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Design and analysis of 1:2 line optical decoder based on linear optics

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ABSTRACT

In this paper, a simple design of all-optical photonic crystal (PhC) based 1:2 line decoder has been proposed and its operating principle is based on light beam interference. The designed structure has a hexagonal arrangement of air holes in Si substrate with a finite slab height. In our proposed structure, different path lengths have been made so that the light beams should interact out of phase. Effective refractive index method has been adopted to reduce the simulation time. The Finite Difference Time Domain (FDTD) and Plane Wave Expansion (PWE) methods have been applied to evaluate the proposed structures. The required footprint area for proposed device is reported as 215 μm^2. Minimum contrast ratio between the logic states of “1” and “0” is obtained as 10 dB. This device is designed based on solely linear optical phenomena in a holes-in-slab PhC structure. Therefore, mechanically stabled, ultra-compact design and simple working mechanism of the proposed optical decoder can be a potential candidate for future generation Photonic Integrated Circuits (PICs).

1. Introduction

The demand of high-speed data computation is ever increasing and the conventional electronic processing units are no more capable to fulfill the demand. Therefore, now, it seems to be inevitable to move towards all optical devices/circuits [1–3] for maximization of the performances of the processing units. Furthermore, this changeover can also improve the communication system by providing high bandwidth and ultrafast switching speed because optical to electrical and vice versa conversion could be avoided. Therefore, to make all the data processing/computation in optical domain, optical devices like logic gates [4–6], optical sensors [7–9], decoder/encoder [10–12], multiplexer/demultiplexer [13], adder/subtractor [14], etc. are highly required. To optimize the advantages of optical network/processing unit, the fabricating platforms play crucial role. In this context, photonic crystal (PhC) has drawn the attention of the researchers for its unique characteristic called photonic band gap (PBG) along with its other advantageous features like ultra-compactness and low power consumption [15,16]. PBG is the prohibited range of frequencies of optical signals that cannot propagate through the PhC. However, if a defect is made, by removing one (or more) row of rods or holes, a narrow band of permissible frequencies can propagate through the defect which acts as a waveguide. An optical signal/light can be highly confined, in nanometer range, along PhC waveguide due to its PBG. In recent past, several logic Gates [17–19], and other devices like decoder [20–23], multiplexer/demultiplexer [24,25], adder/subtractor [26], comparator [27, 28] etc. have been designed by molding, regulating, splitting and converging PhC waveguides and optical signals as well. Flow of optical signals at the junction of waveguides plays very important roles for designing logic devices. Propagation of light can be passed or stopped by means of constructive or destructive interference respectively at a converging junction. To make constructive /destructive interference, proper phase difference of incoming signals has to be maintained at the junction.

Among various optical devices, the all-optical logic decoder is very significant and its design is quite challenging. In recent past, few all-optical logic decoders based on two dimensional PhC platform have been reported. For example, recently, Alidoost et al. [29] have reported a 2:4 optical decoder (footprint of 850 μm^2) in PhC rods-in-air platform using nonlinear ring resonators. Nonlinear ring resonators are made with dopped glass of refractive index 1.4 and nonlinear Kerr coefficient of 10^{-14} m^2/W. The simulation results prove that the reported device delivers more than 80% of input power at the desired output ports and offer contrast ratio of 10.6 dB. Similarly, Asghar Askarian [30] has proposed one 2-to-4-line optical decoder on two-dimensional rods-in-air PhC platform. The proposed device is designed based on the combination of nonlinear ring resonator and light beam interference effect. The footprint, contrast ratio and data rate of his device have been reported as

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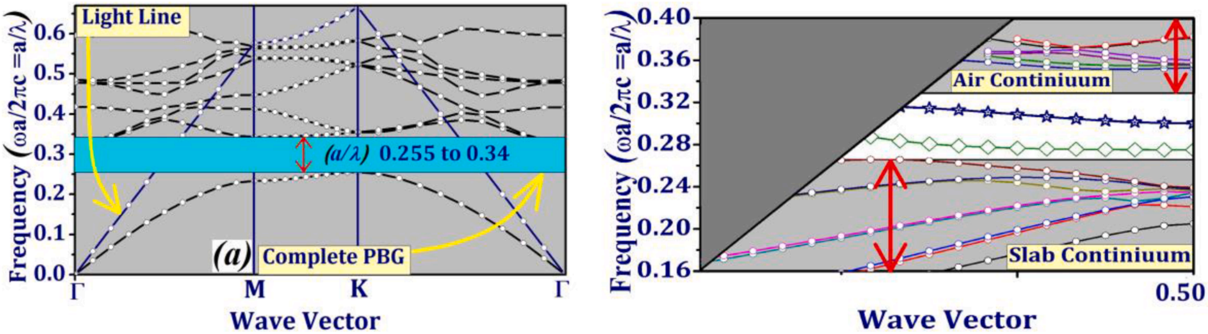

Fig. 1. (a)Band diagram of non-defect structure (b) Projected band diagram of defect structure.

420 μm^2, 7.73dB and 500 Gbps respectively. Moreover, based on nonlinear ring resonator, another 2:4 optical decoder has been reported by Tina et al. in [11]. Their reported device is designed on two dimensional rods-in-air PhC platform. The footprint of the device is reported as ~1900 μm^2, which is quite large compare to the devices reported in [29] and [30]. In addition to that, the device offers substantial low output power of 37% and 10% for logic-1 and logic-0 conditions respectively. The FDTD simulation results prove that the device exhibits cross talk and insertion loss as -38dB and -20dB respectively and it can be operated with the speed of 160 GHz. Another higher order (3:8) decoder has been reported in [31] by Salimzadeh et al. For designing the decoder, they have used 7 nonlinear ring resonators. The refractive index of the of the rods is chosen as 3.46 and radius of the rods is considered as 120 nm. Similarly, Asghar Askarian et al. [32] have proposed a novel design of optical 2 to 4 line optical decoder in PhC based rods-in-air structure. Their reported device is designed based on the principle of nonlinear optics. The footprint of the structure and the contrast ratio of the device have been reported as 561 μm^2 and 9.32 dB respectively. Another 2 × 4 line optical decoder on PhC platform (rods-in-air) has been reported by Rahmi et al. in [33]. They have used the principle of nonlinear ring resonator to make the device function as 2 × 4 line decoder. In addition to that the performance matrices i.e., contrast ratio, maximum crosstalk and insertion loss are reported as 8.7 dB, -22.1 dB and -4.5 dB. Moreover, in [34], Saleh et al have reported PhC based 2-to-4 line optical decoder. They have used nonlinear ring resonator, which is formed by SiO_2 rods coated with graphene nano-shells. The footprint area of the device is reported as 850 μm^2. From the reported literatures [11,29–34], it is observed that all the devices are designed on rods-in-air PhC structure, which incur intrinsic drawback of mechanical instability. Moreover, the performance metrices of the devices have been calculated by considering infinite height, whereas in practical scenario, the height of the device should be finite. Additionally, majority number of decoders, reported earlier, are based on the principle of optical nonlinearity, which makes the device operate with high input optical power.

Therefore, the aforesaid limitations of earlier reported all-optical decoders have motivated the authors to design a 1-to-2-line decoder in linear optical domain. Moreover, as per the best of the authors' knowledge, earlier none have reported the PhC based all-optical decoder in holes-in-slab structure.

In this paper, an all optical 1-to-2-line logic decoder has been proposed in a two-dimensional PhC structure, by exploiting the principle of beam interference. Phase difference between two converging optical signals have been created by making different path length of the waveguides. The dispersion diagram of the lattice structure has been analyzed by using the PWE method whereas FDTD method have been used to simulate the optical behavior and to measure the outcomes/performances of the device. The height of the PhC slab has been considered finite in this design. But, due to the limitation of research recourses, effective refractive index method has been used, that reduces the simulation time and makes the simulation convenient. The simulations results shows that the device can operate at a high bit rate of ~700

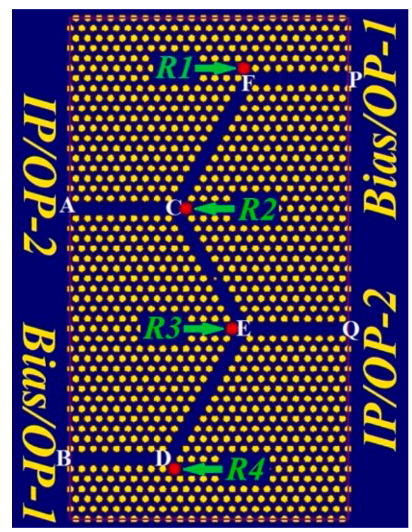

Fig. 2. Schematic representation of proposed decoder.

Gbps and offers a contrast ratio, over 10 dB, between the output logic levels. The other important features of this design are its compact footprint, fast response time and simplicity of the design which make the device suitable in future optical computing device.

Remaining content of this article is structured as follows. Section 2 presents the structural description of the proposed design. In section 3, device performance has been evaluated by analyzing the results of FDTD simulations and the operating principle of the device has also been elaborated in the same section. Finally, section 4 concludes with the findings of the proposed design.

2. Device description

The proposed device has been designed on a dielectric material of finite height having air holes in triangular pattern. The dielectric material used here is Si with a dielectric constant 11.83. The slab height is considered as 0.7a where 'a' is the lattice constant of the crystal. The lattice constant (a) of the crystal and the radius (r) of the air holes are taken as 450 nm and (0.32a) 144 nm respectively. The total structure is made of a matrix of 24 × 51 air holes which makes a footprint of 215 μm^2.

Applying PWE algorithm the band diagram of the PhC has been calculated, as shown in Fig. 1. The band diagram of non-defect crystal is shown in figure 1a. It depicts that a complete PBG have been obtained in the range of 1325 nm to 1765 nm wave length, which includes the standard optical communication wave length 1550 nm in its mid-range. Moreover, the projected band has been calculated for a W1 line defect in Γ-M direction of the crystal, as shown in Fig. 1b. The guided band is

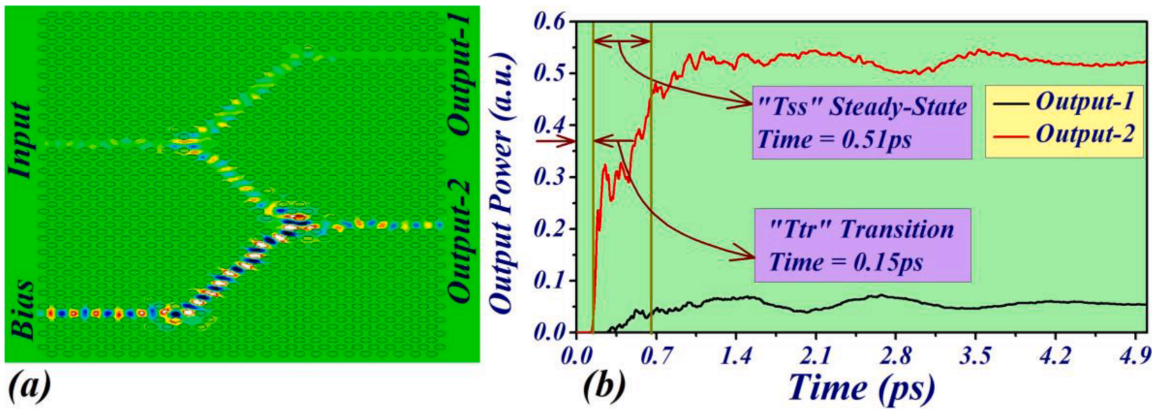

Fig. 3. (a)Propagation profile of the device (b) Graphical representation of output signal power, when no signal is applied at the input port.

found in the wavelength range of 1430 nm to 1630 nm.

The structure is made of two Y shape (APQ & QAB) waveguides combined parallelly as shown in the Fig. 2. Waveguide ACEQ is the common part for both the Y shapes. The W1 waveguides are made by removing a single row of air holes in Γ-X direction. A is the input port whereas P and Q are the output ports (OP-1 and OP-2) of the decoder. B is working as the bias input port for the device, where 0.5 of input signal power is applied as bias signal. AC, BD, FP and EQ are four parallel waveguides. The length of CE is takes as 11a whereas the length of DE and CF is taken as 12a. Waveguides CE and DE are converging at the junction point E. Waveguides CF and FP have made an angle of 60 degree and so as BD and DE. At each bending region (D and F) the radius of one outer hole (known as R1 and R4) has been optimized as 1.5r (r has been considered as radius of other unoptimized holes) so as to minimize the bending loss. Moreover, the radius of one hole at each of the junction points C and E (designated as R2 and R3) has also been optimized as 1.6a to diverge and converge the light beam at the junctions efficiently. Here, junction C is working as a 3 dB power splitter, which splits the signal coming from port A whereas junction E is working as a 3dB coupler that combines the optical signals coming through CE and DE. To minimize the loss in junction C and E, the radius of the holes (known as R2 and R3) has been optimized as 1.6r. The length of CE and DE are optimized in such a way that a part of signal (almost 50%) coming from A meets the bias signal at E out of phase. Owing to the design symmetry of the device port A and port B can also be used as output ports, under this condition port P and port Q should be used as bias and input port. The device is bidirectional.

3. Simulation and discussion

In the proposed structure, 'A' is the input port, 'B' is the bias port whereas P and Q are the two output ports of the decoder. In this simulation procedure continuous optical signals (Gaussian), centered at 1550 nm are launched both at input port (A) and bias port (B). This device is working mainly on the basis of constructive/ destructive interference of light beam at the junction E. If destructive interference happens, no signal appears at output port Q, which is considered as logic '0". On the other hand, if input signals can pass through the junction point, it appears at output port 'Q', producing logic '1". Bias is always ON as long as the device is active. Two different logic input conditions have been considered to simulate the device, which are as follows:

Input signal 0: Under this condition no signal is applied at input port, only the bias signal ($0.5P_i$, P_i is considered as input signal power) is ON at port B. This signal appears at output port Q through junction E and makes the logic level high. A very negligible amount of signal appears at output port P through the path BDECFP which makes the logic level low. The electric field distribution of the device for this condition is shown in Fig. 3. Output power at output port P and Q have been measured as 0.05 P_i and 0.49 P_i respectively.

Table 1
Logic and power lavels at various ports of the 1-to-2 line decoder.

Bias power	Input signal power	Input logic level	Output-1 (P) Power level	Output-1 (P) Logic level	Output-2 (Q) Power level	Output-2 (Q) Logic level
0.5 P_i	0 P_i	0	0.05 P_i	0	0.49 P_i	1
0.5 P_i	1 P_i	1	0.6 P_i	1	0.05 P_i	0

P_i is the input power

Input signal 1: In this case, the input port is excited with (ON) a $1P_i$ continuous wave in same phase with bias signal. The signal coming from port-A is divided into two parts at junction C. Fifty percent ($0.5P_i$) of the input signal, coming from port A, appears at output port P and makes the logic level high. Another fifty percent signal (0.5 P_i) appears at junction E and meets the bias signal ($0.5P_i$) out of phase. Thereafter, a destructive interference occurs, hence no signal appears at output port Q, which makes the logic level low. The electric field distribution of the device for this condition is shown in Fig. 3. Output power at output port P and Q have been measured as $0.6P_i$ and $0.05P_i$ respectively.

The logic levels of the input and output ports and power levels of the output ports for various input logic conditions of the proposed decoder are depicted in Table 1. Moreover, from the FDTD simulation operation, few performance parameters of the proposed device like contrast ratio, response time and data rate have been measured which are depicted in the following subsections:

3.1. Contrast ratio

Contrast ratio (CR) is defined as the ratio of optical powers at the output port when it is under logic '1' to that when it is under logic '0'. Contrast ratio is considered to be an important parameter while designing a logic device and it is expected to be as high as possible. Moreover, contrast ratio is inversely proportional to the bit error rate (BER) and BER is also inversely proportional to the noise margin of a device, therefore contrast ratio has directly proportional relation with noise margin. Mathematically CR can be represented as -

$CR = 10 \log_{10}(P1/P0)$ where P1 is the optical power at the output port under logic '1' and P0 is the optical power at the same output port under logic '0'. In this design CR has been calculated as 10.8 dB and 10 dB for output ports 1 and output port 2 respectively.

3.2. Response time and data rate

From figure 3b and 4b the response time of the proposed decoder has been measured and from response time the data rate of such device has been calculated. The summation of transition time (Ttr) and steady state

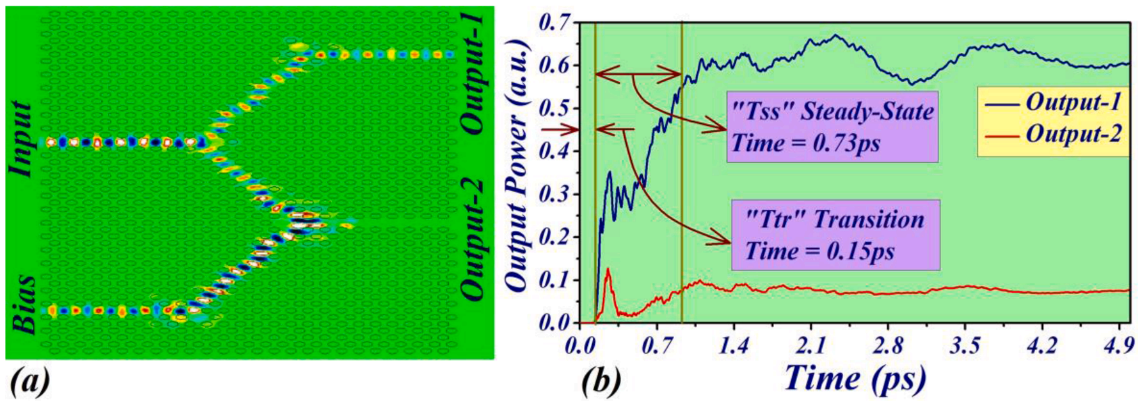

Fig. 4. (a)Propagation profile of the device (b) Graphical representation of output signal power, when TE optical signal is applied at the input port.

Table 2
Comparative analysis of all-optical logic decoder.

Ref.	Platform Used	Operating Principle	Operating Power	Footprint	Contrast Ratio	Data Rate/ Bandwidth	Response Time
[10]	Rods-in-air	Nonlinear ring resonator	2 kW/μm^2	1514 μm^2	—	—	—
[11]	Rods-in-air	Nonlinear ring resonator	2 kW/μm^2	346 μm^2	—	160 GHz	6 ps
[12]	Rods-in-air	Linear point defect	—	91.75 μm^2	—	2 Tbps	0.5 ps
[20]	Rods-in-air	Linear point defect	—	243 μm^2	11.3 dB	625 Gbps	0.77 ps
[21]	Rods-in-air	Nonlinear ring resonator	1.5 kW/μm^2	260 μm^2	—	—	—
[22]	Rods-in-air	Nonlinear ring resonator	1 kW/μm^2	218 μm^2	—	1.05 Tbps	0.95 ps
[23]	Rods-in-air	Nonlinear ring resonator	1 kW/μm^2	1926 μm^2	—	—	—
[29]	Rods-in-air	Nonlinear ring resonator	15 W/μm^2	850 μm^2	10.6 dB	—	2.2 ps
[30]	Rods-in-air	Nonlinear ring resonator	20 W/μm^2	420 μm^2	7.73 dB	500 Gbps	2 ps
[31]	Rods-in-air	Nonlinear ring resonator	—	—	—	—	6 ps
[32]	Rods-in-air	Nonlinear ring resonator	15 W/μm^2	561 μm^2	9.32 dB	500 GHz	1.55 ps
[33]	Rods-in-air	Nonlinear ring resonator	1 kW/μm^2	487 μm^2	8.7 dB	—	—
[34]	Rods-in-air	Nonlinear ring resonator	—	850 μm^2	—	—	1.1 ps
This Work	Holes-in-slab	Linear optics	—	215 μm^2	10 dB	700 Gbps	0.88 ps

time (Tss) altogether produce response time of a device. For a particular output port, the transition time (Ttr) is defined as a required time for an output signal to reach 1% of its steady state power. On the other hand, in a particular output port, when the output signal power reaches to 90% from 1% of its steady state power, is known as steady state time (Tss). From Fig. 3b the transition time and steady state time for output port-2 has been measured as 0.15 ps and 0.51 ps respectively. Moreover, from Fig. 4b the transition time and steady state time for output port-1 has been measured as 0.15 ps and 0.73 ps respectively.

Additionally, the data rate of the device can also be calculated from its time evolving graphs (Figs. 3b and 4b). At output port-2, the rise time of a signal which is equal to the steady-state time (Tss), is measured as 0.51 ps. As the operation domain of the device is in linear optics, hence, the fall time of a signal can be considered as equal to the rise time of the signal (which is Tss). Therefore, width of the pulse, is considered as the summation of rise and fall time, which is equal to 2xTss i.e., ≈ 1.01 ps. This leads to a data rate at output port-2 as 1 Tbps. Moreover, at output port-1, width of the pulse is calculated as 1.46 ps which leads to 685 Gbps.

3.3. Comparative analysis of optical decoder

The working regulation of the decoder that has been conferred in the work is based on linear optical phenomena. As presented in the Table 2 a comparative analysis among all the other known decoders as per literature operates mostly based on the non-linear properties of optics. The Table 2 showcases every work except for one that is being presented in this paper that works on the basis of non-linear optical properties of materials. Thus, there arises a need for threshold optical power for working of the decoders, which is indeed a significant limitation hindering its practical operations. In addition to this, it may also be noted from the below table that the footprint size of all the decoders is bigger in size as when compared with the one that is being presented in this work. This enhances the appropriateness of this decoder for its compact integration in PICs. Moreover, the contrast ratio at the ports of the decoder mentioned here is preferable than the others enrolled in the table which aids in minimizing bit-error-rate in a communication channel. As a consequence, the comparison table concludes about enormous likelihood of the decoder presented in this work with respect to its accomplishment of high data rate and low bit-bit-error-rate without any limitation in its operations by a threshold optical power.

4. Conclusion

In this paper, a new design of a photonic crystal-based all-optical 1:2 decoder has been proposed using two Y-shaped waveguides assembled parallelly. 2D triangular lattice of air holes in dielectric Si slab of finite height has been used to design the structure. The device performance is simulated and analyzed by PWE and FDTD methods. The basic operating principle of the devices is based on light beam interference. A maximum contrast ratio of 10 dB and 11 dB have been achieved at the output ports with substantial high data rate of ~700 Gbps. The 215 μm^2 footprint of this all-optical decoder is suitable for the chip-level integration. It is expected that these proposed designs will be useful for designing high-speed optical ALU to be used in next generation optical processor.

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.

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