Unidirectional Light Propagation Photonic Crystal Waveguide Incorporating Modified Defects

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Abstract:
In this paper, we have proposed a design of an Optical Diode-like in two-dimensional (2D) Photonic Crystal (PC) waveguide. The proposed device consists of 2D square-lattice PC structures, and it is based on two PC waveguides with different symmetric guiding modes, where various configurations of defects, including elliptic or/and semi-circular defects have been incorporated. The proposed one-way light propagation Optical Diode has been designed and optimized by employing in-house 2D Finite Difference Time Domain (FDTD) numerical method. We have reported that the unidirectional light propagation depends strongly on the coupling region between the introduced defects and the adjacent waveguides, and it also depends on the matching and mismatching between the defects and waveguide modes. It has been shown also that owing to its tunable features, the proposed Optical Diode can be potentially applied as a building block in future complex optical integrated circuits.

1. Introduction:

In the last decades Photonic crystals (PCs) have received much interest [1, 2] owing to their unique properties and myriad of applications in the areas of waveguides [3-5], splitters [6-9], and filters [10]. Due to the current advanced production technology and integration into conventional devices, two dimensional (2D) PCs provide the opportunity of building and enhancing all-optical circuits [11, 12]. One such device is the all – optical diode. An all-optical diode is a spatially nonreciprocal device as it offers unidirectional propagation of the light beams. It is the optical equivalent of the electronic diode and operates by allowing a light beam to flow along one direction and blocking it in the opposite direction and plays an important role in the realization of the concept of all-optical integrated components and circuits on a single platform. Furthermore, the unique properties of Optical Diodes (ODs) make them indispensable in the area of optical interconnection networks, optical computing and ultra-high speed information processing systems. ODs can be designed either via spatial symmetry breaking or via time-reversal symmetry breaking which we have employed in this reported work.

The time-reversal symmetry breaking based ODs can be realized through various design routines such as magneto-optical effect [13, 14] and optical non linearity [15-17]. Magneto-optical PCs have the drawback of being difficult to integrate with other components on a single chip[13, 14]. Moreover, this effect is very weak in the near-infrared region [18, 19]. On the other hand, optical non linearity takes place at very high intensities ,which is a limitation for most applications. These shortcomings of the of the above mentioned design routines for realizing the ODs, have led the developments of other design approaches, among them is the unidirectional light propagation in the linear PC devices which is similar to mode converter reported in [20-22]. Consequently, in this paper, we have proposed an on-chip nonreciprocal light propagation design using a 2D PC structure. The proposed device is constructed from a 2D rectangular PC structure where input and output waveguides with different structure geometries have been designed (hence different guiding modes), and defects of different shape geometries based on low index of defect $\varepsilon_{defect} = 5$, such as elliptic and a semi-circle shape have been incorporated. Furthermore, we also intend to reduce (resolve) the back reflection of the light at the structure interfaces. Due to the match and mismatch of the optical modes between the incorporated defects and the adjacent waveguides, the propagation of the fundamental mode at a certain frequency can be allowed along one direction and prohibited along the opposite direction. The spatial electric field distributions through our proposed 2D PC structure and the transmission spectrum of TM-polarized modes *i.e* the electric field is parallel to the rods (z-axis), are calculated by using the in-house- 2D FDTD method with periodic and matching layers conditions [23- 25]. In our simulations we have adopted the supercell technique to calculate the transmission spectra.

2. Unidirectional light propagation in the 2D PC structure with circular and elliptic defects.

2.1 PC structure with semi circle defect

Initially, we consider a PC structure under study which consists of silicon rods with refractive index n = 3.45 and a radius of 0.225a, where a is the lattice constant of the PC silicon rods, all immersed in an air background. In order to launch the TM polarized optical mode into the waveguides, one row of rods along the OX and OY axes are omitted, and then we have incorporated the defects at the bending region of the two waveguides. The defect consists of a semi circular shape with a radius of 0.75a and with a refractive index $n_{defects}$ = 2.23. The proposed structure configuration with defects is shown in Figure 1. The proposed device structure is composed of a cavity and two waveguides with different geometries in a 2D rectangular PC structure. The black arrow indicates the forward propagation and red arrow indicates the backward propagation.

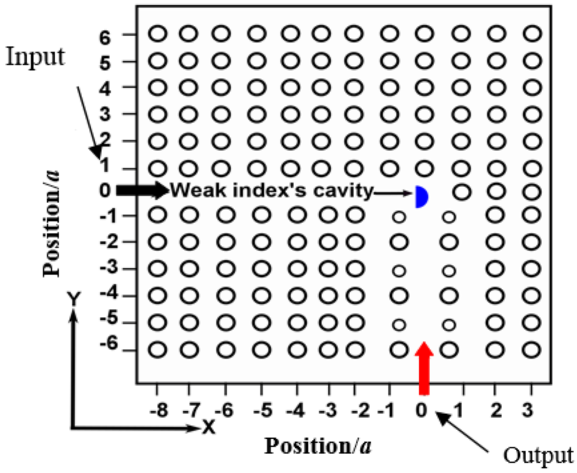

Fig 1. Schematic geometry of the isolator structure consisted of two waveguides and weak index defects.

The proposed PC exhibits a band gap for Transverse Magnetic (TM) polarized modes where the electric field is perpendicular to the x-y plane. The band structure of the PC structure is calculated by employing in-house plane-wave expansion method [26]. The calculated band structure diagram is illustrated in Fig. 2, which shows that the frequency of the TM polarized guided mode is around 0. 32a/λ.

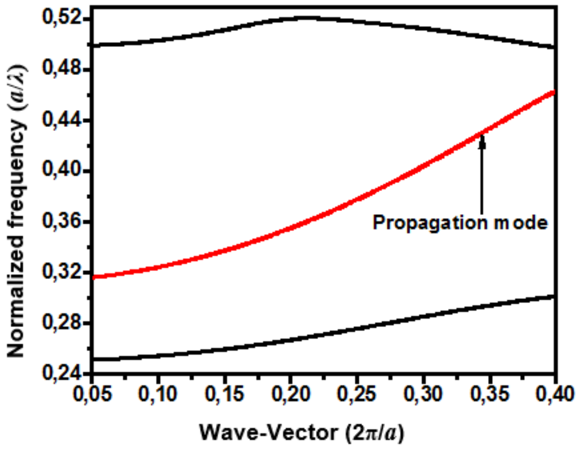

Fig. 2. Band diagram of the proposed PC structure.

The physics principle of the optical diode is based on the coupling effect between the cavity and the adjacent waveguides. In fact, the light beam is launched rightward and arrived at the defect, and no light energy is exported from the bottom waveguide. It is obvious that there are no coupling between the input waveguide and the defect, owing to the mismatch of mode's symmetry as shown in Fig. 3(a). On the other hand, in Fig. 3(b) we illustrate that the light supported by the bottom waveguide can couple with the defect, consequently it propagates through the left waveguide.

Figs. 3(a) and 3(b) illustrate that the light beam resonant at 0.32*a*/*λ*, and it can propagate along the left waveguide. As can be seen, the light propagates only in downward direction of the waveguide down to the left waveguide. From our simulation results we found that the photons propagate towards the outlet of the left guide.

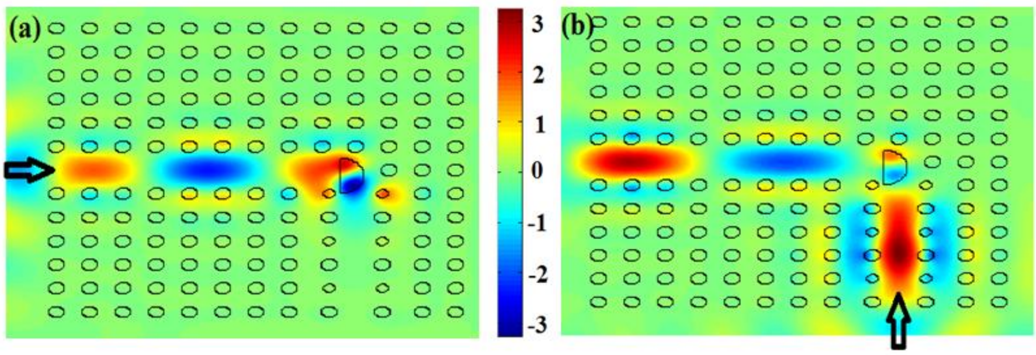

Fig. 3 (a) The light source is set at the left hand side of the PC waveguide and (b) the source is set at the right hand side of the PC waveguide

Next, we calculate the transmission spectra of the proposed structure. Fig. 4 shows the transmission spectra of the proposed diode in the forward and backward directions when the PC structure is excited from the left side. We note that the spectrum in the transmission is low where the amplitude is zero, then we excite the light from the bottom side. The transmission spectra determined at the left side of the wave increases to 0.68 at normalized frequency 0.32*a*/*λ*.

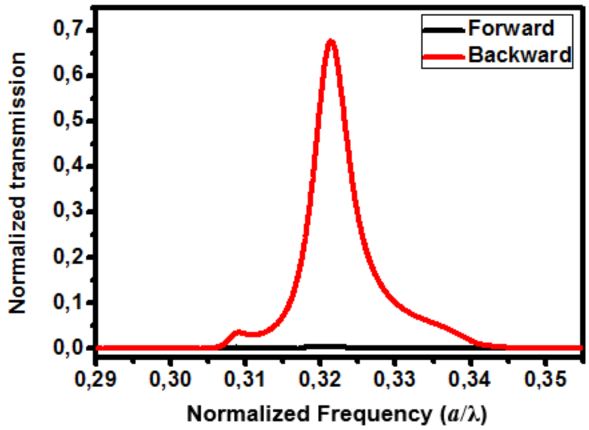

Fig. 4 Transmission of the light when the source is set at the left hand side: light propagates from left to the bottom (forward direction) and transmission of the light when the source is set at the bottom.

From figure 3(a), we notice that the electric field (TM mode) is trapped in the cavity region and the launched light centered at the frequency 0.32*a*/λ cannot reach the second waveguide. The cavity reflects the incident light since its left side behaves like a plane mirror. The relatively weaker refractive index of the cavity causes the symmetry of the trapped mode to be even and odd along the x and y axis respectively. This accounts for the phenomenon whereby the optical mode cannot reach the bottom side of the waveguide, resulting in zero transmission. In contrast, in the backward direction (shown in Fig. 3(b)) the incident light interacts with the curved side (at the 90 degree bend) of the cavity where the symmetry of the mode is even along *x*-axis. The TM mode then propagates in the left waveguide along the *x*-axis where the symmetry of the mode is maintained.

2.1 PC structure with elliptic defect.

The geometry of the introduced defect plays a central role in the coupling of optical modes inside the waveguide. After several iterations of 2D FDTD simulations, the parameters of the elliptic rods are optimized along axis as 0.74*a*. The long side is placed along the OX direction and the small axis is of 0.18*a* (refractive index is 2.23). These are optimized parameters that constitute the design of the proposed optical diode illustrated in Fig. 5. The concept of allowing light to propagate only along one direction and inhibiting for the opposite direction carries huge potential in the optical processing of information. To enhance the character of the light blocking, the structure of the proposed elliptical defect and unidirectional transmission of light is schematically shown in Fig. 6 (a) and (b) respectively. Initially, the light source is placed at the leftmost of the horizontal waveguide centered at the frequency $f = 0.334\ a/\lambda$. It can be observed in Fig. 6 (a) and (b) that as light travels from the left to the right, it radiates and scatters at the defects region, resulting in a very small transmission at the output (bottom of the waveguide). In the next step of our simulation, we proceed to place the light source at the bottom of side of the waveguide to investigate its propagation properties. The propagation profile is shown in Fig. 6 (b).

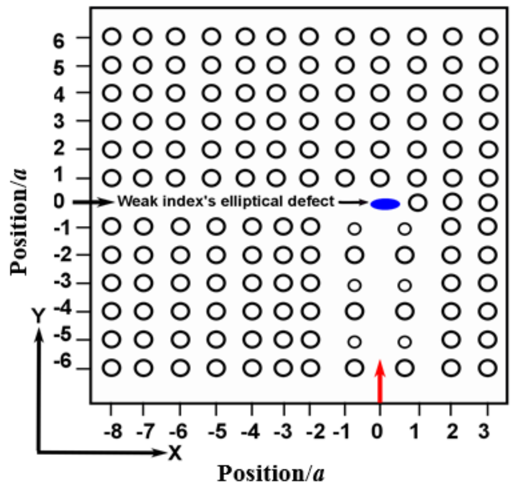

Fig. 5. Schematic geometry of the isolator structure formed by two waveguides and weak index's elliptical defect.

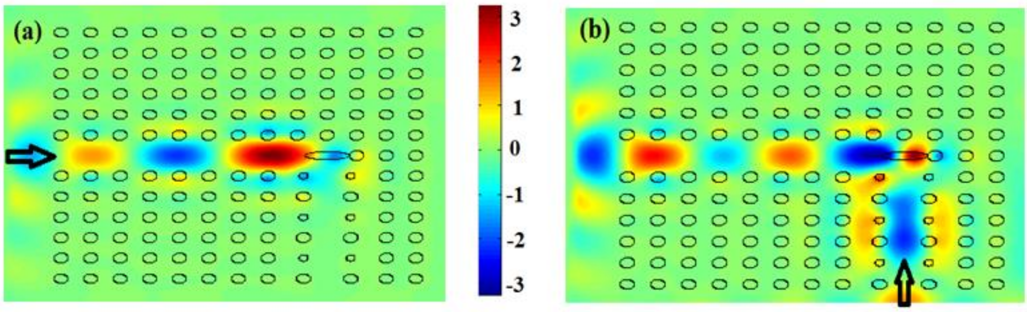

Fig. 6. Snapshot of the electric field (a) where the light is excited (launched) at the left side and the light propagates from the left to the output along the waveguide bend, (b) the light is excited (launched) from the bottom (output) of the waveguide, the light propagates towards the left.

A validation of these results is shown in Fig. 7 which shows the transmission in forward and backward directions. We notice that the forward transmission is very weak and is as small as 0.03. In contrast, the backward propagation shows a transmission of about 0.82, which is twenty five times higher than that in the backward direction. The peak of the transmission is located at the operating frequency 0.334 a/λ. Consequently, this result confirms the coupling between the modes of two guides and a weak index's elliptical defect. Thus the proposed structure acts as an all-optical diode.

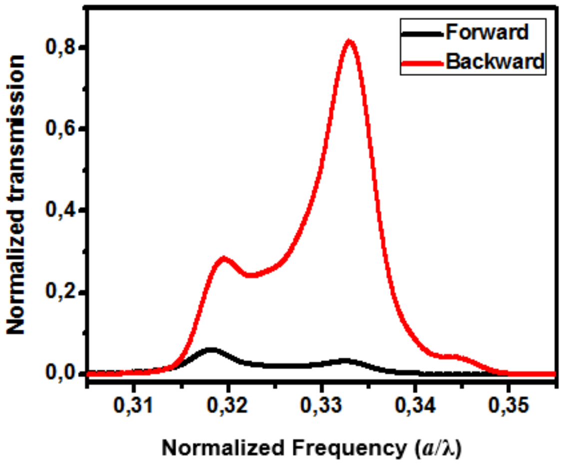

Fig. 7. Transmission of backward light to that of forward light as a function of the length of the nonreciprocal waveguide.

Next, in order to study the effect of the geometry on the unidirectionality of the light, we substitute the D- defect with an elliptic one with the same refractive index. When the light is launched with a frequency of 0.334*a*/λ from the bottom of the waveguide (backward direction), it is able to propagate along the elliptic defect (the cavity) and reach the second waveguide. In order to confirm that, we calculated the transmission spectra, which is displayed in Fig. 7. The peak of transimittivity is about 80% since the mode symmetry is even along the *x*-axis, which is the axis of the waveguide. Compared to the D-defect, the transmission in the backward direction is increased because the shape of the ellipse enhances the propagation along its grand axis.

3. Structure with rectangular rods

This structure is composed of silicon rectangular holes immersed in air background. We use the same scenario, a half circle of a radius 0.5*a* (refractive index is 2.23) used as a cavity is introduced at the defect region. The schematic of the structure is illustrated in Fig. 8. The simulated results using 2D FDTD is reported in Fig. 9. As can be seen, the resonant frequency of the cavity is *f*= 0.275 a/λ, the snapshots of the electric fields are also shown in Fig. 9(a) and Fig. 9(b). It is clear that in figure 9(a) the light is blocked at the defect region where it interacts with the cavity and the transmission in forward direction (from left to right) is about 0.1. However, Fig. 9 (b) shows the light propagates in the backward direction (from right to the left) and the transmission is about 0.68.

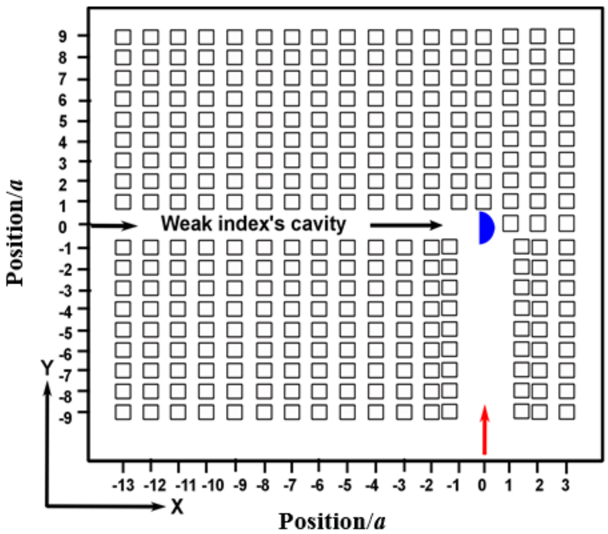

Fig. 8. Schematic geometry of the isolator structure formed by rectangular rods and two waveguide incorporating weak index's defect.

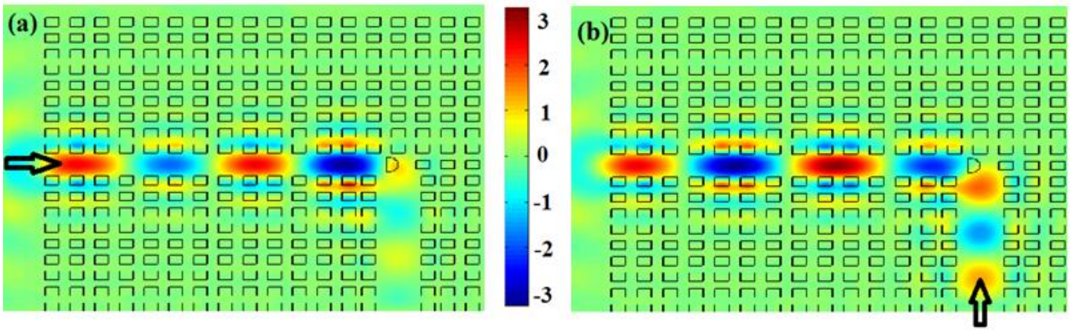

Fig. 9. Snapshot of the electric field for both propagations (a) forward and (b) backward.

Figure 10 shows obtained results of two spectra of two-way transmission where the amplitude of the normalized transmission in forward direction exceeds 0.1, which is a very low transmission. On the other hand a high amplitude of around 0.68 centered at the frequency 0.275 a/λ is achieved for the backward light propagation.

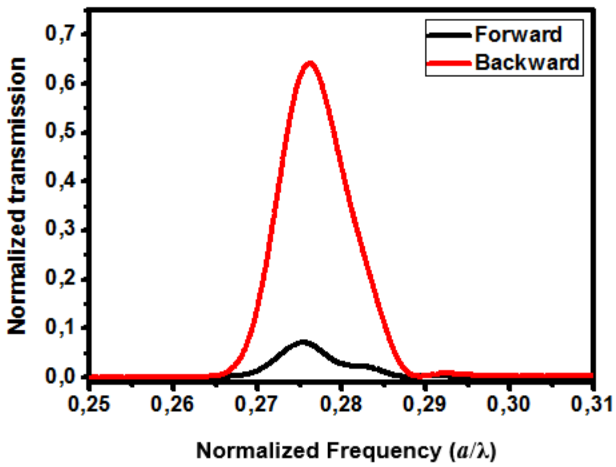

Fig. 10. Light transmission of backward light to that of forward light.

As reported in Fig. 10, the obtained transmission spectra exhibits two peaks, one dominant, which corresponds to the backward propagation, and the other weak one is related to the forward direction. The proposed design may present limitations in optical signal processing as the incorporated cavity presents absorptions at optical frequency. The cavity, however can provide a solution when the loosed optical signal (back reflected light) can be used to modulate the gain of the cavity where it prevents the coupling between the forward and backward optical signals. Therefore, with this proposed isolator we managed to decrease the loss in forward direction and increase it in the backward direction. This design may provide a solution to obtain the unidirectional light propagation and has both the ablities of unidirectional light propagations.

Conclusion:

In this paper, we demonstrate a study of nonreciprocal propagation of the light in a 2D PC device using in-house FDTD method. We have proposed and demonstrated a unidirectional light in a proposed device which behaves as an optical diode. The proposed compact optical diode is based on 2D PC waveguides with introduced single defects in low index which is based on the mode match and mismatch between the defects and the adjacent waveguides, where the unidirectional light propagation at an optimized selected frequency is obtained. We demonstrate that by carefully selecting appropriate defects, the unidirectional propagation of the light can be obtained; thus an all-optical diode is designed. The proposed design may play an important role in inter-connection of various photonic integrated devices in compact optical chip-to-chip platforms.

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