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Electrically resonant terahertz metamaterials: Theoretical and experimental investigations

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We present a class of artificial materials that exhibit a tailored response to the electrical component of electromagnetic radiation. These electric metamaterials are investigated theoretically, computationally, and experimentally using terahertz time-domain spectroscopy. These structures display a resonant response including regions of negative permittivity $\epsilon_1(\omega)<0$ ranging from ~500 GHz to 1 THz. Conventional electric media such as distributed wires are difficult to incorporate into metamaterials. In contrast, these localized structures will simplify the construction of future metamaterials, including those with negative index of refraction. As these structures generalize to three dimensions in a straightforward manner, they will significantly enhance the design and fabrication of functional terahertz devices.

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Shaped dielectric and conducting materials which control the electric component of electromagnetic fields with a designed response have been known for many decades.[1–3] Recently, these "artificial dielectrics" have found renewed interest in the burgeoning field of electromagnetic metamaterials (EM MMs).[4] The excitement about EM MMs stems from the ability of these materials to exhibit an electromagnetic response not readily available in naturally occurring materials including, as examples, negative refractive index[5,6] and artificial magnetism.[7] However, such exotic phenomena only became possible following the realization that artificial materials could be designed to exhibit an effective material response to electric[8] and magnetic fields.[7] To date, artificial magnetic metamaterials have been experimentally demonstrated over several decades of frequency ranging from radio frequencies[9] to terahertz[10] and near infrared frequencies.[11]

The most common element utilized for magnetic response is the split ring resonator (SRR). Since SRRs were first used to create negative index media, important advances have been realized. Researchers have demonstrated designs with higher symmetry,[12] non-planar structures,[13] and generalization to two[6] and three dimensions.[14] In contrast, purely electric metamaterials have experienced little improvement over the past 60 years and conducting wires have primarily been the medium of choice. Wires have a potential for some tunability, i.e., a modified plasma frequency can be obtained by making extremely thin wires[8] or by adding loops, thus increasing their inductance.[15] However, recent research has shown that wire arrays are not desirable in many ways.[16] Limiting factors include the necessity of inter-unit-cell connections and specific surface terminations.[17] For many applications, it would be preferable to have a localized particle with finite extent from which one could construct materials with an electric response.

In principle, the SRR can also be used as an electrically resonant particle as it exhibits a strong resonant permittivity at the same frequency as the magnetic resonance.[18] However, the electric and magnetic resonant responses are coupled, resulting in rather complicated bianisotropic electromagnetic behavior.[19,20] The development of more symmetric designs, which can be predicted by group theoretical methods, eliminates any magneto-optical coupling effects related to bianisotropy and yields electrically resonant structures.[21] Furthermore, in the symmetric particles the magnetic response is suppressed. Thus, such elements will function as localized particles from which one can construct a purely electrical resonant response.

In this Rapid Communication we describe a series of uniaxial and biaxial electric metamaterials. The design of these symmetric structures accomplishes the goal of creating a class of subwavelength particles which exhibit a resonant response to the electric field while minimizing or eliminating any response to the magnetic field. Planar arrays of these structures targeted for the THz frequency regime have been simulated, fabricated, and characterized in transmission. Each of the EM MM structures show a resonant response including a region of negative permittivity $\epsilon_1(\omega)<0$. We discuss the advantages of these localized particles in comparison to conventional wire-segment electric media. In particular, these structures will ease the burden of fabricating additional metamaterial devices including those exhibiting a negative index of refraction.

Our EM MMs are fabricated in a planar array by conventional photolithographic methods and consist of 200-nm-thick gold with a 10-nm-thick adhesion layer of titanium on semi-insulating gallium arsenide (GaAs) substrates of 670 μm thickness. All of the EM MMs have an outer dimension of 36 μm, a lattice parameter of 50 μm, a linewidth of 4 μm, and a gap of 2 μm. The arrays are char-

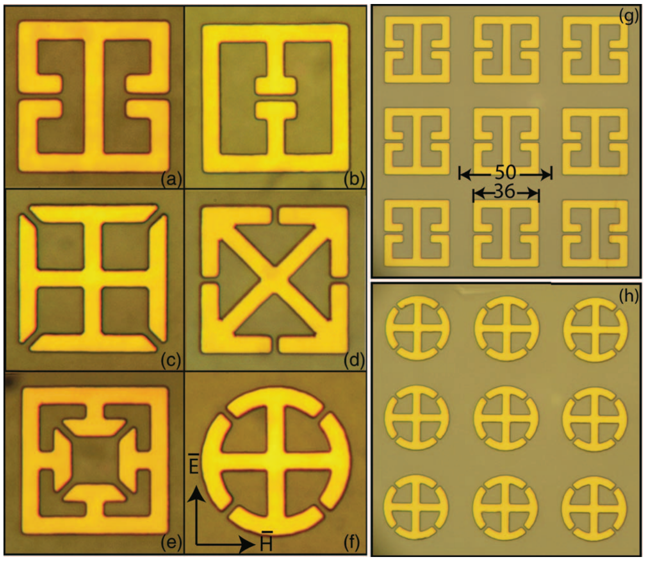

FIG. 1. (Color) Photographs of the electric metamaterials characterized in this study. The pictures of individual unit cells of EM MMs in (a)–(f) are termed, in the text, E_1-E_6, respectively. In (a) and (b) we show EM MMs with a resonant electric response when the electric field is polarized vertically. (c)–(f) show EM MMs which exhibit a electric response where the electric field can be polarized vertically or horizontally, or unpolarized. In (g) and (h) photographs with an expanded view of the samples shown in (a) and (f) demonstrate how the individual particles are arranged into an array. For this study, the polarization of the incident electromagnetic radiation is shown in (f), and two characteristic lengths are shown in (g) where the dimensions are in micrometers.

acterized utilizing THz time domain spectroscopy (TDS) at normal incidence.[22] The time dependence of the electric field is measured and the complex transmissivity is obtained from which we calculate the complex dielectric function $\tilde{\epsilon}(\omega)=\epsilon_1+i\epsilon_2$, assuming a cubic unit cell.[18] The group-theoretical analysis[21] is supplemented with finite-element numerical simulations of the EM MMs using commercial code and Lorentz oscillator fits to the data.

In Fig. 1 we show photographs of the electric metamaterials characterized in this study. As mentioned above, each of these particles is designed[21] to exhibit a resonant response to the electric field while minimizing or eliminating any response to the magnetic field. In Fig. 2 we show simulation and experimental results. The second column shows the calculated surface current density which provides a simple way to visualize the absence of a magnetic response; namely, the magnetic fields created by circulating surface currents cancel due to clockwise and counterclockwise components in adjacent regions of the particle. Thus, any resonant response must necessarily be of electrical origin since there is no net circulation of current in each unit cell. The third column shows the norm of the electric field at resonance. The red regions in the gap indicate a strong local field enhancement which, according to the simulations, can be upwards of 10^4 of the incident field. The last two columns of Fig. 2 show the experimentally measured field transmission $T(\omega)$ and the real part of the dielectric function $\epsilon_1(\omega)$, respectively. Each structure exhibits a very strong resonance with the transmission decreasing to as little as $\sim 10\%$. Additionally, all of the EM MMs characterized in this study display regions of negative permittivity.

In Table I we summarize some characteristic parameters related to the $\epsilon(\omega)$ response. A Drude-Lorentz model[23] was used to fit the $\epsilon_1(\omega)$ data, from which we extract ω_0, which is the center frequency, and ω_p, which is the frequency of the zero crossing of $\epsilon_1(\omega)$. In addition, we list the minimum value of ϵ_1, the oscillator strength $(S=\omega_p^2/\omega_0^2)$, the percentage bandwidth over which $\epsilon_1<0$ is achieved, and the ratio of the free space wavelength to the unit-cell length, λ_0/a.

Next we compare these electrically resonant particles with wires, which are the canonical electric metamaterial.[8,15] As mentioned, typical electric metamaterials utilize straight wires which can be thought of as a bulk metal with a reduction in the effective electron density due to the reduction in volume fraction of the metal. A bulk metal has free electrons that screen external EM fields from penetrating inside the material for frequencies below the plasma frequency, defined as $\omega_p^2=4\pi ne^2/m^*$, where n is the effective electron density and m^* is the effective mass. For an electric field polarized along the wire axis an effective medium response is obtained with a modified plasma frequency. Wires can also be formed with loops to add additional inductance to increase carrier mass and reduce the plasma frequency.[15] Lastly, cuts can be added periodically along the wires to obtain a Drude-Lorentz response for added tunability. However, as discussed above, wires have disadvantages which can limit their functionality as electric metmaterials.

We now highlight several advantageous features of these electric metamaterials which principally derive from their symmetry and localized extent. For THz metamaterials with characteristic lengths $a=50$ μm, the samples are easily fabricated with standard optical lithographic methods. The EM MMs shown in Figs. 1(c)–1(f) do not show polarization sensitivity, and thus a simple single normal incidence transmission measurement is all that is required to characterize their full electromagnetic behavior. As mentioned, samples in Figs. 1(a) and 1(b) lack fourfold rotational symmetry and thus exhibit a different electric response for polarizations shown in Fig. 1 versus polarizations rotated 90° to this (not shown). Issues related to connectivity (as for wires) do not arise since the resonant response derives from particles within individual unit cells. Wires in two and three dimensions, from a fabrication viewpoint, are extremely difficult to implement. However, the electric structures presented here generalize to higher dimensions in a simple and straightforward manner, similar to SRRs.[7] As mentioned above, E_1-E_6 do not exhibit a magnetic response near the resonant frequency (i.e., $\mu=1$). Thus, these particles are natural complements to magnetically active SRRs meaning that it is possible to create negative index materials through appropriate combinations of these two varieties of subwavelength particles.

Although the thickness of the samples characterized in this study was relatively thin (200 nm), E_1-E_6 yielded regions of negative permittivity and decent bandwidth. We note that there are several simple ways to improve the response of the EM MMs in this study, namely, thicker

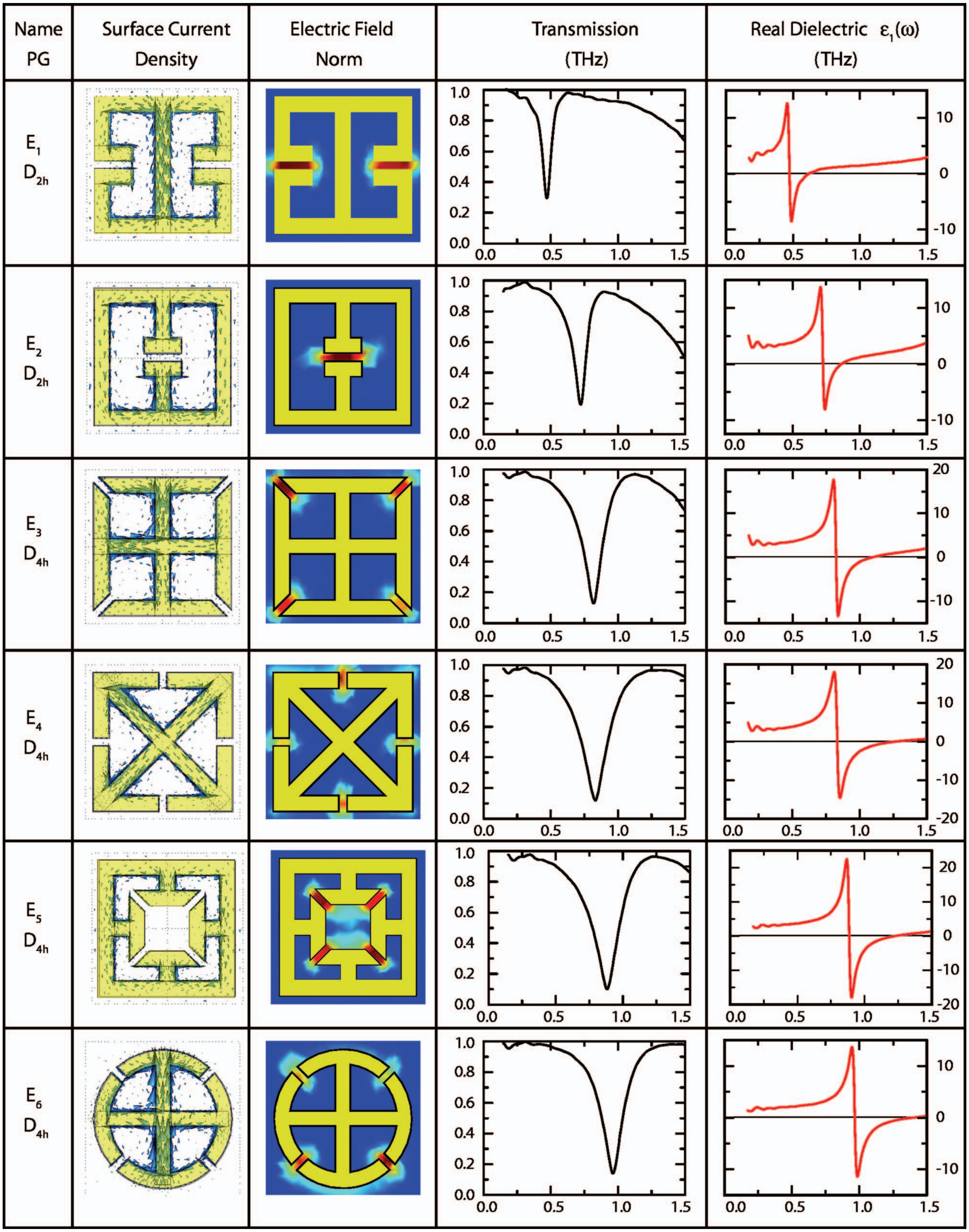

FIG. 2. (Color) Simulation and experimental results for electric metamaterial particles. The left column lists the names of particles as we address them in this article and the point group in Shoenflies notation. The second and third columns show the surface current density and norm of the electric field at resonance, respectively. The last columns show the experimentally measured transmission $T(\omega)$ and the real part of the dielectric function $\epsilon_1(\omega)$.

TABLE I. Key parameters quantifying the electric response of metamaterials characterized in this study. Columns 2 and 3 show the center frequency of the oscillator ω_0 and the zero crossing of the epsilon response ω_p, respectively. The fourth column lists the minimum value of ϵ_1 and the fifth column the oscillator strength. Column six displays the region over which $\epsilon_1 < 0$ is achieved in terms of bandwidth (BW) normalized by ω_0. The last column lists the ratio of the free space wavelength at resonance ($\lambda_0 \sim \omega_0^{-1}$) to the unit-cell length (a=50 μm), an indication of how deep into the effective medium regime the materials are.

Name	ω_0 (THz)	ω_p (THz)	min ϵ_1	$S=\omega_p^2/\omega_0^2$	BW (%)	λ_0/a
E_1	0.473	0.615	−8.55	1.69	30.0	12.7
E_2	0.724	0.862	−8.06	1.42	19.1	8.3
E_3	0.822	1.092	−13.4	1.76	32.8	7.3
E_4	0.834	1.264	−14.5	2.30	51.6	7.2
E_5	0.885	1.220	−17.9	1.90	27.5	6.8
E_6	0.966	1.396	−11.5	2.09	44.5	6.2

samples, increased filling fraction, extension to multiple-layer structures, and utilization of higher-conductivity metals. However, the results presented in Fig. 2 and Table I clearly show that the present metamaterials already display a pronounced and functional terahertz response which, when combined with magnetically resonant SRRs, will facilitate this approach to creating negative index metamaterials.

At terahertz frequencies there is a lack of intrinsic response from natural materials, known as the "THz gap."[24] Taking advantage of this void in THz electromagnetic material response is desirable for many potential applications such as personnel and luggage screening, explosives detection, and all weather imaging. The initial demonstration of several electric metamaterials at THz frequencies highlights their usefulness and versatility. These structures can be expected to play an important role in filling the THz gap.

In conclusion, we have presented designs for metamaterials that exhibit a tailored resonant electrical response investigated using THz time domain spectroscopy. The samples offer significant advantages over current electric metamaterials, in terms of fabrication as well as characterization. Each of the EM MMs characterized in this study exhibits a negative dielectric response, which may be useful for future devices. Further, EM-MM may be constructed to exhibit a polarization-sensitive response. These electric metamaterials will significantly ease the burden of construction for future negative index metamaterial devices, and their initial demonstration at THz frequencies highlights their potential as functional electromagnetic materials.

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