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Ultra-Fast All-Optical Symmetry 4×2 Encoder Based on Interface Effect in 2D Photonic Crystal

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Abstract: This paper deals with the design and simulation of all-optical 4×2 encoder using the wave interference effect in photonic crystals. By producing 4 optical waveguides as input and two waveguides as output, the given structure was designed. The size of the designed structure is 133.9 μm^2. The given all-optical encoder has a contrast ratio of 13.2 dB, the response time of 0.45 ps, and also the bit transfer rate of 2.2 Tbit/s. The results from these structures suggest the high flexibility of the structures, their resolution rates, and appropriate response time relative to that of other structures in this rank as well as their applicability in terms of dividing. To elicit the optical band gap rage for structure design, the plane wave expansion method and also the finite difference time domain methods were used to investigate the results from designed structures.

Keywords: Photonic Crystal, Photonic Bandgap, Logic Gate, Encoder, Interface.

1. INTRODUCTION

The need for increased transfer rate in telecommunication systems has remarkably given the increased demand for optical signal processing. It is predicted that the current digital electronics may not be able to meet this demand in the future. Therefore, all-optical signal processing methods have attracted significantly high attention, with the optical fiber known as the most important factor. The optical fibers are considered as a revolution in the field of communication [1]. Using the optical fibers along with the optical devices rather than electronic devices in optical telecommunications is today recognized as necessary to increase the data transfer rate as well as for increased bandwidth. Today, the bandwidth of optical networks is resulting from the limitations in technology for optimal use of optical fiber bandwidth.

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One of the most suitable and important structures to accomplish this task is photonic crystal (PC) optical devices that have attracted much attention in recent years. The wavelength range that is not allowed to pass is called the photonic bandgap (PBG) [2]. The lack of light emission in the PBG showed that the light could be concentrated to a much lower degree than the diffraction limit. While in electronics the size of integrated circuits was increasingly becoming smaller, the photonics faced the limitations of diffraction devices, which the emergence of PCs, along with other discoveries such as metamaterials, plasmonics and graphene eliminated these limitations for optical devices. Research is underway to solve the problem of PCs, plasmonics, and graphene, and soon we will see the design and fabrication of optical devices below the diffraction limit and integrated optical circuits.

As mentioned above, the PCs can be used in a variety of applications, including optical waveguides & cavities [3], optical fibers [4], optical switches [5], optical flip-flops & logic gates [6-10], optical sensors [11], lasers [12], optical filters [13], optical analog to digital converters [14], optical multi/demultiplexers [2, 15] and optical power dividers [16]. One of the most important and interesting applications of PCs is their use in designing all-optical logic gates.

All-optical logic devices play an important role in the fields of all-optical computing systems, ultra-fast information processing, and optical telecommunications [7]. All-optical systems promise the possibility of achieving higher data transfer rates, lower energy losses, and the ability to process real parallel photons rather than electrons as information carriers, which may be possible using all-optical logic circuits. All-optical logic devices are essentially dependent on how photons and matter interact, and PCs have unique properties in controlling photon emission states through the PBG. Also, 2D-PCs can be easily integrated into integrated optical circuits.

Various all optical encoders have so far been presented [7, 17, 18]. In terms of PC structure, they are divided into two categories: the batch using ring resonators [17] and the other one which uses NRs [19]. Application of the ring resonator raises the delay time and thus limits the data transfer speed. On the other hand, the implementation of the structure becomes harder and the size is increased. In terms of the applied mechanism, they are also divided into two categories: Some of them are based on the nonlinear Kerr effect [19-22], and some are based on the interference effect [7]. The use of nonlinear materials raises the need for optical power. In this paper, based on the above-mentioned materials, we have designed and simulated the entire 4×2 encoder optical structure for use in integrated optical circuits. The structure of the wave interference effect is used instead of using nonlinear effects to simplify its design and manufacture, which in turn is a new design according to the literature in this area. The designed structure has high flexibility along with bit transfer rate and high resolution which makes it very suitable for use in designs. It should be noted that all design and simulations have been done using R-Soft Photonics software.

This article is divided into five general sections: The second part deals with structural analysis methods. The third section deals with structural design. The fourth section deals with simulation and design results and finally the paper concludes in the fifth section.

2. ANALYSIS

The Plane-wave expansion (PWE) and finite-difference time-domain (FDTD) methods are two very popular methods for analyzing and investigating optical properties based on PC structures.

In the meantime, the FDTD method focuses largely on the magnetic properties of PC based devices. The FDTD method is applied extensively using precise meshing as a general and flexible method for analyzing arbitrary structures. The basis of these methods is the discretization of the equations describing electromagnetic fields in a finite area by field approximation in general with the Taylor series. Today, this method is used as a major method in PC calculations and due to being ideal for parallel processing; the time needed to perform calculations can be greatly reduced [23, 24].

The PWE method is one of the methods based on frequency analysis. Generally, the PWE method refers to a computational technique in electromagnetics to solve Maxwell's equations by formulating an eigenvalue problem out of the equation. This method is popular among the photonic-crystal community as a method of solving for the band structure (dispersion relation) of specific photonic crystal geometries [23, 24].

3. STRUCTURAL DESIGN

To design the all-optical logic gate, a 2D PC structure with a square lattice constant of a=519 nm was used. The number of dielectric rods of the 20×23 PC structure (20 dielectric rods along the x-axis and 23 dielectric rods along the z-axis). The dielectric rods were made of silicon with the corresponding refractive index of 3.4 each of which is the radius of each dielectric rod is R=100 nm. With this description, the size of the structure will be 133.9 μm^2. Before any defects within the photonic crystal structure, a PBG was extracted to investigate the permissible and functional areas used in telecommunication domains. The analysis method used in this work is the PWE method. As shown in Fig. 1, the structure has two areas of PBG in TM mode. The range of the PBG in this mode is $0.723 \leq a/\lambda \leq 0.746$ and

$0.287 \leq a/\lambda \leq 0.426$ which is synonymous with 1218 nm $\leq \lambda \leq$ 1808 nm and 695 nm $\leq \lambda \leq$ 717 nm, respectively. In this area, a suitable PBG TM has been evaluated to be used for the design of telecommunication equipment because it covers a wide range of desired telecommunication wavelengths.

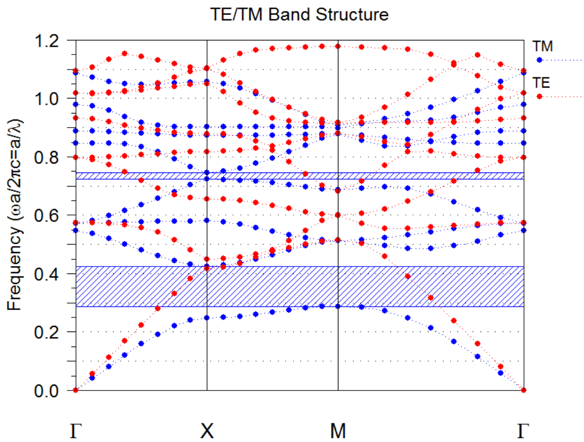


Fig 1. TM/TE bandgap diagram of the PC used in the all-optical 4×2 encoder.

To achieve the desired 2×4 encoder structure, as can be seen in Fig. 2, the removal of dielectric rods and the creation of optical waveguides (W1 to W5) have been used. The structure has 4 inputs: Input 1, Input 2, Input 3 and Input 4; and 2 outputs: Output 1 and Output 2. As can be seen in this structure, there is a slight difference in the input ports to create logical modes. Generally, in an encoder, it has n output ports and 2^n input lines, which produce binary code outputs related to a binary value. Using this gate, in addition to achieving good results, it has achieved high flexibility, a simple and small structure that, along with the use of linear effects, has provided a new, rational, and unique and highly functional design. The resonators used in this structure include nano-resonators at the intersection of waveguides of R_n=30 nm and light coupling resonators of radial sizes R_c=115 nm (green) and R_c = 150 nm (blue). All-dielectric rods are made of silicon and this structure is based on silicon technology.

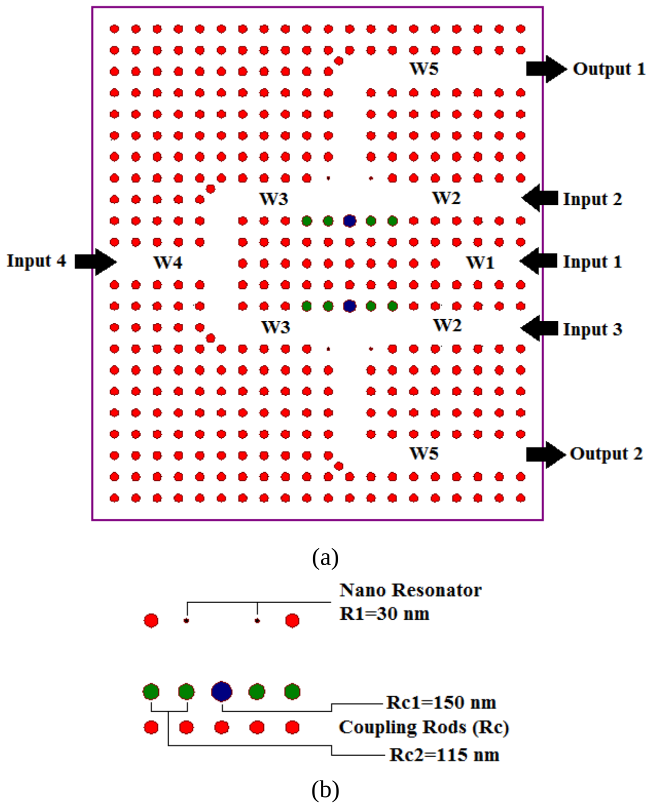


Fig 2. (a) The proposed photonic crystal structure to realize the all-optical 4×2 encoder, and (b) the resonant section in this proposed structure.

4. SIMULATION AND RESULT

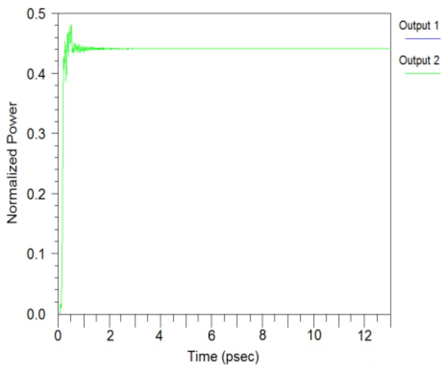
To simulate the structure to calculate the electric field distribution, the FDTD method is used in the field of time. The simulation is done in two dimensions and the mesh size of the structure is equal to $\Delta x = \Delta y = \lambda/16$, where λ is the free space wavelength equal to 1550 nm, also the time step for simulations is 4000. According to the encoder's truth table, the structure for only one input will react to output, and this is a constraint for the encoder structure because if more than one input is activated simultaneously it will produce insensible combinations. According to the encoder's truth table at input 0 0 0 0 where all inputs are zero, outputs will also display 0, which is self-evident, since in this case, the light does not enter the structure.

Where only one input out of 4 inputs is on or 1, 4 different modes are obtained in outputs. In the first case, if the Input 1 is switched on and in the logical mode 1, the two outputs will have the same power output at about 0.021 Pin, indicating 0 logic state for each output. It should be noted that the design of the structure is such that the W1 waveguide acts as a power divider and sends the same power to each output, which is a unique feature of this structure. It should be noted that the power diagrams having the same power at both outputs have the same outputs as shown in Fig. 3.

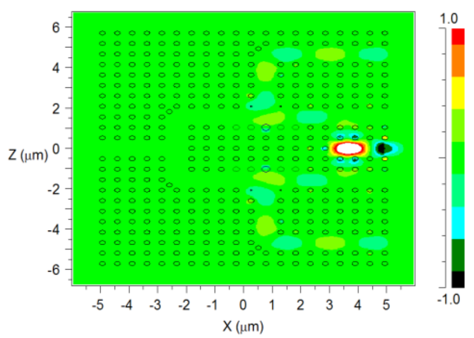
In the next case, if the Input 2 is switched to logic 1 then the Output 1 will obtain 0.76 Pin and the Output 2 will obtain 0.004 Pin, in which case the output 1 will switch to mode 1 and the output 2 will switch to logical 0, as shown in Fig. 4.

Alternatively, if Input 3 is switched on and switched to logical mode 1, then Output 1 will receive a power output of 0.004 Pin and the output 2 the power of 0.76 Pin, where the output 1 will switch to logical mode 0 and output 2 will switch to logical mode 1, as shown in Fig. 5.

In the latter case, if Input 4 is switched on and set to logic mode 1, then both outputs will receive 0.44 Pin power according to the nature of the W4 waveguide power divider, in which case both outputs will be set to logic mode 1. It should be noted that the power diagrams having the same power at both outputs have the same outputs as shown in Fig. 6.

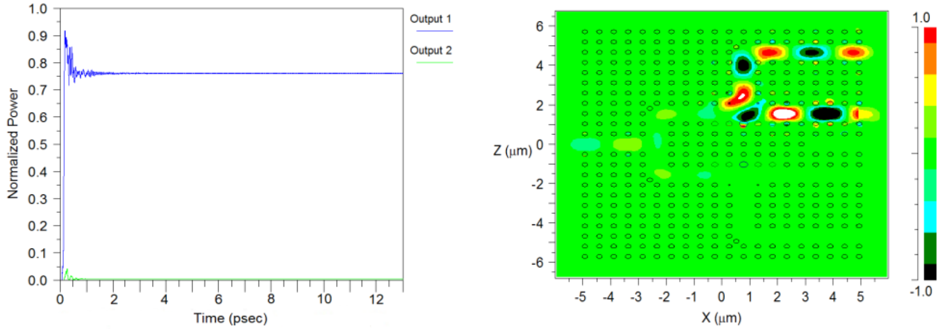


(a)



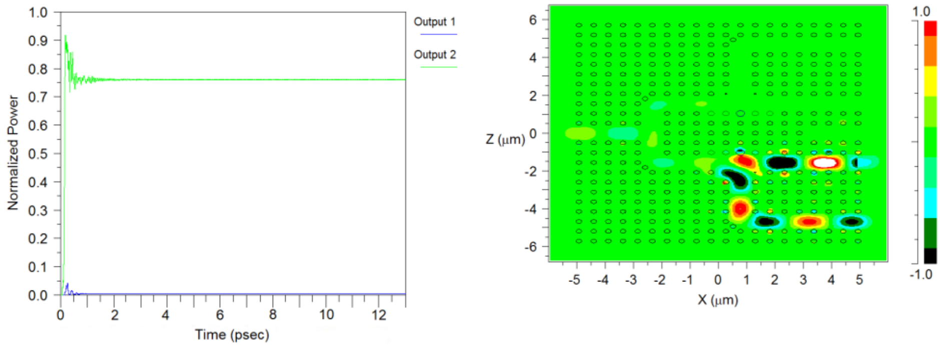
(b)

Fig 3. (a) the power transfer diagram, and (b) The electromagnetic field pattern for the all-optical 4×2 Encoder when input 1 is one. The optical power outputs in the two upper and lower ports have the same value, due to the symmetry of the structure.



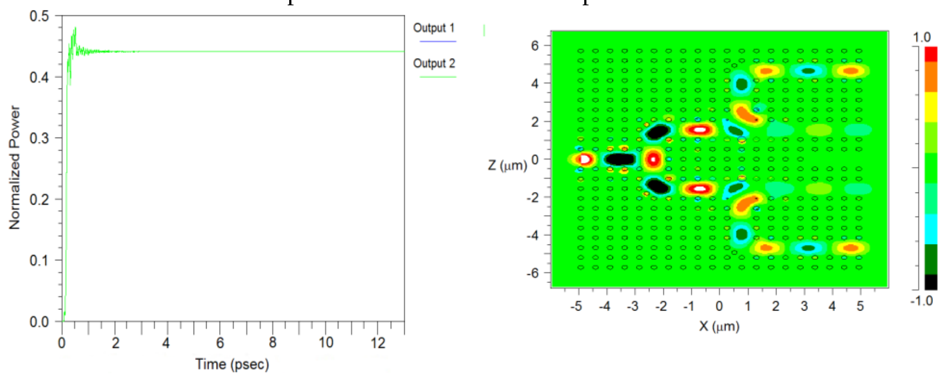
(a) (b)

Fig 4. (a) the power transfer diagram, and (b) The electromagnetic field pattern for the all-optical 4×2 Encoder when the input 2 is one.



(a) (b)

Fig 5. (a) the power transfer diagram, and (b) The electromagnetic field pattern for the all-optical 4×2 Encoder when input 3 is one.



(a) (b)

Fig 6. (a) the power transfer diagram, and (b) The electromagnetic field pattern for the all-optical 4×2 Encoder when the input 4 is one. The optical power outputs in the two upper and lower ports have the same value, due to the symmetry of the structure.

According to the results from the simulation of structure, as shown in Figs, the results are summarized in Table 1. This structure, in turn, is relatively smaller and simpler than the existing structures in the field [10, 13, 22-25]. According to the formula; CR (dB)=10×log (Pon/Poff), the contrast ratio in the structure designed for output of the structure is 13.2 dB. It should be noted that despite the power-distribution nature of the structure, this value is predictable for each output due to the existence of equal capacities in different logical states. For this structure, the maximum response time is 0.45 ps and its bit rate is about 2.2 Tbit/s, which in turn is very suitable and competitive with structures in this domain.

In Table 2, the all-optical encoder based on the photonic crystal is compared with the previous structures. The structure presented in this paper has a smaller size, lower delay time, and higher data transfer speed. Its power consumption is also extremely low, and each input power is <1 mW/μm^2. Besides, its output (in the mode of equivalent to the logical level one) is the same, which does not pose a problem to the next logic gate.

Table 1. Truth table and optical power in output for all-optical 4×2 Encoder.

Input 1	*Input 2*	*Input 3*	*Input 4*	*Output 1*	*Output 2*
Pin	0	0	0	0.021 Pin	0.021 Pin
0	Pin	0	0	0.76 Pin	0.004 Pin
0	0	Pin	0	0.004 Pin	0.76 Pin
0	0	0	Pin	0.44 Pin	0.44 Pin

Table 2. Comparison of the all-optical encoder based on nano resonator with the previous structures.

REF	contrast ratio (dB)	delay time (ps)	bit rate (Tb/s)	Input optical power (mW/μm^2)	Size (μm^2)
This paper	13.2	0.45	2.2	Less than 1	133.9
[18]	***	1	1	1000	726
[17]	9.2	1.8	0.55	***	791
[25]	22.92	1.92	0.52	200	1225

5. CONCLUSION

Using a 2D PC structure with a square lattice constant in this paper, an all-optical 4×2 encoder is designed. The type of resonator used for resonating and separating light is of the type of nano-resonator. Optical waveguides are used symmetrically in this structure. The symmetry of the structure has also made the structure itself a power divider, which is one of the unique features of this structure. This structure, in turn, is relatively smaller and simpler than the existing structures in the field. The simulation results show a contrast ratio of 13.2 dB and a response rate of 0.45 ps.

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