Flexible Terahertz Metamaterials: Towards a Terahertz Metamaterial Invisible Cloak

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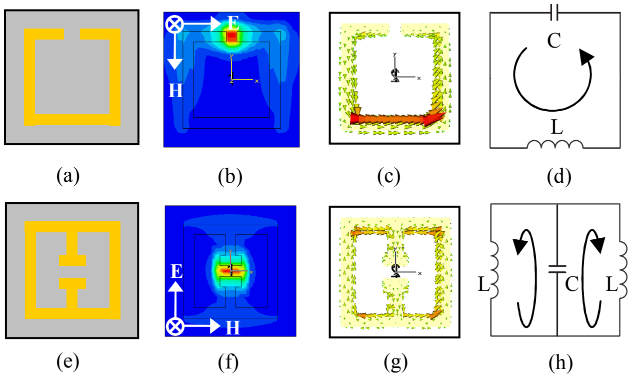
Abstract

In this work, we present flexible metamaterials on free standing polyimide substrates operating at terahertz (THz) frequencies range. The successful demonstration of THz flexible metamaterials provides a path forward for creating multi-layer non-planar metamaterials such as THz invisible cloak. We also present a design for a metamaterial cylindrical shell capable of acting as an invisible cloak at 0.5 THz along with present measurements of the individual elements which constitute the cloak. These results serve as an important step forward in constructing a functional THz cloak.

Introduction

Metamaterials are sub-wavelength composites consisting of shaped metals and supporting dielectrics (Fig. 1) which are capable of accessing regimes of electromagnetic response difficult or impossible to achieve with naturally occurring materials, such as negative refractive index, cloaking and quite generally, coordinate transformation materials design (1). Many of these ideas were initially implanted at microwave frequencies; however, the fabrication of sub-wavelength unit cells becomes increasingly challenging in moving from the microwave to visible region of the electromagnetic spectrum, among which the terahertz (THz) range (100 GHz to 10 THz; 1 THz corresponds to 300 μm) is a particularly interesting region, owing to the lack of significant material response, commonly referred to as the "THz gap". Metamaterials are expected to play an important role in exploring this least developed and therefore the least understood region. There have been demonstrations of metamaterials operating at THz and above. To date, the majority of this work has been on planar composites (2). At THz frequencies and above, creating multiple unit cell structures in the direction of propagation and taking full advantage of coordinate transformation metamaterial design to realize non-planar metamaterial composites requires the development of new fabrication strategies.



(a) (b) (c) (d)
(e) (f) (g) (h)

Figure 1: (color) Two popular THz metamaterial split-ring resonators (SRRs): a) & e) show the resonators' structures; b) & f) show norm of the electric field at resonance; c) & g) show the simulated surface current density; d) & h) show the equivalent circuits. (CST STUDIO SUITE$^{\text{TM}}$ 2006)

Design and Fabrication

In this work, terahertz time-domain-spectroscopy (THz-TDS) was used to characterize the metamaterial response. The functional frequency region of THz-TDS is mainly determined by its optics setup, and was 0.25 ~ 2.5 THz in our case. We designed numerous SRR samples with resonance frequencies within this region. For brevity, we focus on three of these samples, all of which were fabricated on 5.5μm thick polyimide substrates. The samples include purely electric resonator (#1) and canonical split ring resonators (#2 & #3), as shown in Fig. 2. Table I shows the dimensions of these samples.

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Table I

Dimensions of each free standing metamaterial sample (all units in μm): a, unit cell; b, outer dimension; t, thickness of the polyimide substrate; w, line width; l, length of the gap; g, gap distance.

Sample	a	b	t	w	l	g
1	50	36	5.5	4	8	2
2	50	36	5.5	4	4	2
3	50	36	5.5	4	4	4

The SRR structure can be tuned to show either negative electric or magnetic response by being exposed to different orientation of incident radiation and directions of electric and magnetic fields. We were constrained to normal incidence due to limitations in the experimental setup, which prevented us from directly measuring the magnetic responses of our samples. However, we could measure the electric responses by polarizing electric field perpendicular to the SRR gap, which excites the circulating current along the ring path and results in an electric resonance. And it has been shown that this electric response has the same dependence on the geometrical parameters as the magnetically-driven response (3).

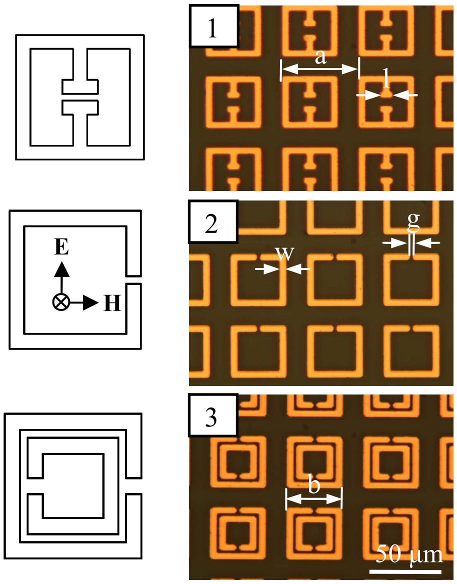

Figure 2: (color) Designs and photographs of the polyimide supported metamaterials. The corresponding dimensions are listed in Table I. The arrows labeled E and H show the electric and magnetic field directions.

The metamaterial structures were fabricated by patterning a 200-nm-thick gold (Au) with a 10-nm-thick adhesion layer of titanium (Ti) on polyimide substrates, as shown in Fig. 3.

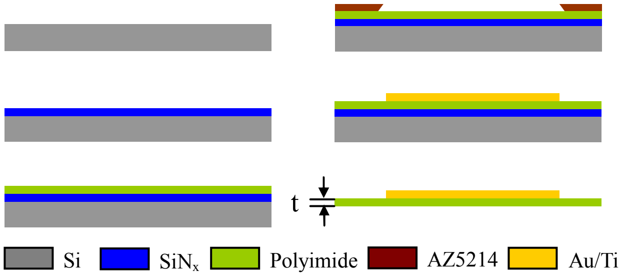

Figure 3: (color) Fabrication process of flexible terahertz metamaterials.

The liquid polyimide of PI-5878G (HD MicroSystems^{TM}) was spin-coated to form the polyimide substrate on a 2 inch silicon wafer coated with a 400 nm sputtered silicon nitride film, which facilitated the separation of the polyimide thin film from the substrate. The thickness of the polyimide substrate can be precisely controlled by adjusting the spin rate and curing temperature. In this work, 5.5 μm thick polyimide was realized by spin-coating the liquid polyimide at 2,000 rpm and curing it for 5 hrs in an oven at 350 °C in a nitrogen environment. Direct laser writing technology, which was intended for making masks, was chosen over traditional mask contact lithography technology to improve the patterning quality on polyimide substrates. AZ5214e image reversal photoresist was first calibrated and then patterned with a Heidelberg^{TM} DWL 66 laser writer. 200 nm-thick Au/Ti was E-beam evaporated followed by rinsing in acetone for several minutes. As a final step, the metamaterial structures patterned on the polyimide substrate were carefully peeled off from the silicon substrate. The as-fabricated samples show great mechanical flexibility, as shown in Fig. 4.

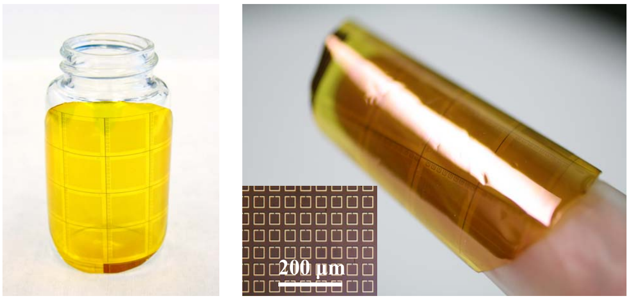

Figure 4: (color) A flexible “cloak” applied to a glass bottle and a finger.

Characterization

THz-TDS was used to characterize the metamaterial response. The experimental set up is shown in Fig. 5. The transmission

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of the THz electric field was measured for the sample and a reference, which in present case is simply air.

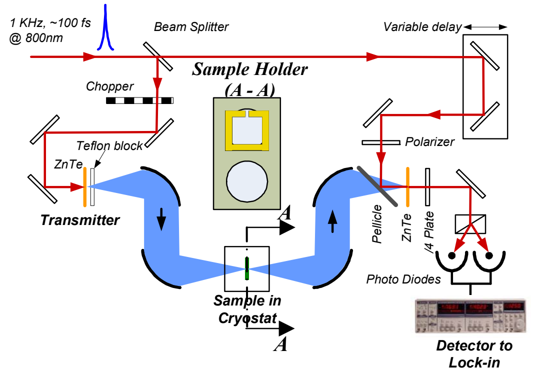

Figure 5: (color) THz-TDS experimental set up for flexible metamaterial measurements. Samples were mounted on the sample holder (top hole) with air as the reference (bottom hole).

The electric field spectral amplitude and phase are determined through Fourier transformation with the complex transmission obtained by dividing the sample by the reference electric field, as shown in Fig. 6.

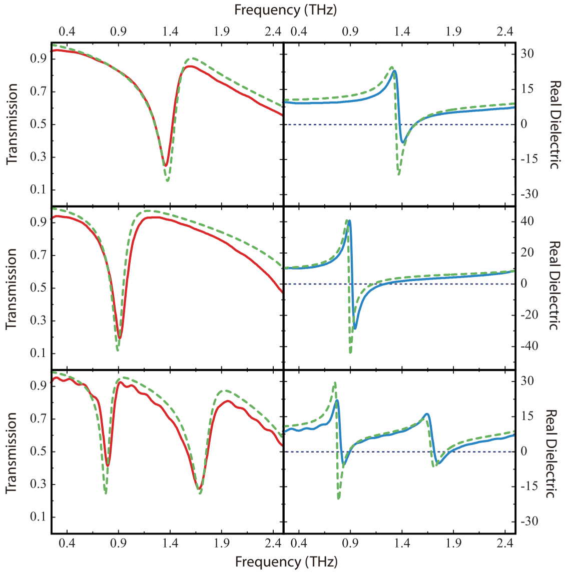

Figure 6: (color) The left panels show the experimentally measured transmission (red) for the corresponding samples in Fig. 2. The right panels show the real part of the dielectric response (blue). The solid lines are determined from the experimental data and the dash lines are determined from the simulations.

In addition, we determined the dielectric response from the simulated transmission. All samples show strong resonances, and negative dielectric constant (ε) right above the resonance frequency. The excellent agreement with the experiment data attests to the high quality of the metamaterial samples.

Application: Cloaking

The successful demonstration of flexible metamaterials at THz frequencies offers opportunities for us to explore the initial steps involved with experimentally demonstrating a cylindrical cloak of invisibility operation at THz frequencies.

A. Concept of a metamaterial invisible cloak

Cloak of invisibility is a particular transformation which permits a region of space to be occluded, such that a near-by observer is unaware that anything is there. Electromagnetic waves which impinge upon the cloak from any angle are guided around and re-shaped on the opposite side without penetrating the inner region. It was shown that Maxwell's equations are form-invariant to coordinate transformations and only the optical constants are affected (4). For the cylindrical cloak design, we perform the optical transformation by introduction of specific gradients in the refractive index realized by multi layers of metamaterials with desired optical constants, permittivity (ε) and permeability (μ), to compress the cylindrical region $0 < r < r_2$ into $r_1 < r' < r_2$ the region where r_1 is the inner radius and r_2 is the outer radius of the cloak, as shown in Fig. 7

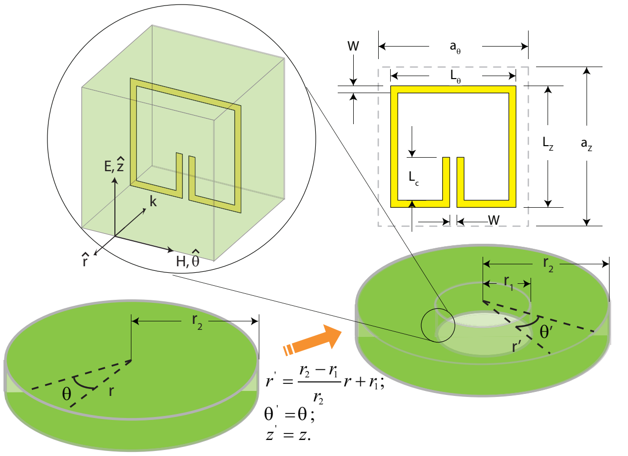

Figure 7: (color) Schematic of the THz cloak design to operate at 0.5 THz.

B. Design and Simulation

It has been shown that the transformations in Fig. 7 lead to optical constants of the form described in (1). Due to the limitation of experiment set up, we can measure our cloak with electric field polarized in the z-direction. Thus for easy

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of fabrication and measurement we use so-called “reduced parameter” cloak equations as described in (2).

Equation. (1)

$$\varepsilon_r = \mu_r = \frac{r - r_1}{r};$$
$$\varepsilon_\theta = \mu_\theta = \frac{r}{r - r_a};$$
$$\varepsilon_z = \mu_z = \left(\frac{r_2}{r_2 - r_1}\right)^2 \frac{r - r_1}{r}.$$

$$\Longrightarrow$$

Equation. (2)

$$\varepsilon_z = \left(\frac{r_2}{r_2 - r_1}\right)^2;$$
$$\mu_r = \left(\frac{r - r_1}{r}\right)^2;$$
$$\mu_\theta = 1.$$

In order to realistically fabricate a reduced parameter THz cloak, we choose inner and outer radii that would allow us to have an integer number of unit cells along each axis, and the dimensions of the cloak and individual layer cell are given in Table II.

Table II

Dimensions of the “reduced parameter” cloak. (For simplicity, only dimensions of outer and inner unit cell are listed. r_1 and r_2 are in units of mm, all others are in units of μm.)

Layer #	r_1	r_2	a_θ	a_z	W	L_θ	L_z	L_c
Outer (50th)	3.33	5.33	41.88	44.37	2.0	35	34.60	16.55
Inner (1st)							33.90	11.97

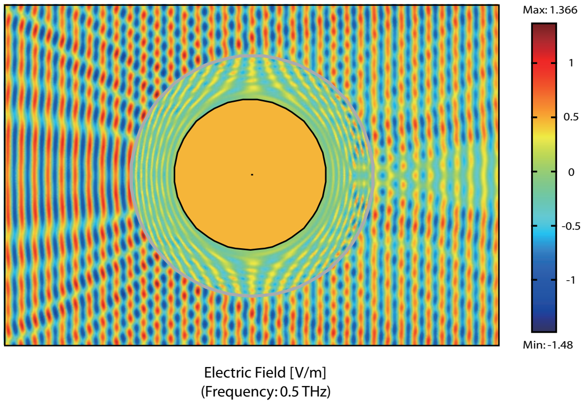

Figure 8: (color) Simulated bare scatter of radius 3.33 mm with a metamaterial cloak. Color map of the electric field is indicated on the right.

The cloak was simulated in COMSOL^{TM} using Hybrid-Mode Solver. A quasi-plane wave was created by a current sheet on the left boundary. Scattering boundary conditions on the top, bottom, and right boundaries approximated an infinite cavity. As shown in Fig. 8, the cloak clearly reduces scattering in both the forward and backward directions. Furthermore, inspection of the wave front verifies that the light exiting the cloak retains the same phase as the light in the surrounding vacuum.

C. Fabrication and Characterization

The individual metamaterial layers were fabricated by depositing 200nm (Au)/10nm (Ti) on a 20μm thick polyimide substrate, followed by coating another 20μm thick polyimide on the top. We characterized the response of the individual unit cell designs for the inner and outer radii using THz-TDS, and there is excellent agreement between the simulated and measured transmission spectra shown in Fig. 9.

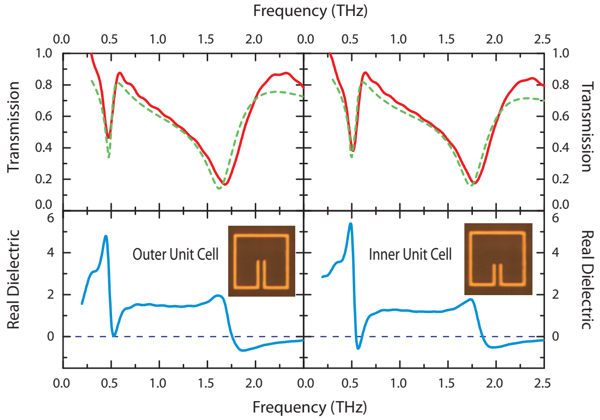

Figure 9: (color) Computational (green dash) and experimental transmission (red solid) and real dielectric constants (blue solid) for the elements which constitute the metamaterial cloak. Insets show images of the as-fabricated individual unit cells.

Conclusion

Flexible resonant terahertz metamaterials built on highly flexible polyimide substrates have been designed, fabricated and measured. These results pave the way for creating numerous multilayered non-planar electro-magnetic composites. In addition, we have taken the first steps towards experimental demonstration of a THz cloak.

Acknowledgements

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