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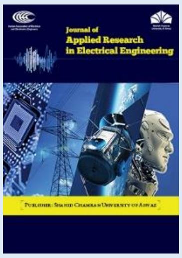

Research Article

A Novel Design for an All-Optical Half Adder Using Linear Defects in Photonic Crystal Microstructure

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Abstract: This paper reports a new optical half-adder design using linear defects in a photonic crystal (PhC) structure. The half adder's proper design obviates the need to increase the input signal's intensity for the nonlinear optical Kerr effect's appearance, which leads to the diversion of the incoming light toward the desired output. The proposed device is composed of silicon rods consisting of four optical waveguides and a defect in a PhC. Two well-known plane wave expansion and finite difference time domain methods are used to study and analyze photonic band structure and light propagation inside the PhC, respectively. The numerical results demonstrate that the ON-OFF contrast ratios are 16 dB for "Sum" and about 14 dB for "Carry". They also reveal that the proposed half-adder has a maximum time delay of 0.8 ps with a total footprint of 158 μm^2. Due to very low delay time, high contrast ratio, and small footprint, they are more crucial in modern optoelectronic technologies, so this structure can be used in the next generation of all-optical high-speed central processing units.

Keywords: High-speed, all-optical, half-adder, photonic crystals, photonic bandgap.

Article history

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1. Introduction

Photon-based devices have been the focus of researchers in recent decades due to their high processing speed, small area, and low power consumption. The design of optical communication systems based on high-speed devices is one of the aims of research groups so that it has been growing at a high speed in recent years [1–3]. The speed of information processing is critical in telecommunication networks. All-optical logic-based devices are required for realizing a high-speed processor. All-optical half adders are one of the important devices for implementing optical data processing systems because all four basic operations in mathematics, including addition, multiplication, subtraction, and division, can be done using optical half adders [4–8]. Photonic crystals (PhCs) play a vital role in all-optical systems [9,10]. Having photonic band gaps (PBGs) in a certain wavelength range enables them to confine and control the light propagation at the appropriate waveguides [11–13]. Therefore, many optical devices such as optical filters [14–18], PhC fibers [19–28], sensors [20], [29–31], demultiplexers [32–37], switches [13, 38, 39], interferometers [40,41], logic gates such as NOT, AND, OR, NAND, encoders, and decoders [42–45], flip-flops [46], comparators [47– 49], adders [50–52], and analog to digital converters (ADCs) [53–57] have been designed using this property of the PhCs. Recently, all-optical half adders have been designed and studied based on PhCs. Most of the previously proposed logic gates are classified into two main categories. The first structures are working based on nonlinear Kerr-effect, and the second ones are based on linear phase-difference. The structures based on the optical Kerr effect need high intensity of light in order to show the nonlinear optical Kerr effect. However, in this case, the structure is likely to be damaged due to the use of a high-intensity input optical signal. Researchers have already presented different structures for half adders. Jiang et al. [8] proposed an all-optical half adder based on self-collimated beams in a 2D PhC. In the presented structure, two-line defects inside the structure were used to operate as a power splitter. Ghadrdan et al. [58] proposed a half adder in a 2D PhC by a combination of AND and XOR gates. Xavier et al. [59] presented a half adder in a 2D PhC where line defects and self-collimated beams were simultaneously used. The proposed structure consisted of AND and XOR logic gates.

Rahmani and Mehdizadeh [60] reported a new optical half-adder design where three nonlinear ring resonators are used in a 2D PhC. The nonlinear resonators were created by adding some rods, composed of nonlinear material, to the ring resonator structure. The maximum rising time and falling time of the half adder were about 1.5 ps and 1 ps, respectively. Several optical half-adder and full-adder devices have been reported by other authors so far [7,44], [50–52], [61–63].

This paper designs a linear phase-difference-based half-adder structure with a low input optical power intensity of 1 W/µm^2. It has a good capability to separate logics 0 and 1 at the outputs. To confine light in the waveguides and defect region and propagate it as desired, we need wavelengths in the PBG of the PhC. Thus, the proposed structure is simulated at the c-band communication window (*i.e.*, at 1550 nm). This half adder is characterized by a relatively large power difference between the two logical levels. It also has low delay time, low input power, and a small footprint, which reduces the error in high-speed data processing systems.

2. The Proposed Physical Structure

Fig. 1 shows the symbol and truth table of a half adder. As can be observed in the figure, a half adder has two inputs and two outputs. X and Y are the input ports while the output ports are S and C, where S represents the "Sum" and C represents the "Carry". To design an all-optical half adder, we employ a 21×21 array of dielectric rods composed of silicon arranged in a square lattice with an air background. The refractive index of the silicon rods is 3.46 at 1550 nm.

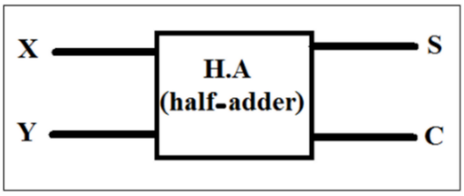
The rods' radius is r=0.2a where *a* is the lattice constant (or pitch size) of the PhC structure, which is 600 nm in this study. We calculated the band diagram of the fundamental structure using the plane wave expansion (PWE) method [64]. Fig. 2 illustrates that there are two PBGs in the TM polarization mode (the blue color areas).

The first PBG in the TM mode that is 0.285<a/λ<0.418 has the appropriate wavelength range for our purposes. By choosing the lattice constant of a = 600 nm, the PBG will be at 1435nm<λ<2105nm, which completely covers the C-band communication window's wavelength range.

For an all-optical half-adder design in a 21×21 array of dielectric rods, four optical waveguides and one resonant cavity are created in the determined regions of the PhC structure shown in Fig. 3. In fact, a combination of W1, W2, W3, and W4 waveguides with resonant cavity builds our optical half adder. The defect region contains ten folds of dielectric rods in which the radius of 9 folds (R_1) is 60 nm. The radius of the last defect rod (R_2) shown by yellow is 30 nm. It is located at the input of W4. X and Y are the half adder's input ports at the beginning of W1 and W2, respectively. The end paths of W3 and W4 are the S and C ports of the proposed half adder.

3. Numerical Results and Discussion

To simulate the proposed structure, we employed the finite difference time domain (FDTD) method [65]. The use of a 3D simulation to study the proposed structure, which is very time-consuming, requires a powerful computer [64]. Due to the time and memory constraints, the effective refractive index method is applied to reduce 3D simulations into 2D simulations with acceptable accuracy in this study [64]. The proposed half adder has two input ports, so we have four different input states. Therefore, we used light waves centered at 1550 nm at the input. All cases of the half adder are shown in Fig. 4 and classified as follows:



(a)

X	Y	S	C
0	0	0	0
1	0	1	0
0	1	1	0
1	1	0	1

(b)

Fig. 1: An illustration of (a) block diagram and (b) truth table of an all-optical half adder.

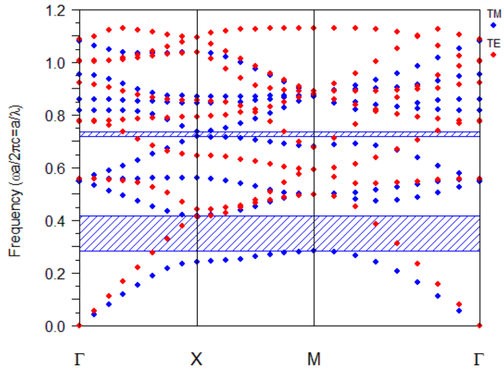


Fig. 2: The photonic band diagram of a fundamental square lattice PhC structure.

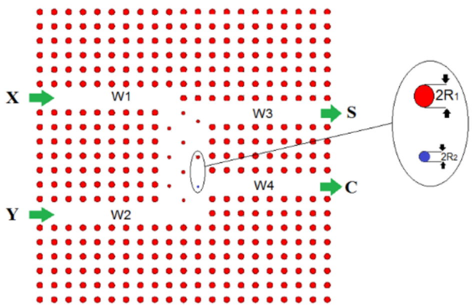
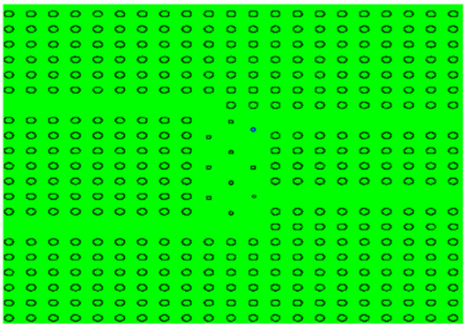


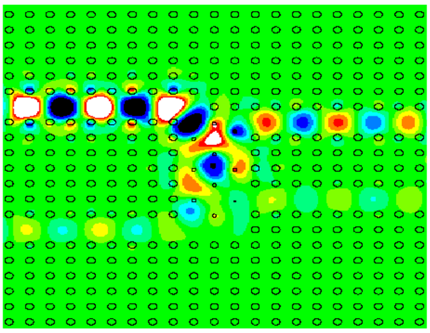
Fig. 3: The proposed all-optical half-adder design in a 21×21 array of dielectric rods consisting of four optical waveguides and one resonant cavity.

Case #1: When both input ports (X and Y) are OFF, there is no optical power inside the structure, so both output ports (S and C) will be OFF (see Fig. 4a).

Case #2 and **#3:** When one of the input ports (either X or Y) is ON, the resonant cavity will couple the optical beams



(a)



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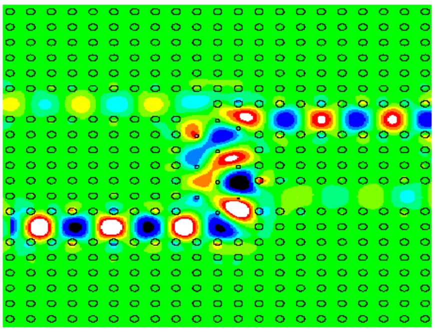
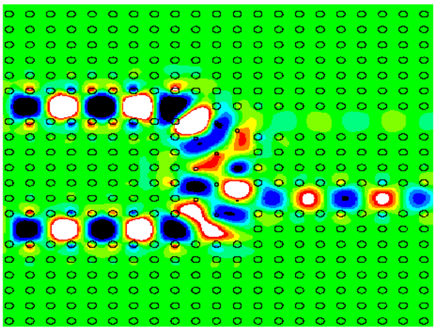


(c)



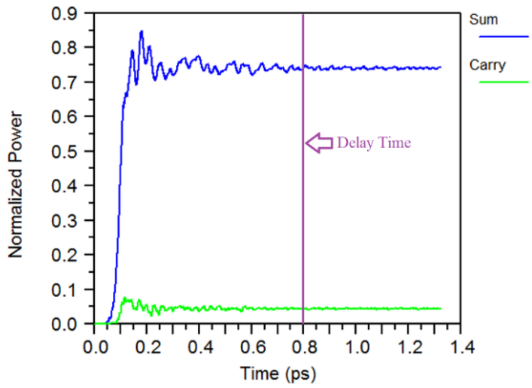
(d)

Fig. 4: Light propagation inside the proposed half adder for (a) Case #1 (b) Case #2, (c) Case #3, and (d) Case #4.

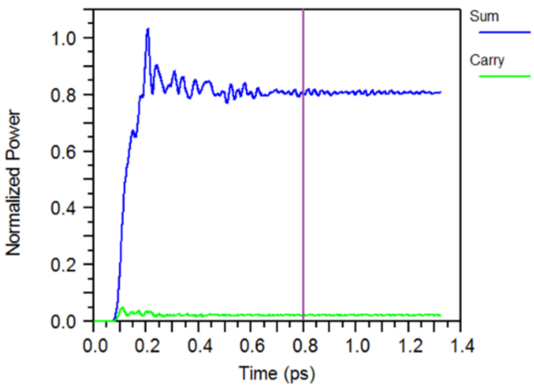
into W3 due to wavelength matching between the resonant mode of the resonant cavity and the input signal. Therefore, in these cases, S will be ON, and C will be OFF (see Fig. 4b, and 4c).

Case #4: When both input ports are ON, the resonant cavity will couple optical beams coming from W1 and W2 into W4. Therefore, in this case, S will be OFF, and C will be ON (see Fig. 4c).

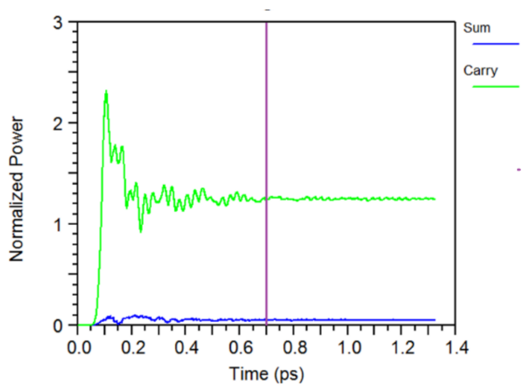
By comparing the results with the truth table shown in Fig. 1b, it is confirmed that the proposed structure can operate as an all-optical half adder. The normalized output of the proposed structure is shown in Fig. 5. As shown in Fig. 5a, when the input port of X is ON, the normalized intensities of the S and C ports are 75% and 5%, respectively. In this case, the time delay (steady-state time) is about 0.8 ps. Fig. 5b demonstrates that when the Y input port is ON, the normalized intensities of the S and C ports are 85% and 2%, respectively. In this case, the time delay is about 0.8ps. Fig. 5c shows when both input ports are ON, the normalized intensities of the S and C ports are 2% and 125%, respectively. In this case, the time delay is about 0.7ps. The results show that our proposed structure has a shorter delay, a lower input intensity (equal to 1 W/μm^2 because nonlinearity is not used), and a smaller footprint compared to previously



(a)



(b)



(c)

Fig. 5: Normalized output power versus time of the proposed half adder for (a) Case #1 (b) Case #2 or #3, and (c) Case #4

Table 1: A comparison of the proposed half adder with other published papers.

Works	Method	Min power for logic 1	Max power for logic 0	Time delay	Footprint
Ref. [8]	Self-collimation	50%	7%	-	-
Ref. [58]	Nonlinear	81%	22%	0.85 ps	168 μm^2
Ref. [59]	Self-collimation	73%	24%	-	169 μm^2
Ref. [60]	Nonlinear	100%	0%	1 ps	-
Ref. [7]	Nonlinear	96%	4%	3.6 ps	250 μm^2
Ref. [44]	Linear	71%	22%	-	-
Ref. [61]	Nonlinear	95%	-	0.91 ps	-
Ref. [66]	Linear	95%	19%	4 ps	1056 μm^2
Ref. [67]	Linear	45%	19%	0.48 ps	171 μm^2
This work	Linear	75%	5%	0.8 ps	158 μm^2

reported structures. Considering these results, the ON-OFF contrast ratios (10×log (P_{ON}/P_{OFF})) for both S and C ports are 16 dB and 14 dB, respectively. Also, according to the presented diagrams, the maximum time delay is about 0.8 ps. We considered the time required for the output port to reach its steady-state as the delay time.

Table 1 compares the proposed device performance with other published papers.

4. Conclusion

In this paper, we designed an ultrafast all-optical half adder based on a photonic crystal microstructure in an area of 158 μm^2. The photonic band diagram was calculated using the plane wave expansion method for TE and TM polarization modes. We also studied the light propagation in the device via the finite-difference time-domain method and calculated the outputs for different input ports' states. One of the most important advantages of our structure compared to similar studies was the non-use of high nonlinear dielectric rods, which eliminated the need to increase the input power to divert the incoming light emission to the desired output. Simulations revealed that the minimum transmission of logic 1 and the maximum transmission of logic 0 are 4% and 75%, respectively. The calculations also demonstrated that the proposed half adder has a steady-state time of 0.8 ps due to its small area.

CRediT Authorship Contribution Statement

Saleh Naghizade: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software. **Hamed Saghaei:** Project administration, Resources, Software, Supervision, Validation, Visualization, Roles/Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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