Highly-flexible wide angle of incidence terahertz metamaterial absorber

Hu Tao, 1 C. M. Bingham, 2 A. C. Strikwerda, 3 D. Pilon, 3 D. Shrekenhamer, 2
N. I. Landy, 2 K. Fan, 1 X. Zhang, 1, * W. J. Padilla, 2 and R. D. Averitt 3, †

1 Boston University, Department of Manufacturing Engineering,
15 Saint Mary’s Street, Brookline, Massachusetts, 02446

2 Boston College, Department of Physics,
140 Commonwealth Ave., Chestnut Hill, MA 02467

3 Boston University, Department of Physics,
590 Commonwealth Ave, Boston, Massachusetts, 02215

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Abstract

We present the design, fabrication, and characterization of a metamaterial absorber which is resonant at terahertz frequencies. We experimentally demonstrate an absorptivity of 0.97 at 1.6 terahertz. Importantly, this free-standing absorber is only 16 microns thick resulting in a highly flexible material that, further, operates over a wide range of angles of incidence for both transverse electric and transverse magnetic radiation.
The initial impetus driving metamaterials research was the realization that a negative refractive index \( n(\omega) = \sqrt{\varepsilon(\omega)\mu(\omega)} \) could be obtained by creating subwavelength composites where the effective permittivity \( \varepsilon(\omega) \) and effective permeability \( \mu(\omega) \) are independently specified \[1\], \[2\], \[3\]. Additionally, metamaterials allow for tailoring the impedance \( Z(\omega) = \sqrt{\mu(\omega)/\varepsilon(\omega)} \) in a manner not easily achieved with naturally occurring materials. This newfound approach to engineering \( n(\omega) \) and \( Z(\omega) \) offers unprecedented opportunities to realize novel electromagnetic responses from the microwave through the visible. This includes cloaks, concentrators, modulators, spoof plasmons, with many more examples certain to be discovered in the coming years \[4\], \[5\], \[6\], \[7\], \[8\], \[9\].

Quite recently, there has been considerable interest in creating resonant metamaterial absorbers which, through judicious design of \( n(\omega) \) and \( Z(\omega) \), offer the potential for near unity absorption \[10\], \[11\], \[12\]. The idea is to minimize the transmission and to simultaneously minimize, through impedance matching, the reflectivity. This has been experimentally demonstrated at microwave and terahertz frequencies \[10\], \[11\], \[12\]. Recently, other approaches have been theoretically put forward to extend these ideas to higher frequencies or to increase range of angles of incidence over which the absorptivity remains sufficiently large for applications \[13\], \[14\], \[15\].

While the idea of designing a resonant absorber could be of potential use throughout the electromagnetic spectrum, this concept is expected to be especially fruitful at terahertz frequencies where it is difficult to find strong absorbers. Such absorbers would clearly be of use for thermal detectors or as a coating material to mitigate spurious reflections using continuous wave sources such as quantum cascade lasers \[10\], \[11\], \[16\], \[17\]. Progress has been promising where the initial design yielded an absorptivity of 0.70 at 1.3 THz \[11\]. This work has been extended to a polarization insensitive design with a demonstrated absorptivity of 0.65 at 1.15 THz \[12\].

In this letter, we experimentally demonstrate a resonant metamaterial with an absorptivity of 0.97 at 1.6 THz. In comparison to previous designs \[11\], \[12\], the current design has several important advantages. Most importantly, the present design is on a freestanding highly-flexible polyimide substrate 8\( \mu \)m thick which enables its use in nonplanar applications as it can easily be wrapped around objects as small a 6 mm in diameter. In addition, we demonstrate, through simulation and experiment, that this metamaterial absorber operates over a very wide range of angles of incidence for transverse electric (TE) and transverse
FIG. 1: THz metamaterial absorber consisting of two metallic layers and two dielectric layers. (a) Electric SRR: unit cell a: 36µm, SRR side length b: 25.9µm, capacitor length c: 10.8 µm, capacitor gap g: 1.4µm, line width w: 3µm. (b) Perspective view of the absorber. Each dielectric layer $t_1$ and $t_2$ is 8µm thick. (c) Photograph of a portion of the experimentally realized absorber.

Maximizing the absorption $A$ is equivalent to minimizing both the transmission $T$ and reflectivity $R$ in that $A = 1 - T - R$. As has been demonstrated [12], in the limit that impedance matching to free space is achieved (i.e. $Z = Z_o$ resulting in $R = 0$), the transmission reduces to $T = \exp(-2n_2dk) = \exp(-\alpha d)$ where $k$ is the free space wave vector, $d$ is the sample thickness, $n_2$ is the imaginary part of the refractive index, and $\alpha$ is the absorption coefficient. Thus, impedance matching is a crucial step yielding a transmission that is determined solely by the losses in the slab of thickness $d$. In the case of a metamaterial absorber the effective $n_2$ is determined by $\epsilon(\omega)$ and $\mu(\omega)$. Thus, the design of a near-unity resonant metamaterial absorber, $\epsilon(\omega)$ and $\mu(\omega)$ must be optimized such that, at the desired center frequency, $Z = Z_o$ with $n_2$ as large as possible.
A compact metamaterial absorber consists of two metallic layers separated by a dielectric spacer. The top layer consists of an array of split ring resonators which is primarily responsible for determining \( \epsilon_\omega \) while the bottom metallic layer is designed such that the incident magnetic field drives a circulating currents between the two layers. However, given the strong coupling between the two layers, fine tuning of the geometry is required to obtain the conditions described in the previous paragraph. Fortunately, using full-wave electromagnetic simulation, rapid convergence to a near optimal design is readily achieved.

Figure 1 presents such an optimized design which we have subsequently fabricated and tested. The top layer (Fig. 1(a)) consists of an array of 200 nm thick Au electrically resonant split ring resonators \([18, 19]\), with the dimensions as listed in the figure caption. In the absence of a second metallic layer, this structure yields a pure \( \epsilon_\omega \) response, and can be thought of as an LC circuit as described elsewhere \([18, 19]\). A dielectric spacer layer 8\( \mu \)m thick separates the top and bottom metallic layers. The bottom metallic layer is a continuous 200 nm thick Au film. As Figure 1(b) shows, there is a second 8\( \mu \)m thick dielectric layer which provides mechanical support but, being behind the continuous Au film, does not contribute to the electromagnetic response. Figure 1(c) shows a photograph of a portion of the structure we have fabricated and tested as detailed below.

The optimized structure presented in Figure 1 was obtained through computer simulations using the commercial program CST Microwave Studio\( ^{TM} \) 2006B.04. The frequency domain solver was utilized where the Au portions of the metamaterial absorber was modeled as lossy gold with a frequency independent conductivity \( \sigma = 4.09 \times 10^7 \) S/cm. The 8\( \mu \)m thick dielectric layer was modeled using the experimentally measured value of polyimide as this is what is used in the subsequent fabrication. Specifically, a frequency independent \( \epsilon = \epsilon_1 + i\epsilon_2 = 2.88 + i0.09 \) was used which corresponds to a loss tangent \( \tan(\delta) = \epsilon_2/\epsilon_1 = 0.0313 \) [20]. The amplitude of the transmission \( S_{21} \) and reflection \( S_{11} \) were obtained and the absorption was calculated using \( A = 1-R-T = 1-S_{11}^2-S_{21}^2 \) where, as expected for the present design, \( S_{21} \) is zero across the entire frequency range due to the ground plane. The optimized structure presented in Fig. 1 was obtained (simulating radiation at normal incidence) through parameter sweeps of the dimensions of the SRR and the dielectric spacer thickness. The optimized parameters are those which yielded the lowest reflectivity at the design frequency of 1.6 THz.

The simulated absorption as a function of frequency for the optimized structure (Fig. 1) is presented in Figure 2 for TE (Fig. 2(a)) and TM (Fig. 2(b)) radiation at various angles
FIG. 2: Simulations of the metamaterial absorber showing the absorptivity as a function of frequency at various angles of incidence for (a) TE and (b) TM incident radiation. The insets depict the orientation of the fields with respect to the SRR. The labels for the curves show the angle of incidence and the corresponding peak absorptivity.

of incidence. For the TE case, at normal incidence a peak absorption of 0.999 is obtained. With increasing angle of incidence, the absorption remains quite large and is at 0.89 at 50°. Beyond this there is a monotonic decrease in the absorption as the incident magnetic field can no longer efficiently drive circulating currents between the two metallic layers. There is also a slight frequency shift of $\sim 30$ GHz from 0° to 80°. For the case of TM radiation shown in Fig. 2(b), the absorption at normal incidence is 0.999 at normal incidence and remains greater than 0.99 for all angles of incidence. In this case, the magnetic field can efficiently drive the circulating currents at all angles of incidence which is important to maintain impedance matching. The frequency shift for TM radiation is $\sim 80$ GHz from 0° to 80°. As these simulations reveal, this MM absorber operates quite well for both TE and TM radiation over a large range of angles of incidence.

An additional aspect to consider in the design of metamaterial absorbers are losses in
the constituent materials comprising the structure. As discussed in the introduction, one of 
the design criteria is to obtain a large value of the imaginary part of the effective refractive 
index. This necessitates having some losses in the metal. Losses in the dielectric spacer are 
expected to contribute as well. For example, in the limit of a perfect electric conductor and 
a lossless dielectric, the absorption in the composite in Fig. 1 is zero. However, losses in 
gold are sufficient to yield a strong narrow band resonance as shown in Figure 2.

Fig. 3(a) and (b) show the calculated surface current density for a TE wave at resonance. 
The currents are in opposite directions on SRR and the ground plane as expected for a 
magnetic resonance. Figure 3(c) shows the absorption as a function of frequency for the 
design in Fig. 1. The black curve assumes a lossless dielectric - i.e. tan(\(\delta\)) = 0. In this case, 
the peak absorption is 0.88 which is smaller than the calculations in Figure 2. This suggests 
losses in the dielectric contribute to increasing the absorption. For example, increasing 
tan(\(\delta\)) to 0.04 (blue curve, Fig. 3(c)) increases the absorption to 0.99 which is an increase of 
0.11 in comparison to a lossless dielectric. However, a point of diminishing return is reached 
for larger values of tan(\(\delta\)) (see Fig. 3(c)) in that the absorption decreases and the resonance 
broadens. These results suggest that optimization of tan(\(\delta\)) of the dielectric spacer can 
maximize the metamaterial absorption. Further, it appears the losses in polyimide (tan(\(\delta\)) = 0.0313) should contribute \(\sim 0.1\) to the absorption of our metamaterial absorber as is 
evident by comparing the black curves in Fig. 2(a) and 3(c).

The free standing absorber structures were fabricated with a surface micromachining 
process on flexible polyimide substrate using a silicon wafer as the supporting substrate 
during the fabrication process. Liquid polyimide (PI-5878G, HD MicroSystems\textsuperscript{TM}) was 
spin-coated on a 2 inch silicon wafer to form the free standing substrate. In this work, 
the polyimide was spin-coated at 1,700 rpm and cured for five hours in an oven at 350C 
in a nitrogen environment yielding an 8 \(\mu\)m thick polyimide layer. A 200 nm thick Au/Ti 
film was e-beam evaporated on the polyimide substrate to form the ground plane. Another 
8 \(\mu\)m thick polyimide layer was spin coated on the top of the ground plane to form the 
polyimide spacer and processed according to the procedure mentioned above. For the SRR 
array, direct laser writing technology was chosen over traditional mask contact lithography 
technology to improve the patterning quality on the polyimide substrates. Shipley\textsuperscript{TM} S1813 
positive photoresist was first calibrated and then exposed with a Heidelberg\textsuperscript{TM} DWL 66 
laser writer to pattern the top layer of electric ring resonators. Another 200 nm thick
Au/Ti film was e-beam evaporated followed by rinsing in acetone for several minutes. The metamaterial absorber fabricated on the polyimide substrate was carefully peeled off of the silicon substrate at the end of fabrication. Our samples show great mechanical flexibility and can be easily wrapped around a cylinder with a radius of a few millimeters.

A Fourier transform infrared (FTIR) spectrometer was used to experimentally verify the behavior of the absorber by measuring the transmission and reflection over the frequency range of 0.6 THz to 3 THz with a resolution of 15 GHz. A liquid helium cooled bolometer detector and 6 µm mylar beam splitter were used to optimize the FTIR performance over the frequencies measured. Prior to measurement, the free standing absorber samples were diced into 1 cm × 1 cm squares. The aperture of the incident beam was 5 mm, which is considerably smaller than the sample dimension. The sample was mounted at normal incidence for the transmission measurement. As expected, the transmitted intensity was essentially zero due to the gold ground plane which blocks all radiation through the absorber.
FIG. 4: Experimentally measured absorption as a function of frequency for (a) TE and (b) TM radiation at 30°, 45°, and 60° angles of incidence.

The achievable incident angle for reflection measurements is constrained within the range from 30 to 60 off-normal due to the experimental limitations. The measurements were performed with electric field perpendicular to the SRR gap to excite the electric resonance. The absorption spectrum was easily obtained from the reflection results (i.e. $A = 1 - R$).

The experimental results are displayed in Figure 4(a) and (b) for TE and TM incident radiation, respectively. For the TE radiation, the absorption peaks at 0.95 for an angle of incidence of 30° decreasing slightly to 0.88 at 60°. This is in reasonable agreement with the simulations though the experimental absorptivity at 60° is ~0.09 higher than for simulation. However, the off-resonance absorptivity is quite large in disagreement with the simulations. This may arise, in part, from scattering of radiation from imperfections arising from the fabrication. For the TM measurements the peak absorptivity is 0.968 at 30° angle of incidence and only drops by 0.024 upon increasing to 60°. Further, the increase in the baseline absorption is much smaller in comparison to the TE measurements and is in better agreement with simulations. A closer inspection of Fig. 4(b) also reveals a slight increase
in the resonance frequency with increasing angle of incidence in agreement with simulation. Overall, these results substantially confirm the simulation results demonstrating that our MM absorber yields a large absorptivity over a broad range of angles of incidence for both TE and TM radiation.

In summary, we have presented the design, fabrication, and characterization of a highly flexible metamaterial absorber that, experimentally, obtains an absorptivity of 0.96 at 1.6 THz, and further, operates over wide angular range for TE and TM radiation. Such a composite THz metamaterial may find numerous applications ranging from the active element in a thermal detector to THz stealth technology.

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* Electronic address: xinz@bu.edu
† Electronic address: raveritt@physics.bu.edu

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