Interference based All-optical 4 × 2 Encoder

Enaul haq Shaik, Krishna Prasad Satamraju, Riyazuddien Shaik, Vasantha Lakshmi Movva

***Abstract**: In this article, we propose the design of all-optical photonic crystal based 4 × 2 encoder by interconnecting cross-shaped waveguide dependent OR gate. Initially the design and operation of photonic crystal based OR gate using cross-shaped waveguide is discussed with an additional reference input. The phase of all the input light signals are maintained at zero in order to have constructive interference to perform OR function. Later, OR gates are interconnected to realize encoder in such a way that the light path from the input ports to cross-shaped waveguide junctions be same. The structure is numerically simulated using Finite Difference Time Domain (FDTD) method and observed that the contrast ratio is 7.98 dB. Also, the size of the proposed structure is quite smaller by 84.7% and 22.07% than self-collimation and resonance based designs existing in the literature so far. With the fair results obtained, it can be concluded that the proposed encoder is suitable as a basic component in future Photonic Integrated Circuits.*

Keywords: Photonic Crystal, All-Optical 4×2 Encoder, Contrast ratio

I. INTRODUCTION

In the recent years, all-optical digital logic design has become an interesting research area for the development of high-speed telecommunication networks [1]. All-optical logic device processes the optical data directly without the need of Optical-Electrical-Optical (O-E-O) conversion that requires additional circuitry and time, and also immune to noise [2]. Hence these devices are faster in response. In order to design these devices, various processes have been used in the literature such as Semiconductor Optical Amplifier (SOA) [3], nonlinearity [4], Fiber Bragg Grating (FBG) [5], Photonic Crystal Fiber (PCF) [6] and so on. All these technologies have their own merits and demerits. Logic devices with nonlinearity are affected with high power consumption though they have many other applications. SOA based designs are inevitably affected by the spontaneous emission of noise and the devices with FBG's showed much difficulty in providing very closed channel spacing.

In order to overcome all these limitations, optical logic designers have been concentrating on the artificial optical materials like Photonic Crystal (PhC) due to its compactness, high speed processing and low power consumption [2] which depends on band gap engineering. Photonic crystal is such a platform wherein light can easily be limited, controlled and guided in nanometer scale [7].

Researchers have developed logic devices based on photonic crystal such as logic gates [2,8-11], de multiplexers [12], encoders [13-15], half adders [16] and so on using resonance, interference and self-collimation phenomena. As per the best of our knowledge, interference is the phenomena which offered higher contrast ratio with compact size compared with others.

In this article, we proposed an all-optical 4 × 2 encoder by interconnecting photonic crystal based OR gates which are created using cross-shaped waveguide. The structure operates with interference phenomenon, leads to acceptable contrast ratio at compact size. The remaining part this article is structured as follows. Section 2 deals with the design methodology of the encoder followed by the discussion over the cross-shaped waveguide based OR gate in section 3. Section 4 describes the design of encoder by interconnecting the OR gates. Section 5 discusses the obtained results and finally concluded in section 6.

II. DESIGN METHODOLOGY

An encoder basically encodes the specific code into binary which consists of 2^n inputs and n outputs. The proposed 4×2 encoder, consists of four inputs and two outputs, converts an input code into 2-bit binary, which. Its block diagram as well as truth table is shown in Fig. 1. All-optical encoder operates with optical input and provides the appropriate optical output. Thus, in the optical digital devices, logic values are determined by the intensity of the light. In these all-optical devices, light is considered as *logic '1'* and no light is considered as *logic '0'*. But, at the output of these devices, threshold level of light intensity may be kept in order to determine the logic values. In our designs, the output transmission of less than 0.15 and more than 0.8 is considered as *logic '0'* and *logic '1'*, respectively. The deviation between the logic levels is determined by the parameter known as Contrast Ratio (CR), given by

$$CR = 10\log\frac{P_1}{P_0} \qquad (1)$$

where P_1 and P_0 are the output transmissions of *logic '1'* and *logic '0'*, respectively.

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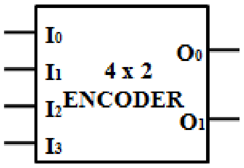
As it is observed in the truth table of encoder, illustrated by Fig. 1(b), the outputs O_0 and O_1 are I_1 *OR* I_3 and I_2 *OR* I_3, respectively. The input applied at I_1 and I_2 comes out through O_0 and O_1, respectively, and the input at I_3 splits up and come out through O_0 and O_1. Thus, in order to design an encoder the waveguides are to be structured in such a way that the input at I_1 takes a way to O_0 and the input at I_2 reaches to O_1 while the input at I_3 splits into O_0 and O_1. In this proposed work, photonic crystal based T-shaped and cross-shaped waveguides are used, in which cross-shaped waveguide operates as OR gate and T-shaped waveguide as power splitter.



(a)

I_3	I_2	I_1	I_0	O_1	O_0
0	0	0	1	0	0
0	0	1	0	0	1
0	1	0	0	1	0
1	0	0	0	1	1

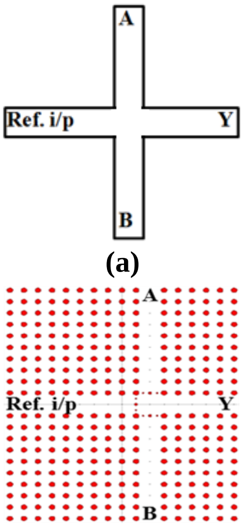
(b)

Fig. 1. 4 × 2 Encoder (a) Block diagram and (b) Truth table

III. PHOTONIC CRYSTAL BASED CROSS-SHAPED WAVEGUIDES

The OR gate in the proposed work is designed using photonic crystal based cross-shaped waveguide. In this cross-shaped waveguide, as Fig. 2(a) shows, the ends of the vertical section of the waveguide are the input ports *A* and *B* and the left side of the horizontal section is used to apply the reference input (*Ref*). Reference input in the optical logic devices is basically used to boost up or reduce the light intensity at the output wherever it is required as explained in [8]. In the OR gate, the applied input (i.e., *A* and/or *B*) need to present at the output (*Y*). It means the applied input light is to be boosted up to preserve the light intensity at the output. In order to do so, the phase of the input light is maintained at zero so that constructive interference can happen in between the inputs applied. Fig. 2(a) is a cross-shaped solid waveguide in which the input light (at *A* or *B*) constructively interfered with *Ref* will come out from other unemployed input section beside *Y*. This is considered to be undesired reflection, and this has to be reduced. In order to do so, photonic crystal is considered to be the base of the cross-shaped waveguide. In photonic crystal based waveguides, defects can be placed at the junction so that the reflection into the unemployed input ports can be reduced [11].

PhC that is being used for the creation of the waveguide consists of an array of Si rods with square-type lattice as shown in Fig. 2(b). The interesting property of the PhC for which it is mostly being used in the optical designs is bandgap engineering. The uniform PhC offers photonic bandgaps of TM and TE modes i.e., the range of wavelengths of the input light which are being reflected by it. The forbidden wavelength range of light or photonic bandgap can be obtained from the band diagram and it is calculated by using Plane Wave Expansion (PWE) method. According to the band diagram, there are three photonic bandgaps out of which two are for TE mode and one is for TM mode as shown in Fig. 3. A photonic bandgap suitable for the telecommunication window has a range from 0.282568 (a/λ) to 0.416924(a/λ). Thus, it completely reflects the light signal of wavelength ranging from 1.44 µm to 2.12 µm. The additional directional rods, r_{s1} and r_{s2} at the center of the cross-shaped waveguides are helpful to direct the light to the output ports. The radii of these rods, r_{s1} and r_{s2}, respectively are adjusted to 0.5 and 0.25 times the radius of the actual rod.



(a)

(b)

Fig. 2. OR gate with (a) solid and (b) photonic crystal based cross-shaped waveguide

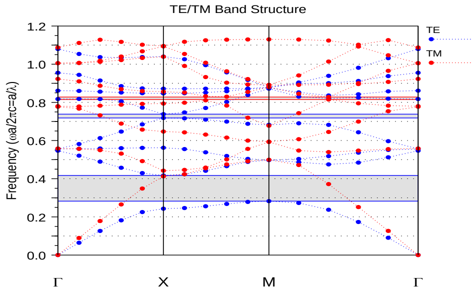
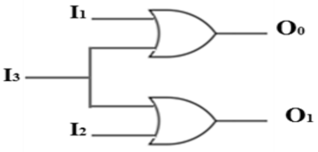


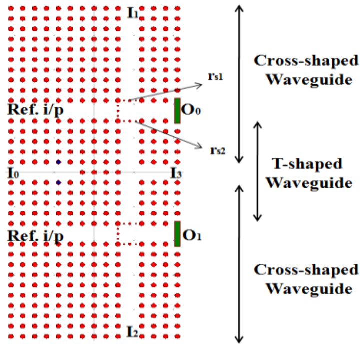
Fig. 3. Band Diagram of the Uniform Photonic Crystal

IV. CROSS SHAPED AND T-SHAPED WAVEGUIDE BASED ALL-OPTICAL 4 × 2 ENCODER

From the schematic diagram shown in Fig. 4(a), it can be said that the cross-shaped waveguides which act as OR gate are interconnected to realize the encoder. The lattice structure of the



(a)



(b)

Fig. 4. Proposed 4 × 2 encoder (a) Schematic Circuit and (b) Lattice Structure

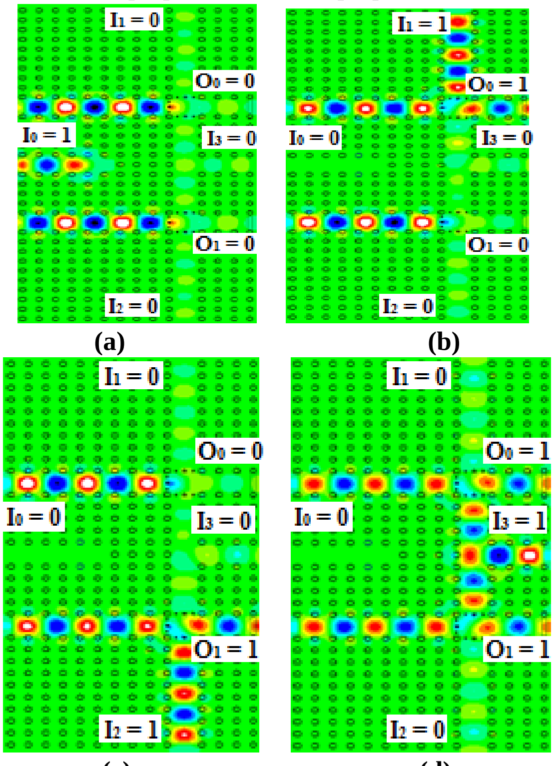
proposed encoder is also shown in Fig. 4(b) wherein only cross-shaped waveguides are interconnected. At the center of the interconnected waveguides, an extra straight waveguide is created which acts as T-shaped waveguide. This is used as a port to launch input light I_3. The structure shown in Fig. 4(b) is an array of 15 × 33 Si rods of square-type lattice with radius 0.2*a* where *a* is the lattice constant of value 600 nm. Except the output ports, the length of input ports are maintained same so that the applied inputs can interfere constructively with zero phase difference. A small straight waveguide is created in between the two *Ref* ports, and the light which passes through it will come back. This waveguide is basically not required because its excitation should not provide light at the output. This output can also be observed with un-excitation of the input ports (means at the idle state).

When one among input ports I_1 and I_2 is excited, the input light interferes constructively with *Ref* and reaches to one of the output port (i.e., O_0 if I_1 is excited or O_1 if I_2 is excited). When port I_3 is excited, the input light splits and interfere with *Ref* at both the junctions. The resultant light will reach out to the output ports O_0 and O_1.

V.RESULTS AND DISCUSSION

The proposed encoder is simulated using FDTD method and observed the output for all the possible inputs. The optical field distribution in the encoder upon applying the input is shown in Fig. 5 As the input port I_0 doesn't activate the output ports, the input that is being applied will not come out. But the applied *Ref* leaks into the output ports whose intensity is very less with a transmission of 0.1305, and so it is considered as *logic '0'*. When input port I_1 is excited, it interferes constructively with *Ref* and come out to port O0 with a transmission of 1.04, read as *logic '1'*. The port O1 is observed with a transmission of 0.123 which is read as *logic '0'*. Similar case happens when only port I_2 is excited but in an inverted manner i.e., $O_0 = 0$ and $O_1 = 1$. When the port I_3 is excited, the input light splits into two halves and interfere with *Ref* signals and come out at O_0 and O_1. The transmission observed at both the output ports is 0.82 which is read as *logic '1'*. The contrast ratio is calculated from the output transmission using equation 1, and it is 7.98 dB. The contrast ratio that is presented here is of maximum value calculated from higher transmission value of *logic '0'* and lower transmission value of *logic '1'*.

As far as the size of the structure is concerned, it is of dimension 19.44 µm x 9.64 µm. When compared with the existing encoders depending on self-collimation [14] and resonance [13,15], the proposed encoder is quite compact. The size of the proposed structure is reduced by 84.7% and 22.07%, respectively compared with the encoders depend on self-collimation [14] and resonance [15].



(a) (b) (c) (d)

Fig. 5. Optical field distribution in the proposed encoder when (a) I0 = 1, I1=I2=I3=0, (b) I1=1, I0=I2=I3=0, (c) I2=1, I0=I1=I3=0 and (d) I3=1, I0=I1=I2=0

VI. CONCLUSION

In this article, a photonic crystal based all-optical 4 × 2 encoder has been proposed by interconnecting OR gates designed with cross-shaped waveguide. Initially, an cross-shaped waveguide was created on a uniform photonic crystal which can be used as OR gate with inputs applied at zero phase difference. These gates were interconnected in such a way that the light path from the input ports to the junction can be same. Later, the structure has been simulated and observed that the structure offers a contrast ratio of 7.98 dB. Further, the compact size of the proposed structure has made it to be superior over the existing designs in the literature so far.

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