Wideband Metamaterial Absorbers Based on Conductive Plastic with Additive Manufacturing Technology

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ABSTRACT: This paper proposes a wideband and polarization-insensitive metamaterial absorber (MA) based on tractable conductive plastic, which is compatible with an additive manufacturing technology. We provide the design, fabrication, and measurement result of the proposed absorber and investigate its absorption principle. The performance characteristics of the structure are demonstrated numerically and experimentally. The simulation results indicate that the absorption of this absorber is greater than 90% in the frequency range of 16.3–54.3 GHz, corresponding to the relative absorption bandwidth of 108%, where a high absorption rate is achieved. Most importantly, this additive manufactured structure provides a new way for the design and fabrication of wideband MAs.

1. INTRODUCTION

Metamaterials are artificial structures which offer extraordinary interactions with the light not readily seen in the natural materials. They have attracted intense scientific attentions because of their unique and peculiar properties. For instance, metamaterials have been recently used for the realization of the negative refraction materials,†‡,§−7 invisible cloaks,†‡,§−4 and miniaturization of antennas and microwave devices.†‡,§−12 The metamaterial absorber (MA) was first presented in 2008 by Landy et al.†‡ with the advantages of thin configuration and compact size. Since then, various MAs have been reported, including dual-band MA,†‡,§−12 triple-band MA,†‡,§,14 multiband MA,†‡,§,15,16 and wideband MA,†‡,§,17−32

Wideband absorbers with high absorption are extremely demanded for imaging, sensing, and nondestructive detection. To increase the absorption bandwidth, one may use a multilayer structure,†‡,§−19 which leads to a complicated fabrication procedure as the absorber thickness is hardly realizable. Recently, it is shown that the absorption peak may be widened by increasing the resistance of the resonator.†‡,§−22 Hence, new materials were adopted to wideband MAs, including the resistive films such as the indium tin oxide (ITO) film,†‡,§−25 tantalum nitride,‡,§,17−24 and graphene.†‡,§,17−32 However, the fabrication of the aforementioned wideband MA is still complicated. For instance, one may hardly acquire a perfect monolayer graphene through chemical vapor deposition.†‡ Moreover, the fabrication of the tantalum nitride based MA is a big challenge with the current state-of-the-art technology.

An additive manufacturing technology is a promising processing technology which provides convenience, high efficiency, and low cost. However, the biggest obstacle for the fabrication of wideband MAs using an additive manufacturing technology is the lack of an appropriate high-resistive film which is tractable and stable. It should be noted that the graphene, ITO film, and tantalum nitride are not compatible with the additive manufacturing method.

In our earlier work, we reported a new type of conductive plastic with proper machinability, high thermal stability, and high conductivity, representing an excellent alternative as the high-resistive film of the MA which is perfectly compatible with the additive manufacturing technology.†‡ This paper introduces a wideband MA based on the conductive plastic with additive manufacturing method. To the best of the author’s knowledge, this is the first demonstration of a wideband MA which employs an additive manufacturing technology. The proposed structure exhibits several advantages in comparison with the previously reported wideband MAs. First, we use an additive manufacturing technology which makes the fabrication of the proposed MA simpler, effective, and low cost. Second, thanks to the high conductivity of the conductive plastic, the absorption bandwidth of the MA may be significantly increased. The proposed structure provides new opportunities for the design and fabrication of wideband MAs.

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2. ABSORBER CONFIGURATION

Figure 1 illustrates a schematic of the proposed wideband MA. It consists of a patterned conductive plastic layer embedded in a polylactic acid (PLA) layer, while the bottom of the PLA layer is covered by a copper ground film. Figure 2a,b depicts the unit cell structure, where the optimal geometrical parameters are found as \( h_1 = 1.3 \) mm, \( h_2 = 1.3 \) mm, \( d = 0.1 \) mm, \( t = 0.017 \) mm, \( a = 8 \) mm, and \( r = 3.7 \) mm. The relative permittivity of the PLA substrate is \( 2.4 + i0.01 \), and the measured surface resistance of the conductive plastic is \( 100 \Omega/\square \).

We next verify the operation of the MA by the numerical simulation of the structure using the finite difference time domain method. We use the unit cell boundary conditions for \( x \) and \( y \) directions. We achieve the absorption spectra under a transverse magnetic (TM)-polarized normal incident wave, where the electric field vector is parallel to the \( y \) axis.

The absorption ratio of the MA, \( A \), may be determined as

\[
A = 1 - |S_{11}|^2 - |S_{21}|^2,
\]

where \( S_{11} \) and \( S_{21} \) denote the reflection and transmission coefficients, respectively. As the transmission coefficient \( S_{21} \) is zero because of the existence of the copper ground film, the absorption ratio \( A \) may be calculated by

\[
A = 1 - |S_{11}|^2.
\]

Figure 3 shows the achieved absorption spectrum of the proposed MA. It is observed that from 16.3 to 54.3 GHz, covering the whole K-band and Ka-band, the absorption ratio is greater than 90%. Moreover, the corresponding relative absorption bandwidth \( W_{RAB} \), that is, \( W_{RAB} = 2(f_U - f_L)/(f_U + f_L) \), where \( f_U \) and \( f_L \) are the upper and lower frequencies with the absorption ratio above 90%, can reach to 108%.

Table 1 compares the performance characteristics of the proposed MA with those of the recently reported wideband MAs. It may be seen from Table 1 that the proposed absorber possesses a relatively thin thickness and a wideband absorption with high absorptivity. In addition, our design offers the polarization insensitivity. Besides the absorption performance of the proposed structure, as stated above, it is the sole one which is compatible with the additive manufacturing technology.

3. ABSORPTION MECHANISM

In order to best show the intrinsic mechanism of the proposed MA, Figure 4 presents the simulation results for the surface current distributions in the conductive plastic pattern and copper ground layer at two peak resonant frequencies, that is, 26.8 and 40.5 GHz. For the first mode, as shown in Figure 4a, the surface current on the conductive plastic layer mainly flows parallel to the direction of the electric field vector of the incident wave. Compared with the surface current distributions in the conductive plastic layer, the current density on the copper ground layer (Figure 4b) is much smaller. This result indicates that the magnetic resonance is weak because of the lack of the antiparallel currents. For the second mode, as shown in Figure 4c, there are two main surface current flows on the conductive plastic layer which excites a high-order electric resonance. Moreover, the magnetic resonance of the second mode is negligible which is due to the absence of the antiparallel current flows on the ground plane. As a result, the electric excitation occurs on the conductive plastic film which...
is responsible for the high absorption across a wide frequency range.

Figure 5a–f illustrates the numerical simulation results for the surface loss in the conductive plastic layer and the copper ground layer and the power loss density in the PLA layer for the two resonant modes. As shown in Figure 5a,d, the conductive plastic layer contributes most power absorption of the absorber for both resonant modes, that is, 97.4% for the first mode and 96.8% for the second mode, respectively. Hence, the conductive plastic layer plays an important role in the wideband absorption.

The retrieved input impedance equation of an MA may be expressed as

\[ Z = \frac{1}{\sqrt{1 - \frac{S_{11}}{S_{21}}}} \]

(1)

To achieve the input matching of the MA, Z should be chosen to match with the impedance of free space of \( Z = 1 \).

Figure 6 shows the normalized input impedance of the
designed absorber. It may be observed from Figure 6 that the normalized impedance of the absorption resonance frequencies are 0.992 + 0.139i and 1.005 + 0.029i and approximately match with the free-space impedance. Meanwhile, the real parts of the impedance are close to unity, and the imaginary parts are close to zero at the frequency range from 16.3 to 54.3 GHz, providing a wideband absorption with a high absorption ratio.

To best understand the absorption mechanism of the absorber, Figure 7 plots the absorption spectra for different loss conditions of the PLA substrate, different dielectric constants of the PLA substrate, and different surface resistances of the conductive plastic. As shown in Figure 7a, the loss condition of the PLA substrate slightly affects the absorption spectra. This implies that the PLA substrate contributes a very small portion of the total energy consumption. Moreover, Figure 7b shows the influence of the dielectric constant of the substrate. It can be seen that with the increase of dielectric constant, the absorption rate at an upper frequency decreases rapidly. As a result, the absorption bandwidth decreases with the increase of the dielectric constant of the substrate. In addition, as shown in Figure 7c, with the increase of the surface resistance of the conductive plastic, the absorption ratio will significantly enhance. This is due to the fact that the concentration of the surface currents on the conductive plastic pattern may cause strong ohmic loss, that is, $P_{\text{loss}} = I^2R$, in which $R$ is the resistance of the resistive film. However, the continuous increase of the surface resistance leads to the decrease of the absorption bandwidth. Hence, the surface resistance of the conductive plastic of 100 $\Omega/\square$ appears to be optimal for the proposed structure.

4. ABSORPTION DEPENDENCE ON THE POLARIZATION AND OBLIQUE INCIDENCE

This section describes the performance dependence of the MA on the polarization and incident angles. Because the polarization insensitivity property is very crucial for a wideband MA, we first analyze the electromagnetic responses of the absorber for different polarization angles. Because the resonant structure is symmetric, the proposed absorber may be studied only for polarization angles up to 45°. Figure 8 plots the absorption spectra for different wave polarizations. It may be observed from Figure 8 that the absorption spectra are constant under different polarization angles, as the structure is independent of the wave polarization.

Now, let us focus on the effect of the angle of incidence on the absorption. Figure 9a plots the results of the effect of angle of incidence $\theta$ on the absorption for the TM polarization. It is observed that for the angle of incident $\theta$ of below 45°, the frequency bandwidth with the absorption ratio of greater than 0.9 remains above 38 GHz. Moreover, with the increase of the angle of incidence, the absorptivity even increases at high-frequency regions. Hence, the proposed absorber exhibits an outstanding wideband absorption performance under TM polarization in the case of oblique incidence. Figure 9b plots the same result for the transverse electric (TE) polarization.
a similar approach, the absorption bandwidth with a high absorption ratio remains nearly the same for the angle of incidence $\theta$ below 45°. However, further increasing the $\theta$ yields decreases the absorption in low-frequency regions. In general, the proposed structure operates in a wide range of angle of incidence for both TM and TE polarizations.

5. FABRICATION AND MEASUREMENT

The MA is fabricated using the additive manufacturing method. We use a SinoTec ST 200 FDM three-dimensional (3D) printer with a print accuracy of 0.05 mm to print the proposed absorber. Figure 10a shows the process of a complete absorber sample. First, a PLA layer with grooves is 3D printed. Next, the patterned conductive plastics were placed in these grooves, and then the PLA is continually printed above the patterned plastics to seal them. Finally, copper is pasted on the bottom surface of the PLA layer. Figure 10b shows an image of the fabricated sample with an array of 10 $\times$ 10 unit cells.

The experiment is carried out in free space. Figure 11 shows an image of the experimental setup, where two horn antennas, one for the K-band and the another for the Ka-band, are connected to a Rohde & Schwarz ZVA 40 vector network analyzer to measure the performance characteristics of the sample in the frequency range 18–40 GHz. Figure 12a plots the actual reflection from the sample by comparison of the reflection from the absorber and the reflection from the identical copper plate. Figure 12b shows the measured absorptivity plot, where a wideband absorption is achieved with the absorptivity greater than 90% from 23.3 GHz, covering the whole Ka-band. Because of the upper frequency limitation of the Rohde & Schwarz ZVA 40 vector network analyzer, the measurement is limited to 40 GHz. Moreover, from Figure 12b, the measured results are in agreement with the simulations except for the lower-frequency region of the K-band, which may be attributed to fabrication tolerance.

6. CONCLUSIONS

We presented a simple and high-performance wideband MA based on the conductive plastic. In contrast to the previously reported wideband MAs, we introduced an additive manufacturing technology to the sample fabrication, which is simple, effective, and low cost. We next demonstrated the absorption mechanism and efficiency by numerical simulations of the absorber. The absorber demonstrates a wideband absorption with an absorption ratio of above 0.9 from 16.3 to 54.3 GHz, corresponding to a relative absorption bandwidth of 108%. Moreover, the design strategy makes the structure insensitive to the wave polarization, as well as the oblique incidences for both TE and TM polarizations. The proposed design is verified by free-space experiments, where a good agreement between the simulated and measured results is achieved across a wide frequency band. This study is expected to reveal the potential applications of additive manufacturing technology in the realization of wideband electromagnetic wave absorbers.
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Notes

The authors declare no competing financial interest.

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