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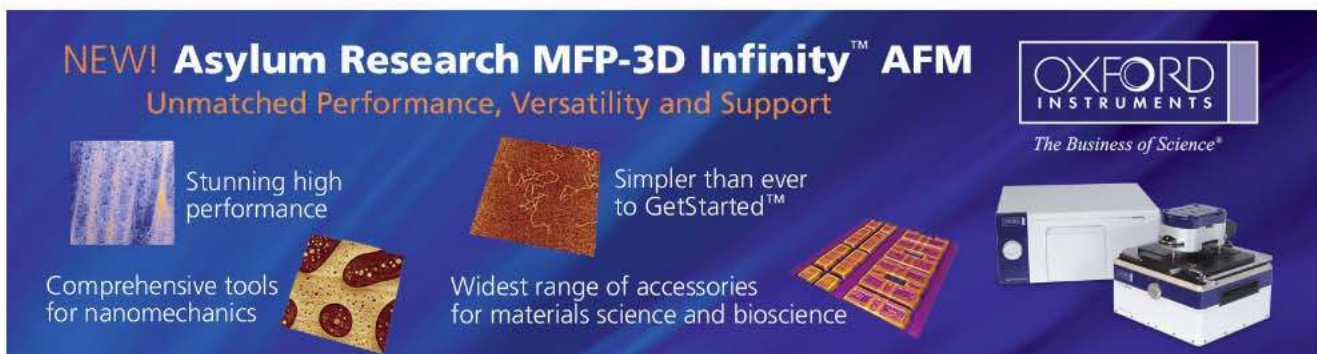
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Integrating non-planar metamaterials with magnetic absorbing materials to yield ultra-broadband microwave hybrid absorbers

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Broadening the bandwidth of electromagnetic wave absorbers has greatly challenged material scientists. Here, we propose a two-layer hybrid absorber consisting of a non-planar metamaterial (MM) and a magnetic microwave absorbing material (MAM). The non-planar MM using magnetic MAMs instead of dielectric substrates shows good low frequency absorption and low reflection across a broad spectrum. Benefiting from this and the high frequency strong absorption of the MAM layer, the lightweight hybrid absorber exhibits 90% absorptivity over the whole 2–18 GHz range. Our result reveals a promising and flexible method to greatly extend or control the absorption bandwidth of absorbers. © 2014 AIP Publishing LLC.

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Microwave absorbing materials (MAMs) with a broad working bandwidth and thin thickness play key roles in diverse fields such as antenna, stealth, and electromagnetic (EM) compatibility.^{1,2} The regime of 2–18 GHz is the most concerned band in radio frequency because of its wide application in Radar and other important communication devices.³ In this frequency range, magnetic MAMs, which are generally comprised of magnetic metals or ferrite nanocrystalline particles dispersed in a polymer matrix, have been intensively investigated and widely used due to their broad bandwidth, effective absorption, light weight, and thin thickness.^{4–7} They can absorb more than 85% of the incident EM wave over the 8–18 GHz range even when the thickness is as thin as 1 mm.^{8,9} However, they cannot simultaneously show high magnetic loss and good impedance matching in the whole frequency range of 2–18 GHz because of the magnetic resonance nature and Snock's limit.^{10,11} As a result, the bandwidth of 90% absorption [i.e., –10 dB reflection loss (*RL*)] is restricted within a few GHz, and the absorption in 2–8 GHz is very weak. Other kinds of thin MAMs such as those containing carbon fibers,¹² nano-sized magnetic fillers,¹³ and in the form of multiple layers¹⁴ exhibit much narrower absorption bandwidth compared to the magnetic MAMs.

Electromagnetic metamaterials (MMs) generally comprised of sub-wavelength metallic elements in periodic patterns are demonstrated to have some peculiar properties including negative reflective index, as well as control over the reflection, absorption, and propagation of EM waves.^{15–17} Recently, Landy *et al.*¹⁸ designed a MM perfect absorber with a simulated absorptivity (*A*) of 99% at 11.48 GHz by using split ring resonators (SRRs) on the top of a dielectric substrate backed with copper strips. This type of MM absorber has unique advantages of easily adjustable

absorption frequency by merely controlling the unit cell parameters, together with near perfect absorption, light weight, and thin thickness.¹⁹ However, it shows such a narrow absorption bandwidth that its application is highly limited.²⁰ To expand the absorption bandwidth, most of the research has been focused on tuning the unit cells of the MMs,^{20–25} and introducing frequency dispersion and/or dissipation in the dielectric substrate or metal unit cells.^{26,27} However, it is still hard for the MM absorber to achieve a wide absorption bandwidth comparable to that of the traditional MAMs in 2–18 GHz. This suggests that there is a great challenge to achieve broadband absorption for the single emerging MM or the conventional MAM due to their own drawbacks.^{10,11,28}

In this work, we combine the two concepts of MMs and magnetic MAMs to create an extreme broadband and lightweight bilayer hybrid absorber, where the top layer of the non-planar MM has its face parallel to the wave propagation direction and stands on the bottom layer of the magnetic MAM. In this bilayer hybrid absorber, the top non-planar MM layer offers strong absorption for low frequency waves while allowing high frequency waves to propagate through without reflection. The bottom layer of the magnetic MAM then strongly absorbs the high frequency EM waves. As a result, a broadband, high efficiency, light-weight, and easily tunable absorber is obtained. This design is flexible, and can be manipulated to meet the requirements of various applications including stealth, EM compatibility, and communication.

If we treat the MM as a homogeneous effective medium, the hybrid absorber can be taken as a two-layer system. Fig. 1(a) illustrates the procedure of EM waves traveling in it. Suppose that the complex S-parameters of the top layer in air are S_{11} , S_{21} , S_{12} , and S_{22} , and the reflection coefficient for only the second layer on a metal back is r . Then the reflection coefficient of the whole two-layer system on a metal back can be written as

$$R = S_{11} + \frac{S_{12}S_{21}r}{1 - S_{22}r}, \quad (1)$$

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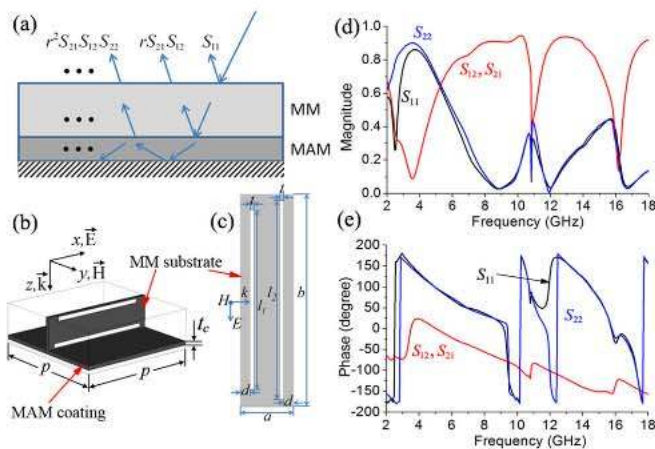


FIG. 1. (a) A schematic showing how EM waves travel in a two-layer absorber. (b) Three-dimensional sketch of the hybrid absorber, and (c) a side view of unit cell of the MM structure annotated with EM wave source and geometric dimensions. (d) The magnitude and (e) phase of the simulated S-parameters of the MM in (c).

where $r = \frac{p}{(z-1)/(z+1)}$, $z = \frac{p}{1/e \tanh(ikd)}$, $S_{21} = S_{12}$, and e , μ , k , and d represent the permittivity, permeability, wave number, and thickness of the second layer, respectively. Note that all the variables except d are complex numbers. Equation (1) indicates that if S_{11} and S_{21} approach zero, the total reflection coefficient of the two-layer system will also be zero regardless of the value of r . Since the absorption in the first layer equals to $1 - S_{11}^2 - S_{21}^2$, smaller S_{11} and S_{21} means stronger absorption. Therefore, we can say that if the top layer is strong enough in absorption, the bilayer system should also be strongly absorptive no matter what is on the second layer. On the other hand, if the top layer is highly transparent, which means a very small S_{11} and a very large S_{21} , the reflection coefficient R for the bilayer system can also be very small provided that r approaches zero. These are the two extreme conditions to achieve strong absorption in a two-layer absorber system. More generally, we require small S_{11} and S_{22} , large S_{21} and S_{12} , as well as small r values to achieve good absorption for the whole two-layer system. Among them, small enough S_{11} is a crucial requirement. Otherwise, it is impossible to get strong loss.

From the above analysis, we can design a two-layer broadband hybrid absorber in such a way: The top layer is an MM absorber which has high absorption at frequencies lower than 8 GHz as well as low reflection in a broadband spectrum so that the high frequency waves can go through it and reach the bottom layer. The bottom layer backed with a metal plate is a traditional thin magnetic MAM with strong absorption in 8–18 GHz as shown in Fig. S1 of supplementary material.²⁹ However, the MM absorbers developed so far are mostly planar ones or so-called metasurfaces.³⁰ They are strongly reflective except in their narrow absorption frequency range, and their microwave absorption behaviors highly rely on the interference and multi-reflection damping effects.³¹ Therefore, this type of MM absorbers is not a good candidate to integrate with the conventional magnetic MAM to get a broadband absorber. Recently, non-planar MM absorbers whose surfaces are parallel to the propagating direction of the incident EM waves were proposed.^{27,32,33} These non-planar MM absorbers do not use back reflectors, and thus the

absorption does not heavily depend on the interference mechanism. Furthermore, they may exhibit near perfect absorption over a certain bandwidth, as well as low reflection in a broadband range. This inspires us to place non-planar MM absorbers on the magnetic MAMs, which possibly provides a rational strategy to achieve a hybrid absorber with ultra-broadband absorption. Meanwhile, we also note that the previous non-planar MM structures^{27,32} are too complicated because of the embedded lumped elements and have an “effective thickness” along the wave propagation direction as thick as 30 mm. In this Letter, we develop a compact-sized and lumped-element-free non-planar MM absorber with high absorption at low frequency and small reflection in a broadband spectrum by using a magnetic MAM as the substrate. As depicted in Fig. 1(b), the as-developed non-planar MM absorber is stacked on the top of another magnetic MAM to obtain a bi-layer hybrid absorber, which has an advantage of inheriting both the broadband absorption of the MAM in 8–18 GHz and the nearly perfect absorption of the non-planar MM absorber at low frequency.

Fig. 1(c) shows a view of the non-planar MM absorber on one side with geometric parameters. It has a symmetric pattern on the other side. To ensure that the resonance frequency falls within the range of 2–4 GHz, the length of the two pair of cut-wires $l_1 = 24$ mm, $l_2 = 26.7$ mm, the width $w = 1$ mm, and the gap between the two parallel strips $g = 5.4$ mm. Other dimensions of the unit cell are set as $a = 8$ mm and $p = 30$ mm. In this work, all the metal aluminum units have a thickness of 0.02 mm and a conductivity of 3.56×10^7 S/m. The frequency (f) dependent complex S-parameters of the MM absorber were obtained by simulation using a commercial finite-element-method (FEM) based solver *Comsol Multiphysics*TM. The resulting magnitude and phase of the S-parameters of the MM are plotted in Figs. 1(d) and 1(e).

The use of magnetic MAMs as a substrate is important for the non-planar MM absorber to obtain a good absorption in low frequency range. Fig. 1(d) indicates that for the MM absorber with the magnetic MAM substrate, S_{11} and S_{21} both show a dip at around 2.4 GHz. This implies that it shows a strong absorption near that frequency. As we know, the total loss from the MM absorber includes three parts: dielectric loss, magnetic loss from the substrate, and Ohmic loss from the metal. In radio frequencies, the metals used in MMs are nearly perfect conductor, making the Ohmic loss negligible.³⁴ Thus, the absorption of the MM absorbers is nearly all from the substrates. When non-magnetic materials (such as, FR-4) are used as the MM substrates, the absorption is from dielectric loss and can be calculated by the dielectric loss power $P_e = (1/2) \times e'' |E|^2$. Here, E represents the electric field in the substrate, x and e'' are frequency and imaginary part of the permittivity, respectively. It is clear that P_e is strongly influenced by the electric field E in the material, which is greatly determined by the MM structure design. That is why the unit cell structure of metals has been the most important factor in the MM design. Certainly, the substrate also has an important impact on the absorption as P_e is directly proportional to e'' . When a magnetic MAM is used as the MM substrates, the absorption includes both the dielectric loss and the magnetic loss. In this case, the total EM energy

dissipation $P_{\text{total}} = P_e + P_m = (1/2) \times e'' |E|^2 + (1/2) \times 1'' |H|^2$. Here, H is the magnetic field in the substrate and $1''$ is the imaginary part of the magnetic permeability. Figure S2 shows that the MM absorber with the magnetic MAM substrate possesses higher loss than that with the FR-4 substrate. This suggests that magnetic substrates can induce more EM energy loss than dielectric substrates. Furthermore, the magnetic one still has a loss of about 20% out of the resonance frequency due to its magnetic inductance and stronger loss,²⁹ while the dielectric one absorbs EM waves only at resonance frequencies.

The metal strip array is known to show a band-stop character,³⁵ which enables the broadband transparency of the MM. Near the resonance frequencies, the electric fields along the strip lines are mostly coupled into the strips and then dissipated or re-radiated back; at the non-resonance frequencies, the strip array becomes transparent.³⁶ Therefore, the MM shows strong absorption near 2.4 GHz as analyzed above. It is also notable that S_{11} has a large value between 4 and 6 GHz. This means the resonance causes large reflection. In the range of 8–18 GHz, which is away from the resonance, S_{11} keeps a low value of below 0.4, indicating the reflection of lower than 16%.

If we combine the MM absorber and the magnetic MAM to form a hybrid absorber as shown in Fig. 1(b), it is expected that the absorption of the hybrid absorber is good in 8–18 GHz and at around 2.4 GHz, but weak in 4–6. To find out this, we calculated the total reflection R by substituting the S-parameters of the MM in Fig. 1 and the material parameters of the magnetic MAM in Fig. S1 into Eq. (1). Since the two-layer hybrid absorber backed with a metal has no transmittance, its absorptivity in 2–18 GHz can be calculated by $A = 1 - R$. As shown in the blue dashed curve in Fig. 2(a), the calculated results are what we expect. Compared with the simulated absorptivities of the non-planar MM absorber and the magnetic MAM [Fig. S1(b) in supplementary material²⁹], it is reasonable to infer that the low frequency absorption peak of the two-layer hybrid absorber at around 2.4 GHz, mainly arises from the top layer of the non-planar MM absorber, and the broadband strong absorption in the f range of 8–18 GHz is primarily attributed to the bottom layer of the magnetic MAM. This suggests that the absorption in 8–18 GHz is governed by the second MAM layer because of the high transparent MM. In addition, the weak absorption in 4–6 GHz derives from the large reflection of the top-layer MM in those frequencies. We also perform the full wave simulation over the hybrid absorber and derive the absorption, which is shown in Fig. 2(a) with a red

dashed-dotted line. The two results are consistent with each other very well, validating the availability of Eq. (1). The slight deviation between the two curves may be explained by the simplification of the periodic top MM layer as a homogeneous effective medium in Eq. (1).

To verify the design experimentally, we have fabricated the two-layer hybrid absorber by the following steps. First, two pieces of magnetic MAMs with 1 mm in thickness (t_s) and 180×180 mm in area were obtained by uniformly dispersing carbonyl iron flaked powders in epoxy adhesives with weight ratio of 2.65:1, and then shaping and curing them at 60 °C. Fig. S1 in supplementary material shows the material parameters and EM wave absorption properties of the magnetic MAMs.²⁹ Subsequently, one piece of the magnetic MAM was sandwiched by aluminum foils, and then patterned into the non-planar MM absorber according to the design by the lithography method. Finally, the as-fabricated non-planar MM absorber stood on the surface of the other piece of the magnetic MAM with the assistance of a thin layer of epoxy adhesive to form a two-layer hybrid absorber. A photograph of the fabricated absorber is shown in Fig. 2(b). The absorption measurement of the as-fabricated two-layer hybrid absorber was carried out using a NRL-arch reflection test system³⁷ equipped with a vector network analyzer (Agilent Technologies, N5230). As shown in Fig. 2(a), the resulting two-layer hybrid absorber shows an absorption peak of near unity at about 2.4 GHz, in addition to the broadband 90% absorption in the f range of 8–18 GHz. This measured absorptivity is also in good consistence with the calculated one except a slight discrepancy, which is caused by the fabrication errors such as thickness and filling fraction errors of the MAM.

The above hybrid absorber has verified the idea that using perfect MM absorber can complement the low frequency absorption of the conventional magnetic MAM. In fact, according to Eq. (1), the requisite property of the MMs used in the hybrid absorber is not the perfect absorption but the low reflection. In the following, we demonstrate this principle and provide a more practical hybrid absorber design with broadband absorption using a SRR based MM.

Figure 3(a) represents a schematic of the two-layer hybrid absorber, which comprises a non-planar SRR MM absorber standing on the magnetic MAM, as well as a magnified image of the unit cell, which has a pitch of 20 mm in both x - and y -axis directions. Its effective thickness in z -axis direction is 9 mm ($a = 8$ mm for the upper layer of the MM absorber and $t_c = 1$ mm for the bottom layer of the magnetic MAM). The MM absorber uses the same magnetic MAM substrate as our previous hybrid absorber in Fig. 1 but with a different thickness $t_s = 0.5$ mm, and only an SRR on one side. The dimensions of the SRR are $a_1 = 7$ mm and $g = w = 0.8$ mm.

The S-parameters of the MM absorber are obtained by FEM simulations and shown in Figs. 3(b) and 3(c). Compared with the MM absorber based on metal strip lines shown in Fig. 1, the MM absorber based on SRR exhibits small S_{11} in the whole investigated f range. This implies that the SRR makes its impedance to match better with that of the air in a broad bandwidth than the strip lines so that the microwaves are allowed to enter the MM absorber and

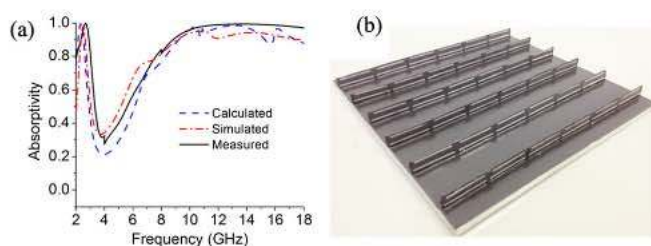


FIG. 2. (a) Simulated, calculated, and measured absorptivity for the two-layer hybrid absorber in Fig. 1. (b) A photograph of the as-fabricated two-layer hybrid absorber with a dimension of 180×180 mm.

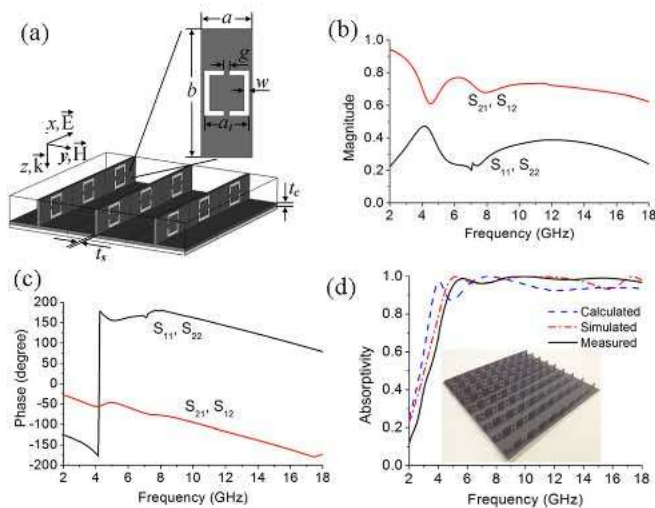


FIG. 3. (a) A sketch showing the hybrid absorber of MAM and MM with SRR. The dimensions of the MM unit cell with SRR are annotated in the enlarged view. (b) The magnitude and (c) phase of the simulated S-parameters of the MM. (d) Simulated, calculated, and measured absorptivity of the non-planar SRR MM absorber. The inset in (d) shows a photograph of the fabricated SRR MM-MAM two-layer hybrid absorber.

subsequently absorbed or transmitted. Meanwhile, S_{21} and S_{12} both drop greatly to around 0.6 at $f \geq 4$ GHz, which indicates that there is only a certain absorption in the MM. However, we will see from Figure 3(d) that in this condition, the two-layer hybrid absorber can still reach a total absorption of $\geq 90\%$ (corresponding to $RL < -10$ dB) in a very broadband range of about 4.5–18 GHz. Moreover, nearly perfect absorption is achieved for most of the frequencies in that range. This is because the EM waves unabsorbed by the top MM layer will further propagate to the bottom layer of the magnetic MAM, where they can experience another extensive attenuation.

It is also worthy of notice that the weight of the as-designed broadband hybrid absorber is quite light, just equivalent to a magnetic MAM layer with a thickness of about 1.2 mm. These are the most major improvements with respect to the MAM coating only. In addition, the supplementary material²⁹ also indicates that for this two-layer hybrid absorber, the absorption performance maintains in a high level for a wide angle of incidence, while the polarization sensitivity can easily be overcome by adding the same MM structure in the cross direction. Using this hybrid absorber concept and design principle, it is even possible to achieve an extremely broadband composite absorber which exhibits an absorptivity of 90% or above in the whole spectral range of 2–18 GHz.²⁹

As demonstrated in the above examples, the hybrid absorber design strategy we proposed here has obviously the advantage that the absorption bandwidth of the non-planar MM absorbers and traditional MAMs can be synergistically integrated into the two-layer hybrid absorber. The non-planar MM absorbers show the rich diversity and tunability in EM wave absorption properties, which makes it feasible to design hybrid absorbers for different purposes. Using magnetic MAMs as the substrate of the non-planar MM absorber further provides them with extra design freedom. It is expected that this design strategy will promote numerous hybrid absorbers of MMs and traditional MAMs with a

variety of EM wave absorption properties by changing the nature of unit cells and substrates in the MM absorber as well as the parameters of MAM. On the other hand, we also note that the effective thickness of the as-fabricated broadband two-layer hybrid absorber is still as large as 9 mm, which should be further reduced in future designs by using a more compact MM absorber. Nevertheless, the hybrid absorber is quite light in weight with respect to traditional MAM absorbers if the excellent absorption performance is considered.

In summary, we have proposed a two-layer hybrid absorber with an extreme broadband and high efficiency absorption by stacking a non-planar MM on the top of a magnetic MAM. In such a design, magnetic MAMs instead of dielectrics in traditional MMs are employed as the substrate of non-planar MM to increase the absorption. Consequently, both the absorption band of the MM at low frequencies and that of the MAM at high frequencies are inherited by the two-layer hybrid absorber, resulting in an extreme broadband and strong absorption. Furthermore, the EM wave absorption properties of the two-layer hybrid absorber can be well predicted and simply optimized. By changing the parameters of the MM, such as the size and structure of the resonators and the nature of the substrate, the magnetic MAM as well as their arrangement, more EM hybrid absorbers can be made to accommodate diverse intended applications.

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