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Effect of the elliptic rods orientations on the asymmetric light transmission in photonic crystals

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ABSTRACT

In this work, we report a novel design of a photonic crystal utilizing elliptic rods. The two-dimensional (2D) photonic crystal consists of an asymmetric distribution of unit cells to ensure the one-way transmission of light. Analysis performed indicated that the orientation of the ellipse along the major and minor axis has an influence on the shift of the transmission. In particular, this results in shift of the transmission towards high frequencies and subsequent oscillation of its magnitude. The peak of the transmission band was also found to be strongly influenced by the orientation angle, θ. It has been demonstrated that the strong asymmetric propagation properties of the proposed photonic crystal structure enables the switching of incident light from one direction to another. The proposed structure may be applied as a building block to integrated photonics applications.

1. Introduction

Photonic crystals (PCs) have been extensively studied during the past two decades. This is due to the fact that these PC structures have potential applications in photonic and optoelectronic devices. This has been possible due to their remarkable properties such as existence of photonic band gap and ability to form inhomogeneous structures with periodic array of different materials [1–3]. Several optical devices based on PC structures such as waveguides [4], resonators [5,6], and channel drop filters [7] have been proposed by several research groups and industries. The electronic diode has become an indispensable electronic component due to its unique ability to ensure unidirectional propagation of electrical current and has formed the basis of several advanced electronic technologies. The optical diode, which is the optical equivalent of the electronic diode, has attracted considerable attention due to its potential applications in optical computing and information processing applications. The design flexibility of photonic crystals which permit asymmetric light propagation makes realization of optical diodes feasible [8–10]. These optical structures are usually nonreciprocal devices, which offer unidirectional transmission of optical signals by means of different forward and backward transmission properties. There have been several approaches to achieving unidirectional propagation of light in photonic structures. There have been reports of earlier approaches employing time-reversal and spatial-inversion symmetry breaking. In addition, various schemes have been proposed to design all-optical diode in nonlinear and magnetic PCs with broken time reversal symmetry [11–13]. However, practical applications of these approaches are limited for silicon photonics due to their incompatibility with conventional complementary metal-oxide semiconductor (CMOS) light generation, modulation, processing and detection technologies and platforms [14]. Optical structures based on asymmetric propagation have the advantage a compact configuration, which make them compatible with existing integrated photonics technologies and devices [15–17]. There have been reports of several attempts at achieving asymmetric light propagation using photonic crystals without anisotropic materials. Recently, Wang et al. proposed a photonic crystal heterojunction diode [18] made of two kinds of square- lattice photonic crystals with different radii of dielectric rods. In addition, manipulation of light propagation direction by assigning asymmetric dielectric corrugations (gratings) are presented in Ref. [19]. However Kurt et al. [20] have presented a new approach to achieve asymmetric light propagation via graded photonic crystal waveguides. This was made possible due to the band gap structure of chirped photonic crystal waveguides. In the proposed structure, to better confine and reduce the scattered light, we introduce reflectors between the elliptic arrays that act mostly like mirrors. The orientation of the elliptic rods plays a fundamental role in the amount of light collected at the outport.

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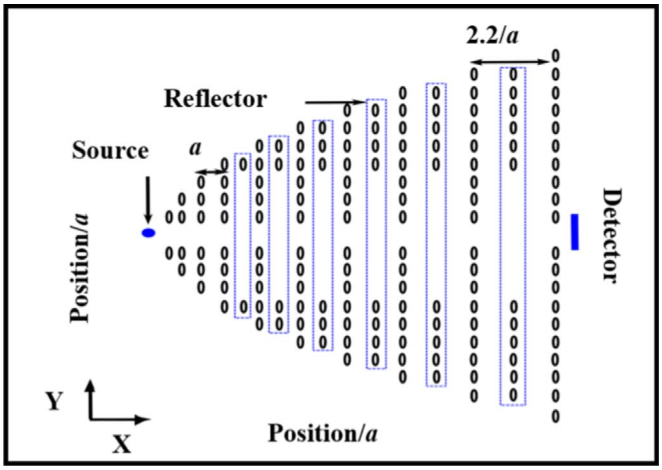

Fig. 1. The proposed PC structure indicating.

2. Unidirectional light transmission through triangular photonic crystal with elliptical scatterers

The aim of this work is to design a photonic crystal structure through which electromagnetic fields can be controlled and manipulated to propagate in forward and backward direction. The proposed structure consist of a 2D PC square-lattice of elliptic silicon rods embedded in air background, whose refractive index is set to n=3.45, the major axis of the ellipse is 0.31a, while the minor axis is fixed to 0.22a, where a is the lattice constant of the structure.

In-house finite-difference time domain method (FDTD) [21–25] is employed to analyse the transmission and the light distributions in the proposed structures. In this study, TM-polarized incident light beams are considered, where the electric field is along the central axis of the rods. We excite the structure using a broad Gaussian source, which is located on the left side, whereas the detector is placed on the right side in order to measure the transmission of the light at the output port. In the opposite excitation, the point source is located at the right side of the structure and the detector is positioned at the left side. The gaussian source is centred at f=0.30a/λ. The proposed structure based on the above two-dimensional square-rod PC, is presented in Fig. 1. It can be seen from the figure that one row of the square silicon rods along the OX direction is removed in order to create a waveguide, and the distance between the first and the second columns is fixed at 0.6a, for the rest of the structure, however this distance is gradually increased according to the following equation d =0.6a+Δx where Δx=0.2a and over all the structure 0.6a≤d≤2.2a. In order to control losses of the scattered light, a reflector between two successive columns is introduced as shown in Fig. 1. The resonant light travels and kept confined along the x-axis direction due to the effect of the introduced the adjacent mirrors. Unidirectional light is based on the directional bandgap difference of two square-lattice photonics crystals break of the spatial inversion symmetry. It is thus the different choice of light path that leads to the difference between the forward and backward transmission.

This perturbation of geometry allows us to achieve the asymmetric propagation of light as described earlier in this paper. In order to obtain the maximal response, one of the ellipse axes is fixed to 0.22a and the other axis set to 0.31a. The transmission spectra and the distribution of fields are calculated for this specific geometry. The spatial field distributions are calculated to verify the light propagation characteristics through the above structure at 0.3a/λ frequency and the corresponding results are shown in Fig. 2a and b respectively.

In Fig. 2a, the light source is positioned on the left side of the structure. The emitted light, which is guided along the center of the structure is spread and seems to be scattered without reaching the output section.

On the other end of the structure, there is a large shifting in the columns of square silicon rods. This proposed geometry shows that the light travels between the columns and not following the principal axis of the waveguide. Hence, the light will be blocked in the same direction as the direction of the forward propagation.

Also, at the output section, the distance between rods is increased and larger than that of their counterpart at the input section. As the light propagates from the left to the right by reaching this part of the structure, the flow of light propagates along the larger space between rods and therefore, deviates from the principal axis of the photonic crystal. Thus the light is blocked in this direction.

On the contrary, Fig. 2b deals with backward propagation: the light source is positioned on the right side of the structure, the light emitted is widely spread in the beginning until it reaches the center of the structure. Thus, the short distance between the rods are leading waveguide to follow the principle axis.

The characteristics of the asymetric propagation of the light is confirmed by the transmission spectra in Fig. 3. It shows that there is a small peak in the forward propagation, a peak that does not exceed 10%, but in the backward propagation, the transmission becomes significantly high, reaching 80%. This peak is centered around the excitation fréquency, which means that we have reached the right value of frequency to find the transmission in this direction. The highest transmission efficiency is observed at 0.3a/λ frequency.

Numerical analysis have shown that the dependence of the transmission spectrum of the side of light entrance is due to scattering losses in the structure, and we have succeed in finding the characteristics of the asymetric device based on unidirectional light propagation phenomena.

The unidirectional propagation of the light is strongly depending on the geometry of the structure. The propagation characteristics of the light are different for both directions due to the break in the periodicity of the PC structure. Due to the introduced reflectors, the light will be reflected and remains confine between the columns where it is unable to scatter and get loosed. The light propagates and reaches the output section where the maximum of transmission is about 0.88. In contrast, in the structure reported by Kurt et al. [20], the light is lost between the columns and a small amount of it can be collected at the outport.

3. The effect of the orientation of the ellipses on the transmission of light

In order to investigate the effects of the orientation of the elliptical rods on the proposed asymetric optical device characteristics, we modified the PC structure as shown in Fig. 4, the large axis of the ellipse is now increased to 0.32a, while the small axis is not modified.

The field distribution in the modified PC is calculated and reported in Fig. 5a for an excitation frequency of 0.32a/λ. This figure shows that the light propagates along the middle of the structure and does not escape beyond the middle of the structure. This result may significantly reduce the complexity of practical realization since the design is dependent on only the orientation of the elliptical rods. In addition, strong light isolation confirmed by the transmission spectra can be evidently seen in Fig. 5a. Numerical results have shown that weak amplitude that does not exceed 3% is achieved.

Fig. 5b illustrates the scenario of backward propagation where the light travels following the same path as the one in Fig. 2b, not only with a higher transmission, reaching 88%, but also centred around the excitation frequency of 0.325a/λ.

Fig. 6a illustrates the one-way propagation of the proposed structure where the transmission spectrum is numerically investigated. Figure shows that the spectrum has a dominant peak located at 0.325a/λ. It can also be seen that the amplitude exceeds 88% in the backward direction, while it drops to 5% in forward direction.

To have an insight look at the orientation angle effects on the