Compact Ultra-fast All-optical Half Adder Based on Photonic Crystal Structure for All-Optical Circuits

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ABSTRACT:
In this paper, we have presented a compact ultra-fast photonic crystal-based half adder with optimized parameters. The design is proposed according to a linear structure that includes combines and improves AND and XOR PhC-based logic gates. We have situated the Si rod at the cross-connect point of the input waveguides and then determined the optimum radius for a high ON/OFF ratio. By optimizing structural parameters, we have achieved the high value of the ON/OFF ratio with the amounts of 12.36 dB and 6.17 dB for outputs of carry and sum, respectively. Also, the response time has been reduced to 0.22 ps which is very low compared with other structures. This device with a compact size of 190 μm^2 can be used as a key element for designing all-optical integrated circuits in the future. We use plane wave expansion (PWE) and finite difference time domain (FDTD) methods to simulate the design.

KEYWORDS: Half adder, Logic gates, Photonic crystals, Band structure, Optimization, Contrast ratio.

1. INTRODUCTION

Recently, photonic crystals (PhCs) have been considered an essential element for the design and generation of optical devices and circuits [1-4]. They have been constructed from different periodic materials with different refractive indices [5-6]. The incident light can propagate inside the PhC waveguides due to photonic band gaps (PBGs) in the band structure [5-7].

Optical switches [8], filters [2, 3], reflectors [9] microcavities [9], splitters [10], ADC [11], isolators [12, 13], circulators [14], logic gates [15-28], flip flops [29], adders [30-40] , and detectors [41] are some of sample from huge applications of PhC in optical field.

In this way, optical data processing systems and elements like adders have been highly modified using PhC-based design [30-35]. Previously, proposed adders can be divided into two types, including linear [30-33] and nonlinear optical Kerr effect-based structures [34, 35]. In linear structures, a low amount of optical power is needed, which is proper for designing optical integrated circuits. The basic working principle is dependent on constructive and destructive interference of optical waves [30-35].

The advantages of our design contain the easy construction, usability in integrated circuits, very low delay time, and high ON/OFF contrast ratio. In this paper, we have proposed a linear structure combining and improving AND and XOR PhC-based logic gates. We have located a rod at the cross-connect point of two input waveguides. Then, we have optimized its radius to increase the ON to OFF contrast ratio. The ON/OFF ratios for sum and carry raised to 12.36 dB and 6.17 dB, respectively. The structure has a low delay time of about 0.22 ps, and the structure's footprint is about 190 μm^2.

2. STRUCTURE AND SIMULATION METHOD

The general block diagram of a half adder has been illustrated in Fig. 1. It has two inputs (Input A and Input B) and two outputs (Carry and Sum). Outputs of half adder are named carry and sum, respectively.

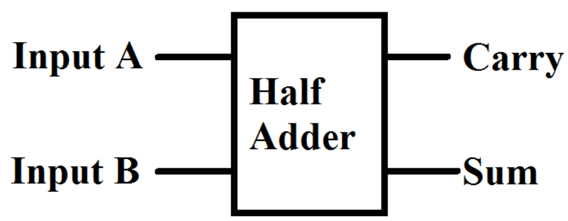

Fig. 1. The block diagram of a typical half adder

The half adder truth table has shown in Table 1. As seen in this table, the sum is logic "1" when only one of the inputs is logic "1" and another input is logic "0". The carry is logic "1" when both inputs are logic "1" and it is logic "0" in the other cases.

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Case	Input A	Input B	Sum	Carry
Case 1	0	0	0	0
Case 2	0	1	1	0
Case 3	1	0	1	0
Case 4	1	1	0	1

Table 1. The truth table of a half adder

Regarding Sum and Carry signals, the schematic of the proposed PhC-based structure as a half adder has illustrated in Fig. 2. The structure consists of a 31×21 array of dielectric rods embedded in air. The lattice arrangement is square, and consists of Si rods with the refractive index of 3.5 and a radius of 0.18*a* immersed in the air where "*a*" is the lattice constant.

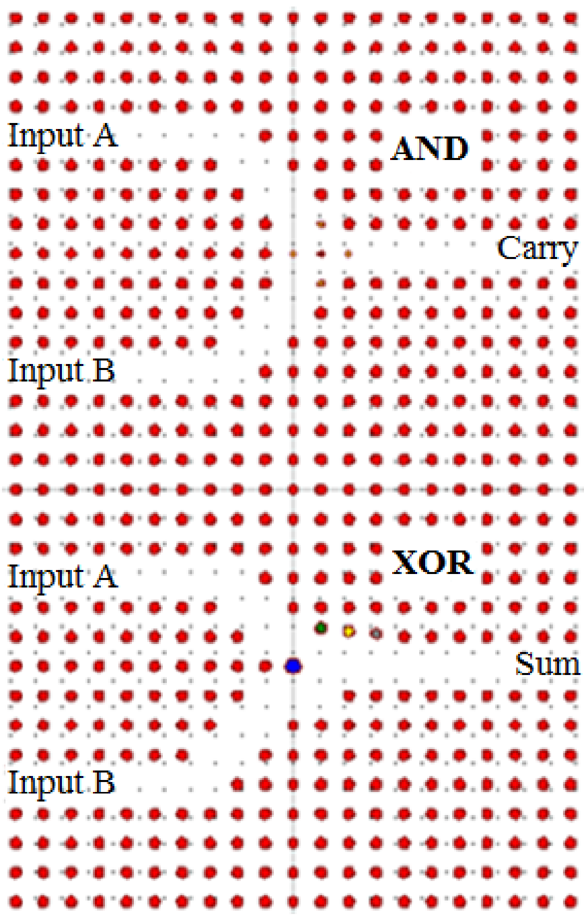


Fig. 2. Schematic structure of proposed PhC based half adder

The photonic band structure of PhC has illustrated for TE mode in Fig. 3. For PBG calculation, the plane wave expansion (PWE) method has been utilized. The wavelength in free space has been set to 1550 nm within the first PBG, which has located at the normalized frequency range of $0.292 < a/\lambda < 0.441$. The proposed structure as, shown in Fig. 2 has composed of AND and XOR logic gates where the outputs of the gates, C and S, are carry and sum, respectively. The working principle of design is related to constructive and destructive interference of optical waves with different phases. For designing AND gate, different configurations have been investigated, and the desired parameter like ON/OFF ratio and response time have been examined to achieve optimized results. The final design for AND gate has illustrated in Fig. 2. As seen in this figure, five AlAs rods with a definite radius of 0.09*a* have been located at the cross-connect point of the input waveguides. The refractive index of these rods is 2.9. Also, similar optimization has been done for designing the XOR gate. The presented structure for an all-optical XOR gate consists of a Si-rod with a radius of 0.2745*a* at the cross-connect point of the input waveguides has been depicted in blue color and three Si rods in the bend with displacement of 0.1*a*, 0.2*a* and 0.3*a* along the Z direction with green, yellow and gray color respectively. These new rods produce a phase difference between the incident beams at the cross-connected point of the waveguides and destructive interference occurs.

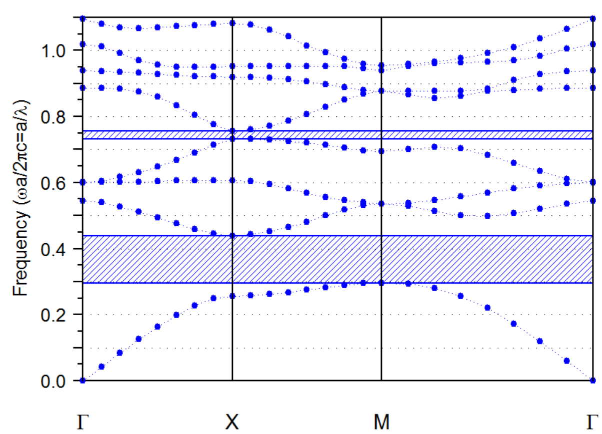


Fig. 3. The photonic band structure diagram of the PhC for TE mode and *n*=3.5 nm and r/*a* of 0.18

3. RESULTS AND DISCUSSION

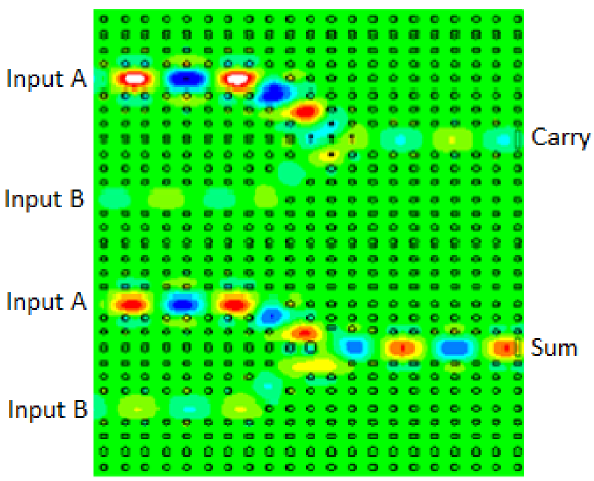
The well-known finite difference time domain (FDTD) method has utilized to simulate the design. The continuous waves (I think pulse is needed!) with λ=1550 nm were used as Input A and Input B. The perfectly matched layer (PML) is considered as a boundary condition in all directions. Considering these conditions, the results for different states of truth table (Table 1) have been calculated and discussed.

In **Case 1**, when two inputs of the device are zero, there is no optical wave in the presented structure and therefore, both output ports are OFF.

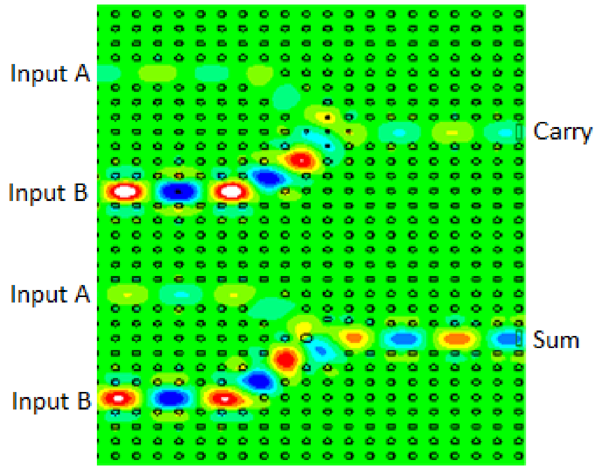
In **Case 2** and **Case 3**, only one of the input ports is ON. In this manner, for the AND gate, the normalized power at Carry will be 0.14. This is less than the threshold of logical HIGH and considered logical zero. This occurred because there are five scattering rods on the cross-point in the face of the incident wave, which prevents light from passing and reflect the power to the input port. In the XOR gate, there is one rod in the passing route the scattering has reduced. So, the optical beam at the cross-connected point of the waveguides is guided to the waveguide ended to the output port, and therefore, the normalized power at Sum will be 0.62. The value is enough to consider a logical High.

In **Case 4**, both input ports are one. In the AND gate, two input beams propagate equal paths and, the phase difference between them is zero. Therefore, constructive interference occurs at the cross-connected point of the waveguides and the normalized output power at Carry will increase to a high value of 0.58 and be considered a logical high. But, in the XOR gate, the light path difference for two inputs produces a phase difference between the incident beams at the cross-connected point of the waveguides. This fact leads to destructive interference occurs and, the normalized output power at Sum decreases down to 0.036.

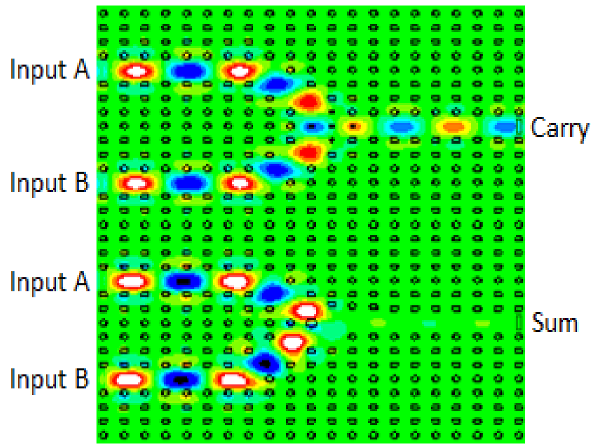
The results have shown in Fig. 4 (the working states corresponding to our design have been illustrated in Fig. 2). Comparing the results with Table 1 demonstrates that the proposed design can work as an all-optical half-adder correctly.



(a)



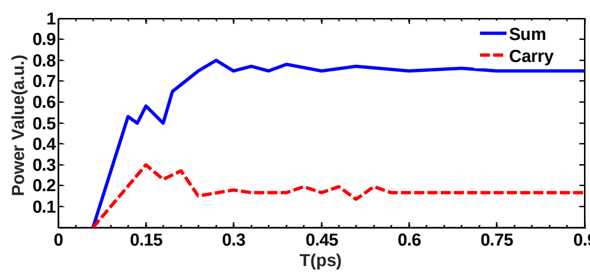
(b)



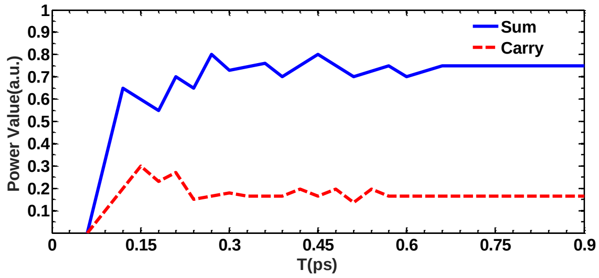
(c)

Fig. 4. The light propagation diagram of our structure when (a) Input A is ON and Input B is OFF, (b) Input A is OFF and Input B is ON, and (c) both inputs are ON.

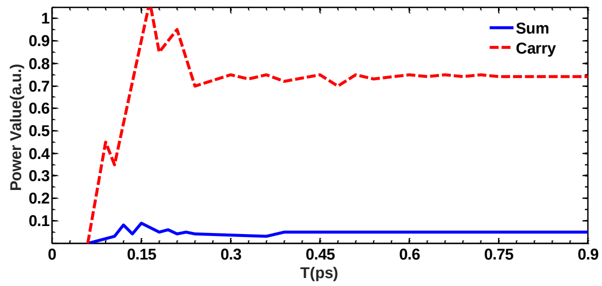
In the following, for studying the contrast ratio and response time of designed half-adder, the output diagram of sum and carry has been calculated and depicted vs. time in Fig. 5. The ON/OFF ratio is 6.17 dB and 12.36 dB for Carry and Sum, respectively and, the maximum response time is about 0.22 ps.



(a)



(b)



(c)

Fig. 5. The output diagram of our structure when (a) Input A is ON and Input B is OFF, (b) Input A is OFF and Input B is ON, and (c) both inputs are ON.

Finally, for the optimization presented design, we study the influence of the variation of the Si-rod radius at the cross-connect point of the input waveguides of the XOR gate (depicted in blue in Fig. 2). The ON/OFF ratio for S output for different radius values has been calculated and illustrated in Fig. 6. The maximum ON/OFF contrast is 12.36 dB for the radius of 0.2745*a*, as shown in Fig. 6.

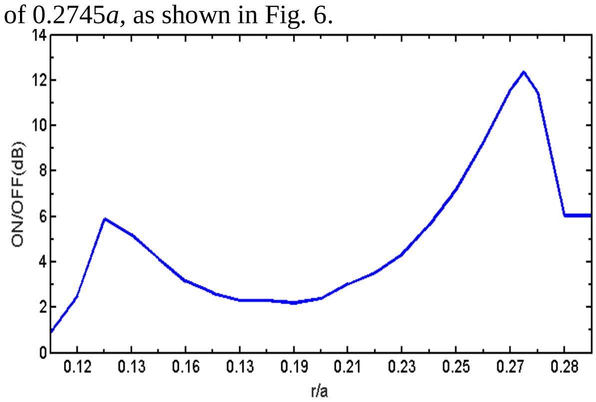


Fig. 6. The ON/OFF contrast for Sum vs. radius of the Si rod at the cross-connect point of the input waveguides

Table 2 compares the calculated parameters of our design and some of the latest photonic crystal-based half adders that operate without (Ref. [31-33]) and with (Ref. [36-37] and [39]) the nonlinear optical Kerr effect.

Structures	ON/OFF ratio (dB)			Footprint (μm^2)	Response time (ps)
	for Sum	for Carry	for Device		
Ref. [30]	**5.08**	**3.258**	**3.258**	**148**	**-**
Ref. [31]	**3.19**	**6.67**	**3.19**	**130**	**0.48**
Ref. [32]	**9.77**	**6.98**	**6.98**	**1056**	**4**
Ref. [33]	**5.11**	**5.02**	**5.02**	**153**	**1.5**
Ref. [36]	**-**	**15.31**	**15.31**	**303**	**3**
Ref. [37]	**5.45**	**5.90**	**5.45**	**75**	**1**
Ref. [39]	**-**	**-**	**12.3**	**-**	**3**
Proposed structure	**12.36**	**6.17**	**6.17**	**190**	**0.22**

Table 2. The obtained results of our structure and some of the latest photonic crystal-based half adders that operate without a nonlinear optical Kerr effect

According to this Table, the proposed structure, which is simple, has the minimum delay time and a suitable ON/OFF ratio.

4. CONCLUSIONS

We have improved a photonic crystal-based structure to increase the ON/OFF ratio of the all-optical half adder. We have situated the Si rod at the cross-connect point of the input waveguides and then determined the optimum radius for a high ON/OFF ratio. The contrast ratio is 12.36 dB and 6.17 dB for outputs of sum and carry, respectively. The structure is very compact and low power. The total size of our structure is 190 μm^2. The response time of our structure is as low as 0.22 ps.

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