad Soroosh
Engineering Faculty, Shahid Chamran University of Ahvaz, Ahvaz, Iran
*E-mail:f-mehdizadeh@phdstu.scu.ac.ir

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In the present paper, an all-optical 3-Input NOR gate based on photonic crystals is proposed. In designing this gate, three resonant rings have been used. By employing high intensity optical power into the device based on Kerr effect, the refractive index of the rods has been varied and the coupling of light into output has been controlled. The consistency of simulation results with the logical table of NOR gate confirms the suitable functionality of the device.

Keywords: Kerr effect, Photonic band gap, Photonic crystal, Ring resonator

1 Introduction

Photonic crystals (PhC) are promising structures proposed for designing all optical devices suitable for optical integrated circuits. These periodic structures can prohibit the propagation of optical waves in certain wavelength region, called photonic band gap[1] (PBG). Due to these excellent characteristic, PhCs have the ability to confine and control the propagation of light waves inside ultra-compact areas and waveguides. Optical filters[2,3], optical demultiplexers[4-6] and optical switches[7] are some examples of optical devices proposed based on PhCs.

Optical logic gates are crucial building blocks for optical signal processing and optical communication networks. One mechanism proposed for designing optical gates, is based on waveguide interferometers[8], however, their dimensions restricts their application in optical integrated circuits. Semiconductor optical amplifiers[9] (SOAs) are another mechanism used for creating optical logic gates, whose performance is limited by spontaneous emission noise and complexity of integration[10]. Recently, different kinds of optical logic gates have been proposed based on PhCs. An optical AND gate has been designed using nonlinear ring resonators by Andalib and Granpaye[11] for designing the proposed gate, two nonlinear resonant rings have been used. Bai *et al*[12]. proposed optical NOT and optical NOR gates based on photonic crystal ring resonators (PhCRRs), their structures are composed of square lattice silicon rods. They used ring resonators with effective radius less than 2.2 μm. In this structure, the switching mechanism is based on phase shift. When the output intensity is more than 70%, the logic state is considered as 1 and for logic 0, the output intensity is at least 35%, however, in our proposed device for logic state 0 the output intensity is less than 5%. Another optical NOR gate based on PhCRRs has been proposed by Isfahani *et al*[13]. By cascading two switches, they have shown the performance of a NOR gate. The simulations show that in the OFF state the transmission of the proposed NOR gate is only about 2% while in the ON state it is about 81%. Danaie and Kaatuzian[14] proposed an optical AND gate based on PhC structures.

In the present paper, a structure for designing all optical 3-input NOR gate based on nonlinear PhCRRs is proposed. PhCRRs are fundamental structures composed of two waveguides namely Bus and Drop and a resonant ring located between them. In these structures, the resonant ring can perform filtering and wavelength selection task, because optical waves propagating in the bus waveguide at a certain wavelength –called resonant wavelength-can drop to the Drop waveguide[15]. It has been shown that the resonant wavelength of PhCRRs depends on the refractive index, radius and dimensions of the core section of resonant ring[16]. The high power optical waves trigger nonlinear effects in dielectric materials such as Kerr effect[17]. These effects arise from dependence of refractive index to light wave intensity. So, we can control the optical behaviour of the PhCRR structure via input intensity, and realize switching task.

2 Design Procedure

The fundamental platform used to design the proposed optical 3 input NOR gate is a 55*41 square array of chalcogenide glassrods with refractive index of 3.1 in immersed air. The chalcogenide glass is used because of its high nonlinear effect and suitability for optical switching[18].The radius of dielectric rods is r=0.265*a, where a=825 nm is the lattice constant of the structure. The plane wave expansion (PWE) method is used to obtain the band structure of the fundamental structure[19]. For this structure, the band structure diagram has been calculated and obtained as shown in Fig. 1.

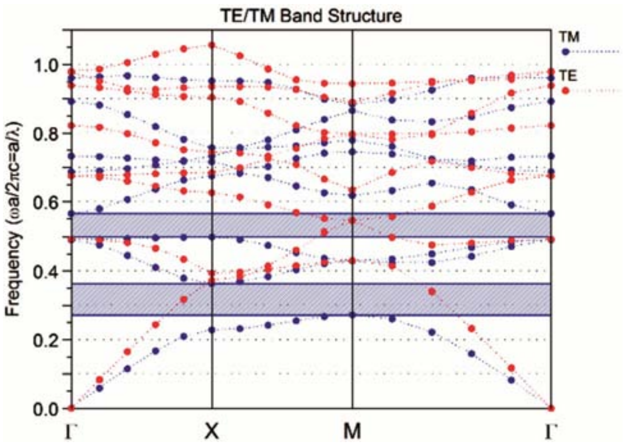

Fig. 1 — Band structure of the fundamental photonic crystal structure

PBG regions are shown at 0.271< a/λ< 0.363 and 0.498<a/λ< 0.567 both in TM modes which are equal to 2272 nm <λ<3044 nm and 1455 nm <λ<1656 nm. The proposed fundamental platform is suitable to be used for designing optical communication devices. This structure has PBGs only in TM mode so all simulations are done in this mode.

To realize the proposed NOR gate, first four waveguides are created by removing complete rows of dielectric rods. These waveguides are labeled as Bus, W1, W2 and Drop waveguides from top to bottom, respectively. Then, Fig. 2 shows the weinsert a resonant ring between every two adjacent waveguides. All the resonant rings are designed such that at same resonant wavelength (i. e. 1550 nm), optical power can be dropped from upper waveguide to lower waveguide of the corresponding ring resonator. Finally, the input waveguides are created, which connect the logic input ports to the corresponding resonant rings.

In summary, the proposed NOR gate has three logic input ports (A, B, and C), one bias port (Bias) and one output port (OUT). In the present structure, the dielectric rods have a high Kerr coefficient equal to $n_2=9*10^{-17}$ m^2/W. It has been shown that the resonant wavelength of the resonant rings depends on the refractive index of the dielectric rods constructing the core of the resonant ring, which in turn depends on the power intensity of the incident optical wave due to Kerr effect. Therefore, by launching high power light

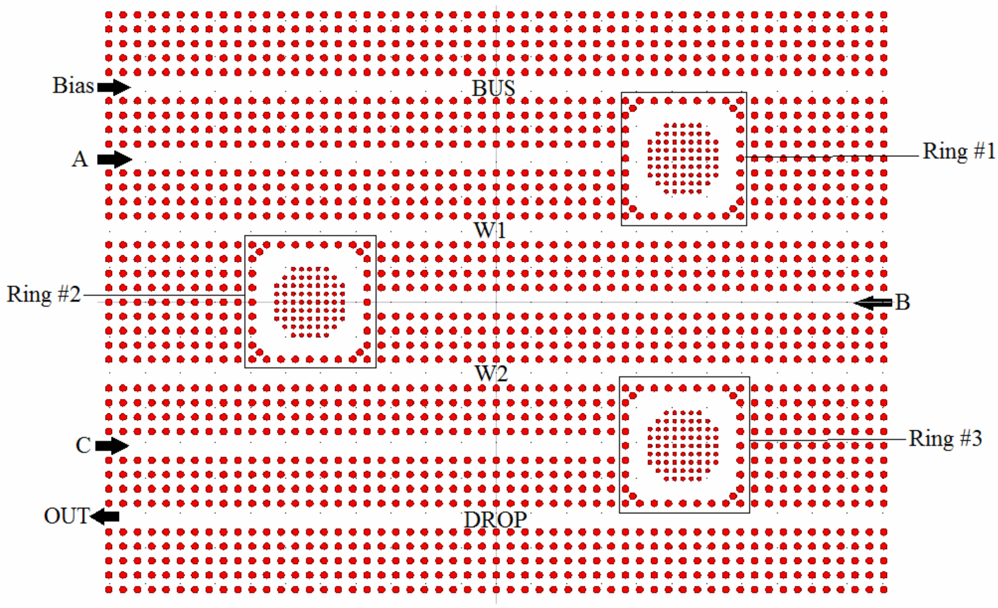

Fig. 2 — Final sketch of the proposed NOR gate

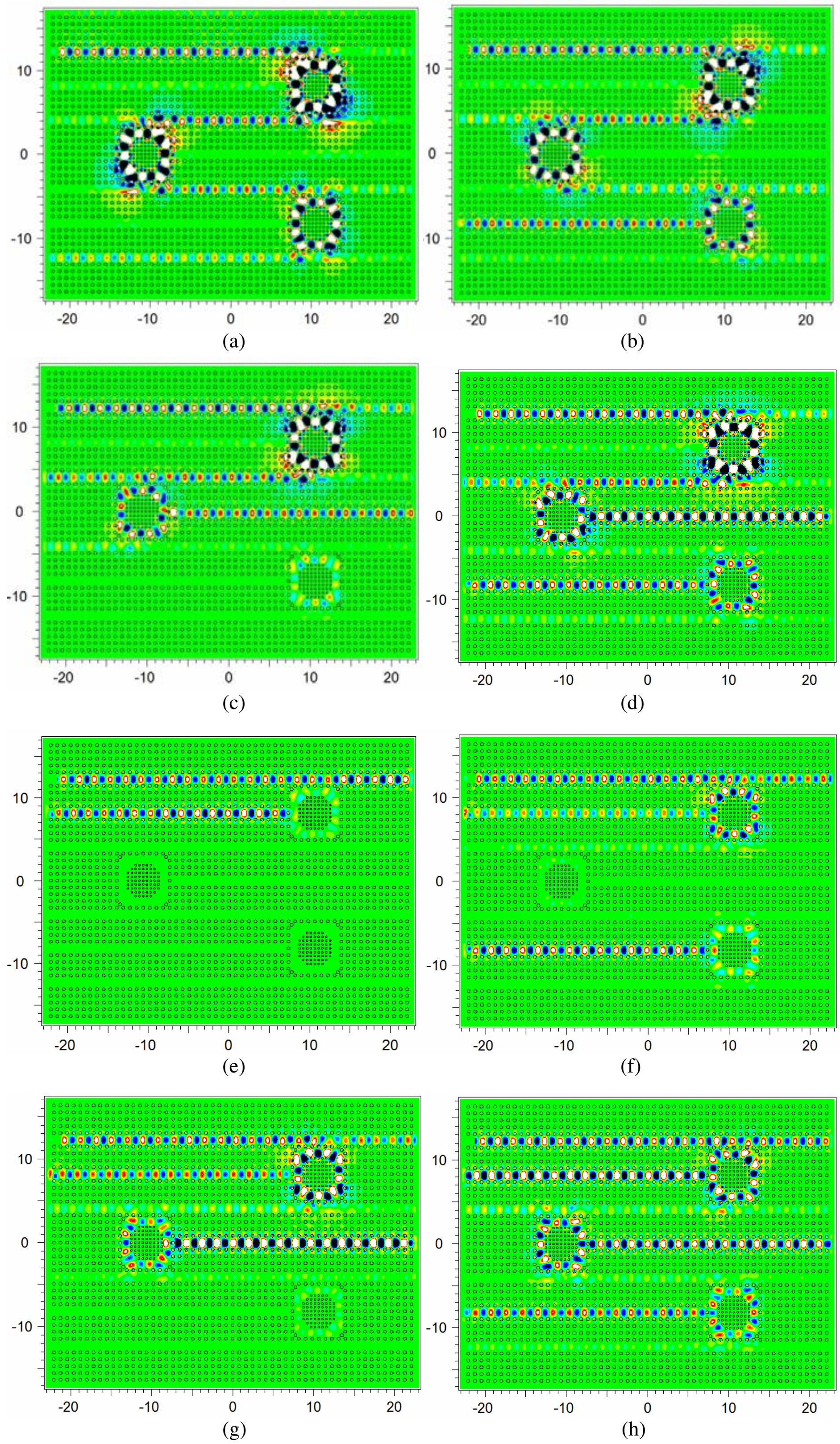

Fig. 3 — Different working states of the proposed NOR gate

into resonant ring, we can control the optical behaviour of the ring resonators. In other words, when the intensity of the optical power near the core of every resonant ring exceeds the switching threshold the resonant rings will not perform their dropping task. The switching threshold for resonant rings employed in this structure is about 1 kW/μm^2.

3 Simulation and Results

In the present work, the finite difference time domain (FDTD) method[20] to simulate the proposed structure is used. The proposed NOR gate has 3 logic input port, so according to the counting principle we have 8 different input states. It is assumed that the power intensity of bias and logic inputs are equal to 0.6 kW/□m^2.When all the logic input ports are OFF (A=B=C=0), all the resonant rings are at linear region and perform their dropping task properly, so the bias signal entering the bus waveguide due to resonant effect of resonant rings will drop into Drop waveguide and travel towards output port. In this case, the output port of the gate will turn ON (OUT=1) as is shown in Fig. 3 (a).

In the second case in which A and B are OFF and C is ON (A=B=0 and C=1), the first and second resonant rings are at linear region and drop the bias signal into their corresponding lower waveguide, therefore, the bias signal can easily reach the W2 waveguide but the overall intensity of optical waves-bias signal intensity plus the port C intensity-near the third ring reach to the switching threshold. In this case, the resonant wavelength of the ring#3 shifts so the bias signal could not drop into Drop waveguide and there is no optical signal in the output port. In result, the gate is at OFF state [Fig. 3(b)].

When port A is OFF and port B is ON (A= 0 and B=1), the first resonant ring is at linear region and drops the bias signal into W1 waveguide but the second resonant ring does not drop the bias signal into W2 waveguide. Because overall intensity of optical waves –bias signal intensity plus the port B intensity-near the second ring reach to the switching threshold and shift the resonant wavelength of the second ring. In this case, we have no optical wave in W2 waveguide, so for any values of port C (C=0 or 1) there is no optical wave at the output port and the gate is OFF (OUT=0). These states are shown in Fig. 3(c and d).

Finally, when port A is ON (A=1) the overall intensity of optical waves –bias signal intensity plus the port A intensity-near the first ring reach to the switching threshold and shift the resonant wavelength of the first ring so the bias signal could not drop into W1 waveguide. In this case because there is no optical signal in W1 waveguide for any combinations of B and C ports (i. e. B=C=0; B=0 and C=1; B=1 and C=0; or B=C=1) the bias signal does not reach to the output port and the gate remains OFF (OUT=0). These states are shown in Fig. 3 (e-h). Different working states of the proposed structure are listed in Table 1. Comparing these results with the truth table of a typical 3 input NOR gate confirms that the proposed structure works as an optical 3 input logic NOR gate. Recently, so many methods have been proposed for fabricating photonic crystal structures such as wedge-shaped cell[21], solvent vapour annealing[22], and self-assembly methods[23]. Considering the period and radius values of the structure the fabrication of the proposed structure is feasible via aforementioned methods.

Table 1 — Different working states of the NOR gate

INPUTS			OUT
A	B	C	
0	0	0	1
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	0

4 Conclusions

In the present paper, using nonlinear regime for ring resonator structures, an optical 3 input logic NOR gate is proposed. The dielectric rods are made of chalcogenide glass, which has a high Kerr coefficient, so it is possible to control the optical behaviour of the resonant rings by launching a high intensity optical power into the resonant rings. In the proposed structure, when all the three inputs are OFF the bias light drops to the output waveguide and the output becomes 1, but when any of the logic input ports turn ON the bias light could not drop to the output waveguide so the NOR gate would become 0.

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