Effect of the Elliptic Rods Orientations on the Asymmetric Light Transmission in Photonic Crystals

A. Soltani[1], F. Ouerghi[1], F. AbdelMalek[1], S. Haxha[2], H. Ademgil[3], and E.K. Akowuah[4]

[1]Advanced Materials and Quantum Phenomena Laboratory, Faculty of Sciences of Tunis, El-Manar University, 2092 Tunis, Tunisia.

[3]Department of Computer Engineering, European University of Lefke, Mersin 10, Turkey, Tel: +90 392 660 2000 Fax: +90 392 727 75 28.

[4]Department of Computer Eng., Kwame Nkrumah University of Science and Technology, Ghana

*[2]Department of Computer Science and Technologies, University of Bedfordshire, University Square, Luton, Bedfordshire, LU1 3JU, United Kingdom, *Shyqyri.Haxha@rhul.ac.uk*

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.

Keywords: Unidirectional light, two-dimensional square photonic crystal, Asymmetric distribution, FDTD method.

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.

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 backround, whose refractive index is set to n=3.45, the major axis of the ellipse is 0.31*a*, while the minor axis is fixed to 0.22*a*, 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 ath 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 centered at $f = 0.30a/\lambda$. The proposed structure based on the above two-dimentional 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 columnes is fixed at 0.6*a*, for the rest of the structure, however this distance is gradually increased according to the following equation $d = 0.6a + \Delta x$ where $\Delta x = 0.2a$ and over all the structure $0.6a \leq d \leq 2.2a$. In order to control losses of the scatred 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.

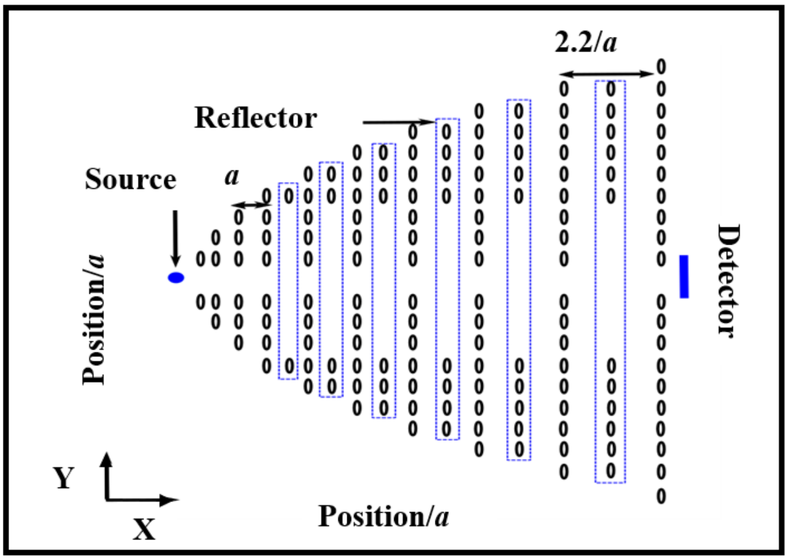


Fig. 1. The proposed PC structure indicating

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 0.22*a* and the other axis set to 0.31*a*. 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 $0.3a/\lambda$ frequency and the corresponding results are shown in Fig. 2a and 2b 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 spreaded 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 conterpart 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 therfore, deviates from the principal axis of the photnic 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 srutcture, 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.

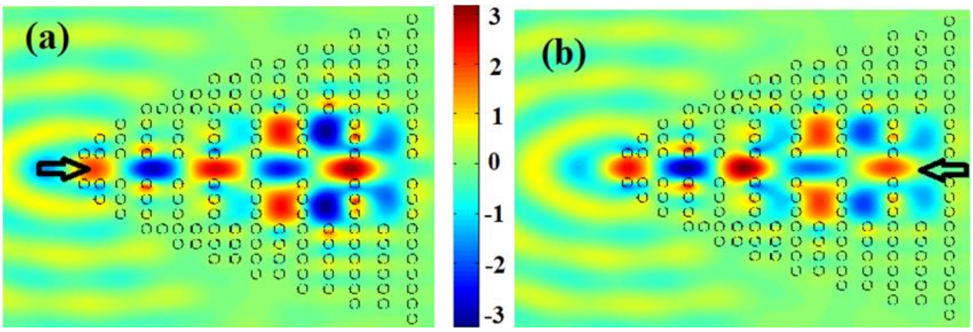


Fig 2. Time domain snapshots of light propagations for two different incidence directions, (a) forward propagation and (b) backward propagation.

The characterstics 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 doesn't exceed 10%, but in the backward propagation, the transmssion becomes significantly high, reaching 80%. This peak is centerd 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 0.3*a*/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 succed in finding the characteristics of the asymetric device based on unidirectional light propagation phenomena.

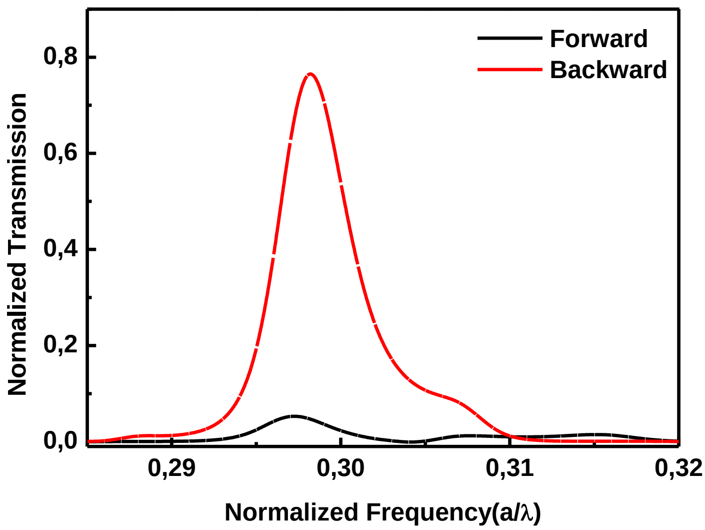


Fig 3. Normalized transmission for forward and backward propagation

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 orrientation 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 realisation 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.

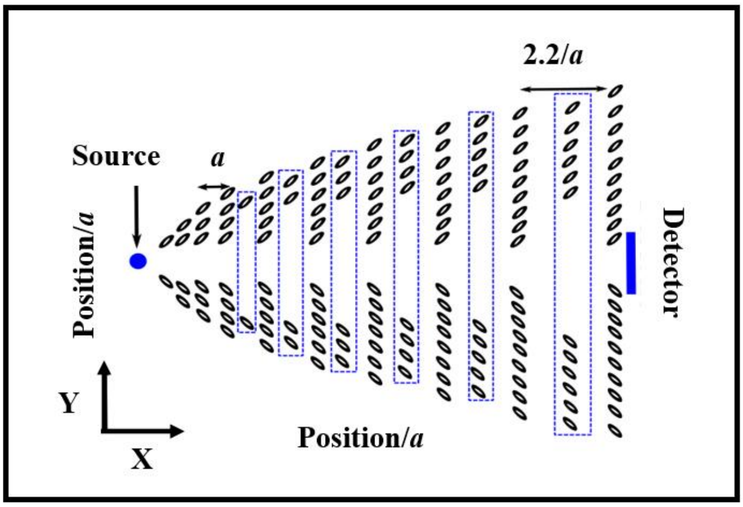


Fig 4. Triangular photonic crystal structure formed by oriented elliptical rods

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 centered around the excitation frequency of 0.325*a*/λ.

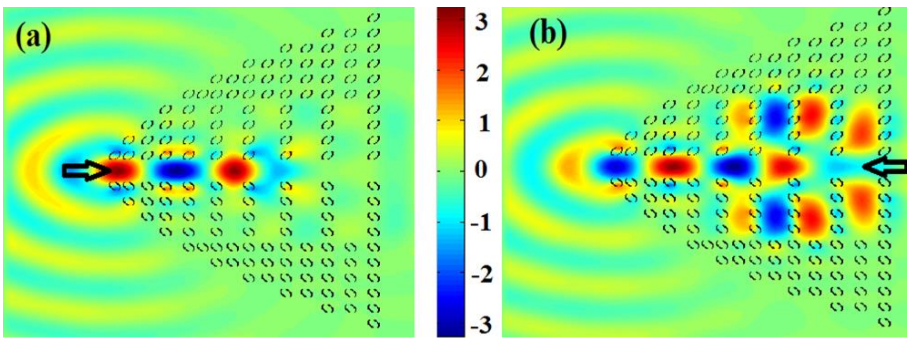


Fig 5. Distributions of electric at the frequency 0.325*a*/λ for input wave launched: (a) from forward and (b) from backward.

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 0.325*a*/λ. It can also be seen that the amplitude exceeds 88% in the backward direction, while it drops to 5% in forward direction.

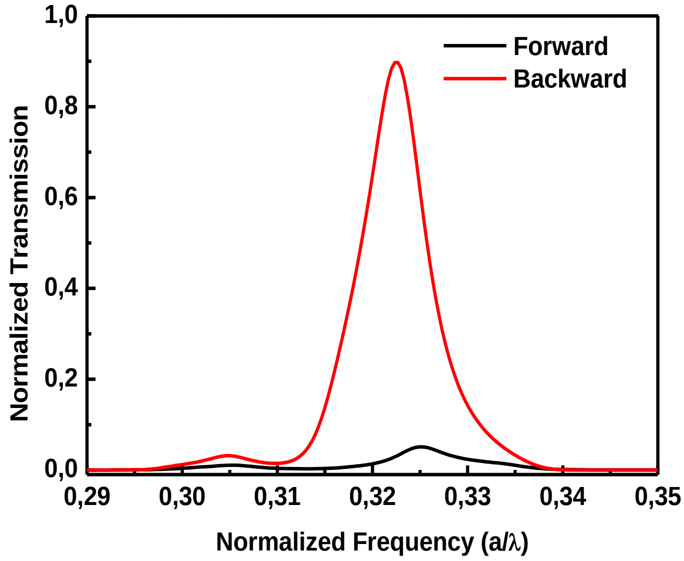
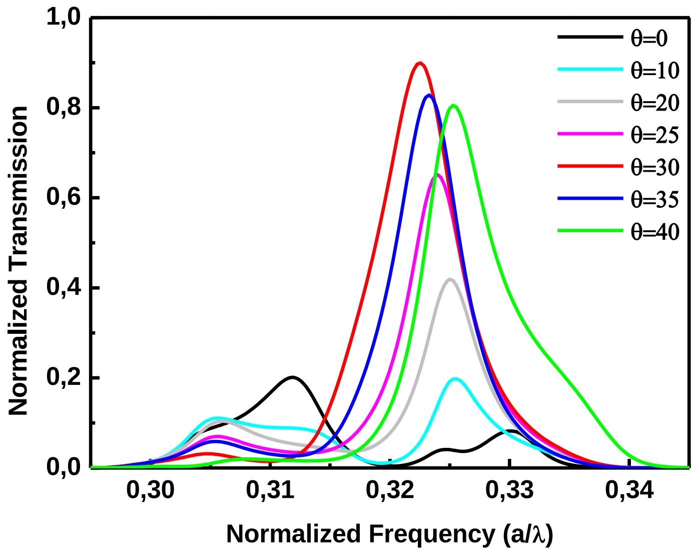
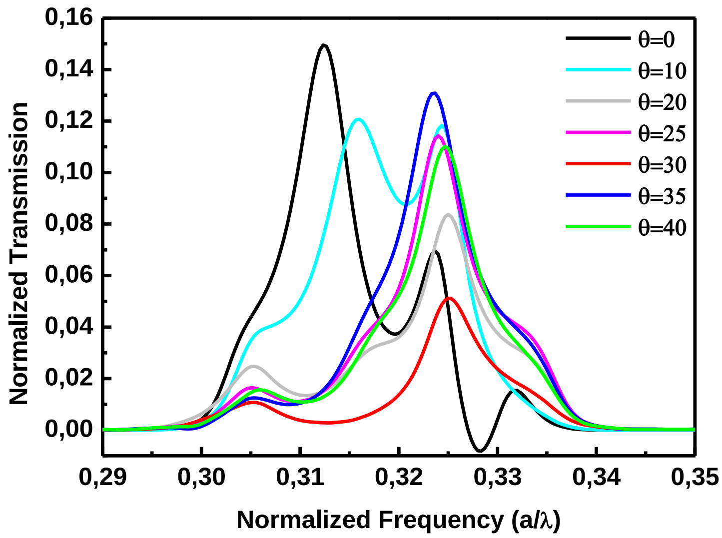


Fig. 6a. Normalized transmission for forward and backward propagation when θ =30° Backward transmission obtained at various orientations angle values, θ.

To have an insight look at the orientation angle effects on the transmission performances of the structure, the excitation frequency is fixed at 0.325*a*/λ and the ellipse orientation should be fixed at an angle that provides a maximum of transmission. In order to accurately identify the optimum angle of ellipse orientation, we performed further simulations and added two curves in the transmission spectra for both directions when θ = 25° and θ=35°, shown in Fig. 6 b and Fig. 6c.



(b)



(c)

Fig. 6. Normalized transmission for forward and backward propagation obtained at various orientations angle values, θ (b) Forward transmission and (c) Backward transmission.

Fig. 6 shows that the transmission increases when θ varies in the interval [10°, 20°, 25°, 30°] whilst it decreases as the orientation angle moves away from this range. By comparing the simulation results reported in Fig. 6a and 6b, we notice that the efficient orientation of the ellipses is achieved when θ = 30°. The results reported in figures 6, show the amplitude varies as the orientation angle θ changes and the peak of transmission shifts towards the high frequency region as θ ranges in the interval [10°, 20°, 25°, 30°, 35°, 40°]. Also, it can be noted that when θ is 20°, 30° and 40° the spectra exhibit one dominant peak located at same frequency f= 0.325 a/λ.

Next, in order to investigate the oscillation behaviour shown in Fig. 6, we determine transmission spectrum of the PC for various angles θ. We start with analysing the curve for θ = 0°, the spectra has two peaks with one dominant positioned at f = 0.305a/λ. However, the small peak is centred at f = 0.325a/λ as shown in Fig. 6b. By increasing θ to 10°, we observe an oscillatory behaviour of these peaks where the dominant peak is now located at approximately f = 0.325a/λ, whilst the small one is shifted to f = 0.305a/λ. Hence, for θ=20° the spectra also has two peaks, the first is localized at f = 0.305 a/λ and an amplitude of 10%, the second peak is centred at f = 0.325 a/λ and an amplitude of 40%. However, the oscillatory behaviour is not found beyond the angle θ of value 20°.

It is apparent that the amplitude is strongly dependant on the orientation of the ellipse and the asymmetric transmission of the light is greatly enhanced at θ=30°. When the angle θ is increased to 40°, the transmission decreases and its peak shifts to f = 0.327a/λ.
Fig. 6c shows the calculated transmission spectrum in the forward propagation for the same values of angle θ used previously (Fig. 6b). According to simulation results, it can be observed that the oscillation behaviour is more accentuated. Thus, for θ = 0°, there are three peaks where the dominant of amplitude 15% is centred at the frequency f = 0.315 a/λ, the second amplitude of 7% located at f = 0.325 a/λ and the third centred at f = 0.332 a/λ with 1% amplitude. By increasing the value of θ to 10°, the transmission spectrum present two peaks symmetrically distributed with an amplitude around the value of 12%, positioned at f = 0.315 a/λ and 0.325 a/λ respectively. When the orientation of the elliptical rods changed to 20°, the two peaks previously observed (at θ = 10°) have a great influence on localized peaks. The first peak has a decrease (8%) in amplitude whilst the second amplitude shifts to the low frequency interval, centred at f = 0.305 a/λ with a transmission tending to zero. By modifying the value of θ to 30°, as shown in Fig. 6c, the first peak moves to f = 0.325 a/λ with an amplitude approximately 5%, while the second one located at the frequency of 0.305 a/λ and it's amplitude decrease to zero. The same phenomenon is also observed for the 40° angle, except for the first significant amplitude of 11%. These results clearly demonstrate that the rod shape has a great influence on the functionality of the PC device. The elliptical cell can induce a fine tuning of the resonant wavelength by changing the angle of the elliptical rods.

We proceed the same scenario as the backward case, the frequency is fixed and we vary the orientation angle the transmission is calculated and reported in Fig. 6c. It can be seen from the figure that the transmission flattens and remains constant.

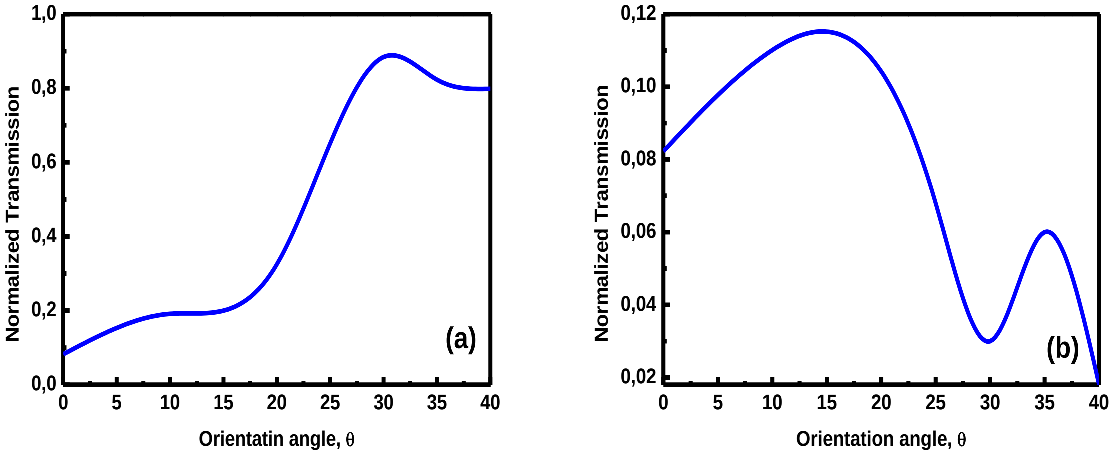


Fig.7. a) Transmission in the backward direction as a function of the orientation angle, θ when the excitation frequency is fixed at 0.325 *a*/λ. b) Transmission as a function of the orientation angle, θ when the excitation frequency is fixed at 0.305 *a*/λ.

In order to identify the angle that corresponds to the oscillation observed in the backward propagation, we fix the frequency at 0.325 a/λ shown in Fig. 7a and 0.305 a/λ reported in Fig. 7b, respectively, however the orientation of the ellipses, θ is varied. The transmission is calculated and reported in Fig. 7a and 7b, we notice that the maximum (0.88) is obtained for θ = 30°, however in Fig. 7b this value rapidly drops to its minimum (0.03).

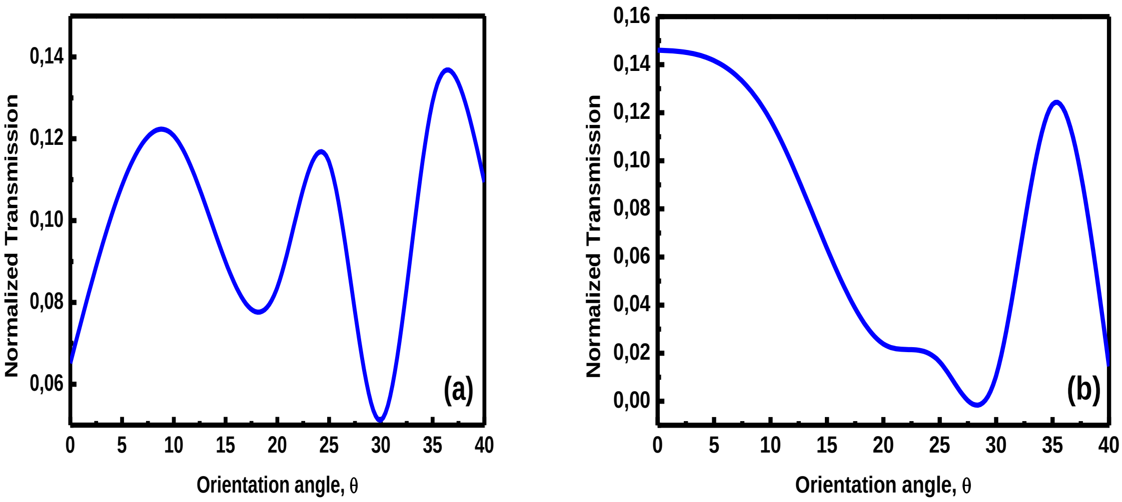


Fig. 8. a) Transmission in the forward direction as a function of the orientation angle, θ when the excitation frequency is fixed at 0.325 *a*/λ. b) Transmission as a function of the orientation angle, θ when the excitation frequency is fixed at 0.305 *a*/λ.

In the forward propagation, the transmission increases slightly when the angle varies from θ= 0° to θ = 20°. The transmission, however is constant when angle varies from θ= 30° to θ = 40° (Fig. 7a). The peak of the transmission is obtained when θ= 30° for an excitation frequency of

0.325 a/λ. However when the excitation frequency is 0.305 a/λ, the transmission drops to a minimum, one may notice that the modes oscillate between the two frequencies.

Fig. 8 shows the transmission in the forward direction for two excitation frequencies which are 0.325 a/λ and 0.305 a/λ. It is obvious that the transmission is minimum when the angle is 30° for both frequencies; these results confirmed the one-way propagation of the light. Comparing the obtained results in Fig. 7 and 8, we observe that the transmission oscillates between 0.88 and 0.03 and this happened when the ellipses are 30 ° oriented.

4. PC unidirectional device based on rectangular rods

Next, we study a structure with rectangular rods as shown in Fig. 9. The elleptic rods are substituted by rectangular rods, with the same refractive index and lattice constant. The dimension of the rods (the length is a, and the width is *a*/2) are optimized in order to have an asymmetric transmission. From this figure, using the same scenareo as adopted in studying the PC of elliptic rods, it is clear that the spectra of the diode exhibits a maximum of transmission in the wavelength range (0.31-0.32 a/λ). The propagation of the light is schematically shown in Fig. 10 (a, b). Due to the expected high field confinement in the material, the light may propagate through the device either from the left or from the right direction, thus the transmittivity depends on the incident light. It can be seen fron Fig. 11 that the transmitted light has a bandwidth of about 0.05 a/λ centred at 0.3125 a/λ for the backward incidence, and is almost reflected with a lower amplitude in the forward direction.

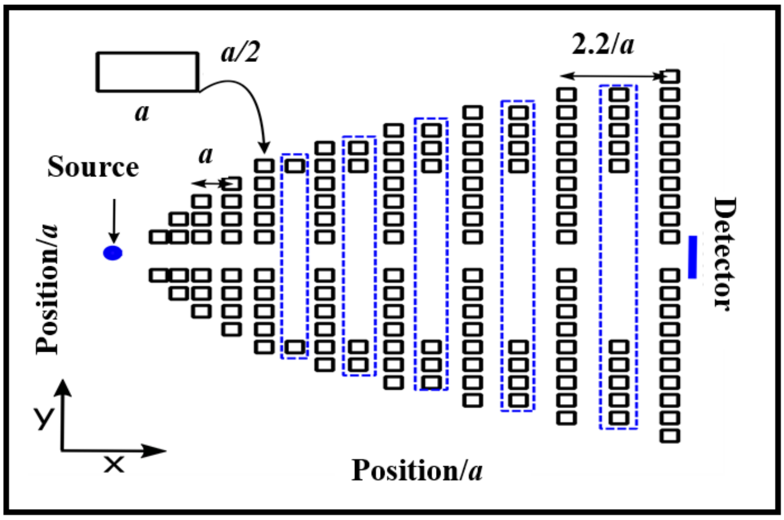


Fig 9. Triangular photonic crystal structure formed by rectangular rods.

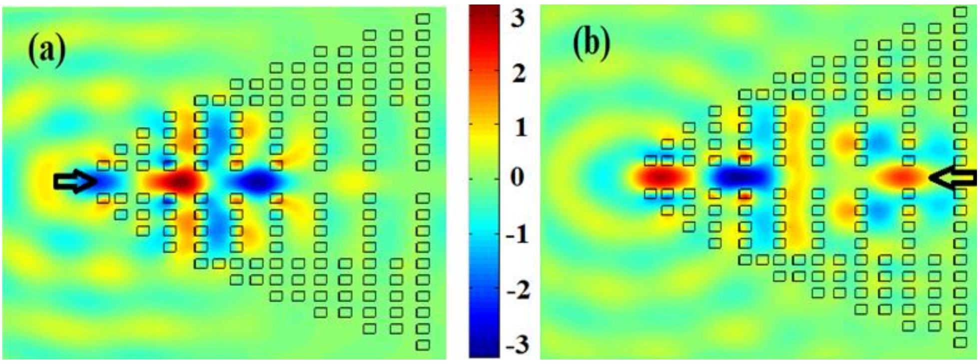


Fig 10. Time-domain snapshot of propagation of light from right to left, (b) snapshot of propagation of right left from to light.

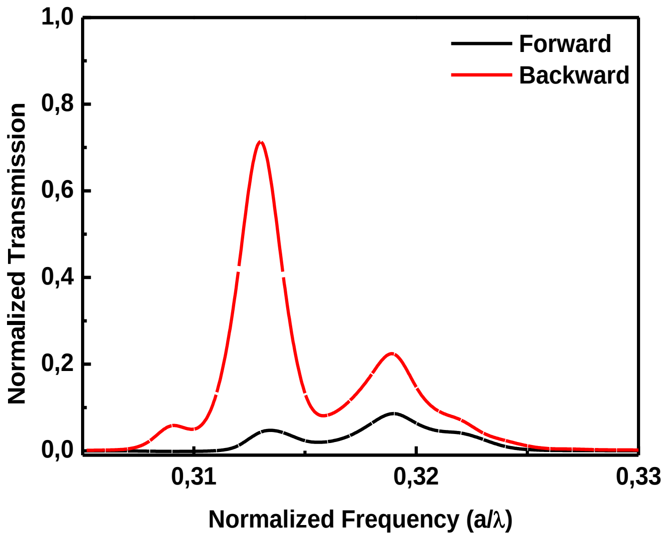


Fig 11**.** Normalized transmission for forward and backward propagation.

To achieve the asymmetric light propagation, the 2D PC plays a fundamental role, which is made by a modulation of the shape of the unit cell, and by breaking the translational symmetry of the lattice. The light is transmitted through the central waveguide by moving the rows and modifying the geometry of the unit cell as elliptical or rectangular rods rather than using periodic sequences of different materials. For an excitation from the left side the transmission is approximately zero. This is due to the fact that the mode mismatch lies in the waveguide with defects of periodicity of the structure since an optically controllable silicon PC is used. A high contrast ratio is obtained (between the forward and backward propagation) by designing the constitutive parameters of the PC and selecting the suitable light frequency. Depending on the orientation of the rods, we found that our results approximately depend on the shape and sample length. The control of the flow of the light is possible by introducing reflectors on the top and bottom sides of the structure and by studying the orientation effect of the elliptic rods. Furthermore the proposed design is comparatively easy to fabricate as compared to using a PC with different materials where the control of light is not easy.

Conclusion

An asymmetric transport of the light in a 2D silicon PC is demonstrated. It is shown that the shape of rods and the asymmetric distribution of the unit cells are necessary to achieve one-way propagation of the light. The topology of the elliptic rods specially, the orientation angle θ of the large axis has a tremendous affects on the transmission of the incoming light. In our proposed design, other structural parameters such as the number of rods, the distance between the rods and the length of the structure may have significant effects on the transport of the light. The optimization of these parameters opens the avenue for the design of optical devices such as optical isolator broadband antennae and optical diodes [26-28]. Our future work will be focused on analysing the performance of the proposed structures using our in-house 3D-FDTD method.

References

[1] O. Beckman, Inhibited Spontaneous Emission in Solid-State Physics and Electronics, Phys. Rev. Lett, 18, 773–775, 1967.

[2] S. John, Strong localization of photons in certain disordered dielectric superlattices, Phys. Rev. Lett. 58, 2486–2489, 1987.

[3] J.D. Joannopoulos, R.D. Meade, J.N. Winn, "*Photonic Crystals: Molding the Flow of Light*," Princeton, New Jersey, 1995.

[4] A. Mekis, J. Chen, I. Kurland, S. Fan, P. Villeneuve, J. Joannopoulos, High Transmission through Sharp Bends in Photonic Crystal Waveguides, Phys. Rev. Lett. 77, 3787–3790, 1996.

[5] S. Robinson, R. Nakkeeran, A Bandpass Filter based on 2D circular photonic crystal ring resonator, Seventh Int. Conf. Wirel. Opt. Commun. Networks, 2010.

[6] A. Melloni, A. Canciamilla, C. Ferrari, F. Morichetti, L. O'Faolain, T.F. Krauss, Tunable delay lines in silicon photonics: Coupled resonators and photonic crystals, a comparison, IEEE Photonics J. 2, 181–194, 2010.

[7] Z. Qiang, W. Zhou, R. a Soref, Optical add-drop filters based on photonic crystal ring resonators, Opt. Express. 15, 1823, 2007.

[8] C. Menzel, C. Helgert, C. Rockstuhl, E.B. Kley, A. Tünnermann, T. Pertsch, et al., Asymmetric transmission of linearly polarized light at optical metamaterials, Phys. Rev. Lett. 104, 1–4, 2010.

[9] S. Feng, Y. Wang, Unidirectional reciprocal wavelength filters based on the square-lattice photonic crystal structures with the rectangular defects., Opt. Express, 21, 1, 220-228, 2013.

[10] J. Xu, X. Zhuang, P. Guo, W. Huang, W. Hu, Q. Zhang, et al., Asymmetric light propagation in composition-graded semiconductor nanowires., Sci. Rep. 2, 820, 2012.

[11] J. Chen, Color separating with integrated photonic bandgap optical diodes: a numerical study, Opt. Express. 14, 10733–10739, 2006.

[12] Z. Wang, Y.D. Chong, J.D. Joannopoulos, M. Solja, Reflection-free one-way edge modes in a gyromagnetic photonic crystal, Phys. Rev. Lett. 100, 1–4, 2008.

[13] R.L. Espinola, T. Izuhara, M.-C. Tsai, R.M. Osgood, H. Dötsch, 05 Magneto-optical nonreciprocal phase shift in garnet/silicon-on-insulator waveguides., Opt. Lett. 29, 941–943, 2004.

[14] M. Levy, Nanomagnetic route to bias-magnet-free, on-chip Faraday rotators, Josa B. 22, 254–260, 2005.

[15] A.E. Serebryannikov, One-way diffraction effects in photonic crystal gratings made of isotropic materials. Condens. Matter Mater. Phys. 80, 1–13, 2009.

[16] A. Cicek, M.B. Yucel, O.A. Kaya, B. Ulug, Refraction-based photonic crystal diode.

Opt. Lett. 37, 2937–9, 2012.
[17] S. Feng, Unidirectional and bidirectional light beam splitting in photonic crystal with elliptical and circular scatterers, Solid State Commun. 217, 53–60, 2015.
[18] C. Wang, C.-Z. Zhou, Z.-Y. Li, On-chip optical diode based on silicon photonic crystal heterojunctions, Opt. Express. 19, 26948, 2011.
[19] L.-H. Wang, X.-L. Yang, X.-F. Meng, Y.-R. Wang, S.-X. Chen, Z. Huang, et al., Asymmetric light propagation based on semi-circular photonic crystals, Chinese Phys. B. 23 034215, 2014.
[20] H. Kurt, D. Yilmaz, a. E. Akosman, E. Ozbay, Asymmetric light propagation in chirped photonic crystal waveguides, Opt. Express. 20, 20635, 2012.
[21] J.P. Berenger, A perfectly matched layer for the absorption of electromagnetic waves, J. Comput. Phys. 114, 185–200, 1994.
[22] W.Aroua; F. AbdelMalek; S. Haxha; S. Tesfa, H. Bouchriha, Mode Converter Optical Isolator Based on Dual Negative Refraction Photonic Crystal, IEEE Journal of Quantum Electronics, 50, 8, 633 – 638, 2014.
[23] F. Ouerghi; F. AbdelMalek; S. Haxha; E. K. Akowuah; H. Ademgil, Design of Multicavities on Left-Handed Photonic-Crystal-Based Chemical Sensors, IEEE Journal of Lightwave Technology, 30, 20, 3288-3293, 2012.
[24] F. Ouerghi; F. AbdelMalek; S. Haxha; R. Abid; H. Mejatty; I. Dayoub, Nanophotonic Sensor Based on Photonic Crystal Structure Using Negative Refraction for Effective Light Coupling, 27, 15, 3269–3274, 2009.
[25] F. AbdelMalek, W. Belhadj, S. Haxha, H. Bouchriha, Realization of a high coupling efficiency by employing a concave lens based on two-dimensional photonic crystals with a negative refractive index, IEEE, Journal Lightwave Technol. 25, 3168–3174, 2007.
[26] W. Wei-jiang, Z. Jin-yun, X. Wan-neng, All-optical diode effect of a nonlinear photonic crystal with a defect. Opt. Lett, V. 2, No 3, 143-282, 2006.
[27] M. Levy, Nanomagnetic route to bias-magnet-free, on-chip Faraday rotators, J. Opt. Soc. Am. B 22, 254–260, 2005.
[28] A. V. Malyshev, J. Knoster, Frequency-controlled localization of optical signals in graded plasmonic chains, Nano letters 8 (8), 2369-2372, 2008.