TERAHERTZ METAMATERIALS WITH SIMULTANEOUSLY NEGATIVE ELECTRIC AND MAGNETIC RESONANCE RESPONSES BASED ON BIMATERIAL POP UP STRUCTURES

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ABSTRACT

In this paper, we present a metamaterial with simultaneously negative electric and magnetic resonance responses in the terahertz (THz) frequency range. The structure is composed of in-plane split resonator rings (SRRs) for desired electric response and out-of-plane SRRs realized by bimaterial pop up structures for magnetic response. Experimental results conducted using THz Time Domain Spectroscopy (THz-TDS) show that the presented metamaterial has both electric and magnetic resonance peaks at 0.5 THz. The performance of the metamaterial can be further improved by optimization of the structure's geometry and the operating frequency of the metamaterial can be tuned by scaling dimensions.

INTRODUCTION

Terahertz Gap

Nearly all optoelectronic devices function on their responses to electromagnetic waves, and the electromagnetic spectrum covers a range of wavelengths and photon energies. However, the electromagnetic response is not evenly distributed across the electromagnetic spectrum due to the difference in working particles interacting with the electromagnetic waves. At lower frequencies such as a few hundred GHz and lower, electrons are the principle particles and the waves can be generated by electronic devices such as those found in radio and cell phones. On the other hand, at higher frequencies such as infrared through optical wavelengths, the lights are generated by optical devices where photon is the fundamental particle of choices [1]. There is one region of the electromagnetic spectrum comparatively devoid of material response, and was found difficult to be reached by either end. This is the terahertz (THz) region, alternatively called the far-infrared, which lies below visible and infrared wavelengths and above microwave wavelengths, ranges from frequencies of about 100 GHz to 10 THz ($1THz = 10^{12}$ Hz). Since it is least developed and therefore the least understood, this region is commonly referred to as the "Terahertz gap" [2]. Metamaterials are expected to play an important role in exploring this gap.

Metamaterials

Recently, artificially structured electromagnetic materials have become an extremely active research area because of the possibility of creating materials which exhibit novel electromagnetic responses not available in natural materials, such as negative refractive index [3]. Such electromagnetic composites, often called metamaterials, are sub-wavelength composites where the electromagnetic response originates from oscillating electrons in highly conducting metals such as gold or copper allowing for a designed specific resonant response of the electrical permittivity (μ) or magnetic permeability (ε). The advent of metamaterials has given rise to numerous electromagnetic functionalities previously unimaged, including superlensing [4-7], cloaking [8-10], and more generally, coordinate transformation materials design [11].

This is especially important for the technologically relevant THz frequency regime which is difficult to be reached due to lack of functional sources and detectors. Many metamaterials were initially implemented at microwave frequencies due to ease of fabrication and characterization [12-13]. However, the fabrication of sub-wavelength unit cells becomes increasingly

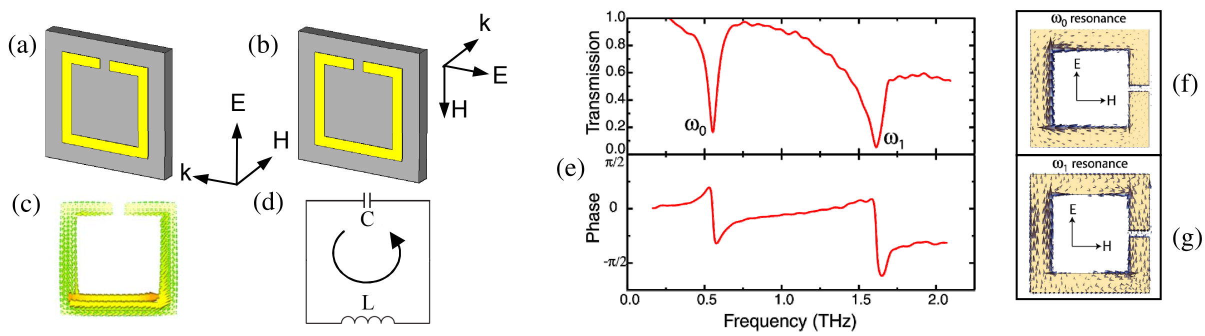

Figure 1: Split-ring resonator (SRR) element for construction of metamaterials: (a) a single SRR with an external alternating magnetic field incident upon it, which induces a circulating current in the ring; (b) the same SRR structure with an external electric field perpendicular to the gap, which also excites a circulating current, as shown in (c), and it has been proven that these two resonances have same dependence on the geometrical parameters; (d) equivalent circuit of SRR with the gap as the capacitance and the current path as the inductance. (e) shows the measured transmission(top) and phase(bottom) spectrum of planar SRR array. Two resonances were observed: the first one (ω_0) comes from the circulating current due to the split gap as shown in (f), which is our aim resonance; the second resonance (ω_1) comes from the dipole coupling from the side bars along the direction of electric field, as shown in (g).

challenging in moving from the microwave to higher frequencies such as THz frequencies and even higher infrared and visible frequencies [14]. Since 1 THz corresponds to 300 μm in wavelength, the critical geometric dimensions of the sub-wavelength unit cells are tens of microns or smaller, where MEMS technologies happen to show extreme power and flexibility in terms of fabrication.

Split ring resonators (SRRs)

Split ring resonator, first theoretically introduced by Pendry et al. in 1999 [15] and experimentally verified by Smith et al. in 2000 [16], has been the element typically used for the narrow band resonance response to the electromagnetic field. 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.

The electromagnetic metamaterial can be designed independently to respond to the electric or magnetic component of an electromagnetic wave. When a varying magnetic field polarized normal to the plane of the SRR, as shown in Fig. 1a, circulating currents will be induced within the ring. Due to the split gap, the induced circulating currents will result in a build up of charge in the gap, which concentrates the electric field and stores the energy as a capacitance. When the frequency of externally varying magnetic field is below ω_0, which is the resonance frequency of the SRR due to the gap, the induced currents in the SRR are able to keep up with the driving force, and thus a positive response is observed. However, as the frequency increases, the currents can no longer keep up and begin to lag eventually, which results in an out of phase or negative *magnetic response*.

Recently, there have been further advances in the development of *electric metamaterials* with similar SRR structures that were initially designed to act as magnetic metamaterials, by applying different electromagnetic polarization to the SRR plane [17], as shown in Fig. 1b. It has been shown that the response induced by electric field has the same dependence on the geometrical parameters as the magnetically-driven response [18].

Furthermore, the resonance frequency can be tuned by geometry because of the universality of metamaterial response over many decades of frequency; the operating region of negative values can be made to occur at nearly any frequency, from microwave to optical. There has been considerable effort to develop various metamaterial structures at THz frequencies, however, most THz metamaterials built on planar structures show only electric response due to fabrication and characterization limitations, which will be explained in the following section.

In this paper, we present the first metamaterial with simultaneously negative electric and magnetic response in the terahertz frequency range using MEMS-based bimaterial pop up structures.

DESIGN

As mentioned above, SRR can show either electric or magnetic response, which depends on the orientations of incident light and electromagnetic fields. However, it is difficult to get magnetic response for the planar THz SRR structures under normal incident light, as in this case the wave has to propagate along the SRR plane with magnetic field normal to the SRR plane to excite the magnetic response, which is difficult to be experimentally fabricated and characterized in the terahertz range since the incident light is usually limited normal to the SRR plane to get reasonable signal strength level for measuring the S-parameters. So to get both electric and magnetic response simultaneously for the planar THz SRR structures, the wave has to propagate so that electric field is perpendicular to the SRR's gap to excite the electric LC response and magnetic field is normal to, or at least has some portion projected into, the SRR plane to excite the magnetic response at the same time, which is barely possible for available planar SRRs.

Here we present a new metamaterial structure showing both negative electric and magnetic resonance responses. One single unit cell (εμ-SRR) consists of two in-plane SRR elements (ε-SRRs) for electric response and another two out-of-plane SRR elements (μ-SRRs) supported by bimaterial cantilever legs for magnetic response, as shown in Fig. 2. The bimaterial cantilever legs consist of seemingly arbitrary 200 nm thick gold (Au) and 400 nm thick silicon nitride (SiN_x) layers. Both ε-SRRs and μ-SRRs are supported on the 400 nm thick SiNx thin film, which is highly transparent to THz radiation. By polarizing electric filed ***E*** perpendicular to the ε-SRRs's gap, we are able to couple to the electric LC response. A magnetically-driven response with the same frequency depended features as the electrically-driven response could be obtained by popping up the μ-SRRs such that there is portion of magnetic field ***H*** projected into the μ-SRRs plane.

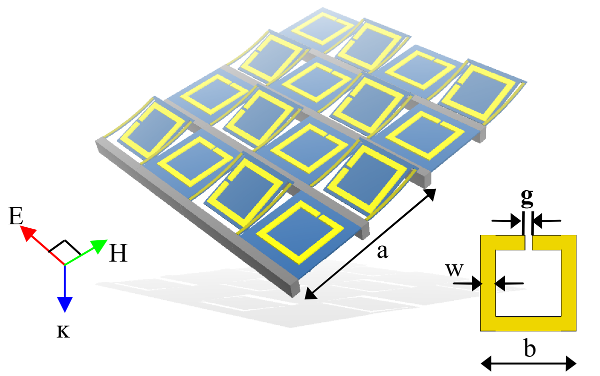

Figure 2: Schematic of the metamaterial structure with simultaneously electric and magnetic resonance responses. The corresponding dimensions are listed in Table I.

*Table I: Dimensions of the presented metamaterial structure (all units in μm): **a**, unit cell; **b**, outer dimension; **w**, line width; **g**, gap distance, t_{Au}, thickness of gold; t_{SiNx}, thickness of silicon nitride.*

Parameters	a	b	w	g	t_{Au}	t_{SiNx}
Dimensions	200	72	8	4	0.2	0.4

FABRICATION

The metamaterial structure was fabricated using a surface micromachining process which typically consists of four steps: 1) deposition of the SiN_x films, 2) patterning of the Au layer for SRRs and bimaterial bending legs, 3) patterning the SiN_x film for supporting plate and bending legs, 4) release of the structure by KOH etching, as shown in Fig. 3a.

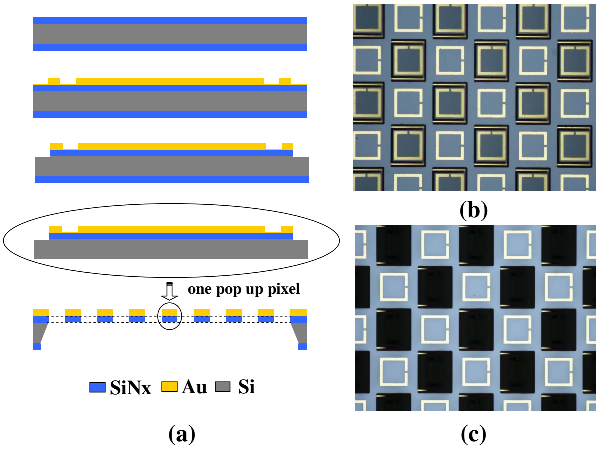

Figure 3: (a) Fabrication process; (b) microscopic image of the as-fabricated sample; (c) microscopic image of the sample after rapid thermal annealing (RTA). (Dark area: out-of-plane pixels/μ-SRRs)

The process started with a 4" silicon wafer with 400 nm thick SiN_x films deposited on both sides. The initial bending angle of the pop up structure originates from residual stress in or between the films. It is well known that the residual stress in LPCVD SiN_x film depends strongly on the deposition conditions such as temperature, pressure and the ratio of the flow rate of source gases during deposition. We purchased 4" (100) 500 μm thick silicon wafers with super low stress LPCVD SiN_x films deposited on both sides (Addison Engineering, Inc.). The SiN_x film on the front side serves as the supporting plate for SRRs and the bottom layer of bimaterial legs whereas the SiNx film on the back side serves as the etching windows for structure release in the last step. Then the SRRs and the top layer of the bimaterial legs were fabricated using standard photolithographic methods and electron beam evaporated deposition of 200 nm of gold following a 10 nm chromium adhesion layer, then undertaking a lift-off process. The next step is to lithograph photoresist mask and it is followed by the removal of unwanted SiNx layer employing reactive ion etching (RIE) technique. Next, the back side SiN_x etching window is patterned by photolithography followed by RIE etching. Finally, the Si substrate beneath the pop up metamaterial elements was etched in KOH solution. The as-fabricated structures were near flat with the initial bending angle under 5° (Fig. 3b), and the bimaterial legs supported SRR elements were then popped up at around 40° by placing the samples in the rapid thermal annealing (RTA) oven at 400°C for 10 minutes (Fig. 3c).

CHARACTERIZATION

THz Time Domain Spectroscopy (THz-TDS) was used to characterize the metamaterial sample performances; the experimental set up is shown in Fig. 4. In THz-TDS, the time-varying electric field of the impulsive THz radiation is recorded, and the electric field spectral amplitude and phase are directly obtained by performing Fourier analysis.

The transmission of the THz electric field was measured for the sample and a reference, which in the present case is simply air. Prior to measurements, the metamaterial samples were diced into 1 cm × 1 cm squares. All experiments were performed at room temperature in a dry air atmosphere (< 0.1% humidity). The THz beam diameter was ~ 3 mm, which was safely covered by our samples.

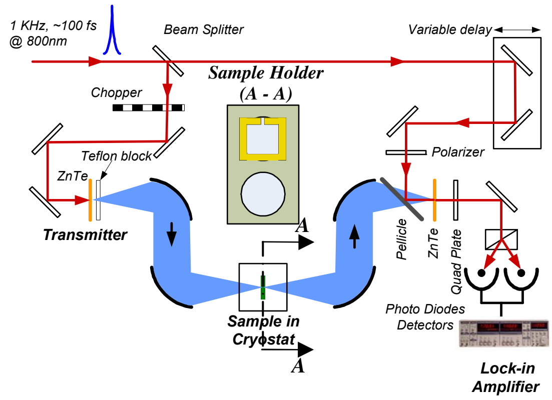

Figure 4: THz-TDS set up for the metamaterial sample performance characterization. (Top hole: sample; bottom hole: reference/air)

The samples, including εμ-SRR, pure ε-SRR and pure μ-SRR, were mounted on the sample holder with air as the reference, and were oriented with THz radiation normal to the sample plane. The electric field is perpendicular to the ε-SRR's gap and parallel to the μ-SRR.

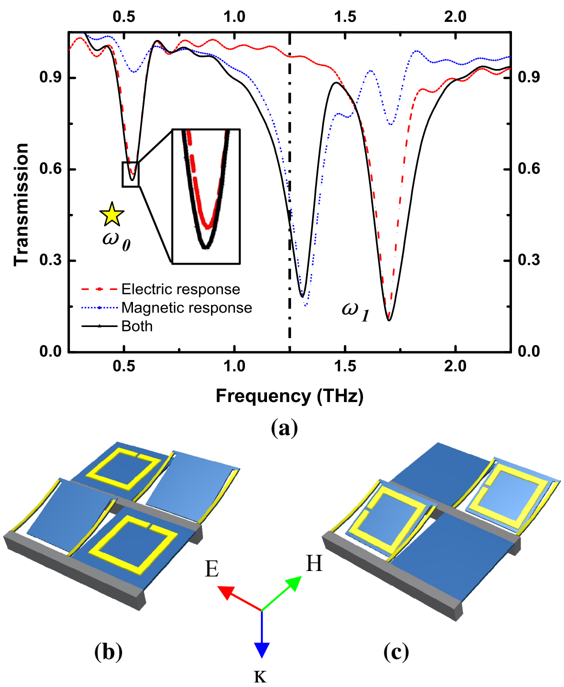

Figure 5: (a) Experimentally measured transmission for the μ-SRRs (Black Solid) along with pure in-plane -SRRs (Red Dash) and pure out-of-plane μ-SRRs (Blue Dot) for comparison; (b) schematic of pure in-plane -SRRs; (c) schematic of pure out-of-plane μ-SRRs.

The transmission spectra were measured and all samples showed resonance responses at ~ 0.5 THz, which originated from the induced circulating currents in the SRRs. εμ-SRR showed the strongest resonance response while μ-SRR showed the weakest as shown in Fig. 5, which verified our expectation since the strength of magnetic response relies on the magnetic field portion incident to the SRR plane decided by the out-of-plane angle, namely ~ 40° in this case. The angle could be further increased by optimizing RTA parameters and geometry of bimaterial legs. A stronger resonance should be expected by increasing the angle and 90° should be the ideal angle for maximizing the magnetic response.

CONCLUSION

In summary, we have experimentally demonstrated a new THz metamaterial structure that shows simultaneously negative electric and magnetic response, based on the MEMS-based bimaterial pop up structure. We anticipate such metamaterials will increasingly find wide variety of applications in the THz frequency range, such as superlens, wave plates, band-pass filters and etc.

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