A Road to Optical Cloaking Using Transformation Media Built from Photonic Crystals

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Abstract: The possibility of replacing metamaterials in transformation media by lossless dielectric photonic crystals is investigated. It is shown that such crystals are capable of both accelerating waves to superluminal phase velocities and bending wave paths around the objects thus providing initial wave front reconstruction beyond the objects. To realize transformation optics prescriptions for the cloak medium, we propose to use crystals with rectangular unit cells. We show that these crystals can provide prescribed anisotropy of directional indices along crystallographic directions.

Keywords: Invisibility cloak, metamaterials, transformation optics, photonic crystals

1. Introduction

The concepts of Transformation Optics (TO) [1] have opened up perspectives for the development of new photonic devices, including invisibility cloaks. Realizing these devices required transformation media with specific properties, such as the ability to transmit waves with superluminal phase velocities. First media with such properties were realized at microwave frequencies using metamaterials, however, scaling metamaterial cloaks to optical frequencies is complicated due to increased losses.

Perspectives of using photonic crystals (PhCs) in transformation media were first mentioned in [2], while approaches to implementing such media from PhCs composed of dielectric rods were proposed in our earlier work [3], where it was revealed that variation of rod permittivity could transform dispersion diagrams of PhCs in such manner that at the bottom of the second transmission band the values of refractive indices became close to zero, while at higher frequencies they grew up to values essentially exceeding 1. This finding pointed out at an opportunity of realizing wave propagation with superluminal phase velocities in PhC-based invisibility cloaks. The cylindrical cloak in [3] was designed by using dielectric rods arranged in PhCs with square lattices. The cloak medium was composed of concentrically placed circular fragments of PhCs with differenf lattice constants. Such arrangement allowed for obtaining requested by TO radial dispersion of the azimuthal index component defining wave propagation along circular arrays of rods in PhC fragments. In the cloak design described in [3], the dispersion of radial index components, which should define bending of wave paths around the hidden space, was not provided. Instead, the self-collimation of propagating waves in PhCs crystals was employed. The cloaking effect in the designed transformation medium was demonstrated. However, increased scattering observed at the boundaries between fragments of PhCs with different lattice constants did not allow for proper decreasing of the total scattering cross-width of the cloaked target compared to that of the bare target. In addition, fine tuning of self-collimation effect was found challenging because of significant distortions of periodicity at the boundaries of crystal fragments.

In this work, we show the possibilities to employ 2D PhCs with rectangular lattices of dilectric rods to solve the above listed problems and to advance employment of PhCs in transformation media.

2. Providing TO-Prescribed Dispersion of Index Components in PhC-Based Cylindrical Cloaks

The possibility to obtain different values of index components of PhCs in two orthogonal directions by using rectangular lattices was mentioned in [4, 5]. In this work, we explored an opportunity of using such index anisotropy in the cylindrical cloak medium to provide prescribed by TO different spatial dispersions of index components defining wave propagation in the azimuthal and radial directions, n_θ and n_r.

First, we had to investigate, whether changes of lattice constants in PhCs with rectangular lattices could be capable of covering the requested by TO index changes in two orthgonal directions. For this purpose, we calculated the dispersion diagrams for wave propagation in X and Y directions in PhCs with rectangular lattices and extracted values of directional index components by using the expression from [6]: $n_{\text{eff}} = \text{sgn}(v_g . k)(\frac{c}{\omega}|k|)$, where c is the speed of light in free space and $v_g = \dfrac{d\omega}{dk}$ is the group velocity, while k and ω are wave vector and angular frequency, respectively.

TO prescibes opposite changes of index values in radial and azimuthal directions within the cloak at increasing the distance from the hidden space. In fact, azumuthal index values are required to grow up from

0 to 1, while radial index values should drop down from values exceeding 1 in inner layers of the cloak to 1 near the outer cloak boundary. Fig. 1 presents extracted from the dispersion diagrams frequency dependencies of index components for X and Y directions in four PhCs with different lattice constants, the values of which were chosen to realize opposite changes of spatial dispertions for n_y and n_x at placing fragments of respective crystals along Y direction.

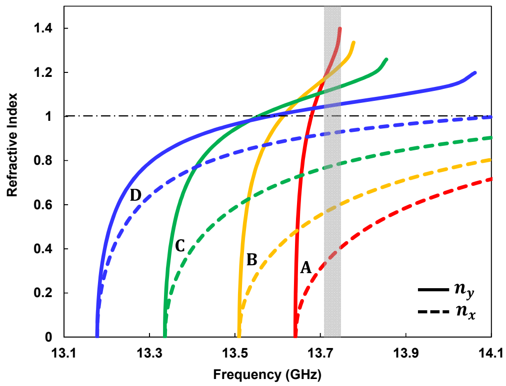

Fig. 1. Frequency dependencies of directional index values in the second transmission bands of four PhCs with rod parameters: ε = 35, R = 1.5 mm, and lattice constants a_x and a_y (in mm): A (5 ; 7.8), B (5.5 ; 8.15), C (6.5 ; 8.6), and D (8 ; 8.9).

The presented data show that increasing the lattice constants in PhCs leads to opposite changes of index values in X and Y directions. If X direction is considered as azimuthal direction and Y direction as radial direction, then cylindrical cloak, composed of properly bent crystal fragments, is expected to provide required spatial dispersions of index values in the cloak medium at properly chosen operating frequency such as, for example, 13.72 GHz in Fig. 1. It was found, however, that highest values of n_r, which could be achieved in PhCs with rectangular lattices, do not correspond to index values prescribed by TO. To overcome this discrepancy, we formulated reduced prescriptions for the spatial dispersion of n_r, with index values lower than those requested by TO near the hidden space and higher values in PhC fragments placed closer to the outer boundary of the cloak. Full-wave simulations of the performance of the cloak with thus reduced disperion performed by using COMSOL Multiphysics software package confirmed the possibility of obtaining TO predicted invisibility effects.

3. Solving the Problem of Increased Scattering

Employing relatively spacy fragments of PhCs in the cloak medium allowed for providing index values in the fragments, well corresponding to values extracted from the dispersion diagrams. However, a lot of distorted unit cells at the boundaries between fragments and impedance changes at these boundaries contributed to scattering from the cloak that did not allow for decreasing the total scattering cross-width far below that of the bare target. To solve these problems, we investigated the possibility to decrease radial dimensions of PhC fragments down to two cells or even one cell. The results of simulations of an example design of the cloak composed of 7 circular arrays representing 4 PhC fragments are presented in Fig. 2.

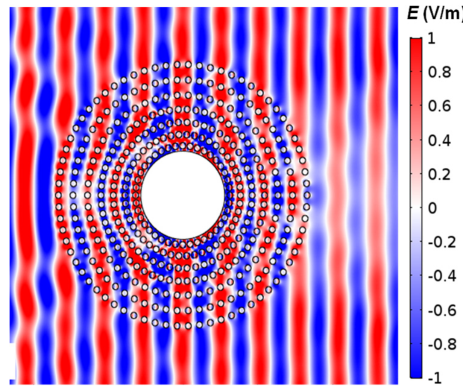

Fig. 2: Simulated snap-shot of e E-field at frequency of 11.5 GHz for TM wave incidence on composed of PhC fragments cloak coceiling metal cylinder (white circle).

As seen in the figure, backscattering from the cloak is very weak, and the cloak does not deteriorate restoration of initial (flat) wave front beyond the cloak, i.e. performs in correspondence with TO predictions. The obtained resuts open up a path towards creating invisibility cloaks for optical frequencies based on practically lossless dielectric PhCs.

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References

[1] J. B. Pendry, D. Schurig, and D. R. Smith. Controlling electromagnetic fields, *Science*, Vol. 312, Issue 5781, 2006, pp. 1780-1782, 2006.

[2] Y. A. Urzhumov and D. R. Smith. Transformation optics with photonic band gap media, *Physical Review Letters,* 105, 163901, 2010.

[3] E. Semouchkina, R. Duan, N. P. Gandji, S. Jamilan, G. B.Semouchkin, and R. Pandey, 'Superluminal media formed by photonic crystals for transformation optics-based invisibility cloaks,' *Journal of Optics*, 18, 044007, 2016.

[4] Y. Takayama and W. Klaus, 'Refractive behavior of 2D square lattice photonic crystals determined by reducing the symmetry of the unit cell,' *Japanese Journal of Applied Physics*, Vol. 41, Issue 11A, 2002, pp. 6375– 6379.

[5] L. Peng, L. Ran, and N. A. Mortensen, 'Achieving anisotropy in metamaterials made of dielectric cylindrical rods,' *Applied Physics Letters*, 96, 241108, 2010.

[6] P.V. Parimi, W.T. Lu, P. Vodo, J. Sokoloff, J. S. Derov, and S. Sridhar, 'Negative refraction and left-handed electromagnetism in microwave photonic crystals,' *Physical Review Letters*, Vol 92, Issue 12, p. 127401, March 2004.