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A dual band terahertz metamaterial absorber

Hu Tao1, C M Bingham2, D Pilon3, Kebin Fan1, A C Strikwerda3, D Shrekenhamer2, W J Padilla2, Xin Zhang1 and R D Averitt3

1 Department of Mechanical Engineering, Boston University, Boston, MA 02215, USA
2 Department of Physics, Boston College, Chestnut Hill, MA 02467, USA
3 Department of Physics, Boston University, Boston, MA 02215, USA

E-mail: xinz@bu.edu and raveritt@physics.bu.edu

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Abstract

We present the design, fabrication and characterization of a dual band metamaterial absorber which experimentally shows two distinct absorption peaks of 0.85 at 1.4 THz and 0.94 at 3.0 THz. The dual band absorber consists of a dual band electric-field-coupled (ELC) resonator and a metallic ground plane, separated by an 8 µm dielectric spacer. Fine tuning of the two absorption resonances is achieved by individually adjusting each ELC resonator geometry.

(Some figures in this article are in colour only in the electronic version)

Metamaterials consisting of artificially constructed electromagnetic (EM) materials have recently attracted considerable interest due to their ability to exhibit engineered exotic EM responses not available in nature, including negative refractive index, superlensing and cloaking [1–4]. Many of these ideas were initially implemented at microwave frequencies due to the simplicity in fabrication. Nevertheless, there has been substantial progress and successful demonstrations of metamaterials extending from the terahertz through the visible frequencies using micro/nano fabrication technologies during the past several years [5–7]. Development of metamaterials at terahertz frequencies is especially important and attractive since there is a strong need to create components to realize applications ranging from spectroscopic identification of hazardous materials to noninvasive imaging. However, researchers have found that such ELC resonators could show similar resonance responses with the EM wave propagating normal to the substrate and the electric field aligned perpendicular to the resonators’ gap [10]. To date, due to the limitations of currently available fabrication and characterization techniques, most terahertz metamaterials were made by patterning periodic SRRs in a single planar form to show effective negative electric permittivity ($\tilde{\varepsilon}$) or negative magnetic permeability ($\tilde{\mu}$). Additional layers or more complex structures need to be introduced for tailoring both $\tilde{\varepsilon}$ and $\tilde{\mu}$, which is important to realize negative refractive index. Tailoring the effective $\tilde{\varepsilon}$ and $\tilde{\mu}$ also provides the means to engineer the impedance.

Recently, a narrow band microwave resonant metamaterial absorber with theoretical unity absorptivity realized through perfect impedance matching was demonstrated [13]. Progress has been made to extend the absorber design to terahertz frequencies by using double metamaterial layers [14, 15]. Although those metamaterial absorbers show decent absorptivity at terahertz frequencies, they are basically single band absorbers with high absorptivity at a specific frequency. Multi-band terahertz absorbers with two or more optimized absorption peaks have yet to be demonstrated, which could be important, for example, in the development of terahertz spectroscopic imagers/detectors [16, 17].

We experimentally demonstrate a dual band resonant metamaterial absorber with two distinct absorption peaks at 1.4 and 3.0 THz. We use an absorber design similar to [15].
The main difference is that we combine two single band ELC resonators together to obtain the dual band resonance responses, inspired by [18]. Remarkably, the two resonance responses can be tuned and optimized independently at desired frequencies with comparatively high absorptivity as with single band metamaterial absorbers. This feature provides more flexibility in multi-band absorber designs and can be readily extended to infrared and visible frequency ranges.

As described in [14, 15], maximizing the absorption (A) is equivalent to minimizing both the transmission (T) and the reflectivity (R) simultaneously at the same frequency range. The near-unity resonant metamaterial absorber can be realized by manipulating the effective ě and µ to get perfect impedance matching with free space (i.e. $Z = Z_0$, resulting in $R = 0$), with the loss dependent imaginary part of the refractive index ($n_2$) as large as possible.

A dual band metamaterial absorber consists of two metallic layers separated by a dielectric spacer. The top layer consists of an array of dual band ELC resonators which is responsible for determining ě(ω), while the bottom metallic ground plane layer is added such that the incident magnetic field drives circulating currents between the two layers, as shown in figure 1. Two single band metamaterial absorbers with only one single ELC resonator on the top layer are first designed and optimized near 1.4 THz (S1) and 2.9 THz (S2), and are then integrated into a single particle, as shown in figure 2. Despite coupling between these two ELC resonators due to the shared bar (see D2), two distinct absorption peaks are obtained by fine tuning of the overall geometry.

The absorber structures were simulated and optimized using commercialized full-wave EM simulation software CST Microwave Studio™ 2008. Unit cell boundary conditions with a tetrahedral mesh were used in the frequency solver, in which case the wave ports were automatically added in the direction of normal incidence to the substrate. The optimized geometries are shown in table 1. The Au portions of the absorbers were modelled as lossy gold with a conductivity $\sigma = 4.09 \times 10^7$ S cm$^{-1}$, and the polyimide layer was modelled using the experimentally determined value of $\tilde{\epsilon} = \epsilon_1 + i\epsilon_2 = 2.88 + i0.09$. The transmission amplitude $S_{21}$ and reflection amplitude $S_{11}$ were obtained and the absorption was calculated using $A = 1 - R - T = 1 - S_{11}^2 - S_{21}^2$, where $S_{21}$ is zero across the entire frequency range. Thus, the absorptivity can be calculated using $\tilde{A} = 1 - \tilde{R}$, which makes optimizing the absorptivity equivalent to minimizing the reflectivity. The optimized parameters are those which yielded the lowest reflectivity at the design frequencies of 1.4 and 2.9 THz.

As observed in [15], a metamaterial absorber based on a different kind of single ELC resonator, referred to as electric SRR (e-SRR), also shows two absorption peaks at two distinct frequencies. However, it is different from the dual band absorber due to the different origin of the absorption. The low frequency resonance is due to countercirculating currents in the e-SRR, while the high frequency resonance derives from a dipolar response [19], analogous to what has previously been observed using frequency-selective surfaces (FSSs) at microwave frequencies [20, 21]. In the dual band absorber, both resonances come from circulating currents in the ELC resonators, while the low frequency response is determined mainly by the upper resonator (S1) and the high frequency response is contributed mainly by the lower resonator (S2). This was verified by examining the surface current distribution on resonance, as shown in figures 2(c) and (d). The two resonance peaks are labelled as I (at 1.4 THz) and II (at 2.9 THz), respectively. To better understand the absorption of each resonance, an absorber based on e-SRR with centre split gap (D1), similar to the design in [15], was designed and optimized with similar absorption peaks as the dual band ELC resonator absorber (D2) near 1.4 and 2.9 THz. In comparison with the e-SRR absorber (D1), the dual band ELC absorber (D2) has a similar low frequency response. However, it has significantly higher and narrower resonance absorption response at the higher frequency.

An additional aspect to consider in the design of metamaterial absorbers is losses in the constituent materials making up 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 figure 1 is zero. However, losses in gold are sufficient to yield a strong narrow band resonance. The absorption as a function of frequency at various

Figure 1. Dual band terahertz metamaterial absorber consisting of a dual band ELC resonator and a metallic ground plane, separated by an 8 µm thick dielectric layer. (a) Perspective view of the absorber. (b) Top view of the absorber. (c) Photograph of a portion of the fabricated absorber. Corresponding dimensions are shown in table 1. (Colour online.)
values of the dielectric loss tangent $\tan(\delta)$ are calculated for the metamaterial absorber designs D1 and D2, as shown in figure 3.

The results in the figure start from a lossless dielectric ($\tan(\delta) = 0$, black curve) and gradually increased $\tan(\delta)$ to 0.2 (while keeping the value of the Au conductivity constant). The e-SRR absorber (D1) shows different absorption responses at two resonant frequencies with increasing $\tan(\delta)$ due to different resonant origins mentioned above. The peak absorption is 0.94 at 1.4 THz with a lossless dielectric, which is smaller than the calculated value in figure 2(b). This suggests losses in the dielectric contribute to increasing the absorption. However, a point of diminishing returns is reached for larger values of $\tan(\delta)$ in that the absorption decreases and the resonance broadens. For the higher frequency resonance, the absorption keeps increasing with larger dielectric losses, which conforms to those FSSs reported previously [22].

The dual band ELC absorber (D2) shows similar absorption responses with various dielectric loss values at both resonant frequencies as the e-SRR absorber (D1) does at low frequency. In the case of $\tan(\delta) = 0$, the peak absorption is 0.86 at 1.4 THz and 0.84 at 2.9 THz, respectively, which are nearly 15% smaller than the calculation value in figure 2(b). The absorption can be increased by increasing the dielectric losses, and it drops back after a certain value, which is $\sim 0.04$ in this case. These results suggest that optimization of $\tan(\delta)$ of the dielectric spacer can maximize the metamaterial absorption. Further, it appears the losses in polyimide ($\tan(\delta) = 0.031$) should contribute $\sim 0.15$ to the absorption of our dual band metamaterial absorber as is evident by comparing the black curves in figures 2(b) and 3(b). Besides optimization $\tan(\delta)$ of the dielectric spacer to maximize the absorption, we can also optimize the absorber
geometry for various dielectric spacers with different losses. By simply tuning the thickness of the dielectric spacer without having to modify the dual band ELC resonator’s geometry, the absorption peaks can be pulled back to near unity at both resonant frequencies, as shown in table 2.

The above-mentioned absorber structures were fabricated on silicon substrates with the parameters shown in table 1. A 50 nm thick Au/Cr film was first e-beam evaporated on a 2 inch silicon wafer to form the ground plane. Liquid polyimide (PI-5878G, HD MicroSystems™) was spin-coated on the ground plane to form the 8 μm thick polyimide spacer. Then the ELC resonator arrays were patterned with a conventional lithography technology on the polyimide spacer. The lift off process was accomplished by e-beam evaporating another 50 nm thick Au/Ti film, followed by rinsing in acetone for several minutes. It is worth mentioning that the whole fabrication process could be easily repeated at other substrates including soft substrates such as polyimide to make it a mechanically flexible dual band metamaterial absorber for non-planar applications.

A Fourier transform infrared (FTIR) spectrometer was used to experimentally verify the behaviour of the absorbers by measuring the reflection response over the frequency range of 1–3.4 THz with a resolution of 15 GHz. A liquid helium cooled bolometer detector and a 6 μm mylar beam splitter were used to optimize the FTIR performance over the frequencies measured. The absorber samples were diced into 1 cm × 1 cm squares and mounted with the electric field perpendicular to the ELC resonator gaps. The samples were mounted on a commercially purchased reflection unit and the minimum achievable incident angle for reflection measurements in our current setup is constrained to 30° off-normal due to the experimental limitations [23]. The measurements were performed with an electric field perpendicular to the ELC resonator gap to excite the electric resonance. The absorption spectrum was easily obtained from the reflection results.

The experimental results for all four absorbers are displayed in figure 4. For the single ELC resonator absorbers, S1 shows an absorptivity of 0.74 at 1.46 THz and S2 shows an absorptivity of 0.93 at 2.99 THz, which is in reasonable agreement with the simulation though the absorption peaks are lower than expected partly due to fabrication imperfections. For dual band resonator absorbers, D1 shows an absorptivity of 0.79 at 1.43 THz and another absorption peak of 0.86 at 2.95 THz; D2 shows two strong resonance absorption peaks of 0.85 at 1.41 THz and 0.94 at 3.02 THz. There is a noticeable frequency shift (∼0.1 THz) at the high resonant frequency between experimental and simulation results in D2, which is mainly due to the inaccuracy of the fabricated resonator gap distance. The off-resonance absorptivity (∼0.3) is quite large in disagreement with the simulations (∼0.1), which may result partly from the scattering of radiation due to fabrication imperfections. Although the absorption peaks are lower than the simulated values, it is clear that the absorber consisting of dual band ELC resonators (D2) shows higher absorption and better spectral resolution than the single e-SRRs (D1), and therefore should be a better candidate to be included as an active absorbing element in spectrally selective terahertz detectors.

In summary, a dual band terahertz metamaterial absorber consisting of two single ELC resonators combined together and a metallic ground plane, separated by a dielectric spacer, has been demonstrated. Two distinct resonant absorption peaks at 1.4 and 3.0 THz were experimentally observed, and the two absorption peaks can be individually tuned by optimizing the corresponding single ELC resonator’s geometries.

![Figure 3. Calculated absorptivity as a function of frequency for various values of the dielectric loss tangent used in (a) single e-SRR metamaterial absorber D1 and (b) dual band ELC metamaterial absorber D2. The electric field (E) is aligned perpendicular to the resonators’ gap. The curves are labelled with the value of tan(δ) used in the simulation. (Colour online.)](image-url)
Figure 4. (a) and (b) Experimental absorptivity as a function of frequency. S1 (red long dash), S2 (blue short dash), D1 (purple dot line) and D2 (black solid line). (Insets: photographs of portions of as-fabricated absorbers.) (c) Photo of the reflection unit used in the measurement. (d) Schematic of the reflection measurement setup. (Colour online.)

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Note added in proof. During the course of this work we were made aware of a paper with similar results [24].

References

[23] Further information could be found on (http://www.harricksci.com/variable-angle-reflection-accessory)