Material–structure integrated design for ultra-broadband all-dielectric metamaterial absorber

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Abstract

Material and structure are the essential elements of all-dielectric metamaterials. Structure design for specific dielectric materials has been studied while the contribution of material and synergistic effect of material and structure have been overlooked in the past years. Herein, we propose a material–structure integrated design (MSID) methodology for all-dielectric metamaterials, increasing the degree of freedom in the metamaterial design, to comprehensively optimize microwave absorption performance and further investigate the contribution of material and structure to absorption. A dielectric metamaterial absorber with an ultra-broadband absorption from 5.3 to 18.0 GHz is realized. Theoretical calculation and numerical simulation demonstrate that the symphony of material and structure excites multiple resonance modes encompassing quarter-wavelength interference cancellation, spoof surface plasmon polariton mode, dielectric resonance mode and grating mode, which is essential to afford the desirable absorption performance. This work highlights the superiority of coupling of material and structure and provides an effective design and optimization strategy for all-dielectric metamaterial absorbers.

Keywords: material–structure integrated design, all-dielectric metamaterial, ultra-broadband, multiple resonances

Supplementary material for this article is available online
(Some figures may appear in colour only in the online journal)

1. Introduction

Microwave absorbers have been attracting significant attention for their widespread applications in electromagnetic compatibility, wireless communication transmission and stealth technology [1, 2]. Many efforts have been devoted to the elaborate component and microstructure design of composites [3–8], with the purpose of achieving a good balance between impedance matching and electromagnetic (EM) energy dissipation. However, the achievement of ultra-broadband absorption with low thickness is an enormous challenge to address owing to the single EM absorbing mechanism of quarter-wavelength interference cancellation [9, 10] or several intrinsic resonances of magnetic materials [11].

Such bottleneck issue might be resolved with the emergence of metamaterials [12–14], which are artificial electromagnetic media consisting of periodic ‘meta-atoms’ with...
the exotic EM properties not readily available in nature [15, 16]. The metamaterial design strategy provides an innovative paradigm to tailor independently electric and magnetic responses to the incident wave, which can be an alternative philosophy for approaching optimal microwave absorption. Many studies on metamaterial absorbers are mainly focused on the design of metallic resonant structures [12, 17, 18]. However, they inevitably suffer from narrow absorption bandwidth limitation due to the nature of strong resonance characteristics. A variety of methods have been developed to broaden the absorption bandwidth, such as the integration of multiple unit cells [19, 20], vertically stacked multilayer structures [21–23], and lumped components [24, 25]. However, these attempts increase the design and fabrication complexity and compromise the flexibility accordingly. Furthermore, the issues of polarization sensitivity and incident angle dependence arising from the anisotropic unit structure are likely to be raised [26], seriously hampering their applications in EM wave absorption.

Recently, all-dielectric metamaterials [27] have exhibited the possibility of achieving perfect absorption with resonance mechanisms different from their metallic counterparts, and offer a simpler and more versatile route for the fabrication of isotropic metamaterial absorbers [28–30]. Many studies have been carried out to explore the microwave absorption of all-dielectric metamaterials, for example, the isotropic Mie resonance-based metamaterial with cubic ceramic material [31], a series of periodic water-based metamaterials with different geometries such as droplet [32] and fishing net [33], and periodic magnetic elements with droplet shape [34]. These researches suggest that large dielectric loss in dielectric metamaterials is helpful to achieve high absorption [32, 34–36]. Structure and material are both essential elements of all-dielectric metamaterials, which allow for a larger degree of freedom in tailoring performance than the metallic ones only with structure design. In the studies of all-dielectric metamaterial absorbers, structure design for specific dielectric materials has been studied while the contribution of materials and synergistic effect of material and structure to absorption performance have been overlooked in the past years. Hence, the motivation of this study is firstly to achieve ultra-broadband absorption by the strategy of material–structure integrated design and secondly to explore the contribution of material and structure to absorption. On the one hand, we tried to introduce a new perspective of the material–structure integrated design strategy to design ultra-broadband absorption of all-dielectric metamaterials more flexibly and comprehensively. On the other hand, we would like to highlight the indispensable contribution of both material and structure factors to absorption performance, which has been ignored in the past years.

Herein, following the materials and structures integrated design (MSID) philosophy [37, 38], we customize the genetic algorithm (GA) combined with a simulation platform to synchronously design and optimize the material and structure of dielectric microwave metamaterial absorbers (DMMA). Furthermore, the contributions of material and structure to absorption are investigated via theoretical calculation and full-wave simulation. A new DMMA with ultra-broad bandwidth over the range from 5.3 to 18.0 GHz (a relative bandwidth of as high as 109%) as well as good tolerance of angles and polarization modes of the incident wave is proposed here. Multiple resonances including quarter-wavelength interference cancellation, spoof surface plasmon polariton (SSPP) mode, dielectric resonance mode and grating mode are reasoned to be responsible for the excellent absorption performance. The influence of material and structure factors on the absorption of DMMA are detailed to reveal that not only structure but also material are responsible for the overall microwave absorption performance.

2. Models and methods

2.1. Material

In the all-dielectric metamaterials, the essence related to the material can be physically interpreted as the constitutive parameters. The component and microstructure design of materials in the micro-level, no matter how elaborate, are essentially about tailoring macroscopic EM parameters. For simplification, different EM parameters are achieved by varying the content of carbon black in the homogeneous carbon black/polylactic acid (CB/PLA) composite with a broad range of permittivity. Figures I(a) and (b) show the complex permittivity of CB/PLA composites with 5wt.%, 7.5wt.%, 10wt.%, 15wt.% and 20wt.% content of CB at 2–18 GHz. With the increase of concentration, both the real part $\varepsilon_r$ and imaginary part $\varepsilon_i$ of permittivity show an obvious upward tendency and strong frequency dispersion. The typical relaxation peak appears at the $\varepsilon_i$ of higher content of 15wt.% and 20wt.%, revealing that CB has a strong response to microwave. The morphology of CB/PLA composite (10wt.% CB/PLA composite) is illustrated in figure S1 (https://stacks.iop.org/JPCM/34/115701/mmedia).

2.2. Structure

Inspired by the traditional honeycomb structure and periodic elements of metamaterials, a DMMA with a multilayer structure comprises an upper PLA honeycomb layer, intermediate anti-honeycomb elements with CB/PLA composites (anti-honeycomb refers to the complementation of honeycomb structure) and a bottom PLA supporting layer backed copper sheet is proposed here, as shown in figure I(c). The top view and side view of the unit cell of the DMMA are exhibited in figures I(c) and (d), respectively. The upper honeycomb structure made of PLA with $\varepsilon_r = 2.1 \times (1 - j0.07)$ has a diameter of $d_{honeycomb}$, wall thickness of $h_{honeycomb}$ and height of $h_u$. The intermediate anti-honeycomb layer consists of an array distribution of hexagonal prisms with a diameter of $d_{anti-honeycomb}$ and height of $h_m$, which is made of CB/PLA composites. The bottom PLA supporting layer with a height of $h_l$ is bounded to a copper sheet on the backside.

2.3. Material–structure integrated optimization

Material and structure are the essential elements of the proposed DMMA, or they constitute the ‘genes’ of DMMA. GA is an intelligent algorithm modeled on the principles
Figure 1. Material and structure parameters of the DMMA. Complex permittivity of CB/PLA composites with different contents of CB: (a) real part and (b) imaginary part. (c) Top view of the unit cell. (d) Side view of the unit cell. (e) Schematic diagram of the whole DMMA with multiple layers.

and concepts of natural selection and evolution [26, 39, 40], which is usually used to seek the global optimal solution of a multi-dimensional target function within the defined parameter space. Herein, GA combined with CST microwave studio (CST MWS) is implemented to optimize the material–structure integrated design of DMMA for broadband absorption. It must be mentioned that the GA integrated in CST MWS can only optimize the structure parameters and does not have the functionality of optimizing the material and structure parameters synchronously, which highlights the necessity of developing an approach for material–structure integrated optimization in this work. In particular, when the option of available materials is numerous, material–structure integrated optimization has absolute superiority of high efficiency and can free one from tedious and repetitive operations of structure optimization of all the materials using integrated GA.

A flowchart of the material–structure integrated optimization via GA combined with CST MWS is illuminated in figure 2. The material and structure parameters of DMMA are encoded into binary strings called genes, and then these genes constitute chromosomes. A certain number of chromosomes are randomly produced as the initial population and each of them represents a DMMA (individual). The broadband absorption is chosen as the fitness evaluation criterion. In the process, GA is realized in the MATLAB environment. MATLAB calls CST MWS via VBA (a scripting language) to send the model of DMMA, control the simulation and obtain the S-parameters at different frequencies. In the full-wave simulation from 2 to 18 GHz, the unit cell boundary is used in the x and y-direction, and the incident wave is assigned to propagate from the +z direction. In addition, because the absorption of the proposed DMMA is not sensitive to the polarization of the incident wave owing to the symmetry of its structure, the transverse magnetic (TM) mode is considered here for simplification. The absorptivity is calculated from S-parameters, which is based on the equation of $A(f) = 1 - |S_{11}(f)|^2$ since there is no transmission due to the backed metal plate. The absorption bandwidth can be represented and the fitness function can be defined by counting the average value of absorptivity higher than 90% at different frequencies. The fitness value returned by the fitness function is utilized to evaluate the goodness of each individual. Some individuals with good fitness in the initial population are then selected as parents for participation in the reproduction process. The parents undergo crossover and mutation, thereby producing new children. These individuals are then
inserted back into the initial population to replace individuals with low fitness, achieving generation replacement. The entire process is repeated until achieving the goal or reaching the iteration limit. Finally, the individual with the best fitness value is picked out, corresponding to the DMMA with the best match of material and structure.

3. Results and discussion

After several iterations of material–structure integrated optimization, the final parameters are obtained: (1) structure parameters ($d_{\text{honeycomb}} = 21.88 \text{ mm}$, $t_{\text{honeycomb}} = 3.61 \text{ mm}$, $d_{\text{anti-honeycomb}} = 16.80 \text{ mm}$, $h_u = 1.48 \text{ mm}$, $h_m = 4.87 \text{ mm}$, $h_l = 1.27 \text{ mm}$); (2) material parameter (10wt.% CB/PLA composite). The simulated absorption spectrum of the designed DMMA with these optimized parameters is shown in figure 3(a). The optimized DMMA achieves 90% absorption over the whole broadband from 5.3 to 18.0 GHz, and the relative bandwidth is up to 109%. Three peak values can be observed at $f_1 = 6.3 \text{ GHz}$, $f_2 = 11.6 \text{ GHz}$ and $f_3 = 16.4 \text{ GHz}$, and their corresponding mechanisms will be discussed in detail later.

For comparison, the structure optimization of DMMA with 5wt.%, 7.5wt.%, 15wt.% and 20wt.% CB/PLA composite
is carried out respectively via GA integrated in CST MWS and the results are exhibited in figure 3(b). The DMMA with 10wt.% CB/PLA composite and corresponding optimized structure exhibits the best absorption performance of all studied cases, qualitatively indicating that ultra-broadband absorption of DMMA entails a certain scale of dielectric loss, but not necessarily the larger the better. The material and structure contributions to the absorption mechanism of the optimized DMMA are further investigated in detail.

3.1. Material analysis

In order to quantify the contribution of material factors, the influence of structure including upper honeycomb and middle anti-honeycomb layer should be ruled out firstly. It is necessary to transform these periodic structures to homogeneous medium models based on the homogenization technique when the periodicity of the structure is smaller than the wavelength. It is necessary to note that the concept of average EM parameter demonstrates effectiveness at several GHz owing to the sub-wavelength structure of the DMMA, but it loses validity at higher frequencies when the elements of DMMA are large or of the order of wavelength due to the diffraction effect. Therefore, the effective parameters are more meaningful at relatively lower frequencies in this work. According to the effective medium theory (EMT) based on the homogenization technique [41–43], the effective permittivity of the periodic structure can be expressed approximately by:

$$\varepsilon_{\text{eff}} = \varepsilon_2 \frac{(1 + f_1) \varepsilon_1 + (1 - f_1) \varepsilon_2}{(1 - f_1) \varepsilon_1 + (1 + f_1) \varepsilon_2},$$

where $\varepsilon_1$ and $\varepsilon_2$ represent the permittivity and $f_1 = 1 - \frac{h_u}{h}$ and $f_2 = 1 - f_1$ are the fractional volumes occupied by phases 1 and 2 within a single period cell (see the honeycomb structure model in figure 4(d)). The effective permittivity of intermediate anti-honeycomb structure with 10wt.% CB/PLA composite is plotted in figure 4(b).

Then, the whole DMMA structure is equivalent to a three-layer absorber backed by a perfect conductor illustrated in figure 4(e) and its microwave absorption performance can be calculated through the transmission line (TL) theory [44, 45] with effective permittivity. The absorptivity of the multi-layered absorber under the normal incident wave of TM mode can be calculated by:

$$A = 1 - \Gamma^2.$$

$$\Gamma = \frac{Z_i - Z_0}{Z_i + Z_0}$$

$$Z_i = \frac{Z_R + Z_c \tan(\beta d)}{Z_c + j Z_R \tan(\beta d)}$$

$$\beta = k_0 \sqrt{\varepsilon_r \mu_r},$$

where $A$ is the absorptivity, $\Gamma$ is the reflection coefficient at the interface of free space and absorber, $Z_i$ is the input impedance between layer $i$ and $i + 1$, $Z_0 \approx 377\Omega$ is the vacuum impedance, $Z_c = \frac{\mu}{\varepsilon}$ is the characteristic impedance, $Z_R$ is load impedance equal to the input impedance of next layer, $\beta$ is phase constant, $d$ is layer thickness, and $k_0 = \omega \sqrt{\varepsilon_0 \mu_0}$ is vacuum wavenumber.

The calculated absorption result is shown in figure 4(a) with a blue line. Obviously, there is a peak value with the near-unity absorption located at 5.5 GHz. The electric thickness of the equivalent three-layered absorber can be calculated based on the effective permittivity:

$$D_{\text{eff}} = \sqrt{|\varepsilon_{\text{eff1}}| h_u + \sqrt{|\varepsilon_{\text{eff2}}| h_m + \sqrt{|\varepsilon_3| h_l}},$$

where $\varepsilon_{\text{eff1}}$ and $\varepsilon_{\text{eff2}}$ are the effective permittivity of honeycomb and anti-honeycomb structure, $\varepsilon_3$ is the permittivity
of bottom PLA layer, and $h_u$, $h_m$, $h_l$ is the layer thickness, respectively. The calculated electric thickness (shown in figure 4(c)) is equal to the quarter-wavelength of the incident wave at 5 GHz near the peak of 5.5 GHz, demonstrating the strong absorption at the peak of 5.5 GHz arising from quarter-wavelength interference cancellation. Furthermore, the calculated absorptivity is well consistent with the simulated one before $\sim$8 GHz, which suggests that the effective method is reasonable until $\sim$8 GHz since the incident wavelength is much larger than the size of the unit cell so that electromagnetic wave cannot ‘see’ the inner structure of DMMA under this condition. Yet at higher frequencies, the structural details cannot be deemed invisible and will have a great effect on the absorption performance. For the reliable portion of the calculated result, the absorption peak of 5.5 GHz is around the first peak at 6.3 GHz of DMMA, indicating that quarter-wavelength interference cancellation plays a significant role in the strong absorption of DMMA. This also verifies that the dielectric material (refer to the CB/PLA composite here) contributes a great deal to the microwave absorption of DMMA owing to its own excellent absorbing capacity.

3.2. Structure analysis

To further elucidate the effect of structure factors on the absorption of DMMA, the field distribution in the DMMA at the resonance frequencies of $f_1$ (6.3 GHz), $f_2$ (11.6 GHz) and $f_3$ (16.4 GHz) are exhibited in figure 5, where the functionality of each layer of structure is analyzed.
The electric field (E-field) and magnetic field (H-field) at $f_1$ in figures 5(a) and (b) reveal that the incident wave is mainly confined between the anti-honeycomb element and the metal plate, which indicates that the SSPP mode is excited at the interface of the metal and artificial dielectric resonator [46, 47]. Additionally, the majority of power loss at $f_1$ in figure 5(c) is distributed at the bottom of the anti-honeycomb element, also indicating that the SSPP mode is excited and incident wave is confined at the metal surface and absorbed by anti-honeycomb element made of 10wt.% CB/PLA composite with good EM energy attenuation. There exists some power loss at the top of the anti-honeycomb unit cell, which can be attributed to the quarter-wavelength interference cancellation. DMMA without the metal plate is simulated for comparison as shown in figure 6(b). Compared with the simulation result of the DMMA (figure 6(a)), the first resonance peak disappears completely, proving that SSPP mode cannot be excited without the metal plate. In addition, the simulated result of DMMA without the bottom PLA layer (figure 6(c)) shows that the first peak intensity decreases dramatically, suggesting that the PLA supporting layer has a crucial effect on the SSPP mode. The above analysis of both material and structure factors reveals that the hybrid mechanism of quarter-wavelength interference cancellation and resonance of SSPP mode is responsible for the strong absorption peak at $f_1$.

Subsequently, from the E-field and H-field distribution at $f_2$ shown in figures 5(d) and (e), it can be observed that one part of the electromagnetic field distributes between anti-honeycomb elements and metal plate, which is similar to that at $f_1$ with less intensity. Another part of the H-field distributes at the top of the anti-honeycomb element which exhibits a typical magnetic-dipole feature [28, 48], while a couple of half loop can be observed in the E-field. The field distribution indicates that the hybrid mode of SSPP mode and magnetic dipole mode of dielectric resonance is excited at $f_2$. According to figure 5(f), the majority of power loss is distributed at the top of anti-honeycomb elements and some at the bottom, suggesting that the dielectric resonance is dominated here. To understand the effect of periodic anti-honeycomb elements, simulation of the absorber with 10wt.% CB/PLA composite plate of the same height replacing the anti-honeycomb structure in DMMA is carried out, and the result is shown in figure 6(d). The average absorptivity is around 70% over the operating band, which is not sufficient for microwave absorption application. Two local absorption peaks can be observed at about 2.5 GHz and 10.1 GHz, which correspond to the interference cancellation of quarter wavelength (2.6 GHz) and the three-quarter wavelength (10.0 GHz), respectively (more details in figure S2). Therefore, these new resonances in the proposed DMMA will not be excited if there are no periodic anti-honeycomb elements.

Further, the E-field, H-field and power loss density at $f_3$ are shown in figures 5(g)–(i), respectively. Apparently, E-field is mainly distributed at the air gap between the adjacent anti-honeycomb elements while H-field is mainly on the top of anti-honeycomb elements, thus the majority of the EM energy is absorbed by the top part of anti-honeycomb elements. The representative phenomenon of field distribution indicates that the grating mode due to the grating diffraction effect is excited [49, 50]. The diameter of the anti-honeycomb element is 16.80 mm which is close to the wavelength of 18.29 mm corresponding to $f_3$. As the periodic elements are at the scale of the wavelength, the scatter radiation will take place. In this situation, the EMT fails so that the array of elements should no longer be treated as an effective dielectric layer, but as a 2D grating instead. For in-depth understanding of the grating mode, the performance of DMMA structure made of PLA (called all-PLA DMMA) is simulated and the absorption spectrum is exhibited in figure 6(e). Obviously, the absorption peak arising from grating mode still exists and the other two

**Figure 5.** Simulated field distribution in the DMMA. (a), (d) and (g) E-field in xoz plane at $f_1$, $f_2$, $f_3$ of 6.3 GHz, 11.6 GHz, and 16.4 GHz. (b), (e) and (h) H-field in yoz plane at $f_1$, $f_2$, $f_3$. (c), (f) and (i) Power loss density in xoz plane at $f_1$, $f_2$, $f_3$, respectively.
peaks disappear completely, indicating that the grating mode is dominantly attributed to the appropriate structure parameters but affected very slightly by material parameters, whereas the material properties have a determining impact on the first and second absorption mechanisms. DMMA without the upper PLA honeycomb structure is also simulated here to evaluate the effect of the upper layer. As illustrated in figure 6(f), the first and second absorption peaks of DMMA without the upper layer are almost equal to that of DMMA, while the third peak shifts to the higher frequency and corresponding absorptivity shows a decreasing trend. Thus it can be concluded that the upper layer can affect the grating mode and hence the absorption performance. In addition, this characteristic feature of grating mode also explains why the third absorption peak at the operating frequencies only occurs to the optimized all-dielectric metamaterial with 10wt.% CB/PLA composite but not with other contents; grating mode can be excited only when the value of periodicity matches that of the incident wavelength. Optimized metamaterials with different contents of CB have different matching structures and only the appropriate structure of the metamaterial with 10wt.% content excites grating mode at the operating frequencies.
Figure 7. Simulated absorption spectra of the proposed DMMA under different angles of the incident wave; (a) TM mode; (b) TE mode.

Figure 8. Simulated and measured absorption spectra of the proposed DMMA; inset is the photos of the DMMA prototype.

Based on the above analysis, it can be concluded that the absorption performance of the all-dielectric metamaterial absorber is the synergistic effect of the material and structure. Therefore, the material and structure parameters control the three resonance frequencies, but different parameters affect different resonances in different degrees. The strong absorption at 6.3 GHz results from the quarter-wavelength interference cancellation and spoof plasmon polariton mode, which will be mainly affected by the material parameters (electromagnetic constitutive parameters), sizes of the periodic anti-honeycomb structure, and thickness of the bottom PLA layer. The second resonance at 11.6 GHz is the hybrid mode of spoof plasmon polariton mode and magnetic dipole mode of dielectric resonance, which is significantly affected by the structure and material parameters of periodic anti-honeycomb elements. The third resonance at 16.4 GHz is the grating mode, closely related to the structure parameters of the periodic anti-honeycomb element and the upper honeycomb structure. The three resonances together result in the ultra-broadband absorption performance.

3.3. Wide-angle and polarization-independent DMMA

The proposed all-dielectric metamaterial absorber with symmetrical anti-honeycomb and honeycomb structures has good angle and polarization tolerances, which can be validated by the simulation results of absorption under different incident angles and polarization modes. This is consistent with previous studies [30, 31, 33, 51] which demonstrate that, as isotropic dielectric materials, the dielectric metamaterial absorbers are insensitive to incident angles because the incident electromagnetic wave sees the same structure for isotropic materials while different structures for anisotropic materials as the incident angle varies. Also, the metamaterial absorbers with symmetrical element structures have good polarization tolerance because periodic elements with multiple rational symmetries maintain similar interactions with incident waves of different polarization modes.

The absorption performance under the incident wave of TE and TM mode with angles varying from 0° to 50° are studied and results are shown in figure 7. The absorptivity for TM mode (figure 7(a)) remains higher than 90% over the whole operating frequency when the incident angles are below 40°. When the angle reaches 50°, the absorptivity is higher than 90% in the majority of the frequency band and higher than 85% over the rest of the band. As for the TE mode (figure 7(b)), the absorptivity decreases at the lower frequency domain with the increasing of incident angle while remains higher than 90% at the higher frequency domain for angles below 40°. The decrease can be understood by the magnetic dipole mode of dielectric resonance at the second absorption peak, which is sensitive to the alternating incident magnetic field. When the incident angle increases for TE mode, the effective magnetic field illuminated on the DMMA is reduced (see the inset.
of figure 7(b)). Consequently, the dielectric mode is weakened and thus the absorptivity drops significantly at the lower frequency band.

Although the proposed metamaterial here has broadband microwave absorption, the absorption band as against −10 dB has not been extended to the lower frequency. Based on the philosophy of the material–structure integrated design, broadly available options of material candidates and structure designs may further improve the absorption at lower frequencies. Firstly, magnetic materials such as carbonyl iron and ferroferric oxide can be good candidates to remedy the situation since they have a good capacity for attenuating electromagnetic wave at lower frequencies by introducing a variety of magnetic resonances such as natural resonance and exchange resonance. Secondly, more structure designs (e.g., combined with metallic metasurfaces) may help excite new resonances at lower frequencies. All these methods can be considered to improve absorption performance at the lower frequency in the future work.

4. Experimental validation

A prototype of the DMMA with a size of 260 mm × 260 mm is manufactured and the preparation process is shown in figure S3. The reflection coefficient of the DMMA from 2 to 18 GHz is experimentally measured by the arch test system, as shown in figure S4. The reflection coefficient of a metal plate with the same size as the sample was first measured as the reference. When the front face of the metal plate is at the same position as that of the material specimen, no phase correction is needed. It follows that the calibrated reactivity of the sample (S_{11}^{\text{cal}}) can be expressed by the ratio of the specimen reflection (S_{11}^{\text{sample}}) to the metal plate reflection (R_{11}^{\text{short}}):

\[ S_{11}^{\text{cal}} = \frac{S_{11}^{\text{sample}}}{R_{11}^{\text{short}}}, \]  

Absorptivity of the absorber is calculated by \( A = 1 - (S_{11}^{\text{cal}})^2 \), and the result is shown in figure 8. The measured absorption of the DMMA is higher than 90% at the operating band with three local absorption peaks, which coincide well with the simulated result. There are some differences between simulated and measured results, which may be caused by fabrication imperfection, measurement error, and the disagreement between simulation and measurement such as idealized assumption of infinite sample mode and plane wave in simulation while the sample is finite and the incident wave is approximately regarded as a plane wave in measurement.

5. Conclusion

An all-dielectric metamaterial with ultra-broadband microwave absorption is proposed here via the strategy of material–structure integrated design and optimization. Synergistic effect of the material and structure excites multiple resonances comprising quarter-wavelength interference cancellation, SSPP mode, dielectric resonance mode and grating mode, resulting in the excellent absorption performance. The indispensable contribution of material and structure factors to microwave absorption of metamaterial absorbers are analyzed, indicating that an excellent match of material and structure is essential for all-dielectric metamaterial absorbers, which has not been carefully considered in the past and will provide a new perspective for designing all-dielectric metamaterials more flexibly and comprehensively. This design methodology possesses huge potential in further improving absorption performances with more diverse material-and-structure designs in the future studies.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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