Terahertz Magnetic Response from Artificial Materials

T. J. Yen,1* W. J. Padilla,2* N. Fang,1* D. C. Vier,2 D. R. Smith,2 J. B. Pendry,3 D. N. Basov,2 X. Zhang1†

We show that magnetic response at terahertz frequencies can be achieved in a planar structure composed of nonmagnetic conductive resonant elements. The effect is realized over a large bandwidth and can be tuned throughout the terahertz frequency regime by scaling the dimensions of the structure. We suggest that artificial magnetic structures, or hybrid structures that combine natural and artificial magnetic materials, can play a key role in terahertz devices.

The range of electromagnetic material response found in nature represents only a small subset of that which is theoretically possible. This limited range can be extended by the use of artificially structured materials, or metamaterials, that exhibit electromagnetic properties not available in naturally occurring materials. For example, artificial electric response has been introduced in metallic wire grids or cell meshes, with the spacing on the order of wavelength (1); a diversity of these meshes are now used in THz optical systems (2). More recently, metamaterials with subwavelength scattering elements have shown negative refraction at microwave frequencies (3), for which both the electric and magnetic properties are simultaneously negative. The negative-index metamaterial rely on an earlier theoret-ical prediction that an array of nonmagnetic conductive resonant elements, and converters. A few natural magnetic materials that respond above microwave frequencies have been reported. For example, certain ferromagnetic and antiferromagnetic systems exhibit a magnetic response over a frequency range of several hundred gigahertz (5–7) and even higher (8, 9). However, the magnetic effects in these materials are typically weak and often exhibit narrow bands (10), which limits the scope of possible THz devices. The realization of magnetism at THz and higher frequencies will substantially affect THz optics and their applications (11).

From a classical perspective, we can view a magnetic moment as being generated by microscopic currents that flow in a circular path. Such solenoidal currents can be induced, for example, by a time-varying magnetic field. Although this magnetic response is typically weak, the introduction of a resonance into the effective circuit about which the current flows can markedly enhance the response. Resonant solenoidal circuits have been proposed as the basis for artificially structured magnetic materials (12), although they are primarily envisaged for lower radio-frequency applications. With recent advances in metamaterials, it has become increasingly feasible to design and construct systems at microwave frequencies with desired magnetic and/or electric properties (3, 13, 14). In particular, metamaterials promise to extend magnetic phenomena because they can be designed to

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1*Department of Mechanical and Aerospace Engineering, University of California at Los Angeles, 420 Westwood Plaza, Los Angeles, CA 90095, USA. 2Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093–0319, USA. 3Condensed Matter Theory Group, The Blackett Laboratory, Imperial College, London SW7 2AZ, UK.

†These authors contributed equally to this work.

*To whom correspondence should be addressed. E-mail: xiang@seas.ucla.edu

References and Notes
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work at high frequencies with broad bandwidth and tunability and can attain large positive or negative values of the magnetic permeability.

A magnetic metamaterial can be formed from an array of nonmagnetic, conducting, split-ring resonators (SRRs) (Fig. 1). An SRR consists of two concentric annuli of conducting material, each with a gap situated oppositely. The gaps enable the structure to be resonant at wavelengths much larger than its physical dimensions, and the combination of many SRRs into a periodic array allows the material to behave as a medium with an effective magnetic permeability \( \mu_{\text{eff}}(\omega) \), where \( \omega \) is frequency. The origin of the effective permeability enhancement stems from a resonance in the SRR, associated with the inductance corresponding to the gaps within and between the rings.

The effective permeability can be expressed in the form (4, 15)

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\mu_{\text{eff}}(\omega) = 1 - \frac{F \omega^2}{\omega^2 - \omega_0^2 + i\Gamma \omega} = \mu'_{\text{eff}}(\omega) + i\mu''_{\text{eff}}(\omega)
\]

where \( F \) is a geometrical factor, \( \omega_0 \) is the resonance frequency, \( \Gamma \) is the resistive loss in the resonating SRR, and \( \mu'_{\text{eff}} \) and \( \mu''_{\text{eff}} \) are the real and imaginary magnetic permeability functions. In the quasi-static limit, the qualitative picture of this magnetic response is straightforward: The external magnetic field with a varying flux normal to the metallic loop will induce a current (Fig. 1) and the currents generated in the loops can no longer keep up with the external field and begin to lag. As the frequency increases above \( \omega_0 \), the induced dipole moment lags further until it is completely out of phase with the excitation field, which results in a magnetic permeability smaller than unity (i.e., a diamagnetic response), including values less than zero. In contrast to conventional ferromagnetism, the magnetic activity associated with these conductive elements is completely devoid of any permanent magnetic moment.

In order to obtain magnetic resonant behavior in the THz range, the appropriate dimensions of the SRRs can be first approximated by analytical methods (4) and then confirmed by numerical simulation. We designed and constructed three different SRR samples on a 400-μm-thick quartz substrate by a self-aligned microfabrication technique called photo-proliferated process (16). The SRRs are made from copper and are 3 μm thick. Their periodicity is subwavelength (λ/7 in our samples, where \( \lambda \) is the wavelength of the excited field at resonance frequency), which allows the composite to behave as an effective medium to external THz radiation (17). Most reported works on microwave metamaterials have focused on characterizing bulk one- and two-dimensional structures, in which waveguide configurations are frequently used. At the submillimeter wavelengths associated with THz frequencies, optical components such as lenses and mirrors are commonly used, making a free-space characterization more convenient to pursue (Fig. 1). We performed the measurements here using spectroscopic ellipsometry at oblique incidence. A Fourier transform infrared spectrometer adapted for S-polarized (Fig. 1) and P-polarized light from 0.6 THz to 1.8 THz was used for the measurements, with a silicon bolometer as the detector. We placed the sample within an evacuated compartment, then focused light from a mercury arc lamp source on the substrate at an angle of 30° from the surface normal.

In the frequency-dependent ellipsometry measurements (Fig. 2), the parameter plotted, \( \tan^2(\Psi) \), represents the inverse absolute square of the ellipsometric parameter \( \rho(\omega) = \tan(\Psi)\exp(\Delta) \), where \( \Psi \) is the amplitude ratio and \( \Delta \) is the phase difference. This ellipsometric parameter displays the reflectance ratio of two polarizations. The SRRs are expected to respond magnetically when the magnetic field penetrates the rings (S-polarization) (Fig. 1) and exhibit no magnetic response when the magnetic field is parallel to the plane of the SRR (P-polarization). Thus, the reflectance ratio (Fig. 2) is the natural function to use, because this parameter provides the ratio of the magnetic to electric response from the SRRs (17).

The reflectance ratio for sample D1 (Fig. 2, red curve) exhibits a resonant peak, centered at ~1.25 THz in the spectrum. The resonance in the reflectance was broad, nearly 30% of the bandwidth of its center frequency. If the magnetic response was due to the constituent SRRs, then this resonance should scale with dimensions in accordance to Maxwell’s equations. In order to elucidate our findings, two more SRRs with different dimensions were characterized (Fig. 2). These SRRs all exhibit a similar magnetic mode, and their resonant frequencies occur between 0.8 and 1.0 THz. We found an expected monotonic redshifting of resonant frequencies as the dimensions of SRRs were scaled up. In addition, the bandwidth of the magnetic response could be tuned by adjusting the parameters of the SRR element.

As further verification that the peaks in Fig. 2 were due to the magnetic response of the SRRs, we performed a numerical simulation using High-Frequency Structure Simulator (HFSS), a commercial electromagnetic mode solver. S-parameter transmission and reflection were calculated as a function of frequency for a periodic infinite array of copper SRRs with the dimensions of the three designed samples (Fig. 2). The calculation was performed to determine the frequency of the resonant magnetic response of the SRRs, for comparison to the ellipsometry measurements (18). The results of the simulation and experimental curves were in good agreement. In Fig. 3, we display the simulated real and imaginary portions of the effective magnetic permeability that corresponds to

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Fig. 2. (Top) The ratio of the magnetic to electric response (described in the text) for three different artificial magnetic structures, D1, D2, and D3 (the red, black, and blue solid curves, respectively), in the THz frequency range. (Bottom) Theoretical magnetic response, as determined by simulation for each SRR (described in the text), \( r_s \) and \( r_p \) are the complex reflection coefficients of the S- and P-polarized light.

Fig. 3. (Top) The ratio of the magnetic to electric response replotted from Fig. 2. Middle and (bottom) the real (\( \mu'_{\text{eff}} \)) and imaginary (\( \mu''_{\text{eff}} \)) magnetic permeability functions as simulated by HFSS for samples D1 (red), D2 (black), and D3 (blue).
samples D1, D2, and D3. For sample D1, the onset of the simulated imaginary permeability peak occurs at ~1.15 THz, which corresponds well with the onset of the experimental peak in tan^{-2}(\psi). The noticeable difference in the actual peak locations is to be expected, because tan^{-2}(\psi) consists of ratios of absolute values; i.e., the resonance width observed is dependent on the strength of the oscillator. Thus, it is important when considering tan^{-2}(\psi) and \mu_{eff}(\omega) to compare the onset of the resonances.

The scalability of these magnetic metamaterials throughout the THz range and potentially into optical frequencies promises many applications, such as biological (19) and security imaging, biomolecular fingerprinting, remote sensing, and guidance in zero-visibility weather conditions. Additionally, the effect is nearly an order of magnitude larger than that obtained from natural magnetic materials (20). Structures with a negative magnetic response, when combined with plasmonic wires that exhibit negative electric permittivity (21–24), should produce a negative refractive index material at these very high frequencies, enabling the realization of needed devices in the THz regime.

References and Notes
16. Materials and methods are available as supporting material on Science Online.
17. SRRs also have an electric response in both the P- and S-polarized measurements. This electric contribution is about the same for both polarizations, thus a further advantage of the reflectance ratio measurements is that the electric response is minimized.
18. For ease of calculation and maximum magnetic response, the propagation of the incident radiation was parallel to the plane of the SRRs (90° to the surface normal of Fig. 1). The electrical conductivity used for the copper elements was \sigma = 5.8 \times 10^7 S/m; for the quartz substrate, we used a dielectric constant of 3.78. The normal component of effective magnetic permeability \mu_{eff}(\omega) can be extracted from the S-parameter simulation results (25) and used to calculate the expected theoretical reflectance ratio tan^{-2}(\psi) (Fig. 2, bottom) (26).
20. The individual S- and P-polarization data were fit with the standard Lorentzian form for a resonance. The oscillator strength S can be extracted from the fits, and we found values around S = 0.6. This is a large effect in comparison with values we calculated from natural magnetic materials, such as FeF_2, which has a value of S = 0.07.
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Discovery of Ancient Silicate Stardust in a Meteorite
Ann N. Nguyen* and Ernst Zinner

We have discovered nine presolar silicate grains from the carbonaceous chondrite Acfer 094. Their anomalous oxygen isotopic compositions indicate formation in the atmospheres of evolved stars. Two grains are identified as pyroxene, two as olivine, one as a glass with embedded metal and sulfides (GEMS), and one as an Al-rich silicate. One grain is enriched in 26Mg, which is attributed to the radioactive decay of 26Al and provides information about mixing processes in the parent star. This discovery opens new means for studying stellar processes and conditions in various solar system environments.

*To whom correspondence should be addressed. E-mail: nguyen@wustl.edu