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Ultra-fast 1-bit comparator using nonlinear photonic crystal-based ring resonators

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Abstract: In this paper, a photonic crystal structure for comparing two bits has been proposed. This structure includes four resonant rings and some nonlinear rods. The nonlinear rods used inside the resonant rings were made of a doped glass whose linear and nonlinear refractive indices are 1.4 and 10^{-14} m^2/W, respectively. Using Kerr effect, optical waves are guided toward the correct output ports. In this study, plane wave expansion and finite difference time domain methods were used for calculation of photonic bandgap and simulation of optical wave propagation, respectively. The size of the proposed structure is 1585 μm^2 which is more compact than the previous works. Furthermore, the obtained maximum delay time is about 2 ps that is proper to high-speed processing. The normalized output power margins for logic 0 and 1 are calculated as 25% and 71%, respectively. According to the obtained results, this structure can be used for optical integrated circuits.

Keywords: Comparator, Kerr effect, Optical devices, Photonic crystal.

1. INTRODUCTION

High-speed processing has attracted great interest in designing and fabrication of all-optical devices. In these devices, the fast processing can be done by controlling and guiding optical waves. Photonic crystals (PhCs) are one of the proper candidates for designing all-optical devices. These structures are made of a periodic arrangement of dielectric materials [1]. Small size, scalability, low power consumption and responding to high-speed pulses have amplified the different applications of photonic crystals. In recent years, researchers have proposed the different PhC-based devices such as optical waveguides [2,3], filters [4–13], demultiplexers [14–18], logic gates [19–23], decoders [24–27], encoders [28–31], adders [32–36], flip-flops [37] and analog to digital converters [38–40].

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Optical comparators are one of the building blocks in optical processing circuits that compare two input codes. Fakouri-Farid and Andalib [41] proposed a 1-bit comparator using 4 nonlinear resonant rings. In this structure, the delay time and the footprint were about 6 ps and 1705 μm^2, respectively. Using doped glass as a nonlinear material reduced the switching intensity to 0.8 W/μm^2. Rathi et al [42] used a T-shape lattice and nonlinear rods for designing a PhC-based structure to compare two 1-bit codes. They used the inputs with different phase angles to obtain the desired interferences at the cross-connect waveguides, so the performance of the structure was sensitive to phase angles. The needed power for device operation was not reported and simulation results were presented on the microsecond scale. Danaie and Kaatuzian [43] proposed a Mach-Zehnder based structure for phase comparator. This structure included a Y-shape cross-connect for wave interferences with different phase angles.

In this paper, a novel structure is proposed for designing a PhC-based optical comparator including 4 nonlinear resonant rings. The fast response of the structure results in possibility for employing in optical processing circuits. Furthermore, the small size of the comparator in compared with the previous works is another advantage of the presented structure.

The next sections are organized as follows: in section 2 we discuss the design procedure for the proposed structure, then the obtained results are presented in section 3 and finally, the conclusion comes in section 4.

2. DESIGN PROCEDURE

A two-dimensional PhC structure composed of dielectric rods was used as the fundamental structure for designing the optical comparator. The refractive index, lattice constant (a) and radii of rods are 3.46, 595 nm and 0.2*a, respectively. The band diagram of the structure is shown in figure 1, in which the main photonic band gap (PBG) of 0.28 to 0.42 for the normalized frequencies is displayed. In respect of the lattice constant a=595 nm, the photonic bandgap of the structure is obtained in the interval 1417-2125 nm for TE mode.

In this study, using the RSOFT Photonic CAD and the plane wave expansion method, the band diagram of the structure was calculated. In this method, the following equations were expressed for electric (*E*) and magnetic (*H*) components of optical waves [1]:

$$\frac{1}{\varepsilon_r}\nabla\times\nabla\times E=\left(\frac{\omega}{c}\right)^2 E \tag{1}$$

$$\nabla \times \frac{1}{\varepsilon_r} \nabla \times H = \left(\frac{\omega}{c}\right)^2 H \tag{2}$$

where ε_r is the relative permittivity, c is the speed of light in vacuum and ω is the frequency of optical waves. Using Fourier series expansions for the fields, the eigenvalues $(\omega/c)^2$ were obtained for different wave vectors.

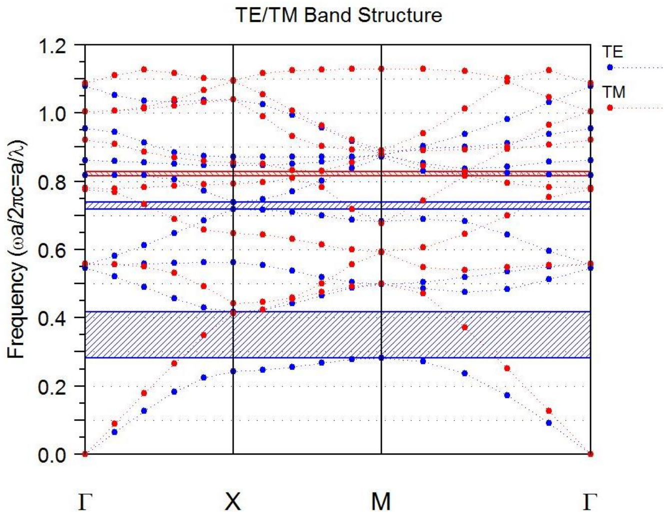


Fig. 1. The band diagram of the fundamental structure.

For designing the optical comparator, three optical waveguides (named as W1, W2, and W3) were created. Then, four resonant rings (named as R1 to R4) were placed between these waveguides. The proposed structure is shown in figure 2. Port B is the bias and X and Y are as the input ports and O1, O2, and O3 are as the output ports. R1 and R2 were located between W1 and W2, also R3 and R4 were located between W2 and W3. In the following, four waveguides (i.e. W4, W5, W6, and W7) were created to connect X and Y input ports to the resonant rings. The nonlinear rods used inside the resonant rings are made of a doped glass whose linear and nonlinear refractive indices are equal to 1.4 and 10^{-14} m^2/W, respectively [40,44].

To form the core section of the rings, 31 rods were placed at the center of the ring as shown in figure 3. Four rods were placed at corners to improve the total internal reflection of the ring. Nonlinear rods (colored as green), were assumed between core and shell to control the effective refractive index of the ring (n_{eff}).

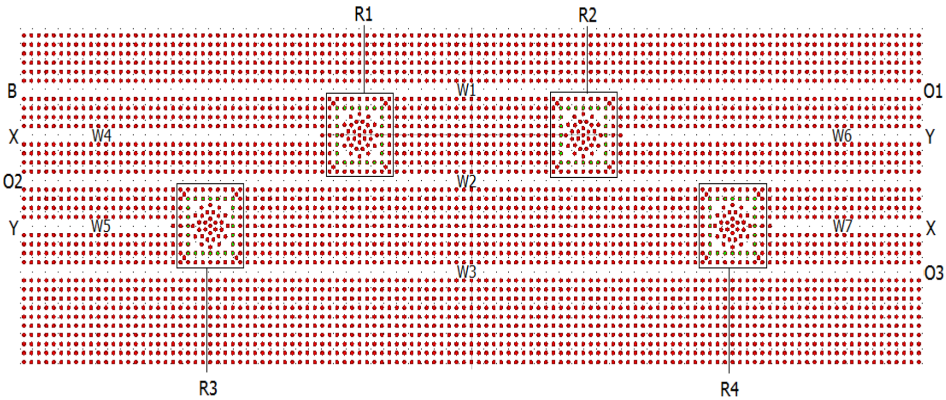


Fig. 2. The proposed structure.

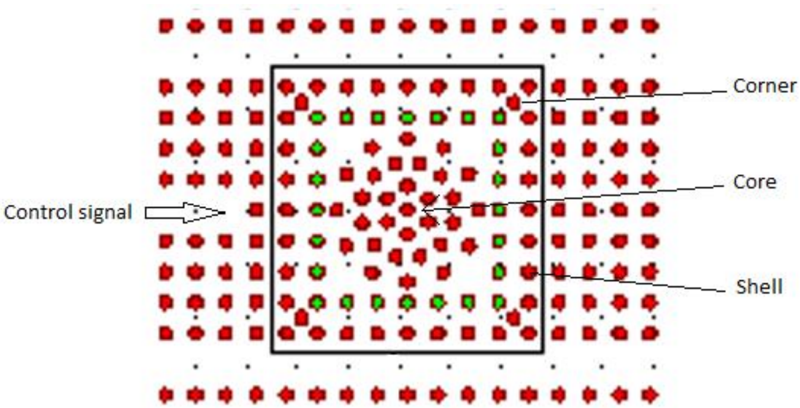


Fig. 3. A schematic of the used resonant ring.

According to the nonlinear Kerr effect, changing the refractive index (n) of the nonlinear materials is in proportion to the optical intensity (I). This effect is defined as follows [44]:

$$n=n_1+n_2I \tag{3}$$

where n_1 is the linear refractive index and n_2 is the nonlinear coefficient.

As a result, n_{eff} can be changed for different incoming optical intensities in the ring. The resonant wavelength of the ring (λ_{res}) depends on n_{eff} and is defined as:

$$\lambda_{res} = \frac{2\pi r}{m\, n_{eff}} \tag{4}$$

where r is the mean radius of the ring and m is the harmonic order of the resonance. Due to applied optical waves from X and Y ports (as control signals) into the ring, λ_{res} is not equal to the wavelength of the optical bias. So, the optical waves from a waveguide to another one (for example from upper to lower waveguides in figure 3) are not transmitted. As a result, both X and Y ports can act as the control ports to guide the optical bias toward the desired output port.

3. SIMULATION AND RESULTS

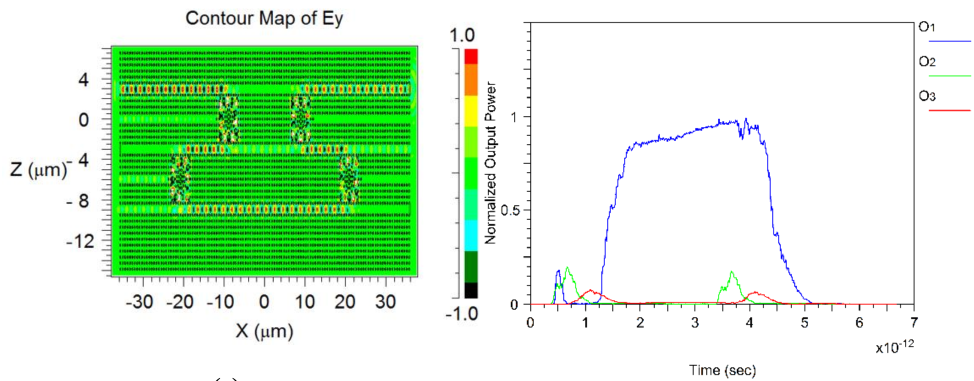
To simulate the optical wave propagation through the structure, Maxwell's equations should be solved. In this study, using the RSOFT Photonic CAD, electric and magnetic fields have been calculated. In this way, the finite difference time domain (FDTD) method was used and two mentioned components were obtained in space and time. Two stability conditions should be carefully considered. The first is known as the Courant condition and in two-dimensional simulation is described as follows [1]:

$$c\Delta t < \frac{1}{\sqrt{\left(\frac{1}{\Delta x^2} + \frac{1}{\Delta z^2}\right)}} \tag{5}$$

where Δt is the time step, and Δx and Δz are the mesh sizes in both x and z directions. The second condition is about the grid spacing that should be less than $\lambda/10$. According to the aforementioned conditions, $\Delta x = \Delta z = 100$ nm and $\Delta t = 0.2$ fs were assumed.

In this study, the optical waves with central wavelength of 1550 nm and the intensity of 10 W/μm^2 were used for incoming light to input ports. The simulation results are as follows:

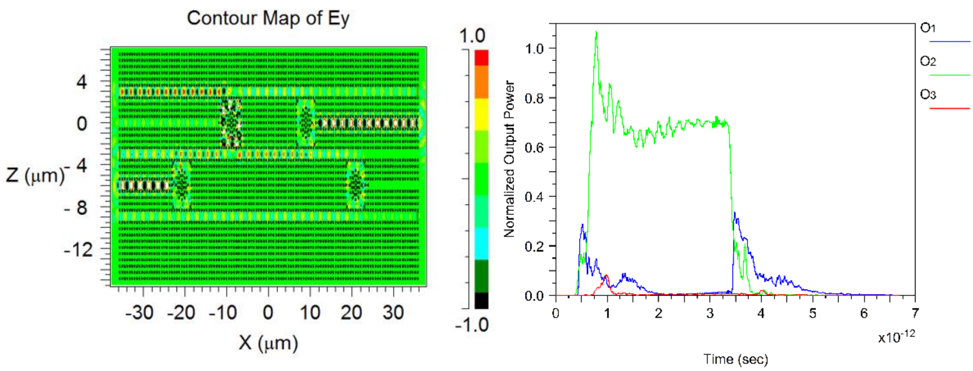
Case #1: When both input ports are OFF (i.e. X=Y=0) all of the resonant rings work in the linear regime and the optical waves can be dropped. Therefore, R1 guides the optical waves coming from B into W2. These waves are introduced inside R3 and are dropped to W3. In the following, R4 drops the waves to W2. Finally, R2 drops the waves to W1 and guide them toward O1. As a result, in this case O1 will be ON and other ports will be OFF (figure 4a). Pulse response of the structure shows that the normalized output power at O1, O2, and O3 ports will be 90%, 18%, and 6%, respectively (figure 4b). The delay time for O1 is calculated about 1.8 ps. In this work, the delay time was defined as the maximum value of rise and fall times.



(a) (b)

Fig. 4. (a) The light propagation and (b) the pulse response of the structure for X=Y=0.

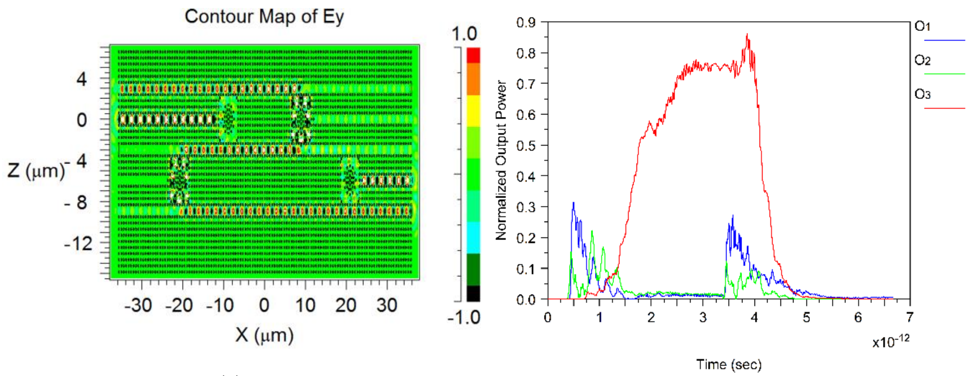
Case #2: When X is OFF and Y is ON, R1 and R4 work in the linear regime, so they drop the waves. Therefore, the applied optical waves to B are dropped to W2 and guided to R3. R3 doesn't drop the waves to W3 (figure 5a). The waves reach to port O2 and as a result the port will be ON and other output ports will be OFF. The pulse response of the structure has been shown in figure 5b and the normalized output powers at O1, O2, and O3 ports have been calculated as 10%, 71%, and 1%, respectively (figure 5b). The delay time for port O2 is obtained about 0.7 ps.



(a) (b)

Fig. 5. (a) The wave propagation in the structure and (b) the pulse response for X=0, Y=1.

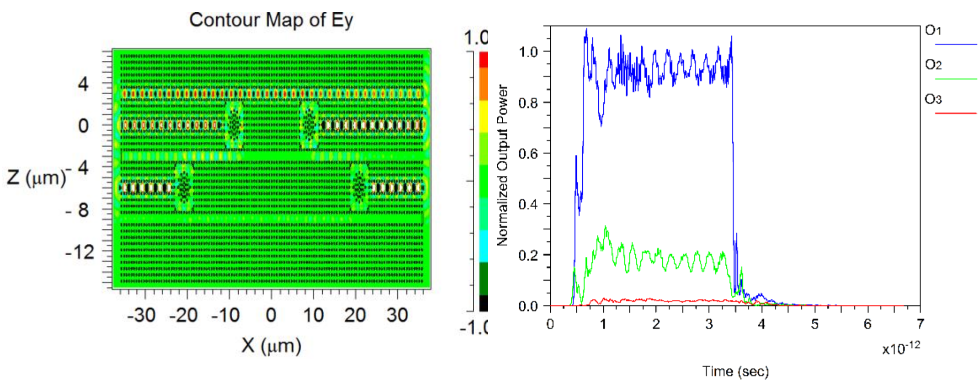
Case #3: for X=1 and Y=0, R2 and R3 drop the waves, but R1 and R4 don't drop them. In this case, the optical waves reach to R2 and are dropped to W2. Due to dropping from R3, the waves are coupled to W3 and are guided toward O3. As a result, port O3 will be ON and other ports will be OFF (figure 6a). The pulse response of the structure shows that the normalized power at O1, O2, and O3 ports are obtained about 25%, 8%, and 75%, respectively (figure 6b). The delay time for port O3 has been calculated about 2 ps.



(a) (b)

Fig. 6. (a) The trajectory of the optical waves propagation and (b) the pulse response of the proposed structure for X=1, Y=0.

Case #4: When both input ports are ON (X=Y=1), all of the resonant rings work in the nonlinear regime and they don't drop the waves. Therefore, the optical waves inside W1 reach to port O1, so O1 will be ON and other ports will be OFF (figure 7a). Figure 7b shows the pulse response of the presented structure. The normalized power at O1, O2, and O3 ports have been calculated about 89%, 20%, and 2%, respectively (figure 7b). In this case, the amount of the delay time for port O1 is equal to 0.7 ps.



(a) (b)

Fig. 7. (a) The optical wave transmission from B to O1 and (b) the pulse response for X=Y=1.

Table I summarizes the simulation results of the proposed structure. One can see the maximum delay time of the structure is 2 ps so it can be proposed for ultra-fast applications. Also, the maximum value for logic 0 and minimum value for logic 1 were calculated 25% and 71%, respectively. Consequently, the difference between logic 0 and 1 is obtained 46% for the structure which is important for coupling to other optical devices.

Table I
The simulation results for the different cases.

Case	Logic for output ports			Normalized output power (%)			Delay time (ps)
	O1	O2	O3	O1	O2	O3	
X=Y=0	1			90	18	8	1.8
X=0, Y=1		1		10	71	1	0.7
X=1, Y=0			1	25	8	75	2
X=Y=1	1			89	20	2	0.7

According to the simulation results, the proposed structure propagates the input waves toward the correct waveguides for different cases, so the output ports correctly become ON. This structure is more compact than reference [41]. Also, the delay time of the proposed structure is less than the obtained result of reference [41]. The simulation results demonstrate that the presented device is capable of being considered for optical processing applications.

4. CONCLUSION

In this paper, an all-optical comparator including four nonlinear rings was proposed. The simulation results show that when the values of both inputs (X and Y) are the same, port O1 will be ON. When X is OFF and Y is ON, port O2 will be ON and when X is ON and Y is OFF, port O3 will be ON. Therefore, the proposed structure works as the optical comparator based on the photonic crystal structure in which the maximum delay time and total size are about 2 ps and 1585 μm^2, respectively. The obtained results show that the proposed structure can be used in optical processing blocks.

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