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A terahertz polarization insensitive dual band metamaterial absorber

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Metamaterial absorbers have attracted considerable attention for applications in the terahertz range. In this Letter, we report the design, fabrication, and characterization of a terahertz dual band metamaterial absorber that shows two distinct absorption peaks with high absorption. By manipulating the periodic patterned structures as well as the dielectric layer thickness of the metal–dielectric–metal structure, significantly high absorption can be obtained at specific resonance frequencies. Finite-difference time-domain modeling is used to design the structure of the absorber. The fabricated devices have been characterized using a Fourier transform IR spectrometer. The experimental results show two distinct absorption peaks at 2.7 and 5.2 THz, which are in good agreement with the simulation. The absorption magnitudes at 2.7 and 5.2 THz are 0.68 and 0.74, respectively.

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Recently, electromagnetic (EM) metamaterials have been extensively studied at wavelengths from the visible to the microwave band [1–3]. One potential application for metamaterials is that they can be designed to make an EM absorber with a high absorption coefficient. The permittivity and permeability of a metamaterial absorber can be engineered to maximize the absorption of both electric and magnetic radiation and minimize the unwanted reflection due to impedance mismatch at the air–metamaterial interface. Metamaterial absorbers have been reported from the microwave to the visible band [4,5]. Most investigators have focused on the design and fabrication of metamaterial absorbers with a single resonant frequency. In the terahertz frequency band, these metamaterial absorbers can be used to make a terahertz detector with a specifically selective frequency band. However, for spectroscopic applications, terahertz multiband absorbers are required. Multiple band metamaterial absorbers have been reported [6,7]. These devices are based on using electric split-ring resonators in the top metal layer. Multiple band absorbers may also be made using multiple vertically stacked metallic layers, each absorption band corresponding to a specific layer [8]. However, both of these structures are very complicated, placing considerable demands on both design and fabrication.

In this Letter, a novel (to our knowledge) single patterned layer (planar) terahertz dual band metamaterial absorber with a simple unit cell structure has been designed and fabricated. The top layer pattern consists of two concentric "square rings" that exhibit two distinct absorption bands due to strong magnetic resonances. In addition, the absorption resonances are insensitive to the polarization of the incident beam due to the symmetric structure in the unit cell, which provides more efficient absorption for the nonpolarized incident beam.

The dual band terahertz metamaterial absorber consists of three layers: a metallic plane layer on the bottom, a dielectric layer, and finally a second metallic layer with square ring unit cells on the top, as shown in Fig. 1. The absorber structure is fabricated on a 400-μm-thick silicon wafer used as the supporting substrate. Polyimide (PI-2545) is used as the dielectric layer to separate the two metallic layers. The thickness of the polyimide layer is 4 μm. On the top layer, there are two metallic square rings in each unit cell. The width of the metal strip is fixed at 0.5 μm. The length of the side of the outer square ring is 19 μm, and the length of the side of the inner square ring is 11 μm. Both of the two metallic layers are made of gold with a conductivity of 4×10^7 S/m and a thickness of 220 nm. The repeat period is 28 μm. We used the finite-difference time-domain method (Lumerical 6.5) to model the terahertz metamaterial absorber structure. The dielectric constant of the polyimide was assumed to be $2.4 + 0.005i$. The incident beam is assumed to be normal to the absorber surface. The thickness of the polyimide layer is adjusted to be 4 μm in order to optimize the impedance matching of the air–sample interface.

Figure 2 shows the calculated absorbance spectrum of the dual band absorber (sample A). The calculated absorption coefficient, A, is obtained by $A = 1 - T - R$, where T and R are transmission and reflection coefficients, respectively. Since the bottom layer is a continuous metallic layer that has a thickness much greater than

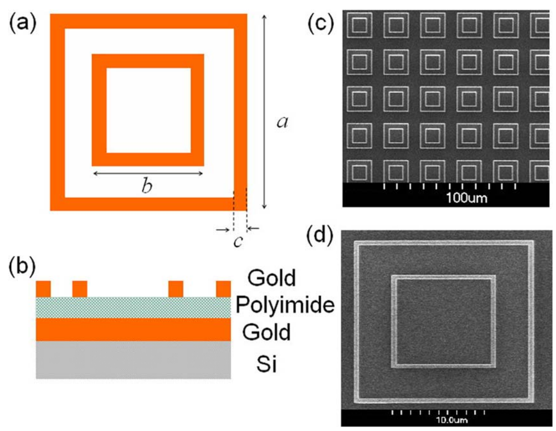

Fig. 1. (Color online) Terahertz dual band metamaterial absorber design and implementation: (a) sketch of the of top metal layer structure, (b) cross section of the absorber layers, (c) and (d) scanning electron micrographs of the dual band absorber.

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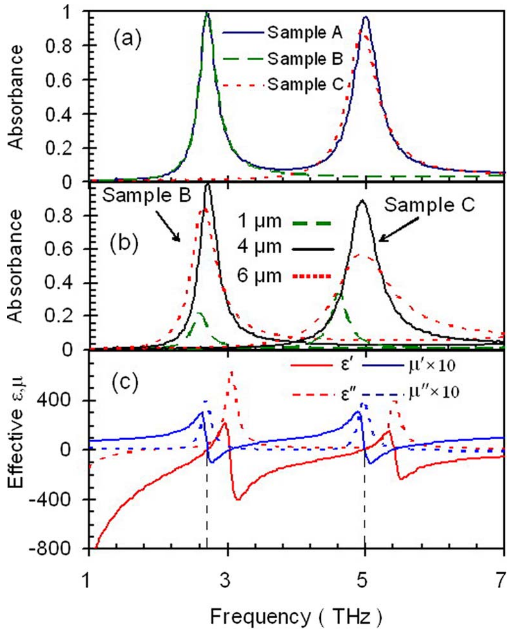

Fig. 2. (Color online) (a) Simulated absorption spectra for three different terahertz absorber geometries, (b) simulated effect on absorption spectra for single band absorbers with different thicknesses of polyimide, (c) calculated effective permittivity and permeability. The permeability is scaled by a factor of 10.

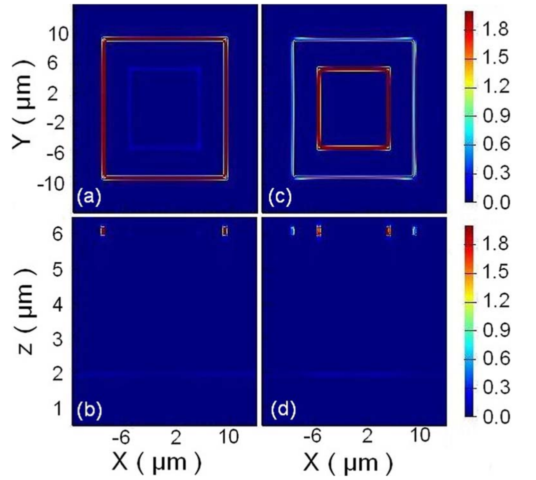

Fig. 3. (Color online) Magnitude of the Poynting vector in the dual band absorbers: (a) plan view of top metal layer at 2.7 THz, (b) cross section through center at 2.7 THz, (c) plan view of top metal layer at 5.0 THz, (d) cross section through center at 5.0 THz.

the skin depth of the incident beam, the transmittance should be zero. Consequently, the calculation of the absorbance can be simplified to $A = 1 - R$. As shown in Fig. 2(a), there are two distinct absorption peaks, which are located at 2.7 and 5.0 THz. In order to verify the origin of these two absorption peaks, we also simulated another two absorber structures with single square rings only for comparison: sample B with the outer square ring pattern and sample C with the inner square ring pattern. The period is the same in all cases. As shown in Fig. 2(a), samples B and C have a single absorption peak located at 2.8 and 5.1 THz, respectively. The simulation results reveal that the two absorption peaks in the dual band absorber are contributed by the outer square ring and inner square ring, respectively. The slight difference in the resonant frequencies is due to the loading effect when both of the square ring patterns are combined into the dual band absorber.

Figure 2(c) shows the calculated effective permittivity ($\varepsilon' + i\varepsilon''$) and permeability ($\mu' + \mu''$) for the dual band absorber. They have similar behavior to earlier work [9]. As shown in Fig. 2(c), both ε' and μ' cross zero at 2.7 and 5.0 THz, which results in the impedance matching at these frequencies. Meanwhile μ'' has two positive resonances at the corresponding frequencies. Therefore the absorption resonances are magnetic resonances. As has been shown, a metamaterial absorber with a cross-shape metallic pattern on the top layer may have strong magnetic resonance results from excitation of a dipole resonance along the metal strip [8]. We suggest that the strong magnetic resonances in our dual band absorber are also induced by the magnetic polariton due to the excitation of a dipole resonance along the side of the square. The resonant frequencies are determined by the length of the sides of the metal square. The resonant strength is tuned and optimized by adjusting the thickness of the dielectric layer, as shown in Fig. 2(b). Both of the two frequency peaks are optimized when the thickness is in the range between 2.9 and 5.0 μm. Figure 3 shows the EM absorption distribution of the dual band absorber at two absorption peak frequencies. As shown in Fig. 3, at 2.7 THz the incident terahertz radiation is mainly trapped in the outer metallic square ring and the adjacent dielectric layer. Similarly, at 5.0 THz the absorption is mainly trapped in the inner metallic square ring and its adjacent dielectric layer. The above results confirm that the two absorption peaks are contributed by the inner and outer square ring patterns respectively.

Experimental devices were fabricated as follows: 20 nm of Ti, followed by 200 nm of Au, was deposited onto the sample as a reflection layer. A polyimide layer (PI-2545 from HD MicroSystems) was then spin-cast as a dielectric layer for the absorber. Electron beam lithography was used to define the metallic pattern layer. Finally, 20 nm of Ti, followed by 200 nm of Au, was evaporated, and the pattern transfer was completed by metal liftoff. Scanning electron micrograph images of the sample are shown in Figs. 1(c) and 1(d). The unit cell structure is repeated in a 28 μm period in both x and y directions. Very good uniformity was achieved across the 1.5 cm × 1.5 cm device area.

We used a Bruker IFS 66v/S Fourier-transform IR spectrometer to characterize the fabricated devices by measuring their reflectance spectra. A wire grid polarizer made on high-density polyethylene was used to ensure the incident beam is linearly polarized [10]. The incident angle of the illumination was at 30° to the normal of the absorber array for the reflectance measurements. Five samples were characterized: two of them (sample B and sample C) are single band absorbers with inner and outer square ring patterns only, respectively. The polyimide thickness of both samples is 4 μm. The other three samples were dual band absorber samples with different polyimide layer thickness. The thickness of the polyimide layer for each sample was measured by a

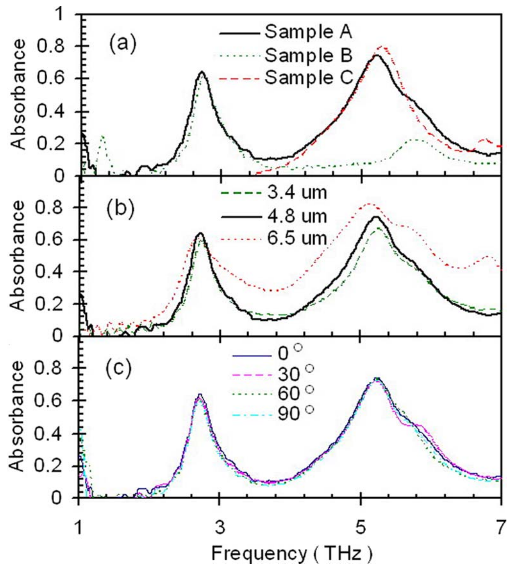

Fig. 4. (Color online) (a) Experimental spectra of three types of absorbers; (b) experimental spectra of terahertz dual band absorber with different polyimide layer thicknesses 3.4, 4.8, and 6.5 μm; (c) polarization dependence of terahertz dual band absorber.

surface profilometer. The measured thicknesses were 3.4, 4.8 and 6.5 μm, respectively. Figure 4(a) shows the measured spectra of the dual band absorber (sample A) compared with two single band absorbers (sample B and sample C). As shown in Fig. 4(a), there are two distinct absorption peaks at 2.7 and 5.2 THz. This result reveals that two peaks originate from the resonances caused by the inner and outer square ring, respectively. Figure 4(b) shows the measured absorption spectra of the three dual band absorber samples with various thicknesses. The absorption increases when the polyimide layer thickness increases from 3.4 to 4.8 μm. Both of the two absorption peaks are at a maximum for the sample with a dielectric thickness of 4.8 μm. The absorption decreases when the thickness is above 6.5 μm, which is also accompanied by a slight redshift of the absorption peak frequency. These trends are in good agreement with the simulation results, as shown in Fig. 2(b). The experimentally obtained absorption is 68% at 2.7 THz and 74% at 5.2 THz, which is lower than in the simulation. The measured absorption peak frequencies are also slightly different from the simulation. We attribute these discrepancies to possible variation in the thickness of the polyimide layer and deviation of the simulation data for the dielectric constant of the polyimide from the actual material parameters. We also have found through simulation that there is a dependence on the angle of incidence of the radiation that gives rise to a small (<5%) shift in the resonant frequencies, which is within the margin of error we observe. The off-resonance absorption is lower than in previous reports for other devices, where 30% was achieved [6,7]. We have also studied the polarization dependence of the dual band absorber devices, as shown in Fig. 4(c). The absorption response is not sensitive to the incident polarization due to the 90° rotational symmetry of the top layer pattern. The Q factors are 6.75 and 4.4 for the two resonant peaks at 2.7 and 5.2 THz, respectively.

In conclusion, we have designed and fabricated a polarization insensitive terahertz dual band metamaterial absorber constructed with simple periodically patterned structures. The fabricated samples were characterized by measuring the reflectance spectra. Two distinct absorption peaks were found at 2.7 THz and 5.2 THz, which is in good agreement with the simulation. The absorption magnitude at two distinct peaks is lower than the simulation but nonetheless is superior to other devices that have been published to date. While we presently envisage normal incidence usage only for the absorber, we note that it would be of interest to further study the effect of angle of incidence on the characteristics of the device. However, the simple structure and design of the dual band absorber will make it easier to fabricate multiple band absorbers as well as broad band absorbers in future.

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