Novel electrically resonant terahertz metamaterials

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We present a new class of artificial materials which exhibit a tailored response to the electrical component of electromagnetic radiation. These electric metamaterials (EM-MMs) 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 $\sim$500 GHz to 1 THz. Conventional electric media such as distributed wires are difficult to incorporate into metamaterials. In contrast, these new localized structures will simplify the construction of future metamaterials - including those with negative index of refraction - and will enhance the design and fabrication of functional THz devices.

Shaped dielectric and conducting materials which control the electric component of electromagnetic fields with a designed response have been known for many decades. Recently, these “artificial dielectrics” have found renewed interest in the burgeoning field of electromagnetic metamaterials (EM-MMs). Excitement in 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, and artificial magnetism. However, such exotic phenomena only became possible following the realization that artificial materials could be designed to exhibit an effective material response to electric and magnetic fields. To date, artificial magnetic metamaterials have been experimentally demonstrated over several decades of frequency ranging from radio frequencies to THz and near infrared frequencies.

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, non-planar structures, and generalization to two and three dimensions. 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 or by adding loops thus increasing their inductance. However, recent research has shown that wire arrays are not desirable in many ways. Limiting factors include the necessity of inter unit cell connections and specific surface terminations. 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. However, the electric and magnetic resonant responses are coupled resulting in rather complicated bianisotropic electromagnetic behavior. The development of more symmetric designs, which can be predicted by group theoretical methods, eliminate any magneto-optical coupling effects related to bianisotropy and yield electrically resonant structures. Furthermore, in the symmetric particles the magnetic response is suppressed. Thus, such elements would function as localized particles from which one can construct a purely electrical resonant response.

In this letter we describe a series of new uniaxial and biaxial electric metamaterials. The design of these symmetric structures accomplishes the goal of creating a class of sub-wavelength particles which exhibit a resonant response to the electric field while minimizing or eliminating any response to the magnetic field. Planar arrays of these new structures targeted for the THz frequency regime have been simulated, fabricated and characterized in transmission. Each of the EM-MMs structures show a resonant response including a region 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 new structures will ease the burden of fabricating new metamaterials 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 line width of 4 μm, and a gap of 2 μm. The arrays are characterized utilizing THz time domain spectroscopy (THz-TDS) at normal incidence. The time dependence of the electric field is measured and the complex transmissivity is obtained from which we calculate the complex dielectric function \( \tilde{\epsilon}(\omega) = \epsilon_1 + i\epsilon_2 \). The group-theoretical analysis 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 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 counter-clockwise 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 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 ~10 percent. 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 was used to fit the \( \epsilon_1(\omega) \) data, from which we extract \( \omega_0 \) which is the center frequency, and \( \omega_p \) which is the frequency of the zero-crossing of \( \epsilon_1(\omega) \). In addition, we list the minimum value of \( \epsilon_1 \), 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 \( \lambda_0/a \).

### Table I: Key parameters quantifying the electric response of metamaterials characterized in this study.

| Name | \( \omega_0 \) (THz) | \( \omega_p \) (THz) | \( \min \epsilon_1 \) | \( S = \omega_p^2/\omega_0^2 \) | BW (%) | \( \lambda_0/a \) |
|------|----------------------|----------------------|----------------------|----------------------|---------|----------------------|
| E_1  | 0.480                | 0.587                | -1.63                | 1.50                 | 22.3    | 12.5                 |
| E_2  | 0.730                | 0.837                | -1.50                | 1.31                 | 14.7    | 8.2                  |
| E_3  | 0.826                | 1.046                | -2.80                | 1.60                 | 20.6    | 7.3                  |
| E_4  | 0.840                | 1.178                | -3.12                | 1.97                 | 40.2    | 7.1                  |
| E_5  | 0.892                | 1.152                | -3.26                | 1.67                 | 29.1    | 6.7                  |
| E_6  | 0.972                | 1.270                | -2.08                | 1.71                 | 30.7    | 6.2                  |
FIG. 2: Simulation and experimental results for new 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 experimental the experimentally measured transmission $T(\omega)$ and real part of the dielectric function $\epsilon(\omega)$. 

| Name PG | Surface Current Density | Electric Field Norm | Transmission (THz) | Real Dielectric $\epsilon(\omega)$ (THz) |
|---------|-------------------------|---------------------|-------------------|-----------------------------------------|
| $E_1$ $D_{2h}$ | ![Image](image1) | ![Image](image2) | ![Graph](graph1) | ![Graph](graph2) |
| $E_2$ $D_{2h}$ | ![Image](image3) | ![Image](image4) | ![Graph](graph3) | ![Graph](graph4) |
| $E_3$ $D_{2h}$ | ![Image](image5) | ![Image](image6) | ![Graph](graph5) | ![Graph](graph6) |
| $E_4$ $D_{2h}$ | ![Image](image7) | ![Image](image8) | ![Graph](graph7) | ![Graph](graph8) |
| $E_5$ $D_{2h}$ | ![Image](image9) | ![Image](image10) | ![Graph](graph9) | ![Graph](graph10) |
| $E_6$ $D_{2h}$ | ![Image](image11) | ![Image](image12) | ![Graph](graph11) | ![Graph](graph12) |
with loops to add additional inductance to increase carrier mass and reduce the plasma frequency.\cite{24} 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 metamaterials.

We now highlight several advantageous features of these new electric metamaterials which principally derive from their symmetry and localized extent. For THz metamaterials with characteristic lengths  \(a=50\mu m\), the samples are easily fabricated with standard optical lithographic methods and a simple normal incidence transmission measurement is all that is required to characterize their full electromagnetic behavior. 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.\cite{2} 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 samples, increased filling fraction, extension to multiple layer structures, and utilization of higher conductivity metals. However, the results presented in Figure\cite{2} and Table\cite{1} clearly show that the present metamaterials already display a pronounced and functional terahertz response which, when combined with magnetically resonant SRRs, will facilitate a new approach to creating negative index metamaterials.

At terahertz frequencies there is a lack of intrinsic response from natural materials, known as the “THz gap”.\cite{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 new electric metamaterials at THz frequencies highlights their usefulness and versatility. These new structures can be expected to play an important role filling in the THz gap.

In conclusion, we have presented new 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, both in terms of fabrication as well as characterization. Each of the EM-MMs characterized in this study exhibit a negative dielectric response, which may be useful for future devices. Further, EM-MMs 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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