Polarization Controllable THz Stereometamaterial Absorber

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Abstract—Spatially different arrangements of identical meta-atoms in a unit cell bring about distinct properties in stereometamaterials. Integrating the stereometamaterial into a perfect metamaterial absorber, we designed, fabricated, and characterized a device with single or double band absorption responses and an absorption/reflection switching characteristic dependent upon the polarization of the incident THz wave. Two non-concentric Cu rings tightly coupled via a polyimide layer form the stereometamaterial frequency selective surface (FSS). The FSS is placed on another polyimide layer deposited on a Cu backplane. Despite the rotational symmetry of the rings, non-circularity breaks the reflection symmetry of the FSS, leading to a unique interaction between the rings and a Cu backplane. Interaction between dipoles on an FSS and their mirror images due to Cu backplane is studied to gain a better understanding of this device.

I. INTRODUCTION

The Terahertz (THz) spectral region remains a scientifically rich but technologically underdeveloped research area. Since many molecules possess THz spectral fingerprints (ranging from 0.1THz up to 10 THz), and a large variety of non-conductive materials are transparent to THz radiation, THz radiation promises various potential applications [1]. Nonetheless, there exists a shortage of natural materials capable of interacting with THz radiation from which useful THz detectors, emitters, switches, and other devices may be manufactured. Metamaterials, artificially designable structures that render desired optical properties at a given wavelength, could be a solution. They are made by assembling sub-wavelength unit cells called meta-atoms [2]. Of growing interest are the asymmetric transmission properties of metamaterials that achieve customized functionalities like negative refractive index and circular polarization rotation, sharp Fano resonances, and anomalous refraction and light spin-Hall effect. The asymmetric transmission arises from the rotational asymmetry of individual meta-atoms or the reflection asymmetry between meta-atoms in adjacent layers. A case which has not been considered so far is the asymmetric behavior of stereometamaterials [3] in subwavelength proximity of a perfectly conducting plane, where the conducting surface interacts with asymmetric stereometamaterial structure. Although, metamaterial perfect absorber has been studied intensively [4], the effect of breaking the reflection symmetry in three dimensional stereometamaterial FSS has not been investigated.

II. DESIGN, SIMULATION, AND EXPERIMENT

Figure 1(a) shows schematic representation of designed structure. Front and side view illustrations of this structure are also demonstrated in Figs.1(b) and (c), respectively. The structure is composed of two tightly coupled Cu rings as an FSS which are located in a subwavelength proximity of a Cu backplane. Polyimide fills the space between Cu rings and backplane. When center of rings are relatively shifted with respect to each other unique interaction between rings and backplane are expected in various incident polarization angles.

In order to study these interactions and design the desired stereometamaterial absorber Comsol Multiphysics software was utilized to perform simulations by using Finite Element Method (FEM). A continuous THz wave with periodic condition for side boundaries and scattering condition for front and back boundaries were used in simulations. Successive simulations were resulted in a desired stereometamaterial absorber with dimensions summarized in table 1.

Table 1. Dimensions (µm) associated with designed stereometamaterial absorber discussed in this article.

<table>
<thead>
<tr>
<th>R1₁</th>
<th>R1₂</th>
<th>R2₁</th>
<th>R2₂</th>
<th>Lon</th>
<th>t</th>
<th>Sep</th>
<th>d</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>42</td>
<td>33</td>
<td>36</td>
<td>1.7</td>
<td>0</td>
<td>9</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

Designed stereometamaterial absorber were fabricated through standard lift-off photolithography approach. For measurement, reflection mode THz time domain spectroscopy was used to measure the reflectivity of fabricated samples at normal incidence whereas absorption was calculated through A = 1 - R where A and R stand for absorption and reflection, respectively. The details of the fabrication process and measurement setup have been reported in the previous work [5].

III. RESULTS

Figures 2(a) and (b) illustrate absorption versus frequency and lateral shift of center of rings (Lat) obtained by FEM at
0° and 90° incident polarizations, respectively. Depending on polarization direction and lateral shift of the rings, absorption spectrum exhibits multifunctional characteristics of the device including single band, dual band absorption, and an absorption/reflection switching functionality depicted by a white line where $L_{at} = 12 \, \mu m$. Switching functionality of the device, which happens between 0.725 THz and 0.790 THz (Fig. 1(c)), is highlighted and studied in detail in this article.

![Fig. 2. (a) and (b) Absorption versus frequency and lateral shift of the center of the rings ($L_{at}$) obtained by FEM at 0° and 90° incident polarizations, respectively. (c) Absorption versus frequency under 0°, 45°, 67°, and 90° polarization angles for both simulation and experiment where $L_{at} = 12 \, \mu m$. (d) Comparison of absorption spectra for single ring absorber of front and back rings and stereometamaterial absorber in 0° and 90° incident polarizations.](image)

To gain a better understanding of functionality of the device, electric field distribution on rings and backplane at both resonance frequencies under 0° and 90° incident polarizations are studied. Figures 3(a), (c), and (e) respectively show the electric field on front ring, back ring, and backplane at both 0.725 THz and 0.790 THz. Arrows numbered 1 to 4 depict interaction between dipoles in both polarizations. Parallel currents in the rings, shown as $J_F$ and $J_b$ in the Figs. 3(g) and (n), result in centrifugal (×) and centripetal (.) magnetic fields in the region between the two rings (shown also as S→N and N→S) as well as magnetic fields parallel to the z axis that couple to each other to reduce the resonance frequency according to the frequency level scheme of two coupled magnetic dipoles [3].

![Fig. 3. Electric field and current density distribution on rings and backplane at 0.725 THz (a–g) and 0.790 THz (h–n), where the incident polarization angle is 90° and 0° respectively.](image)

Figures 3(g) and (n) show side view illustrations of electric field at 0.725 THz and 0.790 THz. Arrows numbered 1 to 4 depict interaction between dipoles in both polarizations. At 90° (Fig. 3(g)), front ring with larger radius has the main contribution in making resonance where poles 1 and 3 are excited first and then their induced poles on backplane (image poles) excite poles number 2 and 4 on back ring. Due to the asymmetry in this case, the intensity of pole 4 on back ring is slightly less than the others. When incident polarization is 0° (Fig. 3(n)), back ring with smaller radius contributes majorly in creating resonance and then the imaged poles due to backplane induce a symmetric dipole on front ring. A red shift of resonance frequencies of stereometamterial absorber compared to single ring absorbers (Fig. 2(d)) can also be explained by dipoles interactions. Parallel currents in the rings, shown as $J_F$ and $J_b$ in the Figs. 3(g) and (n), result in centrifugal (×) and centripetal (.) magnetic fields in the region between the two rings (shown also as S→N and N→S) as well as magnetic fields parallel to the z axis that couple to each other to reduce the resonance frequency according to the frequency level scheme of two coupled magnetic dipoles [3].

**IV. CONCLUSION**

We presented a stereometamaterial device that functions as a single band or dual band absorber, and as a polarization dependent passive absorption/reflection switch, depending upon the relative positions of rings. By focusing on passive switching characteristics and coupling of electric and magnetic dipoles, we explained how dipoles on FSS and their images on backplane interact with each other to produce asymmetric absorption features.

**REFERENCES**