Stand-up magnetic metamaterials at terahertz frequencies

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Abstract: We present a detailed study of non-planar or ‘stand-up’ split ring resonators operating at terahertz frequencies. Based on a facile multilayer electroplating fabrication, this technique can create large area split ring resonators on both rigid substrates and conformally compliant structures. In agreement with simulation results, the characterization of these metamaterials shows a strong response induced purely by the magnetic field. The retrieved parameters also exhibit negative permeability values over a broad frequency span. The extracted parameters exhibit bianisotropy due to the symmetry breaking of the substrate, and this effect is investigated for both single and broad side coupled split rings. Our 3D metamaterial examples pave the way towards numerous potential applications in the terahertz region of the spectrum.

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1. Introduction
Since Pendry proposed a canonical building block for metamaterials [1], numerous intriguing
phenomena not exhibited in naturally occurring materials have been realized. This includes neg-
ative refractive index materials [2, 3], invisibility cloaking [4, 5], and perfect absorption [6, 7].
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with advanced characterization to deepen our understanding of the fundamental electromagnetic properties of artificial ‘atoms’ and the resultant functional properties.

Three dimensional metamaterial research beyond the microwave range is still in its relative infancy because of technical hurdles. Fabrication of subwavelength elements with sub-micron dimensions typically requires advanced lithography techniques such as nanoimprint lithography [8], e-beam lithography [9] or focused-ion beam writing [10]. Some of these techniques have been used for 3D structuring in near-IR [3] and mid-IR [11] range. Recently, a cutting edge technique based on multi-photon polymerization was introduced for three-dimensional nanofabrication [12–14].

These techniques are, however, limited to small-scale patterning and can be very time consuming for patterning metamaterial arrays over areas of square centimeters or larger. Furthermore, they are currently incapable of complicated 3D structuring in the terahertz (THz) range, where the metamaterial structures extend tens of micrometers in three dimensions. In this mesoscopic range, creating 3D functional metamaterials requires the implementation of alternative fabrication strategies. In short, while the concept of metamaterials spans the electromagnetic spectrum, a given fabrication technique is specialized to a particular length scale.

Progress in metamaterials at far-infrared wavelengths (1 THz → 300 μm) has been quite rapid since conventional photolithography can be utilized. For example, the development of active terahertz metamaterials has been particularly fertile [15–18]. To date, most of these studies have been based on planar metamaterials either in single layer or multiple layer geometries [19–22]. However, the aspect ratio required for creating three-dimensional metamaterials is a challenge that requires going beyond conventional planar metallization strategies [23, 24].

In this paper, we present our recent progress on 3D magnetic metamaterials at THz frequencies. A multilayer electroplating (MLEP) technique [25, 26] with the combination of conventional optical lithography is utilized to fabricate the split ring resonators (SRR) at the wafer scale. We have fabricated 3D SRR arrays on rigid and flexible substrates to which normally incident radiation is magnetically coupled. A straightforward extension enables the fabrication of broadside coupled SRRs which are often utilized to eliminate bianisotropy at the unit cell level. However, our results highlight that residual bianisotropy is present because of the symmetry-breaking presence of the substrate [27]. The successful creation and characterization of these 3D structures from well-defined building blocks of SRRs represents a ‘bottom-up’ fabrication paradigm towards bulk metamaterials at THz frequencies.

2. Stand-up split-ring resonators

Figure 1 details the structure of the 3D SRRs with Fig. 1(a) and 1(b) depicting a portion of the array and individual resonator, respectively, and Fig. 1(c) and 1(d) showing SEM pictures of the as fabricated structures on a silicon substrate. The MLEP fabrication process for 3D SRRs begins with electroplating a bottom bar on a silicon substrate by patterning a thin layer of photoresist (PR). After the thin PR is removed, a thick layer of PR is coated. Pillars on both ends of the bottom bar are electroplated through patterned holes. The first thick layer of PR is removed and a second thicker PR layer is coated. Only one side of the pillars is patterned and electroplated, while the other side is still filled with PR to form the SRR gap. Without removing the PR, a third layer of thick PR is patterned on a new evaporated seed layer for electroplating new pillars resulting in a gap on one side. Finally, a long top bar is electroplated on patterned thin PR to connect the pillars on both sides. At this point the resulting structure is still embedded in PR, which is removed with acetone, and the copper seed layers are etched away in acid. Using MLEP, the lateral dimensions can be easily defined by the lithography masks.

The gap size and the total height of the SRR are determined by the thickness of photoresist,
which can be tuned by the spinning rate. A series of metamaterial samples with lengths of 28 \( \mu m \), 30 \( \mu m \), 36 \( \mu m \) were fabricated. Each SRR array has a height of 33 \( \mu m \), gap size of 6 \( \mu m \) and lateral periodicity of 50 \( \mu m \). The SEM images of the stand up SRR arrays show good uniformity over 2 inch wafers as depicted in Fig. 1(c) and 1(d). Terahertz time domain spectroscopy (THz-TDS) was used to experimentally characterize the electromagnetic response of the metamaterials. The spectral transmission (amplitude and phase) was obtained by dividing the sample by a reference of a bare silicon with the same thickness.

It is well known that incident electromagnetic radiation can resonantly couple to the LC resonance of an SRR through either the electric or magnetic field. This occurs either when the electric field (E) is parallel to the side containing the SRR gap or when the magnetic field (H) has a component normal to the plane of the ring [28]. For planar SRRs at normal incidence, magnetic excitation does not occur. This is in contrast to out of plane SRRs, where when the incident THz radiation is polarized as indicated in Fig. 1(b), the excitation is purely magnetic. For this orientation, there is no bianisotropy due to the SRR geometry; however, this would not be the case if the gap were parallel with the surface (see the discussion of substrate effect below). If the normally incident polarization is rotated by 90 degrees then neither magnetic nor electric excitation of the metamaterial LC resonance occurs.

Experimental transmission data for the three samples is shown in Fig. 2(a). With the polarization as shown in Fig. 1(b), a strong resonance is observed for the sample with \( l=36 \mu m \) (green
Fig. 2. Frequency dependent THz electric field transmission relative to a silicon substrate reference on three samples with different bottom-bar length. (a), Experimentally measured. (b), Simulations. The inset shows simulated circulating current at the fundamental resonance of SRRs with $l = 28 \mu m$. The incident THz wave is normal to the substrate and the electric field for the green, blue and red lines is polarized as shown in Fig. 1(b) with magnetic field perpendicular to the plane of SRRs. The H field for the orange line is parallel to the plane of the ring.

line). When the incident polarization is rotated by 90 degrees no resonance is observed (orange line), consistent with the discussion in the previous paragraph. A blue-shift of the fundamental resonance $\omega_0$ from 1.19 THz to 1.38 THz occurs as the length decreases from 36 $\mu m$ to 28 $\mu m$, consistent with the LC model of SRR. With a shorter bar, the equivalent inductance of the ring decreases and shifts the LC resonance to a higher frequency. Numerical simulations using CST Microwave Studio$^{TM}$ 2010 were conducted to compare with the measured results. The copper was modeled as a lossy metal with a frequency independent conductivity of $5 \times 10^4 \ (\Omega \cdot cm)^{-1}$ which is based on four-point probe measurements of an electroplated continuous Cu film, and the permittivity of silicon was set as 11.9. At the fundamental resonance, a circulating current is induced by the magnetic field as depicted in the inset of Fig. 2(b). The simulation results in Fig. 2(b) show very good agreement with experiment, demonstrating that the observed surface roughness in the SEM pictures does not significantly degrade the electromagnetic response.

MLEP can also be utilized to fabricate conformally compliant metamaterials on flexible substrates such as benzocyclobutene (BCB), polyimide, or parylene [19–22, 30]. These flexible metamaterials have the potential to make multilayer stacked electromagnetic composites and implantable devices. Figures 3(a) and 3(b) show the flexible 3D metamaterials fabricated on polyimide. The dimensions are the same as the for those on silicon (Fig. 2) except the gap width is 4 $\mu m$. Three samples with side lengths of 28 $\mu m$, 30 $\mu m$ and 36 $\mu m$ were characterized using THz-TDS relative to a reference of air (Fig. 3(c)). For the simulated results in Fig. 3(d), the thickness of polyimide was set as 30 $\mu m$ as experimentally measured. The refractive index of polyimide is $n = 1.8 + 0.05i$ [20] and is constant over the spectral bandwidth. Clearly, the measured results show a very nice agreement with simulation. Furthermore, the resonances are of comparable quality to those fabricated on rigid substrates (Fig. 3).

The SRRs presented in Fig. 2 and Fig. 3 are intrinsically bianisotropic meaning that a magnetic (electric) field can also induce an electric (magnetic) polarization [29]. This indicates that in addition to the complex permittivity ($\varepsilon$) and permeability ($\mu$), a magneto-electric coupling parameter ($\xi$) is required to describe the full electromagnetic response of SRRs. This bianisotropy arises from the lack of inversion symmetry in the structural plane. Thus, for the
SRR configuration in Fig. 2 and Fig. 3 (for normal incidence) the bianisotropy would not be present if not for the symmetry breaking induced by the substrate. Therefore, neglecting the effect of the substrate could lead to improper characterization of the electromagnetic response. For planar structures oriented normal to the propagation direction or uniformly embedded in a dielectric “substrate”, this effect would be minimal, but for non-planar structures the effect of the substrate cannot be neglected and requires careful consideration [27].

To further analyze the electromagnetic response, the real and imaginary parts of $\varepsilon$, $\mu$, and $\xi$ were extracted from simulation using a bianisotropic retrieval method [12,31,32]. As discussed previously, when the fundamental resonance of the SRR is excited purely by the magnetic field, inversion symmetry along the propagation direction indicates no magneto-electro coupling. To verify this we first determined the parameters for a free standing SRR with the same dimensions as the fabricated $l = 28 \mu m$ structure. These results (Fig. 4(a)) show that without a substrate there is no resonant contributions to $\varepsilon$ or $\xi$, while the permeability is a Lorentzian-like resonance with $\text{Re} \{\mu\} < 0$ achieved over a certain frequency interval. A pure magnetic resonance is obtained and no bianisotropy is observed in agreement with symmetry principles. As shown in Fig. 4(b), negative permeability values are obtained between 1.25 THz and 1.5 THz showing significant magnetic response to the incident radiation. However, as the $\xi$ in Fig. 4(b) reveals, the inclusion of a substrate breaks the symmetry and induces bianisotropy for 3D metamaterials even at normal incidence. This substrate induced bianisotropy is also present for the flexible
metamaterials as shown in Fig. 4(c), but with a much smaller value compared to the SRRs on the silicon substrate since polyimide is much thinner and has a smaller permittivity. The permeability response remains a Lorentzian resonance shape in Fig. 4(c), while the Lorentzian shape in Fig. 4(b) is distorted.

3. Broadside-coupled metamaterials

For many applications it is desirable to eliminate the magneto-electric coupling arising from bianisotropy. To eliminate this cross coupling effect, several novel designs have been created, such as electric inductive-capacitive (ELC) resonators, and broadside-coupled SRRs (BC-SRRs) [29, 33]. The planar ELC resonator is easily fabricated from the microwave through optical range. However, the BC-SRRs necessitates three dimensional structure in the propagation direction to couple to the magnetic field. As such, magnetically excited BC-SRRs have not been obtained at terahertz frequencies.

Using MLEP we fabricated 3D BC-SRRs on a GaAs (\(\varepsilon_{GaAs} = 12.9\)) substrate. THz-TDS characterization and numerical simulations were performed on three samples with different distances \(d\) between two SRRs as shown in Fig. 5. The BC-SRRs capacitance is dominated by the coupling between the two rings and depends significantly on the distance between the rings. Compared to the single SRR, this increased capacitance shifts the fundamental resonance to a lower frequency resulting in a smaller electrical size. In Fig. 5(a), we show experimental and simulated redshifting as a function of decreasing distance. With a 12-\(\mu m\) distance \(d\), the electric size at 0.71 THz is about 1/9 of the corresponding wavelength. Note that \(d\) is the distance
between the center of the two SRRs, so that the distance between their edges is only 6 \mu m.

Figure 5(b) shows the parameter retrieval for the BC-SRRs with d = 12 \mu m. For an ideal free standing BC-SRR, the inversion symmetry eliminates bianisotropy at the unit cell level (in contrast to the single ring structures in Fig. 1 and 3, for BC-SRRs this would hold for any angle of incidence). Nonetheless, Fig. 5(b) reveals a bianisotropic response that is several times larger than the single SRR on polyimide. These results seem counterintuitive, but given our discussion in Fig. 4, this can be understood as being induced by the substrate, highlighting that even highly symmetric structures such as BC-SRRs require extreme care to fully characterize and understand the electromagnetic response.

4. Conclusion

In summary, using a multilayer electroplating technique, we have successfully demonstrated 3D metamaterials at THz frequencies. This technique can create metamaterials on silicon and flexible polyimide, and broadside-coupled SRRs. Under the normal incidence, these metamaterials are magnetically excited and show a negative permeability over a broad band. The parameters retrieval also shows a substrate induced bianisotropic response, which is highly dependent on the substrate permittivity. Our approach enables fabrication of complex 3D metamaterials and
can be easily extended to numerous other structures.

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