

PROCEEDINGS OF SPIE

SPIDigitalLibrary.org/conference-proceedings-of-spie

Using self-collimated wave-guiding in invisibility cloaks

Jamilan, Saeid, Semouchkina, Elena

Saeid Jamilan, Elena Semouchkina, "Using self-collimated wave-guiding in invisibility cloaks," Proc. SPIE 11769, Metamaterials XIII, 117690K (18 April 2021); doi: 10.1117/12.2596457

SPIE.

Event: SPIE Optics + Optoelectronics, 2021, Online Only

Using self-collimated wave-guiding in invisibility cloaks

Saeid Jamilan^{*a}, Elena Semouchkina^a

^aDepartment of Electrical and Computer Engineering, Michigan Technological University,
Houghton, MI, USA, 49931

^{*}sjamilan@mtu.edu

ABSTRACT

We employ the known in photonic crystals phenomenon of self-collimation (SC) for modifying the performance of invisibility cloaks composed of dielectric rod arrays. Incorporation in the cloak design two circular sections, supporting SC, allows for refusing from Transformation Optics (TO) based prescriptions for the cloak medium, which request too challenging material parameters. In addition to SC sections, unidirectional cloak contains two TO-based transition sections with easily realizable parameters of rod arrays. These sections control wave paths between cloak input and output and SC sections. At plane wave incidence, the designed cloak was found to provide as restoration of initial flat wavefront behind the hidden object, so significant reduction of wave scattering by the object.

Keywords: invisibility cloaks, photonic crystals, dielectric rod arrays, self-collimation, transformation optics

1. INTRODUCTION

An ideal cylindrical invisibility cloak should guide incident waves around a hidden object without scattering and reflection. Transformation Optics (TO) prescribes the values of material parameter in the cloak medium suitable for such guiding [1]. However, realizing TO prescriptions is very challenging, since they request close to zero values of azimuthal index components and values of radial index components, far exceeding 1. Such values are necessary for providing superluminal phase velocities of waves along elongated paths around the target, on one hand, and for proper turning wave trajectories to support circular wave movement, on the other hand. While metamaterials have been conventionally considered as the best candidates for the cloak media, we have earlier shown that there are advantages of forming the transformation media from fragments of photonic crystals (PhCs) [2, 3]. However, it was also found that at building up the cloak of desired thickness from arrays of dielectric rods with rectangular lattices, it was not possible to realize in full all TO-prescribed values for radial components of refractive indices in the cloak medium. At the same time, it was revealed that in the cloaks, composed of concentric circular rod arrays, waves could be sent around the target using the phenomenon of self-collimation (SC) [3]. Realizing such SC effects requires turning crystallographic axes of PhC fragments that could be accomplished by gradually altering the orientation of unit cells [4]. In this work, we investigate the possibility to employ self-collimated wave-guiding, instead of using prescribed by TO high values of radial index components, at designing the cloak. The cloak was composed of rods with relative permittivity of 37.2 and radii of 3 mm for performing future experiments in microwave range. The design of the cloak can be re-scaled for optical range at using silicon nano-rods.

2. UNDERLYING CONCEPT, DESIGN, AND PERFORMANCE OF THE CLOAK

Figure 1 illustrates the concept of the cloak design. The wave paths controlled by SC are shown by two big arcs in the central areas of the cloak. These cloak parts were built up of rod array composed of identical unit cells with the same lattice parameters along azimuthal and radial directions. These lattice parameters had to provide the values of refractive index components equal to 1, i.e., corresponding to free space, at the cloak operation frequency. While lattice parameters were not varied on the wave paths within SC parts of the cloak, turning of wave paths was provided by SC. Orientation of unit cells, constituting SC regions, was changing from cell to cell, so that azimuthally directed sides of cells followed circular paths, while their radially directed sides were normal to them. Such reorientation of cells mimics bending of

crystallographic axes in PhC. In the SC parts of the developed cloak design, we used four parallel rows of unit cells, bent along circular paths. Identical lattice parameters of four arrays excluded impedance mismatch at the wave movement along arcs within SC regions. Two additional transition regions at the cloak input and output (see Figure 1) were designed using TO approaches. These regions had to transform, first, wave movement along straight path at the cloak input into circular movement within SC controlled areas and then, from circular movement into straight movement at the cloak output. Figure 2 presents the results of modelling wave propagation throughout the output region at the right end of SC controlled circular arc in the upper half of the cloak. At solving the transformation problem, we employed TO-based approaches used in [5].

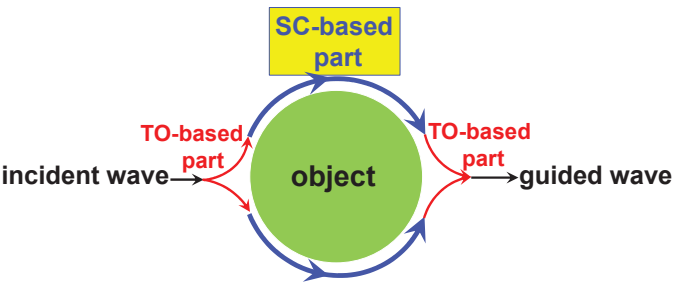


Figure 1. Cross-section of the schematic of wave flow through unidirectional cylindrical invisibility cloak, hiding cylindrical object. The cloak is employing self-collimated wave movement along circular paths between input and output.

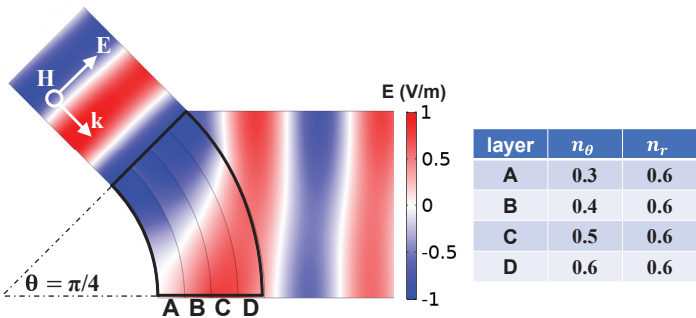


Figure 2. Schematic of wave pattern provided by TO-based transition section of the cloak medium at the end of upper arc-type self-collimated path. Transformation medium operates with waves passing along four arc-type layers (A, B, C, and D) and starts to modify the wave movement at the dashed-dotted line marking the upper edge of θ angle. Presented field-pattern is based on the solution obtained by using COMSOL Multiphysics software.

Chosen coordinate transformation was aimed at redirecting waves, propagating along four arc-type circular paths, into output straight paths. Redirection was equivalent to turning the wavefront counterclockwise by $\pi/4$ radian. This turning was provided due to radial dispersion of azimuthal index component in the medium of TO-based cloak section at fixed values of radial index components, controlling the four arc-type paths (as seen in the Table in Figure 2). TO-prescribed azimuthal index component had the lowest value for the path A and the highest value for the path D that caused increased phase velocity of wave moving near the lower edge of the transformation medium and much slower wave propagation along the path D. As seen in Figure 2, defined by the Table dispersion of azimuthal index component allowed for realizing the desired counterclockwise turning of wavefront within the transformation medium. On the left side of the cloak, we had to form the transformation medium, inverted relatively one presented above, to allow wave moving along straight path enter the region with four arc-type wave paths (from D to A). Thus, in the left transition section, the transformation medium had to provide turning of wavefront by 45 degrees to make it parallel to dashed-dotted line marking the upper edge of θ angle. The resulting wave flow, normal to this line, had to initiate SC-controlled wave flow in the upper part of the cloak.

Figure 3 (b) shows frequency dependencies of index components for rod arrays representing four layers (A, B, C, and D in Figure 2) of TO-based cloak parts. These layers should respond identically in radial direction at the operating

frequency of 7.5 GHz providing $n_r = 0.6$, while their indices in azimuthal direction should experience changes on the wave paths. At building the layers of arc-type transformation media, we oriented unit cells with their short sides along x direction and elongated sides along y direction that corresponded to azimuthal and radial directions, respectively, in the cloak medium. Thus, the curves in Figure 3 (b) were calculated for two orthogonal directions x and y , within the 2nd transmission bands of arrays. It is worth noting here that building TO-based parts of the cloak from rod arrays was performed at relying on the concept of graded index (GRIN) PhCs [6]. Respective fragments of four PhCs (A, B, C, and D) included single circular arrays.

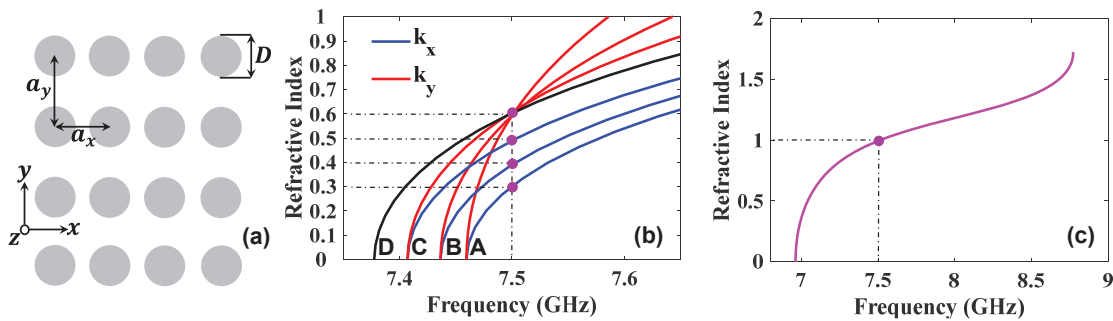


Figure 3. (a) Schematic of 2D rod array with rectangular lattice in xy cross-section (diameter and relative permittivity of rods: $D = 6$ mm and $\epsilon = 37.2$). (b) Frequency dependencies of orthogonal refractive index components for four rod arrays within their 2nd transmission bands under TM wave incidence, used in TO-based transition regions. Lattice constants (a_x and a_y) in four layers of transition regions are, respectively (in mm): A (7.32, 8.74), B (7.55, 8.62), C (7.84, 8.48), and D (8.24, 8.24). (c) Frequency dependence of refractive index (2nd band for TM wave) in rod array with square lattice: $a_x = a_y = 9.9$ mm used in SC-based region. MPB (MIT Photonic Bands) software was used for calculating the dispersion data of rod arrays [7].

Two arc-type wave paths in the central SC-based part of the cloak were formed by the rows of unit cells properly oriented to mimic bent arrays with square lattices. The responses of these arrays are represented by the frequency dependence of their index presented in Figure 3 (c). It is seen in the figure that arrays with square lattices provided at the operation frequency of 7.5 GHz the value of index equal to 1, i.e., the value characteristic for free space. In addition, to avoid index mismatch at the boundaries of SC-based parts and TO-based regions, we properly adjusted the refractive index values in neighboring unit cells. We used matching arrays (A', B', C', and D') between SC-parts and TO-sections (A, B, C, and D). Matching arrays had to provide median indices, given in the table in Figure 4, with respect to the index of SC-parts ($n = 1$) and indices of TO-part layers. Frequency dependencies of index components within 2nd transmission bands of four rod arrays with rectangular lattices A', B', C', and D' are plotted in Figure 4. Considering the operation frequency of 7.5 GHz, lattice parameters of these PhCs were properly chosen for realizing the desired matching arrays.

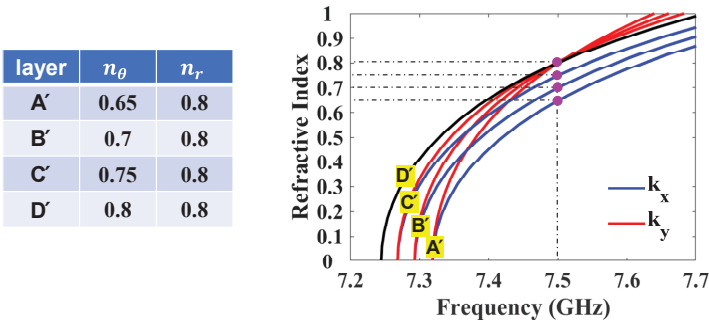


Figure 4. Frequency dependencies of orthogonal index components (2nd band for TM wave) in rod arrays for matching layers. Lattice constants (a_x and a_y) are, respectively (in mm): A (8.03, 8.81), B (8.22, 8.78), C (8.42, 8.74), and D (8.66, 8.66).

Complete cloak medium was formed using SC-parts, TO-based regions, and matching layers composed from identical dielectric rods. The diameter of cylindrical metal object was 100 mm, and a TM polarized plane wave was used for excitation. Figure 5 allows for comparing wave patterns, observed at wave scattering by the bare metal cylinder and by the cloaked cylinder. It is seen in the figure that at the operation frequency, the designed cloak demonstrates a very good restoration of the flat wavefront beyond the object. In Figure 6, calculated total scatterings cross-width (TSCW) curves show that the cloak is reducing scattering by 40%.

SC-based cloak has a relatively small thickness, so that $R_{\text{out}} / R_{\text{in}} = 1.79$, where R_{out} and R_{in} are, respectively, inner and outer radii of the cylindrical cloak medium. For a cloak that was designed fully using TO-prescribed material parameters by employing rectangular-lattice arrays of similar dielectric rods, this ratio was $R_{\text{out}} / R_{\text{in}} = 3$ [8]. In addition, newly designed SC-based cloak is operating under plane-wave illumination, while SC-based devices typically work with electromagnetic beams [9]. With described above characteristics, SC-based cylindrical cloak composed of dielectric rod arrays is a promising candidate for practical applications in microwave and optical ranges.

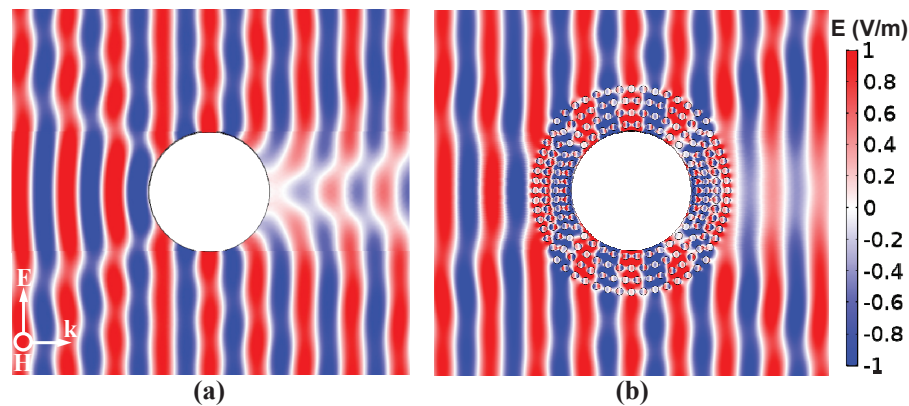


Figure 5. Simulated using COMSOL Multiphysics software wave patterns for wave passing (a) bare metal cylinder and (b) cloaked cylinder at the operation frequency (7.66 GHz).

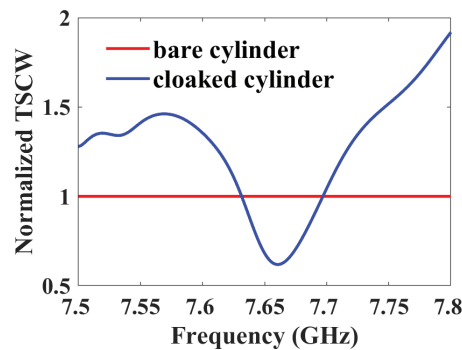


Figure 6. Total scatterings cross-widths (TSCWs) calculated for bare metal cylinder and for metal cylinder cloaked with SC-based cloak.

ACKNOWLEDGEMENT

This work was supported by the National Science Foundation (NSF) under Award No. ECCS-1709991. S. Jamilan would also like to thank graduate school of Michigan Technological University for awarding him a Finishing Fellowship for 2021 spring semester.

REFERENCES

- [1] Kundtz, N. B., Smith, D. R., and Pendry, J. B., "Electromagnetic design with transformation optics," *Proceedings of the IEEE* 99(10), 1622-1633 (2011).
- [2] Semouchkina, E., Duan, R., Gandji, N. P., Jamilan, S., Semouchkin, G., and Pandey, R., "Superluminal media formed by photonic crystals for transformation optics-based invisibility cloaks," *Journal of Optics* 18, 044007 (2016).
- [3] Jamilan, S., Semouchkin, G., Gandji, N. P., and Semouchkina, E., "Spatial dispersion of index components required for building invisibility cloak medium from photonic crystals," *Journal of Optics* 20, 045102 (2018).
- [4] Rumpf, R. C., Pazos, J., Garcia, C. R., Ochoa, L., and Wicker, R., "3D printed lattices with spatially variant self-collimation," *Progress In Electromagnetics Research* 139, 1-14 (2013).
- [5] Jiang, W. X., Cui, T. J., Zhou, X. Y., Yang, X. M., and Cheng, Q., "Arbitrary bending of electromagnetic waves using realizable inhomogeneous and anisotropic materials," *Physical Review E* 78, 066607 (2008).
- [6] Zhu, Q., Jin, L., and Fu, Y., "Graded index photonic crystals: a review," *Annalen der Physik (Berlin)* 527, 205-218 (2015).
- [7] Johnson, S. G., and Joannopoulos, J. D., "Block-iterative frequency-domain methods for Maxwell's equations in a planewave basis," *Optics Express* 8(3), 173-190 (2001).
- [8] Jamilan, S., Semouchkin, G., and Semouchkina, E., "Implementing photonic crystals, instead of metamaterials, in the media of transformation optics-based devices," 2018 IEEE Research and Applications of Photonics In Defense Conference (RAPID), Miramar Beach, FL, USA, 1-4 (2018).
- [9] Noori, M., Soroosh, M., Baghban, H., "Self-collimation in photonic crystals: applications and opportunities," *Annalen der Physik* 530, 1700049 (2018).