Three-dimensional Invisibility Cloaking Operates at Terahertz Frequencies

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Abstract

In this paper we aim to explore novel approach of using dielectric material with gradient index to manipulate terahertz (THz) waves. As an example, we demonstrated such gradient index material could enable invisibility in broadband THz frequencies, so called cloaking. Transformation optics technique was used to design the index distribution, which can bend electromagnetic wave and make it propagate in the desired manner. The scalable and parallel 3D lithography (microstereo-lithography) technique was employed in the cloak fabrication process and shows the strong capability and potential in fabricating THz metamaterial with complex structures. Finally the invisibility was characterized by reflection terahertz time-domain spectroscopy (THz-TDS).

1. Introduction

Terahertz (THz) wave, featured with the frequencies between 0.1-10 THz, has unique properties that offer it great potential in biomedical imaging, quality control and communication. THz wave can easily penetrate a range of materials like wood, plastic and ceramics without causing ionization in material. Compared to its neighbouring infrared and microwave regimes, extreme challenges exist to impede wide application of THz wave. THz regime has been proven very challenging to access due to the lack of electromagnetic materials with efficient response at THz frequencies, so that important elements widely used in infrared and microwave regimes, such as waveguides, lenses, and beamsplitters, are still hardly applicable to THz wave. The presence of metamaterial initiates new possibilities to extend the range of material properties at THz frequencies and improve the efficiency of electromagnetic devices. Metamateirals, depending on each sub-wavelength element with carefully tailed structure, can exhibit the unique macroscopic refractive index distribution that are impossible to achieve with natural materials and is considered as the simple and beneficial approach to manipulate electromagnetic waves [1]. Thereafter, applying transformation optics to metamaterial has become the general approach for designing novel electromagnetic devices. However, when performing coordinates transformation, complex material with anisotropy and magnetic response is usually generated, thus metal structure need to participate in, resulting in limited device functionalities with narrow band and high loss. By choosing appropriate transformation function, one can design the gradient index metamaterials made of dielectric that is nonmagnetic, inhomogeneous and isotropic [2].

More and more people are exploring the unique EM wave manipulation by gradient index metamaterials. As a representative example, carpet cloak can merge all scattering from the object and resume only one single reflection beam with the identical profile of reflection beam from a flat surface, thus making the object perceived as not even exist. Liu *et al.* demonstrated the carpet cloak at microwave frequencies by assembling a series of various I-shaped elements with gradient index [3]. Then similar strategies were performed at optical frequencies by tuning the index gradient via nanofabrication techniques [4-6]. In this paper, we present the process of design, fabrication and characterization of the THz carpet cloak made of dielectric with gradient index distribution. Based on this, such methodology may inspire many other THz wave manipulation devices by controlling refractive index, for example, beam shifter, beam bender, etc.

2. Cloak design and fabrication

The design strategy is based on the invariance of Maxwell's equations during coordinates transformation that suggests the medium with desired functionality can be made by directly performing coordinate transformation on the permittivity and permeability tensors. Thus, one can design the medium with specific properties in which the light trajectory is kept as the same as that in distorted space. For carpet cloak, the coordinates transform can map a given nonflat conducting surface to a flat surface [2]. In order to get the medium with a uniform dielectric profile with unit magnetic permeability, quasi-conformal mapping, which is generated by minimizing Modified-Liao's functional with slipping boundary condition, is chosen as a proper coordinate transform for grid generation. The index distribution of the cloak is found by computing the Jacobian matrix that relates the physical system (perturbed surface) and virtual system (flat surface) numerically. Fig. 1 shows the two-dimensional spatial refractive index distribution of the cloak in our particular design, with the TM polarized (magnetic field perpendicular to the bottom plane) THz wave. The minimum of refractive index occurs at the center of the inner cloak boundary while the maximum occurs on the inner cloak boundary adjacent to the perturbation. The refractive index values range from 1.018 to 2.624 with the background index of 1.47.

We fabricate the cloak using micro-stereolithography system by extruding the 2D design into 3D. In the fabrication, a high resolution optical image projected on the top surface of photocurable polymer resin (1,6 Hexanediol Diacrylate, HDDA) defines the shape of a solidified thin polymer layer. Using a dynamic mask (1400x1050 pixels), the projected optical image can be controlled electronically. Rapid fabrication of the 3D structure according to the designed geometry is accomplished in a layer-by-layer fashion. The cloaking device shown in Fig. 1(c) is fabricated using 220 layers with each layer 20 µm thick, for a total thickness of 4.4 mm. Sub-wavelength holes of varying dimension in a square unit cell are used to obtain the desired permittivity profile under the effective media approximation. The gray-scale of individual pixel can be adjusted so the holes can be fabricated with sub-pixel precision.

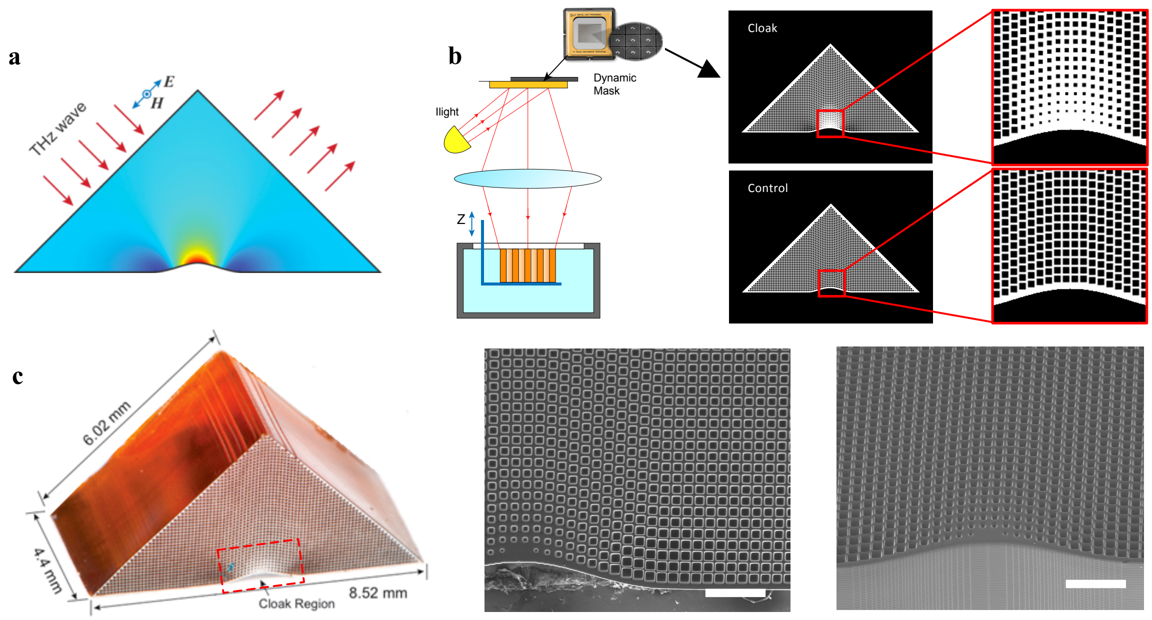

Fig. 1: Fabrication and characterization of 3D THz cloak. a, 2D spatial refractive index distribution of the cloak structure for TM polarized THz wave. b, Schematic diagram illustrating projection micro-stereolithography system being used to fabricate 3D cloaking device and the mask design for cloak sample and control sample. c, Optical and SEM images of fabricated cloaking device. Bar: 500 µm.

3. Characterization

Reflection terahertz time-domain spectroscopy (THz-TDS) was employed to characterize the cloaking samples due to its excellent sensitivity to the material response on both the amplitude and the phase of the THz wave. The measured spectra map of the flat surface (case I), uncloaked bump (case II) and cloaked bump (case III) are plotted in Fig. 2. The horizontal and vertical axes represent scan positions and frequencies, while the color represents the normalized amplitude of the spectra. In case (I), the THz wave incident at 45° is reflected from the gold-coated flat surface. The half-space above the reflective bump has an refractive index of 1.47. The measured reflected beam is clearly confined in both frequency and space, as the characteristic of a collimated THz beam. In case (II), the reflected THz wave exhibits three peaks, indicating the apparent scattering from the bump geometry. This is in agreement with the simulation result (0.6 THz) shown in Fig. 2b. Three distinct reflection peaks can be clearly observed across a broad frequency range. In contrast, the spectral map of the cloak sample in case III shows that the wavefront is relatively smooth with a single peak observed near the 0 degree position. The THz cloak sucessfully change the THz wave routes and conceals the bump, which closely resembles the case (I) as a flat reflective surface and simulation result in Fig. 2b.

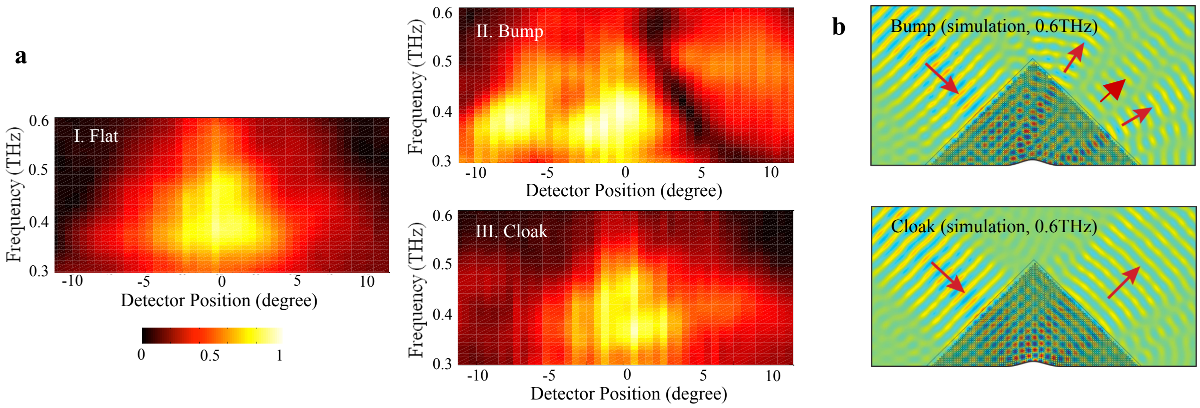

Fig. 2: a, Reflection measurement results for case I. flat metal surface, case II. bump, and case III. cloak. b, Simulation results for case II and case III at 0.6 THz.

4. Conclusion

Based on the 3D cloak demonstration, we successfully prove a way to manipulate THz wave using dielectric gradient index metamaterial. The cloak is fabricated via projection micro-stereolithography technique, which offers a simple but robust way in fabricating metamaterials with complex structures. In addition, we use transformation optics to design the gradient index material in high accuracy. Unlike the conventional optical components, which bend lights depending on the sudden change of geometries or the materials properties at the interface and cause scattering, transformation optics methodology effectively overcome the drawback and definitely inspire more intriguing devices in the THz regime.

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