An extremely wideband and lightweight metamaterial absorber

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This paper presents a three-dimensional microwave metamaterial absorber based on the stand-up resistive film patch array. The absorber has wideband absorption, lightweight, and polarization-independent properties. Our design comes from the array of unidirectional stand-up resistive film patches backed by a metallic plane, which can excite multiple standing wave modes. By rolling the resistive film patches as a square enclosure, we obtain the polarization-independent property. Due to the multiple standing wave modes, the most incident energy is dissipated by the resistive film patches, and thus, the ultra-wideband absorption can be achieved by overlapping all the absorption modes at different frequencies. Both the simulated and experimental results show that the absorber possesses a fractional bandwidth of 148.2% with the absorption above 90% in the frequency range from 3.9 to 26.2 GHz. Moreover, the proposed absorber is extremely lightweight. The areal density of the fabricated sample is about 0.062 g/cm², which is approximately equivalent to that of eight stacked standard A4 office papers. It is expected that our proposed absorber may find potential applications such as electromagnetic interference and stealth technologies. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4922421>]

I. INTRODUCTION

Sub-wavelength materials with the basic unit of artificially designed structures are often called metamaterials (MMs), which possess unprecedented electromagnetic (EM) properties, and have attained great interests in the fields of microwave, THz,^{1,2} IR,³ optical,^{4,5} and photonic science.^{6,7} It has been shown that MMs can couple with either electric or magnetic fields to generate electric or magnetic resonant responses described by the Lorentz model.⁸ These resonant responses can be tuned by changing the geometric dimension and the shape so as to ameliorate the effective permittivity and permeability.⁹ For example, Landy *et al.* have achieved a perfect metamaterial absorber by tuning the effective permittivity and permeability to be matched with each other.¹⁰ Since then, MMs used as absorbers have gained considerable interests in the fields of military and civil technologies. However, these absorbers suffer from relatively narrow bandwidth, particularly limiting their potential applications in the microwave region. In order to broaden the bandwidth, the assorted resonators are usually used to excite multiple overlapping absorption modes,^{11–14} while most attempts are still limited except for some extraordinary designs based on the destructive interference mechanism,¹⁵ the slow-wave effect,¹⁶ and the corrugated surface structures.¹⁷ Meanwhile, resistive frequency selective surface can also be thought as an alternative way for the design of the broadband absorbers.^{18,19} This method can achieve broadband absorption with the aid of strong ohmic loss effects. However, all these

designs are limited to the planar single-layer or multilayer structures, and the wideband absorption is achieved at the sacrifice of the desired feature of lightweight. In fact, a three-dimensional (3D) structure typically having multimode cavities can be controlled to obtain a desired performance.²⁰ So it is expected that the outstanding performance can be gained when the MMs absorbers made of resistive films are extended to the 3D configuration.

In this work, we proposed a 3D metamaterial absorber based on the stand-up resistive film patch-enclosed array. First, we discussed the unidirectional stand-up resistive film patch array backed with a metallic plane. The resistive film array exhibits a feasible and ultra-wideband absorbing performance resulting from the excitation of multiple standing wave modes. We then proposed a metamaterial absorber by rolling the unidirectional stand-up resistive film patches as a square enclosure to achieve a polarization-insensitive feature. The simulated result and measurement indicate that the proposed absorber has absorption more than 90% in the frequency region from 3.9 to 26.2 GHz. Furthermore, our absorbers are made of the resistive films and thus the weight is very light.

II. DESIGN FOR THE 3D METAMATERIAL ABSORBER

The unidirectional stand-up rectangle resistive film patch array has been discussed first. The unit cell of the array is presented in Fig. 1, in which the height and the width of the resistive film patch are d and p , respectively. The conductivity of the resistive film is σ_s and the thickness of the resistive film patch is t_1 . The period of the unit cell is l . The

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FIG. 1. Schematic of the unidirectional stand-up resistive film patch.

resistive film array is terminated by a metallic plane with an electric conductivity of 5.8×10^7 S/m.

In the simulation, it was assumed that the electric field is along the y -axis direction and the magnetic field is along the x -axis direction, as shown in Fig. 1. The absorber was simulated by using one unit cell with perfect magnetic boundary in the x -axis direction and perfect electric boundary in the y -axis direction in CST Microwave Studio 2011. A linearly polarized planar electromagnetic wave was expected to be normal to this structure. The absorptive efficiency of an absorber can be defined as $A(\omega) = 1 - R(\omega) - T(\omega) = 1 - |S_{21}|^2 - |S_{11}|^2$, where $A(\omega)$, $|S_{11}|^2$, and $|S_{21}|^2$ are the absorbance, reflectivity, and transmissivity, respectively. Because of the backed metal plate, the transmission (S_{21}) is zero. Thus, the absorbance can be calculated by $A(\omega) = 1 - |S_{11}|^2$ in this paper. The geometric parameters of the unidirectional stand-up resistive film unit cell are given as follows: $d = 11$ mm, $p = 10$ mm, $\sigma_s = 1 \times 10^3$ S/m, $t_1 = 0.01$ mm, and $l = 12$ mm. Figure 2 shows the simulated reflectivity spectrum of the absorber with the absorption over 90% ranging from 6.2 to 24.4 GHz. The structure displays an extremely wide absorption band with a fractional bandwidth of 119.0%, but it should be noted that it is of polarization dependence.

Now we design a polarization-independent metamaterial absorber by rolling the resistive film patches as a square

FIG. 2. The simulated reflectivity spectrum of the absorber consisting of unidirectional stand-up resistive film patches.

FIG. 3. Geometry of the proposed absorber: (a) Top view of the unit cell, (b) side view of the unit cell, and (c) perspective view of the absorber.

enclosure. The structure of the metamaterial absorber is displayed in Fig. 3. Considering the fact that some dielectric medium is needed to support the resistive film in the future fabrication, an ultrathin dielectric layer is introduced here as an upholder. Because of the ultrathin thickness, the dielectric layer will not influence the absorption performance of the absorber. As shown in Fig. 3, the resistive film patches are attached on the dielectric material in the structure of square enclosure, and each stand-up resistive film patches are the same dimensions with dielectric upholder. Figure 3(c) gives the perspective view of the absorber under investigation. The period of the unit cell is l . The conductivity and thickness of the resistive film are still σ_s and t_1 , respectively. The width, the height, and the thickness of the dielectric material are p , d , and t_2 . The dielectric constant and loss tangent of the dielectric material are 3.8 and 0.018, respectively. The geometric parameters of the unit cell are shown as follows: $l = 12$ mm, $\sigma_s = 1 \times 10^3$ S/m, $t_1 = 0.01$ mm, $t_2 = 0.1$ mm, $p = 10$ mm, and $d = 11$ mm. The simulated reflectivity spectra for the absorber under normal incidence are shown in Fig. 4. The absorber has ultra-wideband absorption more than 90% in the frequency range from 3.9 to 26.2 GHz, and its absorption almost achieves 81.2% of the theoretical bandwidth limit²¹ with the integration from 0.1 to 30 GHz. In

FIG. 4. The simulated reflectivity spectrum of the designed absorber under normal incidence.

FIG. 5. The electric field distribution of the resistive film patch at various frequencies: (a) $f_1 = 5.5$ GHz, (b) $f_2 = 13.6$ GHz, (c) $f_3 = 20.0$ GHz, and (d) $f_4 = 25.0$ GHz.

FIG. 6. The height of the resistive film patches compared with the half wavelengths at various frequencies.

addition, because of the rotationally symmetry structure, the absorber has the polarization-independent property.

To intuitively understand the existence of the extremely wideband absorption originated from multiple standing wave modes, we first give the electric field distributions of the resistive square enclosure in the yo z plane at various frequencies in Fig. 5. Figures 5(a) and 5(b) indicate that the electric fields are enhanced on the upper edge of the resistive film patches and the gap between adjacent patches at the frequencies of $f_1 = 5.5$ GHz and $f_2 = 13.6$ GHz, while the electric fields are mainly distributed on the areas below the upper edge of the resistive patches for the cases of the frequencies of $f_3 = 20.0$ GHz and $f_4 = 25.0$ GHz. Meanwhile, the height of standing wave generated on resistive film patches is just half wavelength

$$\frac{\lambda}{2} = \frac{c}{f}, \quad (1)$$

where c is the velocity of light. In order to illustrate the absorption mechanism more clearly, Figure 6 gives the height of the resistive film patches compared with the half wavelengths at the various frequencies aforementioned. If the height of the resistive film patch $d \leq \lambda/2$, the electric fields of the standing wave are relatively weak on the resistive film patches and most concentrate on the patch upper edge, as shown in Figs. 5(a) and 5(b). However, the electric fields are enhanced at the position below the upper edge of the resistive film patches when the $d > \lambda/2$, and one can further find that the higher the absorption frequency, the closer the position to the backed metal plane [see Figs. 5(c) and 5(d)]. Therefore, the absorption mechanism of this resistive square enclosure can be thought as multiple standing wave modes as expected.

The power loss density distributions at various frequencies above mentioned are also illustrated in Fig. 7. It is clearly indicated that the power loss distributions are similar to that of the electric fields, as shown in Fig. 5. Figures 7(a) and 7(b) indicate that the power loss mainly distributes on the upper edge of the resistive film patches at the frequencies of $f_1 = 5.5$ GHz and $f_2 = 13.6$ GHz, while on both the upper edge and the middle position of the stand-up patches for the cases of $f_3 = 20.0$ GHz and $f_4 = 25.0$ GHz, as, respectively, shown in Figs. 7(c) and 7(d). Furthermore, since the resistive film patches are continued in the corner of each unit cell, some induced charges in the x -axis direction can move to the y -axis direction instead of just concentrate on the patches in the x -axis direction and thus the weak power loss density

FIG. 7. The power loss density distributions on the absorber at various frequencies: (a) $f_1 = 5.5$ GHz, (b) $f_2 = 13.6$ GHz, (c) $f_3 = 20.0$ GHz, and (d) $f_4 = 25.0$ GHz.

FIG. 8. Photograph of the fabricated prototype.

distributions can be observed on the resistive film patches in the y -axis direction. One can also find that the similar phenomena exist at other frequencies. So all these loss modes at different frequencies results in the extremely wideband absorption performance.

III. EXPERIMENTAL MEASUREMENT AND DISCUSSION

To experimentally investigate the absorptive properties of the proposed absorber, we fabricated the sample presented in Fig. 8. The overall size is $240 \times 240 \text{ mm}^2$, which consists of 20×20 unit cell. The resistive film was fabricated by the conductive carbon paste, which was printed on the dielectric layer by means of the silk screen printed technology. The commercial PET film with the thickness of 0.1 mm used here as the ultrathin dielectric layer. Our fabricated absorber is quite lightweight. The areal density is about 0.062 g/cm^2 without regarding of the metal plate, approximately equaling to that of eight stacked A4 office papers.

The experimental study of the fabricated absorber was performed by the arch measurement system in a microwave anechoic chamber. The system is based on an Agilent E8363B network analyzer with three pairs of broadband antenna horns, respectively, working in the frequency bands of 1–8 GHz, 8–18 GHz, and 18–26 GHz. In the measurement,

FIG. 9. Comparison between the experimental and simulated reflectivity spectra.

the reflection from a pure metal plate with the same size as the fabricated sample was used for normalization. The measured absorption spectrum is presented by the solid line in Fig. 9. On the whole, the measured result is in a good agreement with the full-wave simulation when taking into account of the roughness in the fabrication process as well as the errors in the experimental measurement.

IV. CONCLUSIONS

In conclusion, we have proposed a 3D metamaterial absorber made of the stand-up resistive film patch array. It is indicated that the ultra-wideband absorption can be achieved by the multiple standing wave modes excited by the stand-up resistive film patches as well as the strong ohmic loss. By rolling the resistive film patches as a square enclosure, the polarization-independent property can be obtained. The simulated result indicates that the proposed absorber has more than 90% absorption ranging from 3.9 to 26.2 GHz. The good agreement between simulation and measured results demonstrates the validity and potential of our design. Furthermore, the absorber is quite lightweight. The areal density of this fabrication is about 0.062 g/cm^2 . Finally, it should be noted that our design is of similar configuration with the conventional honeycomb absorbers coated with high-lossy carbon materials,^{22,23} but has a wider absorption band and more easily tunable performance.

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