

A metamaterial absorber for the terahertz regime: Design, fabrication and characterization

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Abstract: We present a metamaterial that acts as a strongly resonant absorber at terahertz frequencies. Our design consists of a bilayer unit cell which allows for maximization of the absorption through independent tuning of the electrical permittivity and magnetic permeability. An experimental absorptivity of 70% at 1.3 terahertz is demonstrated. We utilize only a single unit cell in the propagation direction, thus achieving an absorption coefficient $\alpha = 2000 \text{ cm}^{-1}$. These metamaterials are promising candidates as absorbing elements for thermally based THz imaging, due to their relatively low volume, low density, and narrow band response.

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The electromagnetic response of natural materials forms the basis for the construction of most modern optoelectronic devices. However, this EM response is not evenly distributed across the electromagnetic spectrum. At frequencies of a few hundred gigahertz and lower, electrons are the principle particles which serve as the workhorse of devices. On the other hand, at infrared through optical / UV wavelengths, the photon is the fundamental particle of choice. In-between these two fundamental response regimes there exists a region comparatively devoid of material response, commonly referred to as the "terahertz gap" (0.1-10 THz, $\lambda=3\text{mm}-30\mu\text{m}$) [1, 2]. Although enormous efforts have focused on the search for "terahertz" materials or alternative novel techniques to enable the construction of device components, much work remains. There is a wide range of natural phenomena that could be probed with terahertz (THz) devices. Specifically, a THz detector would be useful for imaging in areas such as biology [3, 4] and security [5, 6, 7, 8, 9].

Recently, there has been considerable effort to construct engineered electromagnetic materials for operation specifically within the void of natural material response described above

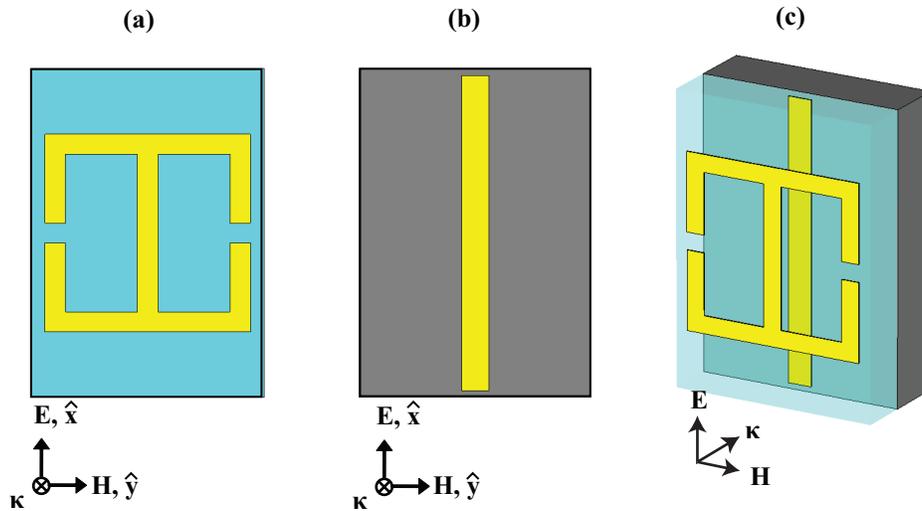


Fig. 1. (color) Schematics of the THz absorber: (a) electric resonator on the top of a polyimide spacer; (b) cut wire on GaAs wafer; (c) single unit cell showing the direction of propagation of incident EM wave. The unit cell is $34 \mu\text{m}$ wide and $50 \mu\text{m}$ in length. The line width and gap of the electric resonator is $3 \mu\text{m}$. The side length of the square electric resonator is $30 \mu\text{m}$, the side length of the cut wire is $48 \mu\text{m}$, and the width of the cut wire is $4 \mu\text{m}$. Thickness of the electric resonant ring and cut wire is 200 nm . The spacer of polyimide is $8 \mu\text{m}$ thick, and the GaAs wafer is $500 \mu\text{m}$ thick.

[10, 11, 12, 13]. These artificial systems, called metamaterials (MMs), are composites whose EM properties originate from oscillating electrons in unit cells comprised of highly conductive and shaped metals such as gold or copper. The sub-wavelength unit cell is replicated to form a material, which allows for a designed resonant response of the metamaterial's electrical and magnetic properties. Metamaterials can be regarded as effective media and characterized by a complex electric permittivity $\tilde{\epsilon}(\omega) = \epsilon_1(\omega) + i\epsilon_2(\omega)$ and complex magnetic permeability $\tilde{\mu}(\omega) = \mu_1(\omega) + i\mu_2(\omega)$. Resonant structures that couple strongly to either the electric [10] or magnetic [11] fields have been demonstrated at terahertz. Significant growth in metamaterial research has been due to efforts to create negative refractive index (NRI) materials [14, 15, 16] and, more recently, invisibility cloaks [17, 18]. As such, the primary focus has been on the index of refraction defined as $\tilde{n}(\omega) = \sqrt{\tilde{\epsilon}(\omega)\tilde{\mu}(\omega)} = n_1 + in_2$, where one desires $n_1 < 0$ for negative index or $0 < n_1 < 1$ for cloaks. To create such structures, it is important to minimize losses over the operating frequency range, which is associated with the imaginary portion of the index, and thus strive for $n_2 \rightarrow 0$. Conversely, for many other applications it would be desirable to maximize the metamaterial loss which is an aspect of metamaterial research that, to date, has received very little attention. A recent example is the creation of a resonant high absorber which has been demonstrated at microwave frequencies [19]. Such an absorber would be of particular importance at terahertz frequencies where it is difficult to find naturally occurring materials with strong absorption coefficients that are also compatible with standard microfabrication techniques. By fabricating bilayer metamaterial structures it becomes possible to simultaneously tune $\tilde{\epsilon}(\omega)$ and $\tilde{\mu}(\omega)$ such that a high absorptivity can be achieved. In principle, this tunability could lead to near unity absorptivity. In practice this is limited by achievable fabrication tolerances.

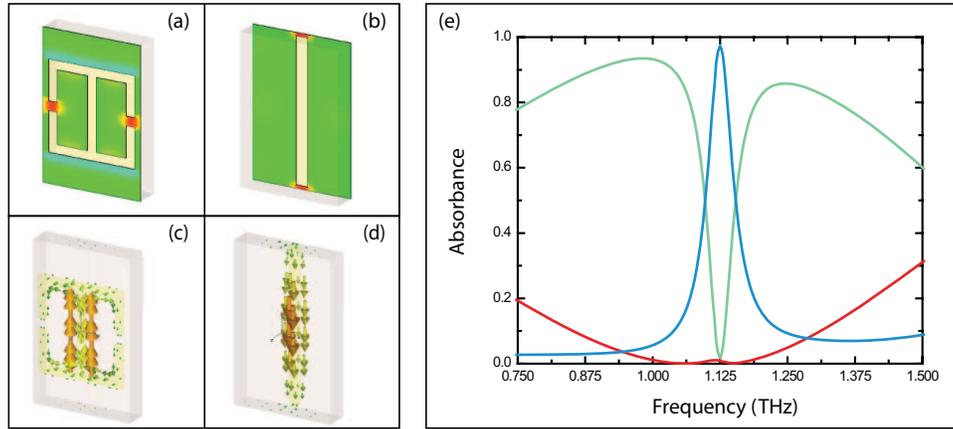


Fig. 2. (color) Simulation results for the electric resonator ring and cut wire. (a) and (b) show the x-component of the electric field of the electric resonator ring and cut wire at resonance, respectively; (c) and (d) show the anti-parallel currents driven by magnetic coupling. (e) The absorptivity (blue) yields a value of 98% at 1.12 THz. Reflection (green) and Transmission (red) are both at normal incidence.

We present a first generation terahertz metamaterial absorber which achieves a resonant absorptivity of 70% at 1.3 THz. Given the $6 \mu\text{m}$ thickness of our metamaterial, this corresponds to a power absorption coefficient of $\alpha = 2000 \text{ cm}^{-1}$ which is significant at THz frequencies. The strong absorption coefficient makes this low volume structure a promising candidate for the realization of enhanced, spectrally selective, thermal detectors. A single unit of the absorber consists of two distinct metallic elements: an electrical ring resonator (ERR) Fig. 1 (a) and a split wire Fig. 1 (b). The electrical ring resonator (ERR) consists of two single split rings sitting back to back. The two inductive loops are of opposite handedness and thus couple strongly to a uniform electric field, and negligibly to magnetic fields [10, 20]. The magnetic component of light couples to both the center section of the electric resonator and the cut wire, thus generating antiparallel currents resulting in resonant $\mu(\omega)$ response. The magnetic response can therefore be tuned independently of the electric resonator by changing the geometry of the cut wire and the distance between elements. By tuning each of the resonances it is possible to approximately match the impedance ($Z = \sqrt{\mu/\epsilon}$) to free space, i.e. ($\epsilon = \mu$) \Rightarrow ($Z = Z_0$) and minimize the reflectance at a specific frequency. When the material is impedance-matched, the transmission [21] is governed by the quantity n_2kd , which can be simultaneously tuned with Z to obtain high absorption.

Computer simulations were performed using the commercial finite-difference time domain solver CST Microwave Studio TM 2006B and 2008. The metamaterials depicted in Fig. 1 were modeled as lossy gold with a conductivity of $\sigma = 1.0 \times 10^7 \text{ S/m}$. The bottom substrate was modeled as gallium arsenide with a dielectric constant of 10.75. A $8 \mu\text{m}$ thick layer of dielectric, $\tilde{\epsilon} = 3.5 + i0.02$ was used as the spacer between the two metallic metamaterial elements. We first investigated the S-parameters of transmission (\tilde{S}_{21}) and reflection (\tilde{S}_{11}) of a single unit cell with Perfect Electric (PE) and Perfect Magnetic (PM) boundary conditions along the \hat{x} and \hat{y} directions, respectively, (see Fig. 1). The absorptivity was calculated using the equation $A = 1 - |S_{21}|^2 - |S_{11}|^2$. The electric and magnetic fields were examined at resonance to verify that we were coupling to the correct resonant mode of each metamaterial element. In Fig. 2, the resonant component of the electric field at resonance is plotted for the electric ring resonator (ERR) (a)

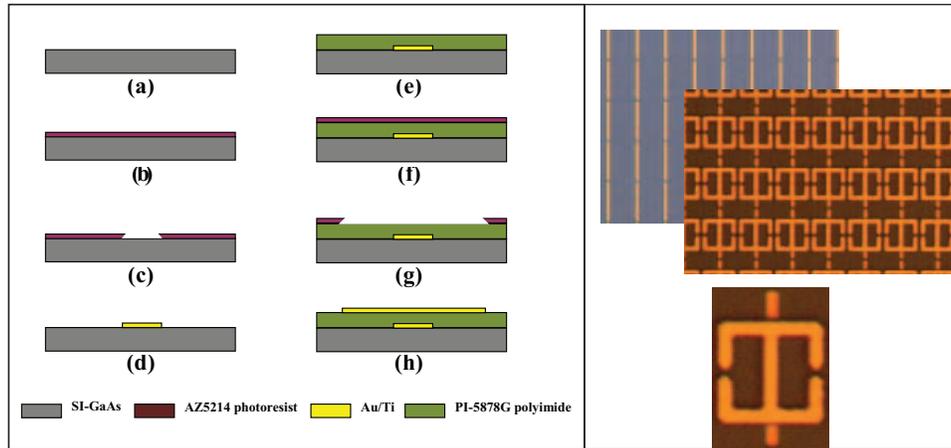


Fig. 3. (color) Left panel describes the development process for fabrication of the terahertz absorber. Right panel shows photographs of the split wire (top) electric ring resonator and split wire (middle) and an individual unit cell of the terahertz absorber (bottom).

and the split wire (b). The electric field is concentrated strongly in the gaps of the ring resonator and at the edges of the split wire in accord with previous results [10, 20]. Figures 2 (c) and (d) show a vector plot of the surface current density for the ERR and the split wire, respectively. Notice that at resonance currents are anti-parallel in the two metamaterial elements, which is the basis of the magnetic response and consistent with previous results [19, 22].

By changing the electric and magnetic resonances individually, we were able to create a condition such that the material was at an impedance near the free space value in a region of very low $T(\omega)$. The simulated transmission is relatively low across the entire range shown in Fig. 2 (e), whereas the reflectivity is relatively high except near the resonance at 1.12 THz where it drops to a value of 2%. Near unity absorption is theoretically possible and here we achieve a simulated value of 98% at 1.12 THz, as shown in Fig. 2(e). It should be noted that at THz frequencies the magnetic response of both natural materials and metamaterials is significantly weaker than the electric. Thus, matching the exact form of the $\epsilon(\omega)$ and $\mu(\omega)$ resonances becomes increasingly difficult at these and higher frequencies. Further, from a viewpoint of spectrally selective thermal imaging, it is desirable to have a narrow-band absorber. Thus we strive for two requirements of our metamaterials at our target frequency, i.e. $Z = Z_0$ so that $R = 0$ and $n_2kd \gg 0$ so that $T \rightarrow 0$. With these two goals we can achieve a significant and narrow-band $A(\omega)$, but tolerance limits associated with microfabrication can reduce the absorptivity from unity.

We fabricated the metamaterial shown in Fig. 1 using a surface micromachining process, as shown in Fig. 3. A semi-insulating GaAs wafer was chosen because it is highly transmissive at THz frequencies. AZ5214e image reversal photoresist was spin-coated and patterned using standard photolithography. A 200 nm-thick Au/Ti film was E-beam evaporated to create the cut wire on the bottom layer. Lift off of the photoresist was achieved by rinsing in acetone for several minutes. The liquid polyimide, HD Microsystems TM PI-5878G, was spin-coated at 2,000 rpm on the GaAs wafer to form an insulating spacer with a thickness of 8 μm , and cured for five hours in an oven at 275 $^\circ\text{C}$ in a nitrogen environment after the soft bake at 110 $^\circ\text{C}$ for 6 minutes on a hot plate. AZ5214e image reversal photoresist was spin-coated, aligned, and patterned using standard photolithography. Another 200 nm-thick Au/Ti was E-beam evaporated

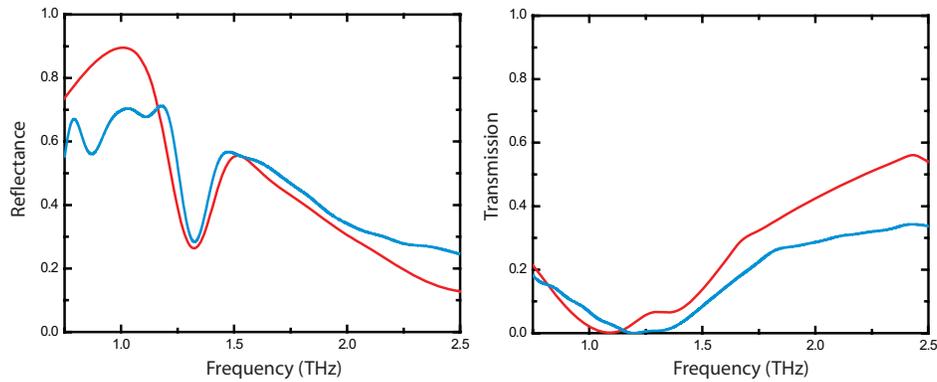


Fig. 4. (color) Experimental results showing the transmission intensity and reflection intensity. The blue lines are experiment and the red line the simulations. The reflectance measurement was performed at 30° off-normal. The transmission measurement was performed at normal incidence.

as the material of the electric resonant ring on the top layer and then lifted off. Microscopic images of the as-fabricated samples are shown in Fig. 3 (right).

We experimentally verified the behavior of the absorber by measuring the transmission and reflectance of a large ($1\text{ cm} \times 1\text{ cm}$) planar array. We used an evacuated Fourier transform infrared (FTIR) spectrometer in the range from 300 GHz - 3 THz ($10 - 100\text{ cm}^{-1}$) with 15 GHz (0.5 cm^{-1}) spectral resolution. For transmission measurements the sample was mounted in the FTIR at normal incidence with the electric field perpendicular to the gap of ERR, as depicted in Fig. 1(a). Reflection was performed at an angle of 30° due to experimental limitations. The blue curves in Figs. 4(a) and (b) show, respectively, the measured reflectivity and transmission. Measured $R(\omega)$ and $T(\omega)$ differ significantly from that simulated as shown in Fig. 2(e). However, it should be noted that values used in simulation for the polyimide spacing layer were estimated based on published values at lower GHz frequencies. Further, the thickness of the polyimide layer was measured to be closer to $6\mu\text{m}$ rather than the $8\mu\text{m}$ used in simulations. Taking both of these factors into account, we are able to match measurements using an experimentally determined value for polyimide of $\epsilon = 2.5 + i0.2$. The red curves are the corresponding simulations which are in good agreement with experiment. The simulated reflectance matches reasonably well near the resonance with slight deviations at lower and higher frequencies. The simulated transmission also agrees well with experiment, particularly in the vicinity of the resonance. Further, the simulated $T(\omega)$ reproduces the same qualitative features as experiment, including a distinct kink near 1.75 THz.

From experimental data presented in Fig. 4, the corresponding absorptivity is determined as shown in Fig. 5. These results demonstrate that the as-fabricated MMs have a strong resonance at around 1.3 THz and a high absorptivity of approximately 70%. Simulations show good agreement with experiment (red). The simulated absorptivity at resonance matches very well with the measured value. The off-resonance absorptivity is higher in experiment than in simulation due to differences in the experimental and simulated S-parameters. The response of absorber could be further improved through refinement and optimization of the fabrication process.

The absorber presented in this work absorbs strongly for light polarized along the \hat{x} direction, as shown in Fig. 1, but poor for \hat{y} polarized light, as shown in Fig. 6. In this polariza-

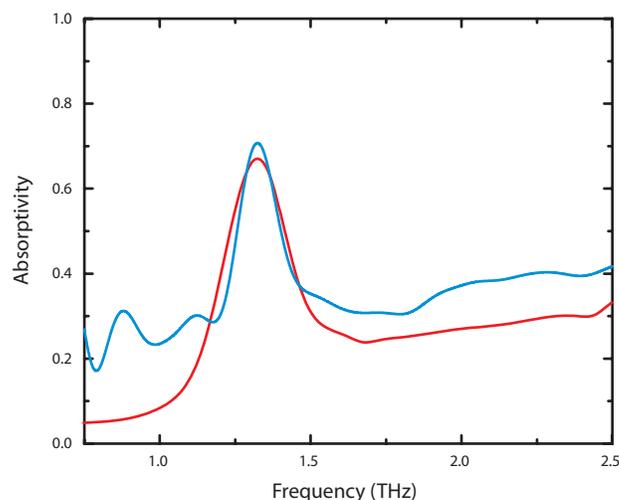


Fig. 5. (color) Experimental results showing absorptivity. Experimental results are in blue and simulation is in red. The experimental absorptivity reaches a maximum value of 70% at 1.3 THz. The simulated absorptivity reaches a value of 68% at the same frequency.

tion, the electric field is perpendicular to the center stalk of ERR, so an electric response cannot be driven. Similarly, there are no parallel wires for the magnetic field to develop a flux through and thus no net magnetic response. Such a polarization-sensitive device is desirable for both mm-wave and THz imaging as reflections from metallic objects often saturate the imager, thus significantly degrading its performance, in a problem known as “glint”. Additionally, polarization-sensitive detection has been shown to aid in discrimination of objects in a scene [23, 24]. However, by incorporating higher symmetry metamaterials, (similar to those presented here), a polarization-insensitive design could be achieved.

The performance of a THz radiation detector depends on the efficiency of converting radiation energy to an output signal. Therefore, maximizing the THz radiation absorption efficiency is integral to the development of a functional THz detector/imager. It is difficult to find strongly absorbing materials at THz frequencies that are compatible with standard photolithography. Thus, a potential application of these metamaterial structures is as the absorbing elements in thermal detectors. A strong absorption coefficient is also necessary to have a small thermal mass. This is important for optimizing the temporal response of thermal detectors. The metamaterial presented here has a 6 micron thick film and 70% absorptivity, which yields an absorption coefficient of 2000 cm^{-1} . With better fabrication tolerances we could approach the simulated results (Fig. 2). This would yield an absorption coefficient three times greater than experimentally demonstrated here.

Many micro thermal detectors (typically based on bolometric detection and appropriately termed microbolometers) utilize several materials as the sensing element such as VOx [25], poly-Si-Ge [26], YBCO [27], or metal resistors such as, titanium [28] and niobium [29]. Some of these materials are not fully compatible with microfabrication processing. For those that are, however, it is difficult and thus expensive to prepare or deposit a high quality film. Additionally, most of these materials show broad-band absorption. This limits potential applications, such as spectroscopic detection of explosive materials, which show unique responses at var-

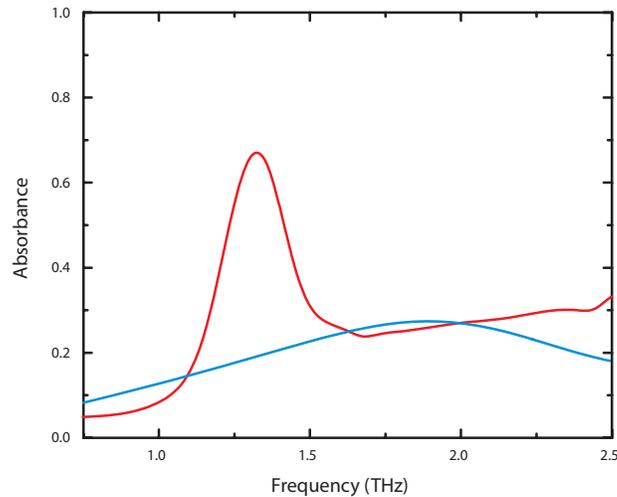


Fig. 6. (color) Simulation results comparing absorptivity for both polarizations. When the electric field is polarized parallel to the center stalk of the ERR (red) absorption reaches 70%. In the opposite polarization, the absorption only reaches 27%

ied frequencies [9]. The narrowband absorptivity of metamaterials presented here, on the other hand, enable spectrally selective detection. Furthermore, MMs are geometrically scalable and have been demonstrated over many decades of frequency. Thus, our results are not limited to terahertz frequencies and may be used over much of the electromagnetic spectrum. Another salient feature of the design presented here is that it may be combined with semiconducting materials or ferroelectrics to enable optically or electrically tunable frequency agile terahertz metamaterials. This would further permit a hyperspectral metamaterial focal plane array imager able to imaging over a relatively large band [33]. Planar metamaterial absorbers consisting of different unit cells with distinct resonance frequencies may permit “multi-color” imaging.

In summary, we have demonstrated that the electromagnetic response of metamaterials can be tailored by manipulating the geometries of electric and magnetic resonators individually to create a highly selective absorber over a narrow band at THz frequencies. The successful demonstration of the high absorber holds great promise for future applications which includes metamaterial-based structures for creating a narrow-band, low thermal mass absorber as required for thermal sensing applications.

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