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# Photonic Crystal Waveguide Based Optical Encoder

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**ABSTRACT: -** In this present work, ultra-high speed nano-optical encoder is proposed and designed using a two-dimensional photonic crystal platform. The proposed logic device contains five waveguides and reflector in a square lattice with silicon rods arranged in the air-substrate. The proposed nano-encoding platform is working based on the resonance and interference effect. The photonic band diagram and performance characteristics of the encoder namely bit rate, delay time, switching speed and optical signal distribution are analyzed using a Plane Wave Expansion (PWE) and Finite Difference Time Domain (FDTD) method. The four logic states of designed encoder result will be shown in simulation. Furthermore, the presented device has numerous advantages such as simple structure, very low power consumption, high speed of operation, high data rate and a good contrast ratio. The response time and total chip area of the proposed encoder are 400 fs and 21 μm ×17 μm, respectively. Hence, it is tremendously suitable for optical logic systems and photonics integrated circuits.

**Key Words—**Optical encoder; Silicon; Response time; Square lattice

## I. INTRODUCTION

In recent years, the micro photonic device is extraordinarily attractive for the optical digital signal processor as it is perfectly satisfied everlasting demands namely low power consumption, very low loss, long-term stability and fast response [1].Very high speed of operation with ultra –compact size for optical integrated circuits, and more number of nodes are needed to design a complex network in photonics. Designing the miniaturized photonics components for integrated circuits is recently the subject of tremendous research [2]. In general, Photonic Crystals (PC), Micro Electro-Optical-Mechanical Systems (MEOMS), Planar Light wave Circuits (PLC) and Plasmonics platform are highly suitable for photonic integrated circuits. Among them, the PC based medium is a good candidate due to their attractive features such as flexible design, more temperature resilient, better lifetime, very low group velocity and low radiation loss [2]. PCs are artificial nanostructure with two different materials that are composed in a single substrate to regulate the electromagnetic signal within a nanostructure. In PC, the most fundamental property is a Photonic Band Gap (PBG) which is used to control the light signal at an optical wavelength. Basically, the PBG is extracted by using the line or point defects in a fundamental PC structure [3].

The PC platform is spatially designed as 1D, 2D and 3D where 2DPC is highly attractive and it is used to develop the various Nano photonics devices such as sensors [4, 5], filters [6], logic gates [7], flip-flops [8], and encoders [9-18]. Among all, the encoder is a key device and plays an important role in Optical Code Division Multiple Access (OCDMA) network and all-optical logic systems. Moreover, this device utilized as a binary code generator in analog-to-digital converters.

In the literature, the 2DPC based encoder is realized by using various techniques such as self-collimation [9], nonlinear effect [12, 14] and interference [15,17]. The self-collimation method based encoder needs phase shifters, in turn, it is occupied the large footprint which relatively increases the device cost. Although the nonlinear material based encoder occupies the small area which in turn decrease the device cost, however, the encoder operates with high input power which is not suitable for ultra-compact circuits [10].Alternatively, the interference phenomena based encoder is designed using the linear material which consumes less power and it is designed with a small footprint. Moreover, this technique

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provides a good contrast ratio and fast response time [15, 17].

So far, the different 2DPC based encoders were designed with waveguides, square lattice basedencoder provides high contrast ratio, flexible coupling, scalability in size and high-quality factor [15]. In recent research, the different Photonic Crystal Ring Resonator (PCRR) based encoders are designed in the hexagonal and square lattice platform. The resonator designs including quasi-square [11-13,16], square [14], hexagon [15] and ellipse [18]. The aforementioned encoders were designed with a large footprint and it operates with high input signal power which leads to increase the power consumption of an encoder.

In the present work, a novel structure of dual nanocavity coupled quasi square PCRR based encoder is proposed and designed to offer ultra-compact size, very low input power, high output efficiency and fast response time. The proposed logic device PBG and guided modes are calculated using a 2D-PWE method. The performance features like contrast ratio, delay time and data rate theoretically investigated using the 2D-FDTD methods. These methods are commonly used to reduce the CPU memory spacing, computation time and also it provides the accurate output by comparing with experimental results of 3D simulation [19].

The rest of the paper is structured as follows. The basic digital encoder design is discussed in Section 2. The perfect structure band diagram and the ring resonator based encoder design are focused on Section 3. The different states optical signal distribution and its output intensity level addressed in Section 4. Finally, a conclusion added in Section 5.

## II. BASIC DIGITAL ENCODER

The digital encoder is a high speed logic device that produced N bit coded outputs from $2^N$ input signals. The 4×2 digital encoder has four binary inputs and two binary outputs. The encoder has four input ports named as A, B, C and D and two output ports are labelled as X and Y which is clearly shown in Fig.1. The encoder has four binary inputs [1000], [0100], [0010], [0001] and its corresponding binary outputs are [00], [10], [01] and [11], respectively which is clearly presented in Table 1.Binary encoded signal produced at the output ports will be based on the input port in a 4×2 encoder.

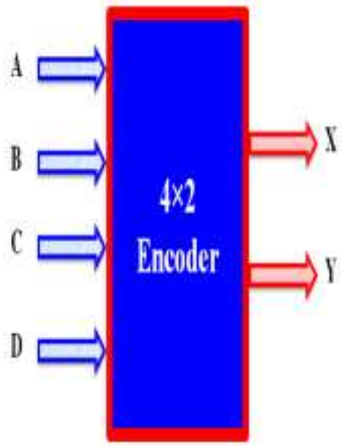


**Fig.1 Block diagram of 4x2 encoder**

**Table 1** The truth table of the 4x2 encoder

| Inputs | | | | Outputs | |
|---|---|---|---|---|---|
| A | B | C | D | X | Y |
| 1 | 0 | 0 | 0 | 0 | 0 |
| 0 | 1 | 0 | 0 | 1 | 0 |
| 0 | 0 | 1 | 0 | 0 | 1 |
| 0 | 0 | 0 | 1 | 1 | 1 |

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## III. DESIGN OF OPTICAL ENCODER BASED ON SQUARE RING RESONATORSTRUCTURE

The proposed asymmetric structure is based on a two- dimensional PC platform. It consists of four input ports (A, B, C, and D), two main output ports (X and Y), the design includes one photonic crystal ring resonator (PCRR) and four arm waveguides (W1, W2, W3, W4and W5). The structure is arranged on a square lattice of 21 × 17 cylindrical silicon (Si) rods suspended in air, corresponding to an area of 128.52 µm². The lattice constant (a), refractive index (n), and rod radius (r) of the silicon were chosen to be 0.6 µm, 3.4, and 0.12a, respectively. The inner rods have a different rod radius of ri to achieve the best operation for the selected wavelength. The resulting structure in shown in Fig.3. The right-angle W- shaped waveguides are denoted W1, W2, W3, W4, and W5 being created by removing some of the Si rods along their length to form a linedefect.

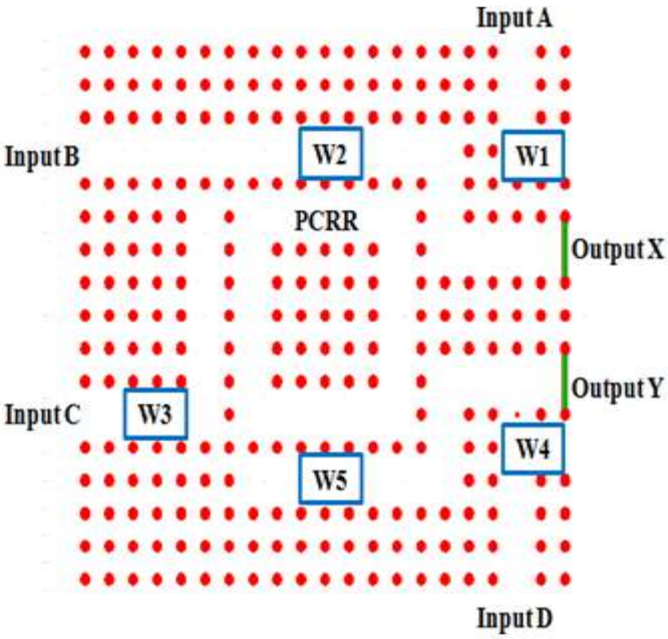


**Figure .2** The structure of layout with optical encode

## IV. SIMULATION RESULTSAND DISCUSSION

The structure resulting from the above-mentioned optimization process is presented in Figure 3. The design is simple, as shown by the absence of auxiliary inputs or external phase shift unit. A compact fabrication size with area of 128.52 µm²is achieved. When the applied input power is Pi, the following logical scenarios take place during itsoperation:

**Case 1**. For the input pattern ABCD 1000, logic level 0 is obtained at both outputs 1 and 2. The applied power does not interfere with the two outputs X and Y, while low power will escape from the ring resonator. The corresponding steady state field distribution is shown in Figure 3a. In this case, the power level is 0.05042Pi at output X and 0.0823Pi at output Y. Both outputs thus fall below the threshold for logic level 0, confirming the first state in the encoder truth table, i.e.,XY=00.

**Case 2**. When the input is ABCD 0100, logic level 1 is found at output X and logic level 0 at output Y. The corresponding field distribution is shown in Figure 3b. The input power will propagate inside W3. Interference will occur as a result of the one-row separation between W3 and W5, affecting one of the two output ports X with a power level of1.9882Pi.

The obtained power will be indicated as logic level 1 (> 0.55). Output X2 will have a tiny amount of power equal to 0.211767Pi, resulting from worming in the ring resonator. This level of power will be considered as logic level 0 (< 0.2). As a consequence, the output pattern will be XY=10, verifying the second state of the encoder operation.

**Case 3**: Figure 3c shows the field distribution for the input C pattern ABCD 0010, the input power is

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confined to input C with logic level 1, The corresponding outputis directly connected to X and Y. How- ever, couplinill occur between W1 and the PCRR, as the ring resonator enters the resonant state. The resulting constructive interference will thus affect the two outputs X and Y,achieving power levels of 1.5238Pi and 0.4066Pi, respectively.

**Case 4**: Finally, for the pattern ABCD 0001, the input power is confined to input A with logic level 0, while the other inputs are disabled. . The output X provides logic level 0 with a power level of 0.0545Pi. The constructive interference and coupling exhibited by the ring resonator make a remarkable contribution to this result. The output Y will present logic level 1 with power of 0.5714Pi.

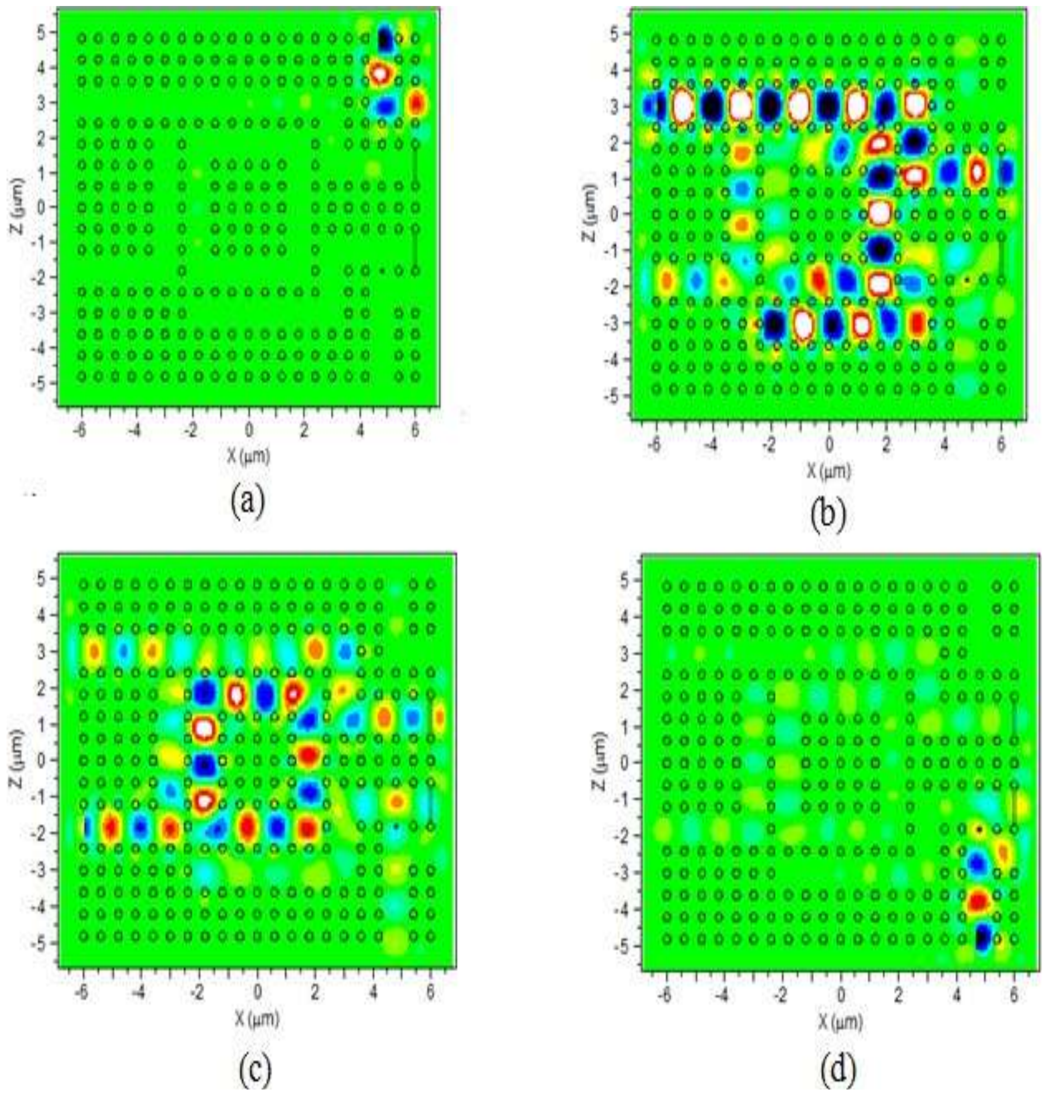


**Figure .3 Steady-state distribution for the input patterna ABCD=1000, b ABCD=0100,cABCD=0010,dABCD=0001.**

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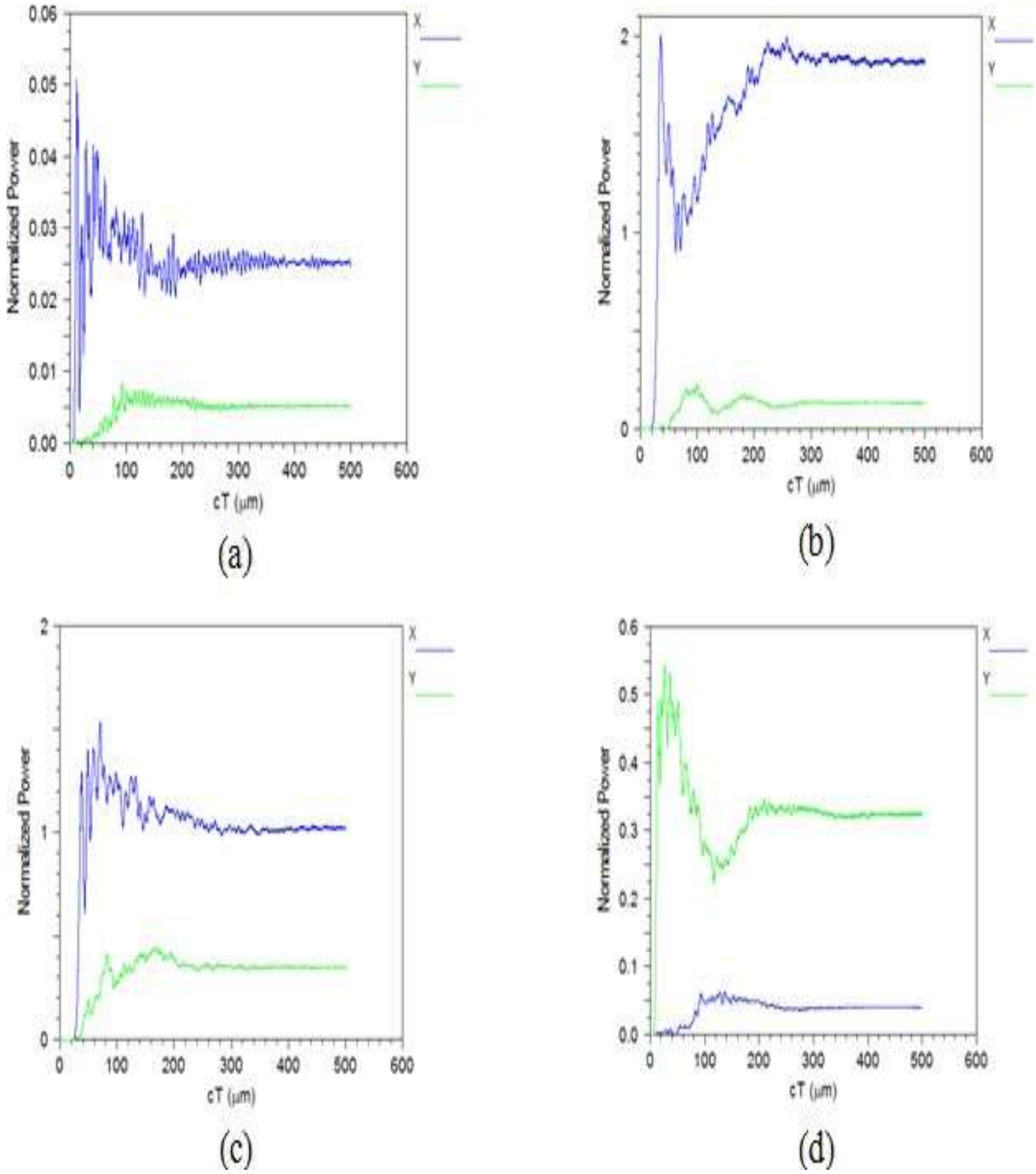


**Figure 4** The time response of the normalized output power for a ABCD=1000, b ABCD=0100, c ABCD=0010, d ABCD=0001

## 4.1DELAY TIME AND SWITCHING SPEEDCALCULATIONS

The time evolution curves for the all-optical encoder are shown in Figure 4c These curves can be used to extract the delay time for the designed encoder, takenas the time required for the outputpowertoclimbfrom 0 to 10 % of its steady-state value. The switching speed can then be calculated as the reciprocal of thisdelay. For the input pattern ABCD 1000, the time response of the outputs is shown in Figure 4a. As the output is all zero for this case, it is not considered in these calculations.

The temporal evolution of the normalized power for the input ABCD=0100 is shown in Figure 4b. The output XY=10 is obtained in this case. As X=1, the delay time can be extracted as CT 50 µm.

The delay time (t) and switching speed are thus calculated to be 0.166 PS and 6 THz, respectively, representing the minimum delay time and maximum switching speed that can be obtained using this structure. This switching speed is approximately seven and half times faster than the best result published to date.

Figure 4c shows the normalized response for the input state ABCD=0010 with output XY=11. As shown in this figure, Y=1 and CT=499.5 µm. Thus, td= 0.01665 PS, and the switching speed is 0.606 THz. The final state of the encoder operation is shown in Figure 4d, corresponding to input of ABCD=0001 and output of XY=01. The time response in this case shows that the delay time is approximately equal to 30 µm for both outputs.Thus, td= 0.1663 PS, and the switching speed is 0.606THz.

### 4.2CONTRAST RATIO (CR)CALCULATION

The contrast ratio can be calculated, being definedasCR=10 log($P_1/P_0$)(dB)(1)where $P_1$ is the minimum output power for logic level 1 and $P_0$ is the maximum output power for logic level 0. For output X, the lowest logic level 1 is 1.9882Pi while the largest for logic level 0is 0.21176Pi, yielding a CR of 9.726dB. Similarly the CR calculated for output Y is10.2094dB the overall CR for the encoder circuit is therefore 7.1138 dB, which is acceptable for cascading with other optical circuits.

## V. CONCLUSION

In this paper, all optical 4×2 encoder is proposed and designed using ring resonator structure. The resonance and interference effect play a vital role in the logic device and ferro electric material is used to realize the nano-encoding platform. The guided mode and functional parameters of the proposed 4×2 encoder are investigated using 2D-PWE and 2D-FDTD method, respectively. The normalized output power of the proposed design is about 95.3 %, contrast ratio is 9.82 dB and data rate is about 0.12 Tbps. The response time and switching speedof the proposed encoder is calculated as 400 fs and 0.12 THz, respectively. The footprint of the logic device is 128.82 µm$^2$. Hence, it is extremely suitable for high speed photonics integrated circuits and optical signal processor.

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