Collimation Effect in Strongly Modulated Anisotropic Photonic Crystals with Near-Zero Refractive Indices

Saeid Jamilan* and Elena Semouchkina
Department of Electrical and Computer Engineering, Michigan Technological University, Houghton, MI, USA
*sjamilan@mtu.edu

Abstract: A strongly modulated photonic crystal with rectangular lattice was designed to realize the collimation effect for diverging waves entering the crystal at frequencies, providing near-zero refractive indices at unidirectional transmission. © 2020 The Author(s)

1. Introduction

Development of the media with near-zero refractive indices (NZRIs) has opened new opportunities for controlling electromagnetic wave propagation [1]. Such media could be employed for realizing various unusual effects including cloaking. Especially, effective control of wave processes is expected at anisotropy of NZRI media [2, 3]. Since natural materials could not possess with NZRI, creating such media requires employing metamaterials or photonic crystals (PhCs). In particular, all-dielectric media of such types were considered as the best choice, since they allowed for overcoming the loss problems. Following [4], we have operated in this work with 2D dielectric rod arrays, which demonstrated PhC-type responses. The MPB and COMSOL software packages were used to simulate the dispersion data, S21 transmission spectra, and wave-patterns. Rods had the permittivity of 37.2 and diameter of 6 mm and were considered to be infinitely long along z-axis. We fixed directional lattice constant a_x at 8 mm and changed a_y from 8 mm to 14 mm.

2. Unidirectional Transmission in Rod Arrays

The idea underlying the design of anisotropic NZRI media was based on the properties of dielectric rod arrays with rectangular lattices. We have found previously that such arrays could demonstrate significant differences in wave propagation along two orthogonal directions, defined by long and short sides of unit cells [5]. In this work, we detected that extending the lengths of unit cells at fixed width caused shifting of the dispersion diagrams, characterizing wave propagation in long side direction, to lower frequencies. At proper cell lengths, the 2nd stop-band for waves moving in this direction became observed at the frequencies, corresponding to the 2nd transmission-band in the orthogonal direction, thus introducing strong anisotropy in the array properties. Figure 1 shows the changes of array dispersion diagrams at transforming the original square lattices in rectangular ones and then increasing the cell lengths at keeping their widths fixed. As seen in the figure, the second branch of dispersion diagrams for the direction defined by the long sides of unit cells gradually becomes less steep, compared to its original shape and even acquires a negative slope at the cell length equal to 14 mm. As the result, transmission spectra (S21) of arrays shift along the frequency axis, so that the 2nd transmission band for the long side direction appears located at the frequencies, corresponding to the bandgap for wave propagation along the short sides of unit cells (see Figure 1 (d)). It means that the described lattice transformation makes the array demonstrating unidirectional transmission.

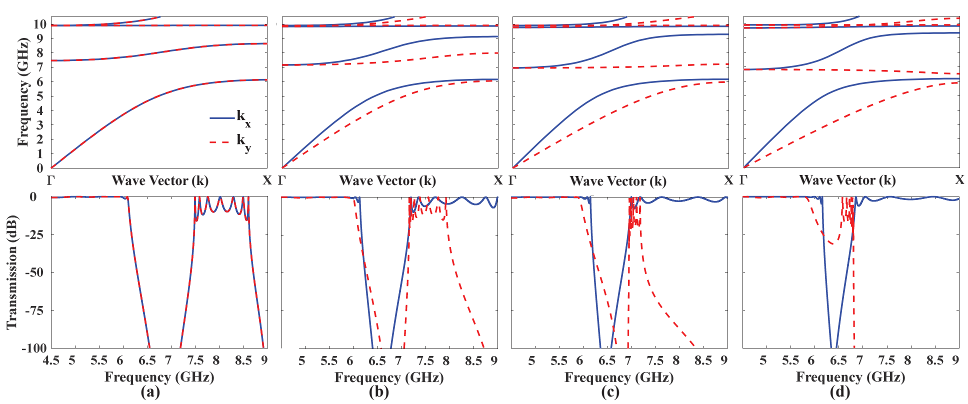

Fig. 1. Dispersion diagrams and transmission spectra for PhCs with unit cell width a_x = 8 mm and the lengths: (a) a_y = 8, (b) 10, (c) 12, and (d) 14 mm, when TM wave propagates in either x or y directions.

3. Performance of Anisotropic NZRI Medium

To realize anisotropic NZRI media, we intended to employ the specifics of rod arrays with square lattices, which demonstrated close to zero values of refractive indices near the lower frequency edges of 2nd transmission band [4]. Before employing these specifics, we had to ensure that the above property could be conserved at transforming the square lattices into rectangular ones with a_y approaching 14 mm. Figure 2 (a) shows the result of calculating the refraction index values for wave propagation along the short sides of unit cells, i.e. in x direction in arrays with a_y changing from 8 mm to 14 mm. It is seen in the figure that at increasing a_y, the range of frequencies providing NZRI becomes wider, so that at a_y = 14 mm, the index values remain less than 0.5 between 6.75 GHz and 7.0 GHz. It is worth noting that at these frequencies, propagation is fully suppressed along y-direction. Figures 2 (b) and (c) demonstrate the transformations of equi-frequency contours (EFCs) from elliptically shaped curves into flat ones at increasing a_y. Such flat EFCs are expected to cause strong collimation effects in PhCs. To illustrate the response of unidirectional NZRI media, we obtained wave patterns, presented in Figure 3. Fragments of dielectric rod arrays with square lattice ($a_x = a_y$ = 8 mm) and with two rectangular lattices (a_x = 8 mm and a_y equal to either 12 mm or 14 mm) were placed in front of the source of TM waves, which provided spreading of radiation around x-direction in free space. Comparison of Figures 3 (a), (b), (c), and (d) demonstrates that the media with rectangular lattices, providing unidirectional NZRI response (a_x = 8 mm and a_y = 14 mm), forms and guides x-directed electromagnetic beam, preventing it from becoming divergent, at the proper operating frequency of 6.85 GHz. Due to NZRI realization and superluminal wave propagation along x direction in Figure 3 (d), wavelength inside PhC media (λ_{PhC} = 130 mm) is much longer than the wavelength in free-space (λ_{air} = 43 mm), corresponding to the refractive index value of 0.3.

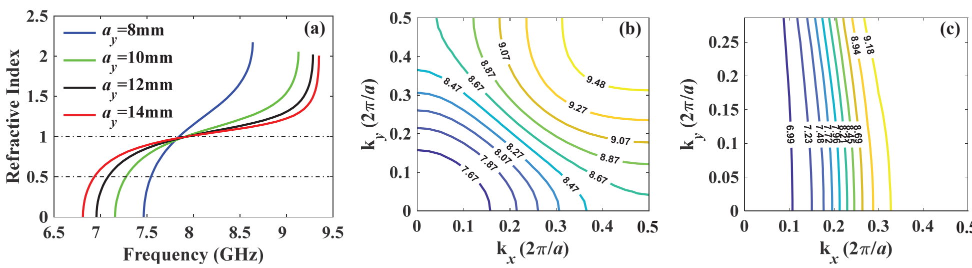

Fig. 2. (a) Frequency dependencies of refractive indices within 2nd transmission band for TM waves, propagating along x-axis in PhCs with unit cell width a_x = 8 mm and the lengths: a_y = 8, 10, 12, and 14 mm. EFCs of f_{GHz} (k_x, k_y) in irreducible Brillouin zone at a_y = (b) 8 and (c) 14 mm.

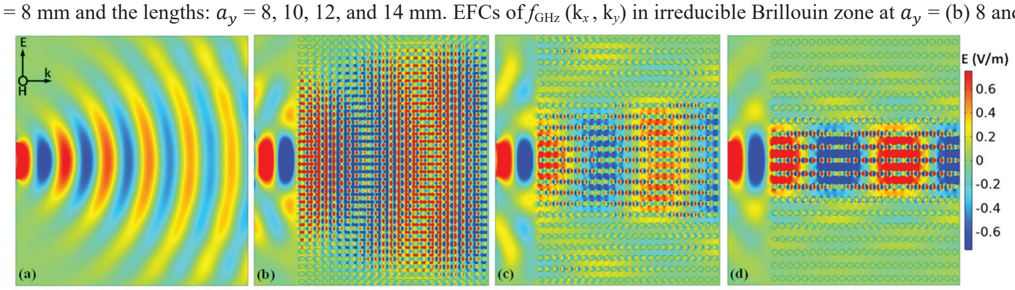

Fig. 3: Wave patterns for (a) radiation of wave source with TM polarization in free-space and in PhC media with a_x = 8 mm and a_y equal to: (b) 8, (c) 12, and (d) 14 mm. Frequency corresponded to the lower frequency edge of 2nd transmission bands for x-directed wave propagation.

Thus, the conducted work has shown an opportunity to design PhC-type media with NZRI properties, providing full transmission at wave incidence along one crystallographic directions and stop-band at wave incidence normally to this direction. Such types of PhCs, performing as anisotropic NZRI media, can offer collimating effects for wave sources used in microwave and photonic systems.

4. Acknowledgment

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5. References

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