Absorption modulation of terahertz metamaterial by varying the conductivity of ground plane

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Most research focuses on varying the resonator and dielectric spacer to configure the absorption and resonant frequency of terahertz (THz) metamaterial absorbers (MAs), where a metal ground plane is used as a perfect reflector of incident THz waves. In this paper, we modulate the MAs absorption by varying the conductivity of the ground plane. Two THz MAs were fabricated by replacing the gold ground planes with cobalt silicide films, and the measured absorptivity decreases by 4% for the electric resonance and increases by 44% for the dipole resonance. Our quantitative analysis reveals that when the conductivity of the ground plane decreases from 1.8×10^7 S/m to 3.0×10^5 S/m, the absorptivity of the electric resonance decreases by 23%, while that of the dipole resonance increases by 62%. Our approach also provides a practical method to measure the electric conductivity of conductive films in the THz regime. © 2014 AIP Publishing LLC.

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In the past decade, advances in artificial materials, known as metamaterials, have opened up a path for photonic structures that offer unique light-manipulation functionalities. Various metamaterial structures naturally couple to either the electric and/or magnetic components of light in the frequency ranges from microwave,¹ through terahertz (THz)² to optical.³ The engineered features of metamaterials yield a variety of intriguing electromagnetic (EM) effects, such as negative refraction,³⁻⁵ invisible cloaks,^{1,6,7} and super lenses.^{8,9} Such effects are particularly important at THz frequencies, the least developed region in the EM spectrum due to the relative paucity of suitable materials for sources, detectors, and optics.¹⁰

With a continuous metal film beneath the metamaterial, metal resonator/dielectric spacer/metal ground plane metamaterial absorbers (MAs) were realized with high loss, which can achieve near perfect absorption theoretically.¹¹ It was initially thought that the high absorption came from the electronic response from the resonator and the magnetic responses between the top resonator and the bottom metal film of absorber, and the effective impedance matching between the MA and the free space.^{11,12} The recent studies showed that the absorber can be decoupled into two parts: the metamaterial, composed of metal resonator and dielectric spacer, responds to the incident EM wave, and the metal ground plane functions as a reflector.¹³ By using multi-reflection interference theory, the underlying physical principle of the MA was revealed.^{14,15}

Highly conductive metals, such as Au, Al, or Cu, are typically used as ground planes,^{15,16} and are modeled as perfect electric conductors (PEC) in the THz regime with the reflection coefficient of -1 . Other conductive films, such as metal alloy and metal silicide, also reflect the incident THz wave effectively, but few of them were considered as ground planes. Due to the relatively lower conductivity, the model of PEC cannot be applied anymore if they are used as the ground plane.

In this paper, an approach to modulate the absorption of MA by varying the conductivity of the ground plane is developed. The influences of the conductivity of ground plane on the absorption are first studied theoretically with the theory of EM wave propagation in a multilayer medium,¹⁷ and then numerically simulated with commercial software. This approach is finally confirmed with experimental results.

The typical metal resonator/dielectric spacer/ground plane structure of MAs is modeled by considering the EM wave propagation as depicted in Fig. 1. Including the air on both sides of the structure, there are four numbered zones and three interfaces in the decoupled model of MA. The normally incident EM wave from the front air region (zone 1) will propagate through the dielectric spacer (zone 2) and the ground plane (zone 3) successively until it reaches the back air region (zone 4). Transmission and reflection occurs at each interface. The reflection and transmission coefficients at interfaces II and III can be calculated from the permittivities of the dielectric layers and ground plane. The complex reflection ($\tilde{r}_{ij}$) and transmission ($\tilde{t}_{ij}$) coefficients with EM wave incident from zone i to j can be calculated by

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FIG. 1. The EM wave propagation model of a MA.

$$\tilde{r}_{ij} = (\sqrt{\epsilon_i} - \sqrt{\epsilon_j}) / (\sqrt{\epsilon_i} + \sqrt{\epsilon_j}), \quad (1)$$

$$\tilde{t}_{ij} = 2\sqrt{\epsilon_j} / (\sqrt{\epsilon_i} + \sqrt{\epsilon_j}), \quad (2)$$

where $\tilde{\epsilon}_i$ and $\tilde{\epsilon}_j$ are the permittivities of zone i and j , respectively. At the interface I, the normally incident THz wave is partially reflected back to the air and transmitted into the spacer, and the transmission and reflection coefficients can be obtained from simulations.

Based on the theory of EM wave propagation in a multi-layer medium, the overall reflection and transmission coefficients of different zones in the MA can be assembled in matrices whose product can be analyzed to obtain the overall reflection coefficient $\tilde{r}(\omega)$ and transmission coefficient $\tilde{t}(\omega)$ of the MA

$$\tilde{r}(\omega) = \tilde{r}_{12} - \frac{e^{i2\tilde{\beta}_d}(\tilde{r}_{23} + \tilde{r}_{34}e^{i2\tilde{\beta}_m})\tilde{t}_{12}\tilde{t}_{21}}{-1 + e^{i2\tilde{\beta}_d}\tilde{r}_{21}(\tilde{r}_{23} + \tilde{r}_{34}e^{i2\tilde{\beta}_m}) - e^{i2\tilde{\beta}_m}\tilde{r}_{23}\tilde{r}_{34}}, \quad (3)$$

$$\tilde{t}(\omega) = -\frac{e^{i\tilde{\beta}_d+i\tilde{\beta}_m}\tilde{t}_{12}\tilde{t}_{23}\tilde{t}_{34}}{-1 + e^{i2\tilde{\beta}_d}\tilde{r}_{21}(\tilde{r}_{23} + e^{i2\tilde{\beta}_m}) - e^{i2\tilde{\beta}_m}\tilde{r}_{23}\tilde{r}_{34}}, \quad (4)$$

where $\tilde{\beta}_d$ and $\tilde{\beta}_m$ are the complex propagation phases of the spacer and the ground plane, respectively. The complex propagation phases are defined as $\tilde{\beta} = \sqrt{\tilde{\epsilon}}k_0d$, where k_0 is the free space wavenumber, d is the layer thickness, and $\tilde{\epsilon}$ is the complex permittivity of the zone. In the THz regime, the imaginary part of the permittivity is much bigger than the real part for a conductive film, and its complex permittivity $\tilde{\epsilon}_m$ is determined by the approximate equation: $\tilde{\epsilon}_m = 1 + \frac{i\sigma}{\omega\epsilon_0}$, where σ is the conductivity of the film, ω is the angular frequency of the incident EM wave, and ϵ_0 is the permittivity of vacuum. With Eqs. (3) and (4), the reflectance and transmittance of the MA can be calculated, and the absorptivity $A(\omega)$ can be easily retrieved from the equality, $A(\omega) = 1 - |\tilde{r}(\omega)|^2 - |\tilde{t}(\omega)|^2$. Conversely, it should also be easily understood that with all other parameters and reflection spectrum known, the conductivity of the ground plane at THz regime could be retrieved from Eq. (3).

Equations (3) and (4) show that besides the geometry of resonator, and the thickness and permittivity of the dielectric spacer, which have been fully studied by researchers,^{18,19} the thickness and permittivity of the conductive ground plane are also vital to the absorption of MA. To simplify the model, we assume that the thickness of the ground plane is much larger than its skin depth, in which case it can be

modeled as PEC,^{13,14} and therefore functions as a perfect reflector with reflection coefficient $\tilde{r}_{23} = -1$. Then, Eq. (3) reduces to¹⁴

$$\tilde{r}(\omega) = \tilde{r}_{12} - \frac{e^{i2\tilde{\beta}_d}\tilde{t}_{12}\tilde{t}_{21}}{1 + e^{i2\tilde{\beta}_d}\tilde{r}_{21}}. \quad (5)$$

At the same time, $\tilde{t}(\omega)$ equals zero. On the other hand, a ground plane with relatively lower conductivity, where the skin depth exceeds the film thickness, cannot be modeled as a PEC. In that case, the magnitudes of $\tilde{\beta}_m$, $\tilde{r}_{23}$, and $\tilde{r}_{34}$ will decrease with the decrease of the conductivity of the ground plane. Equation (1) implies that both $\tilde{r}_{23}$ and $\tilde{r}_{34}$ vary with the conductivity of the ground plane, and their magnitudes are both smaller than 1. Meanwhile, the propagation phase $\tilde{\beta}_m$ also decreases rapidly because it satisfies the following relation with the conductivity of ground plane: $\tilde{\beta}_m \propto \sqrt{\sigma}$. Thereby, the overall reflection coefficient of the MA would be changed. At the same time, the transmission coefficient $\tilde{t}(\omega)$ would not be equal to zero anymore.

To verify the theory presented above, we designed a typical back-to-back split-ring resonator (BSRR) in the MA, as shown in Fig. 2, which is also known as electric-field-coupled resonator²⁰ and provides low-order electric resonance at lower frequency and a high-order dipole resonance at higher frequency.¹² In this model, the resonator is made of 100 nm thick gold with the measured conductivity of $\sigma_{Au} = 1.8 \times 10^7$ S/m, the dielectric spacer is made of parylene C with a complex dielectric constant $\tilde{\epsilon}_d = 2.46 \times (1 + 0.04i)$ ²¹ and a thickness of 9.3 μm , and the ground planes have fixed 100 nm thicknesses and various conductivities. The length and width of the BSRR are optimized by finite-difference time-domain (FDTD) software to be 34 μm and 32 μm , respectively, and the line width and gap are both 3 μm , with a lattice constant of 36 μm .

For BSRR MA, the complex reflection and transmission coefficients at interface I were simulated with the normally incident THz wave under the polarization shown in Fig. 2. The top row in Fig. 3 shows the calculated reflection (Fig. 3(a)), transmission (Fig. 3(b)), and absorption (Fig. 3(c)) spectra with Eqs. (3) and (4) when decreasing the conductivities of the ground plane from 1.8×10^7 S/m to 3.0×10^5 S/m. An electric resonance around 0.89 THz and a dipole resonance around 2.62 THz are presented in all spectra. It can be seen that as the conductivity decreases, the transmittance increases from 0 to 0.034, and the absorptivity of the electric resonance decreases by 23% from 0.84 to 0.65, while that of the dipole resonance increases by 62% from 0.55 to 0.89. In addition, the Q factors of the dipole peaks decrease from 2.7 to 2.1, which means that the bandwidths of the absorption

FIG. 2. Perspective view of BSRR MA.

FIG. 3. Calculated reflection (a), transmission (b), and absorption (c) spectra of BSRR MA (top row); simulated reflection (d), transmission (e), and absorption (f) spectra of BSRR MA (bottom row). The conductivities of the ground plane decrease from 1.8×10^7 S/m to 3.0×10^5 S/m.

peaks increase by 22%. It is also noted from Fig. 3 that both resonances shift slightly to lower frequency with the decrease of the conductivity. The same structure was also simulated with the FDTD software with the same parameters, and the simulated spectra are plotted in the bottom row of Fig. 3. It can be seen that the simulated and calculated results are in excellent agreement.

To reveal the physical insight of the absorption modulation, we analyzed the effective impedances ($\tilde{z}(\omega)$) of the MAs for ground plane conductivities of 1.8×10^7 S/m and 8.3×10^5 S/m, which could be calculated using the following equation:^{22,23}

$$\tilde{z}(\omega) = \sqrt{\frac{(1 + \tilde{r}(\omega))^2 - \tilde{t}(\omega)^2}{(1 - \tilde{r}(\omega))^2 - \tilde{t}(\omega)^2}}. \quad (6)$$

The retrieved effective impedances are normalized relative to the impedance of free space. For clarity, the imaginary and real parts of electric and dipole resonances in the impedance spectra are plotted in Figs. 4(a) and 4(b), respectively. It can be seen that the imaginary parts of the impedances are almost the same at different conductivities for both resonances. On the other hand, the real parts of the impedances decrease from 0.76 to 0.50 for electric resonance and increase from 0.27 to 0.46 for dipole resonance as the ground plane conductivity decreased from 1.8×10^7 S/m to 8.3×10^5 S/m. Thus, as the conductivity of the ground plane decreases, the effective impedances of the MAs match better to free space for the high order mode and worse for the low order mode. With better matching, the reflection coefficients of the MAs decrease, which leads to higher absorption.

The BSRR MAs shown in Fig. 2 were fabricated using optical lithography. Gold and cobalt silicide (Co-Si) were used as ground planes separately to verify the theory above. First, a 200 nm thick SiO_2 film was deposited on a 400 μm double polished Si substrate as an insulating layer. Then, a 20 nm/100 nm Cr/Au film was sputtered to produce the gold ground plane MA. To prepare the Co-Si ground plane

sample, a 100 nm poly-Si film was deposited followed by phosphorus ions implantation and activation at 1050 °C for 30 s. After that, a 40 nm cobalt film was sputtered. Two rapid thermal processes (RTP) were applied to achieve a Co-Si film with a thickness of 100 nm before and after wet etching of the unalloyed cobalt. Third, a dielectric spacer of parylene

FIG. 4. The retrieved normalized impedance spectra around electric peak (a) and dipole peak (b) with the conductivity of the ground plane as 1.8×10^7 S/m and 8.3×10^5 S/m. Gray grid lines mark unity impedance and the resonant frequencies.

C layers was deposited on the surface of the ground plane at room temperature and a pressure of 22 mTorr. Finally, Cr/Au resonator arrays with a thickness of 20 nm/100 nm were patterned by a lift-off process. Fig. 5 shows the microscope images of the fabricated BSRR MAs. The chip size is 15 mm $\times$ 15 mm for measurement convenience.

The thicknesses of parylene C were measured to be 9.3 μ m by a thin film reflectometry system (K-MAC ST2000-DLXn). The electrical conductivities of the gold and Co-Si films were measured to be 1.8×10^7 S/m and 8.3×10^5 S/m, respectively, by a four-probe meter.

The fabricated MAs were characterized by a Fourier-transform infrared (FTIR) spectrometer (Bruker IFS125HR) extended to the THz range by a mercury vapor source. We measured reflection and transmission spectra with the FTIR beam incident at $<5^\circ$ from the normal of the absorber arrays with the polarization shown in Fig. 2, which was proven to have no influence on the absorption and resonance.¹² The absorption $A(\omega)$ can be retrieved by $A(\omega) = 1 - R(\omega) - T(\omega)$.

The measured transmission and absorption spectra of the gold and Co-Si ground plane MAs are plotted in Fig. 6. The transmittance of the Co-Si sample is below 0.02 in the entire experimental range and only a little higher than the zero transmittance of the gold sample in the entire experimental range, which agrees well with the calculated and simulated results. In both absorption spectra, there are two clear absorption peaks at 0.89 THz and 2.67 THz, which originate from electric resonance and dipole resonance, respectively. The absorptivities of the gold and Co-Si sample are 0.84 and 0.81, respectively, at the low frequency peak, and 0.55 and 0.79, respectively, at the high frequency peak. The absorptivity of the Co-Si ground plane MA increases 44% compared with that of the gold sample at the dipole resonance. At the same time, the absorptivity decreases only 4% for the electric resonance. The shapes of the two absorption curves and especially the variation tendencies of the two peaks in the measured results are exactly the same as the calculations and simulations.

The measured resonance frequencies and absorptivities are slightly different from the calculations. We believe that the variations are caused by process errors during fabrication. In particular, the round corners of the resonator patterns, shown in Fig. 5, can result in differences between the modeled and actual resonator. Pinholes and roughness of the spacers would also have impacts on the measured results.

FIG. 5. The microscope images of the fabricated BSRR MAs with gold (a) and Co-Si (b) as the ground planes.

FIG. 6. The measured transmission and absorption spectra of the gold and Co-Si ground plane BSRR MAs.

In practical applications, by utilizing phase-change materials, such as vanadium oxide (VO_x),²⁴ with high temperature coefficient of resistance (TCR), for the ground planes, the conductivity can be thermally modulated in a wide range. In addition, the ground planes can also be replaced with doped semiconductor films, whose conductivity can be tuned with optical lasers which can be switched at ultrafast speed.²⁵ Therefore, the absorption of the MAs can be effectively tuned with these two methods.

In summary, we have modulated the absorption of THz MA by varying the conductivity of the ground plane. Both the decoupled model of MA with EM wave propagation theory and numerical simulations were used to analyze the performance of MA. As the conductivity of ground plane decreases from 1.8×10^7 S/m to 3.0×10^5 S/m, the theoretical absorptivity of the dipole resonance increases by 62%, while that of the electric resonance decreases by 23%. The measured absorptivity of the Co-Si ground plane MA decreases by 4% for the electric resonance and increases by 44% for the dipole resonance compared with the gold sample. This approach could also be effectively extended to microwave, infrared, and optical regions. Meanwhile, the theory presented also provides a practical method to measure, e.g., as a function of temperature, external magnetic field, optical excitation, or gate voltage, the THz rather than DC conductivity of the ground plane, and this could be helpful both for the development of THz devices as well as materials physics and chemistry.

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