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All-optical photonic crystal two bit adder design

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Abstract

In this paper, all-optical photonic crystal two bit adder based on nonlinear ring resonator is designed. The proposed structures includes threshold detectors and junctions. In our proposed structure, in order to resolve the low transmission problem in input junction, an enhanced junction is cascaded by a threshold detector to implement full adder cells. By cascading two optimized full adder a two bit adder has been designed. Nonlinear rods of the proposed structures are made of Silicon nanocrystal to create the required frequency shift for implementation of the proposed structures. In order to evaluate the performance of the proposed structures, the plane wave expansion and finite difference time domain methods are used. The proposed optimized full adder cell occupy an area about 340 μm^2 with maximum power 5 W for switching mechanism. Our simulation results show that the proposed full adder can operate with a bit rate of more than 580 Gbits/s.

Introduction

All-optical devices are fundamental elements which can widely affect performance of optical integrated circuits. All-optical photonic crystal (PC) full adder cells are one of the key building blocks in all-optical arithmetic logic units that are essential components in signal processors and next generation optical communication networks [1, 2].

Photonic crystals are the most promising candidate that have potential applications for generation of optical systems [3, 4]. PC structures provide photonic band gap (PBG) which provides the ability of guiding and engineering the flow of light inside waveguides with small dimensions [5, 6]. High switching speed and total compactness obtained by use of PC structures makes them suitable to implement fast devices such as waveguides, logic gates and switches [7-13]. Introducing defects in PC lattice and use of nonlinear materials can be utilized to create waveguides, couplers [14-18] and logic gates [19-25].

In this paper, we focus on the design of all-optical PC adders. First, an all-optical PC half adder (HA) cell has been proposed using nonlinear PC ring resonator. The proposed HA cell is employed to design an all-optical PC full adder cell based on cascading two HA cells. Second, applying some modifications in the proposed junction and threshold detector an optimized FA cell has been proposed which provides less area and propagation delay than the previous design. Finally we have designed a two bit adder using the presented optimized FA. We have employed a square lattice of Si rods in air with nonlinear Kerr effect of Si nanocrystals (Si-nc) to implement the proposed structures. In order to evaluate performance of the proposed devices, the plane wave expansion (PWE) and 2D finite difference time domain (FDTD) methods are used [26]. The reported contributions for all-optical photonic crystal FA structures in the literature [27-29] suffer from a critical problem which make it impractical in the realization of all-optical system design. The mentioned problem is related to the transmission ratio of the input junction in the FA structures which causes these structures deliver incorrect logic values in some input permutations. Our proposed structures resolve this problem by introducing novel input junctions. Moreover, the comparison of the proposed structure with the state-of-the-arts PC full adder cells confirms the superiority of our design in terms of propagation delay and occupied area [27-29]. The rest of this paper is organized as follows: in section 2 the design procedure of the proposed HAs and FAs is explained. The proposed optimized FA cell is designed in section 3. Finally, we present the conclusion in section 4.

PC structure of HA and FA cells

The proposed structures are designed by 2D PC square lattice of Si rods in air. The radius of rods are $0.2a$ which a is the lattice constant. The refractive index of Si used in our simulations is 3.46 for wavelengths around 1550 nm that offers a considerable bandgap for TM polarization. The band structure diagram of the structure which is depicted in Fig. 1 is calculated using plane wave expansion method. There is two frequency gap in which the larger one is from $0.2825(a/\lambda)$ to $0.4169(a/\lambda)$. A nonlinear PCRR has been used to propose all-optical PC half adder and full adder cells.

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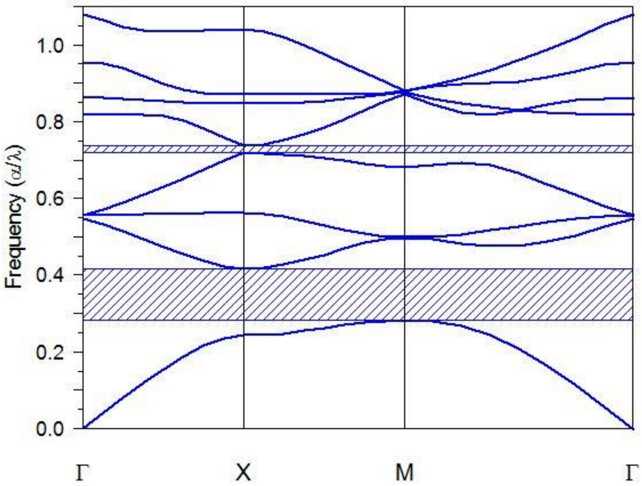


Fig. 1. Band structure of a PC square lattice of Si rods in air for TM polarization

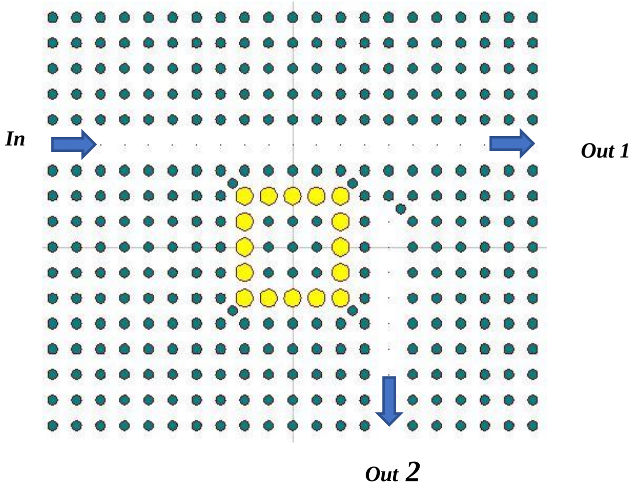


Fig. 2. The basic topology of the nonlinear PCRR

The basic topology of the nonlinear PCRR utilized in this paper in order to design desired threshold detector is displayed in Fig. 2 [30]. The proposed structure consists of waveguides coupled to a PCRR that has one input port 'In' and two output ports 'Out1' and 'Out2'. As can be seen in Fig. 2, in order to create a nonlinear PCRR, a ring defect is formed in the structure by Si-ns with radius of $0.35a$. The nonlinear Kerr effect of the silicon nanocrystals (Si-nc) is used in the proposed device. The Si-nc has linear refractive index of 1.5 and nonlinear Kerr effect of $10^{-16} m^2 / W$ at wavelength of 1550 nm [31, 32]. In materials with Kerr-type nonlinear effect, the refractive index changes proportional to applied signal intensity as:

$$n = n_0 + n_2 I \tag{1}$$

Where, n_0 is the linear refractive index, n_2 is the nonlinear Kerr coefficient and I is the optical field intensity. The logic functions of the outputs of a HA are as follows:

$$Sum(A,B) = A \oplus B \tag{2}$$
$$Carry(A,B) = A \cdot B \tag{3}$$

Also, the logic functions of the outputs of a FA are as follows:

$$Sum(A,B,C) = A \oplus B \oplus C \tag{4}$$
$$Carry(A,B,C) = A \cdot B + A \cdot C + B \cdot C = Majority(A,B,C) \tag{5}$$

The output transmission spectrum of the proposed structure is obtained using discrete Fourier transform (DFT) analysis. In this method, a Gaussian pulse is applied to the input port In and the output transmission is measured at ports Out1 and Out2. As shown in Fig. 3, the resonance frequency ω_0 is obtained equal to $0.349(a/\lambda)$. Applying the resonance frequency of ω_0 to the input port, the input light couples to the ring resonator and will be guided to the output port Out2. However, by increasing the input signal power, the refractive index of the nonlinear material changes, which results in a shift in the transmission spectrum.

The XOR logic operation is one of the most important operations in FA and HA design procedure. In order to create an appropriate threshold detector for implementation of XOR logic

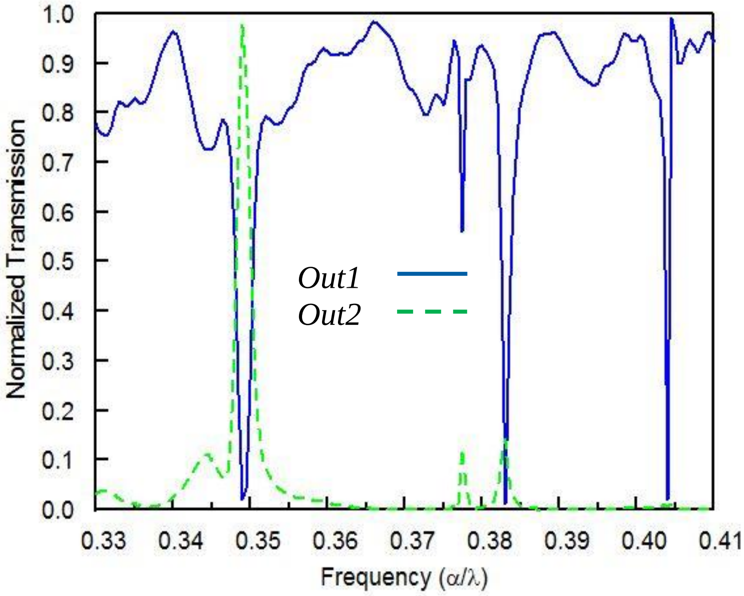


Fig. 3. Normalized transmission spectrum of the designed nonlinear PCRR

operation, it is necessary for the threshold detector to pass low intensity signals and drops high intensity signals. Therefore, the frequency of $0.346(a/\lambda)$ is assigned as the operational frequency of the proposed threshold detector structure. In this condition by applying a continuous wave with input power of 1-12 W/µm to the proposed structure, the amount of transmission to the outputs is obtained and displayed in Fig. 4.

As shown in Fig. 4, when the input signal power is less than 5 W/µm, a large amount of input power is transmitted to the Out1. Conversely, by intensifying the input signal, the resonance frequency of the PCRR will change which causes the input signal couples to the nonlinear PCRR and drops to the port Out2. The mentioned behavior of the proposed threshold detector in Out2 provides the required switching mechanism of a XOR logic operation. On the other hand, the Out1 of the proposed structure provides the desired behavior for design of AND logic operation. Therefore, based on equations Eq. 2 and Eq. 3 the proposed TD could be utilized to create an all-optical PC HA.

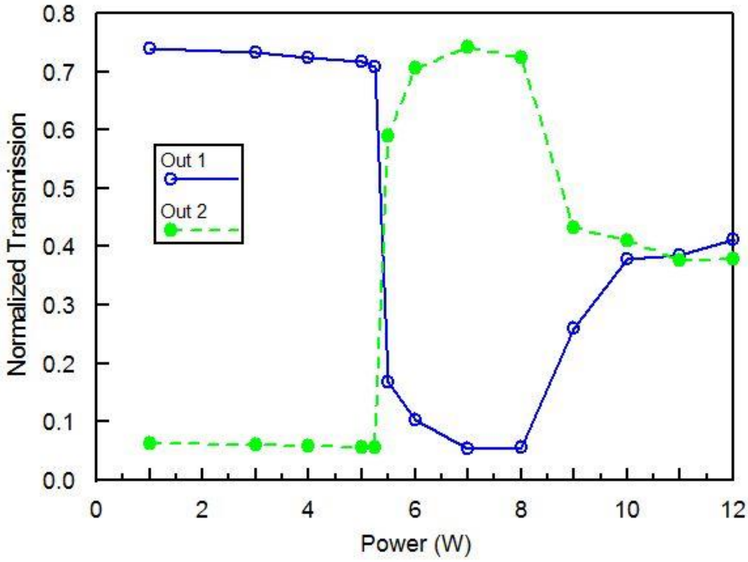


Fig. 4. Normalized transmission vs. input power curve.

A 2-input junction can be used to provide summation of the inputs that should be connected to the input of the proposed threshold detector in order to implement an all-optical HA cell. By performing the FDTD simulations the field distribution and time-domain response of the proposed HA are illustrated in Fig. 5. A continuous wave (CW) signal with power equal to 4 W/μm has been applied to the input ports. When only one of the inputs is ON, the input power to the TD is lower than the threshold value. Therefore, most of the input power is directed towards the Out1. Thus, Out1 and Out2 would have high (logic 1) and low (logic 0) power values respectively. On the other hand, when both the inputs are ON, the input power to the TD is higher than the threshold value. So, most of the input power is transmitted to the Out2. Consequently, Out1 and Out2 would have low (logic 0) and high (logic 1) power values respectively. As it can be seen in Fig. 5, the correct operation of the proposed HA is confirmed. However, weak high logic value (logic 1) in the Sum output is an important drawback of the proposed HA.

The mentioned problem restricts utilization of the proposed HA in optical system design. Cascading this HA to another one causes the high logic value (logic 1) in the output of the next stage to be very close to low logic value (logic 0). Therefore, the HA in the second stage will not operate correctly. This problem is because of low transmission coefficient of the 2-input junction used in this structure (when one of the inputs is ON). The simulation results show the maximum transmission coefficient to the output (when one of the inputs is ON) for the junction shown in Fig. 5 does not exceed 52 %. So the transmission coefficient for the output of the HA in the second stage is less than 26 % that is very low to indicate high logic value (logic 1).

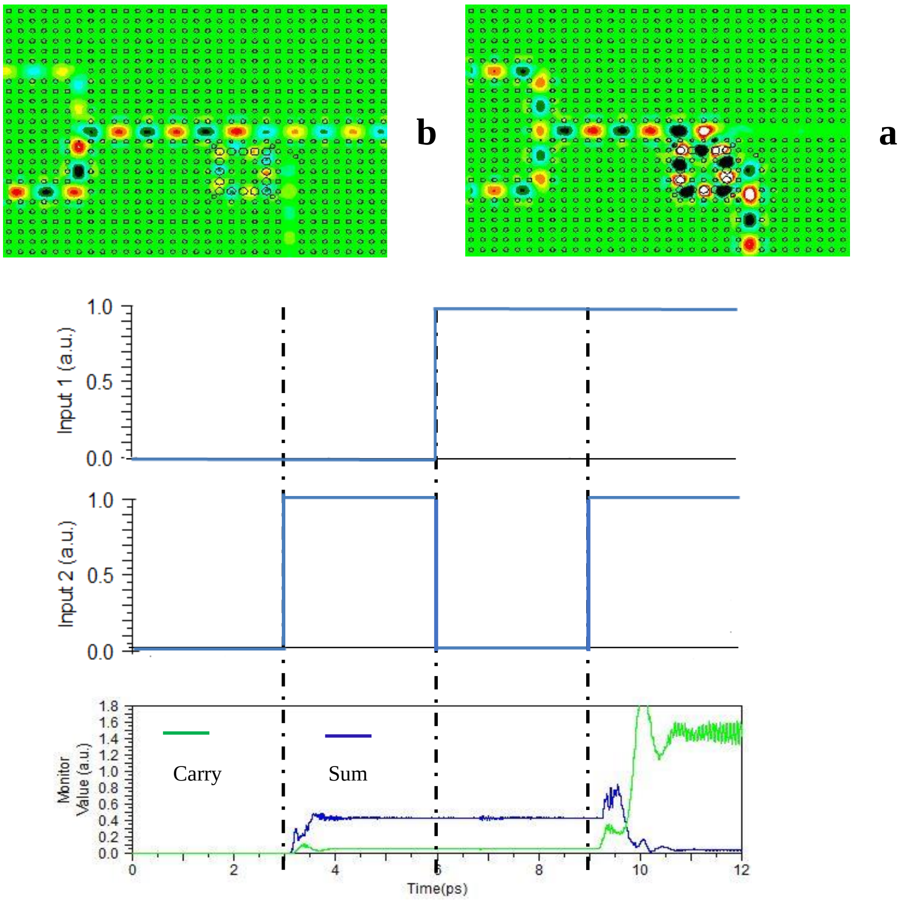


Fig. 5. The field distribution of the proposed all-optical HA. a) Both the inputs are ON. b) One of the inputs is only ON.

In order to design an efficient HA, the transmission coefficient of the junction should be enhanced. In the enhanced junction the transmission to the output should be the most fraction of power applied to one of the inputs. A solution to this problem is to form point defects in the junction center and using optimization method to modify the radius of rods in order to improve the transmission coefficient of the junction [16]. Creating precise radius size of the rods in the junction structure is a critical issue in the explained solution. So, in this procedure, the process variation is a considerable problem and makes the fabrication process unfeasible. On the other hand, in this paper a method has been proposed to overcome the low transmission problem in the junction which is robust against process variation. We have modified the junction structure that is shown in the Fig. 6. In this structure a third input is added to the junction which is assigned to the reference signal that always exists and half the input power will apply to it. Constructive interference between reference and input signals improves the transmission ratio in the proposed junction that is about 92 %.

Replacing the proposed junction in the HA structure an optimized HA is designed which is depicted in Fig. 7. By performing FDTD simulations time-domain response and field distribution of the optimized HA is calculated and illustrated in Fig. 7. Two HA are cascaded in order to implement a FA cell which is shown in Fig. 8. In the proposed structure, Carry outputs of two HAs are connected by a PC junction which performs OR logic operation to obtain Carry output of the proposed FA structure. Simulation results of the proposed FA are depicted in Fig. 9 and Fig. 10 respectively.

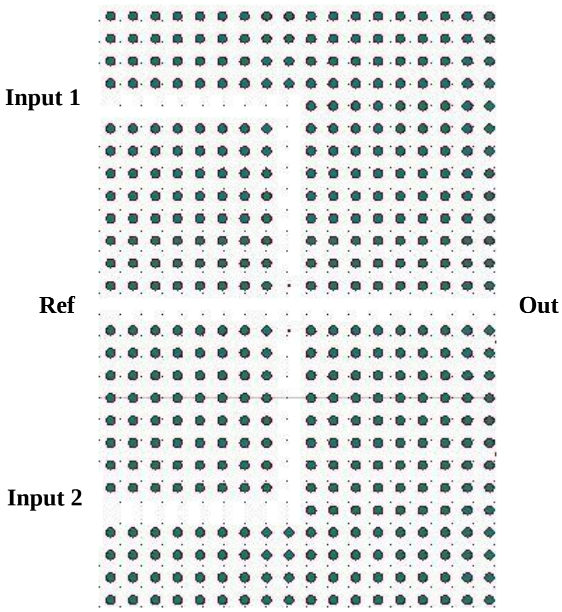


Fig. 6. The proposed enhanced junction structure

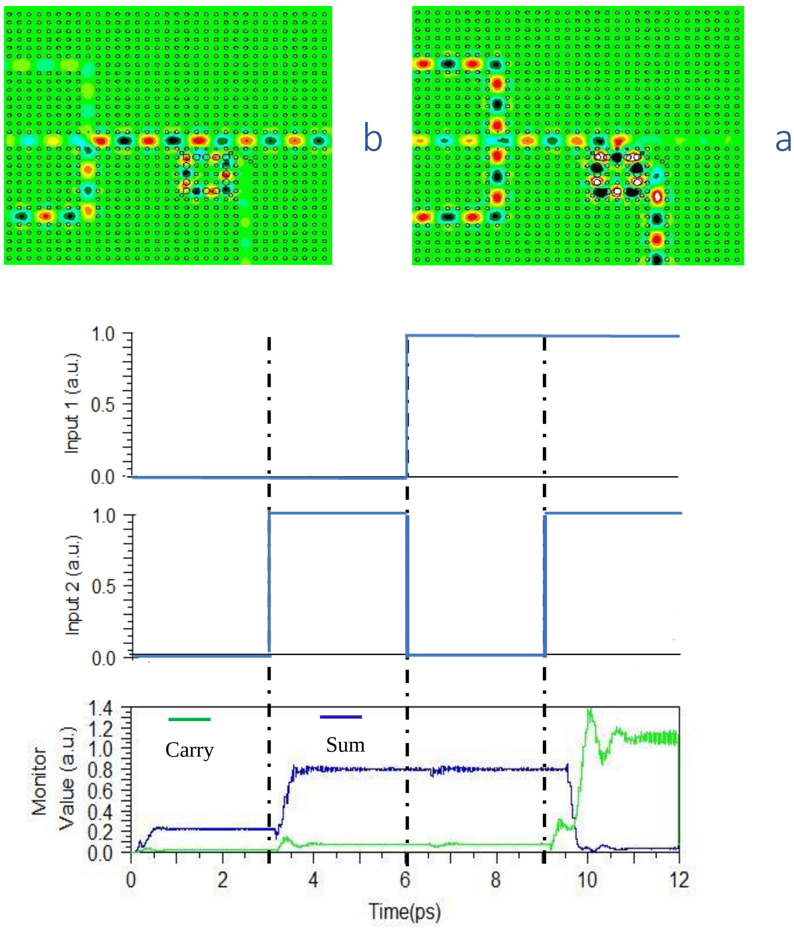


Fig. 7. The field distribution and time-domain response of the proposed optimized all-optical HA. a) Both the inputs are ON. b) One of the inputs is only ON.

Optimized FA design

By applying some modifications in the previous structure, a new FA structure has been designed that offers lower delay as well as area than the previous structure. The optimized FA structure is based on the nonlinear PCRR which has been designed in previous section. We have proposed a three-input PC XOR logic gate that can be utilized in the FA structure. The optimized FA structure is shown in Fig. 11 that consists of a three-input junction which is cascaded by a threshold detector. The three-input junction used in this structure, is based on the proposed optimized junction which has been designed in previous section. The

Ref signal in the junction is always ON and constructive interference between Ref signal and inputs resolves the transmission problem in the junction.

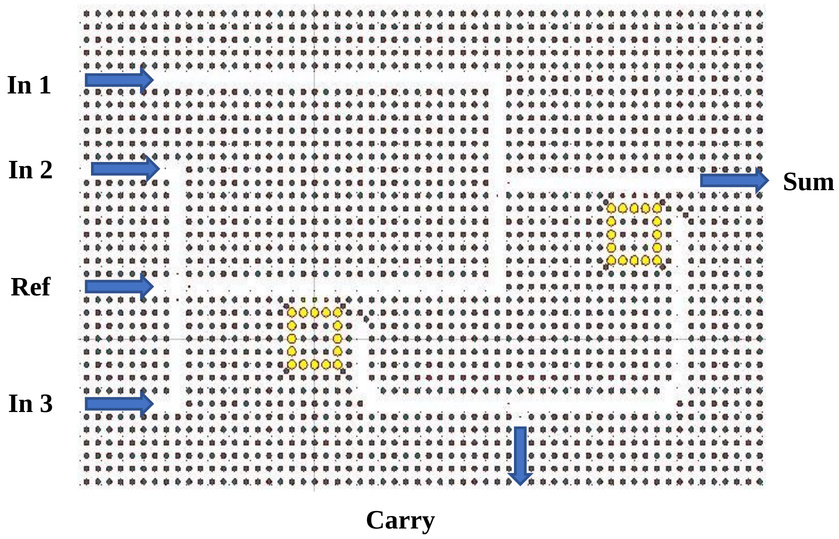


Fig. 8. The proposed structure of all-optical FA

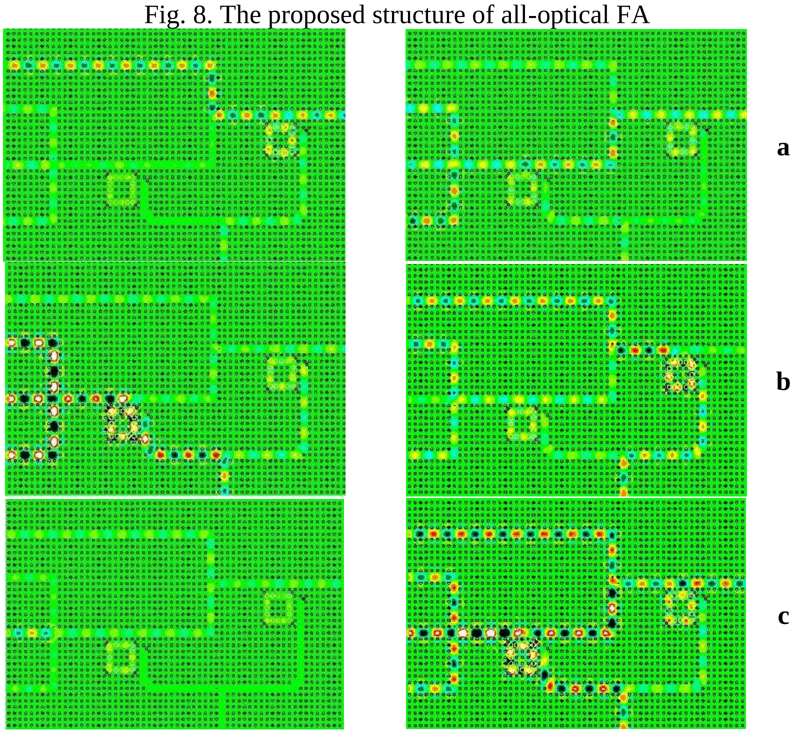


Fig. 9. The field distribution of the proposed all-optical FA. a) One of the inputs is only ON. b) Two out of three inputs are ON. c) All the inputs are ON or OFF

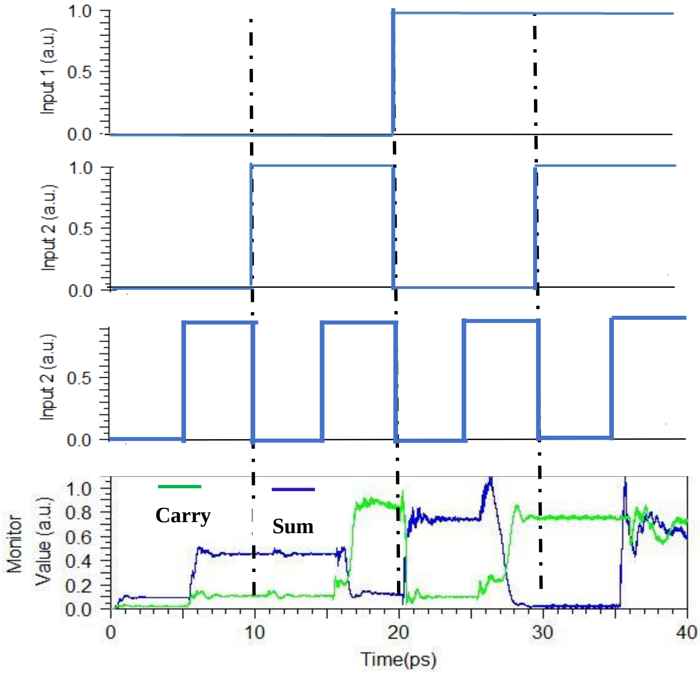
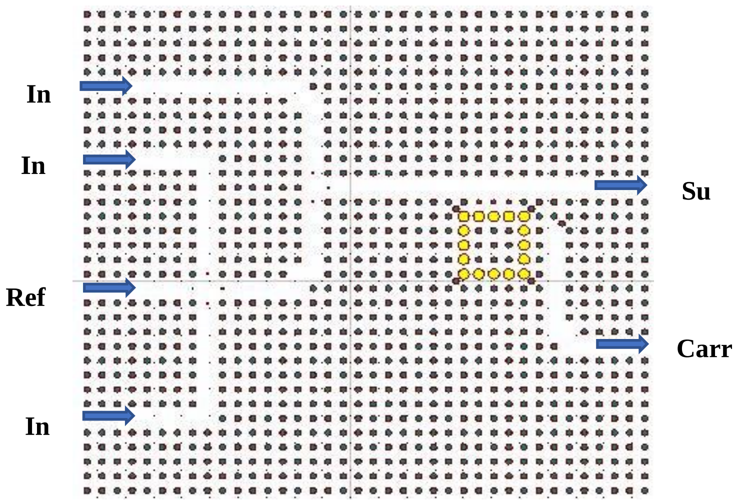


Fig. 10. The time-domain response of the proposed all-optical FA

The switching operation of the proposed optimized FA is based on the nonlinear PCRR which introduced in previous section. The radius of the nonlinear rods employed in this structure is equal to $0.32a$. The switching operation of FA structure can be explained based on the transmission curve depicted in Fig. 4. When only one of the inputs in the proposed structure is ON, the input signal of the threshold detector is less than the threshold power value. So, the Sum and Carry output will have high (logic 1) and low (logic 0) power values respectively. On the other hand, activating two inputs of the structure, will provides input power that is higher than the threshold value in the threshold detector. Thus, the Sum and Carry outputs will have low (logic 0) and high (logic 1) respectively. Finally, when all the inputs of the proposed FA are ON, as can be seen from the transmission curve, the normalized transmission to the Sum output decreases. However, the large amount of power which is the summation of three inputs compensates decreasing the output transmission. Therefore, the transmitted power to the Sum and Carry outputs of the FA will be high (logic 1).



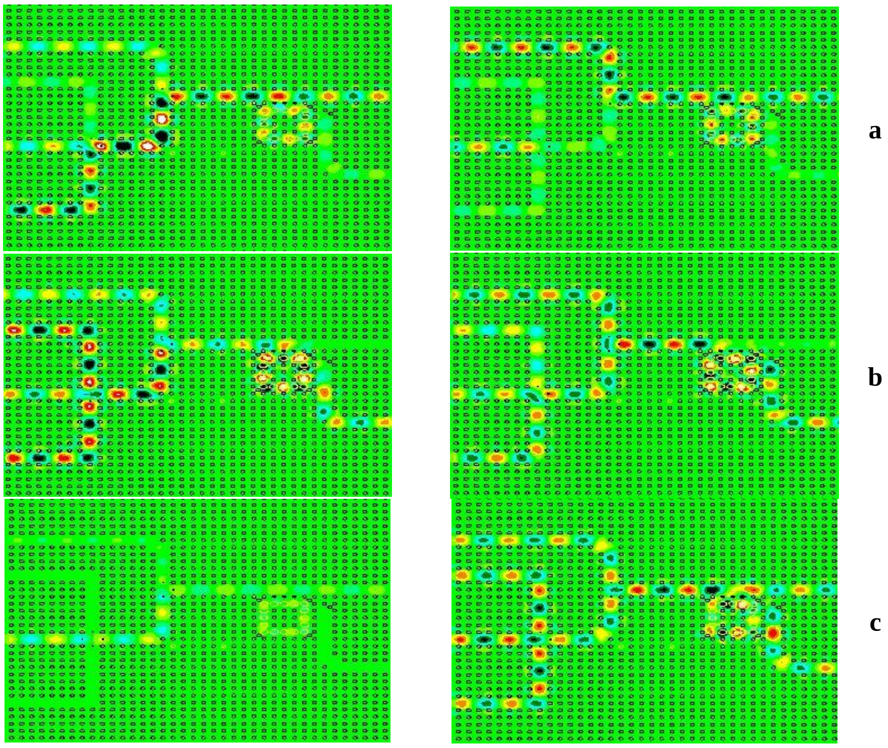


Fig. 11. The proposed optimized all-optical FA and field distribution in the structure. a) One of the inputs is only ON. b) Two out of three inputs are ON. c) All the inputs are ON or OFF

The FDTD simulations have been done in order to verify the right switching operation of the proposed optimized FA structure. Field distribution and time-domain response of the optimized FA are shown in Fig. 11 and Fig. 12 respectively. The simulation results of two proposed FA structures have been depicted in Table 1. Although the input power required for the correct switching of the optimized FA is about 25 percent higher than the FA designed in previous section, delay time and occupied area of the optimized proposed FA are about 2 times less than the previous design.

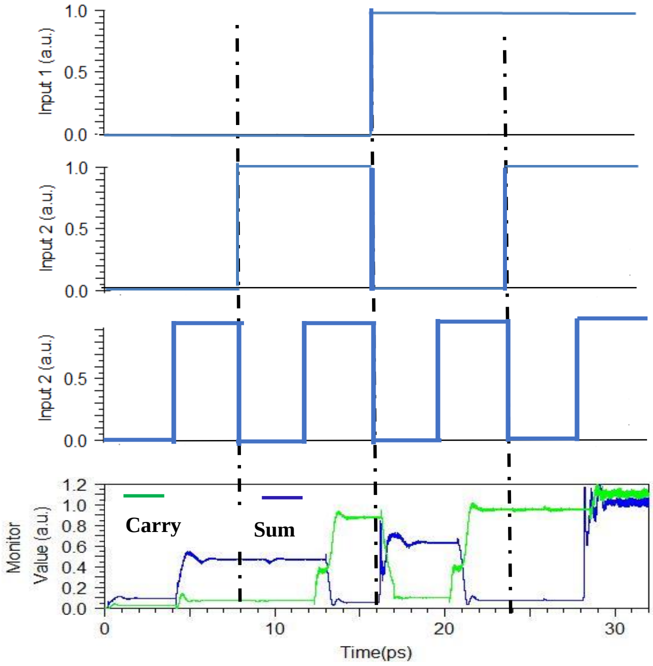


Fig. 12. The time-domain response of the proposed optimized all-optical FA

Designs	Delay (ps)	Avg Power (W/µm)	Area (µm^2)
Full Adder RR based	3	4	607
Optimized Full adder	1.7	5	341

We have used two optimized FA to design a two bit adder and connect the carry output of the first FA to the carry input port of the second FA. In order to verify the correct switching operation of the proposed two bit adder, FDTD simulations have been performed and the results have been shown in Fig 13.

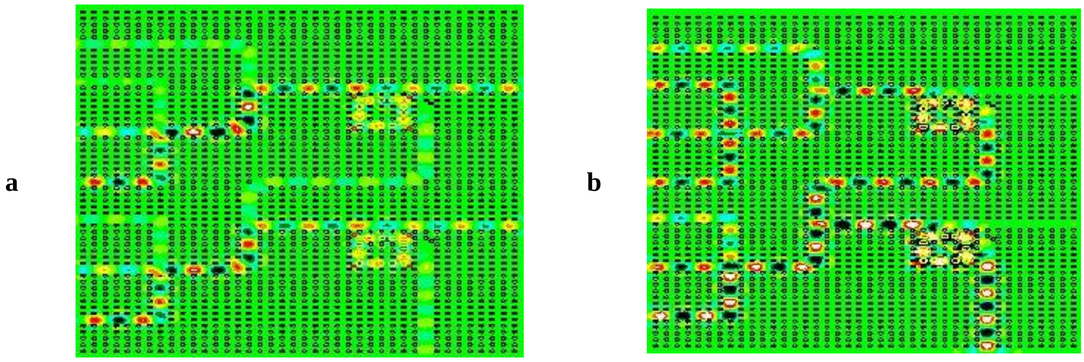


Fig. 13. The proposed two bit all-optical adder and field distribution in the structure. a) Carry out of the first FA is OFF. b) Carry out of the first FA is ON.

Conclusion

This paper has presented a two bit all-optical PC adder. Nonlinear PC ring resonator is employed to realize proper threshold power level detector. An enhanced junction is cascaded by an appropriate threshold detector to make all-optical full adders. Si nanocrystals have been employed as the nonlinear material for its proper properties. The total area of the optimized FA cell is about 340 µm^2 with propagation delay of 1.7 ps.

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