A Wide-Spaced Dual-Band Metamaterial Absorber Based on 2.5D Frequency Selective Surfaces and Magnetic Material

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Abstract: By applying meander-line for electrical loss and magnetic material for magnetic loss, we present a metamaterial absorber which is wide-spaced and dual-band (1.35—2.24 GHz and 10.37—12.37 GHz). The novelty of this study mainly lies in a combination of two kinds of losses to consume electromagnetic energy, which can get better dual-band absorption. In the electrical loss layer, meander-line structures are printed on both surfaces of the substrate and the structure series with resistors. Considering the need for miniaturization, we connect eight metallic vias with these meander-line areas to form a compact 2.5-dimensional (2.5D) structure. The dimension of the unit cell is miniaturized to be 5.94 mm×5.94 mm, about 0.035λ at the center frequency of the lower absorption band. In the magnetic loss layer, the 0.4 mm thick magnetic material is employed on a metallic ground plane. In addition, the complex permittivity and complex permeability of the magnetic material are given. Finally, we fabricate a prototype of the proposed absorber and obtain a measurement result which is in good agreement with the full-wave simulation result.

Key words: metamaterial absorber; dual-band; frequency selective surfaces; magnetic material

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0 Introduction

As a hot topic in electromagnetic wave field, metamaterial absorbers have been widely studied due to its multiple applications in radome[1], electromagnetic interference (EMI), electromagnetic compatibility(EMC) as well as antenna stealth technology. Because metamaterial structure is a periodic structure, the use of frequency selective surface (FSS) is a significant way to design the structure of the absorber[2-13]. It is important that as many studies focus on this topic, the requirements for metamaterial absorbers are increased. To meet the needs of multifrequency antennas in the satellite communication systems, the authors presented multi-band absorbers based on FSS[7,9]. However, there is not enough space between the operating frequency bands of these absorbers. As for the need for miniaturization, the multilayer technique and application of some meandered shapes can be used to miniaturize FSS structures[10-11]. But multi-layer structures are complex and costly to manufacture. When the absorption band of the absorber is at a low frequency, it is difficult to obtain the ideal absorption effect by only using meandered shapes, especially when the miniaturization of the absorber is required. Fortunately, the magnetic material can be used for low-frequency absorption[14]. In addition, high permeability and permittivity of magnetic material enable absorber structure to be thinner and smaller[15-18]. It is important to note that absorbers only using magnetic loss tend to perform a single band or a single broadband absorption. This feature makes it a limited application.

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In this work, a wide-spaced and dual-band absorber that combines both electrical and magnetic losses is proposed. To create an electrical loss, lumped resistors and meander-line are loaded on both sides of the top layer[19-20]. Meanwhile, metallic vias pass through the dielectric substrate of the top layer. This forms a 2.5-dimensional (2.5D) closed-loop structure, which can be processed with only one dielectric substrate. A magnetic material layer is attached to the metal plate. In order to match the impedance of free space, we introduce an air layer which is added between the electrical loss structure and the magnetic material. Two lossy structures are combined to realize a wide-spaced and dual-band absorption which ranges from 1.35 GHz to 2.24 GHz and from 10.37 GHz to 12.37 GHz for −10 dB reflectivity at vertical incidence. The highest frequency is about 9.16 times that of the lowest frequency. The wide-spaced characteristic of the absorber can be used in stealth technology for broadband antennas because it can absorb electromagnetic energy outside the working frequency band when it acts as a ground plane of antennas.

1 Metamaterial Absorber Design

The 3D sketch diagram of the proposed unit structure is shown in Fig.1, which contains an electrical loss layer and a magnetic one. The two layers are separated by an air layer in the middle and have a metal ground plane at the bottom. Metal meander-line is lined up on both sides of the dielectric substrate by rotation and mirroring. The material of the dielectric substrate is F4B, the relative permittivity is 2.65, the tangent loss is 0.01, and the thickness is 2 mm, which can provide some electrical loss. To form a 2.5D closed-loop structure, the meander-lines are connected by eight metallic vias, and the dimension of this miniaturized unit cell is 5.94 mm× 5.94 mm, about 0.035λ at the lower operating frequency of 1.77 GHz. Since the electrical loss structure part is centrally symmetrical, its polarizations are insensitive. The magnetic loss part consists of a single layer of magnetic material with a thickness of 0.4 mm, which is close to a metal ground plane.

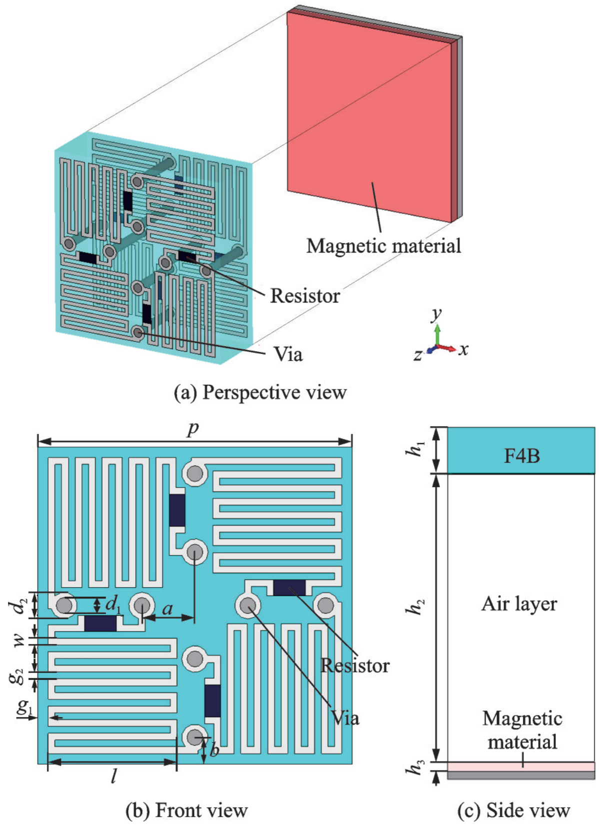


Fig.1 Proposed absorber unit cell

The resistance of the eight lumped resistors is 180 Ω. The optimized geometric parameters of the absorber structure are as follows: p=5.94 mm, l= 2.31 mm, a=1 mm, b=0.5 mm, w=0.127 mm, g_1=0.2 mm, g_2=0.127 mm, d_1=0.3 mm, d_2= 0.5 mm, h_1=2 mm, h_2=15.5 mm, h_3=0.4 mm. We perform simulations in CST software. The mesh type is tetrahedral. Adaptive tetrahedral mesh refinement is applied.

Fig.2 shows the complex permittivity and complex permeability of the magnetic material. This ma-

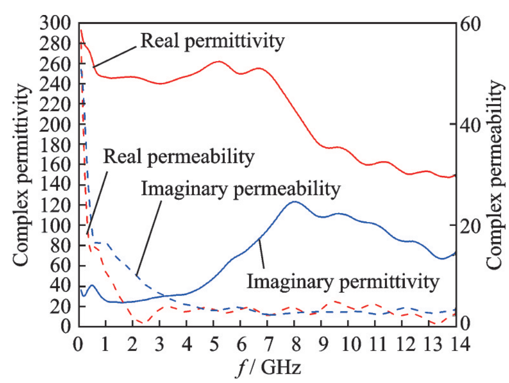


Fig.2 Complex permittivity and complex permeability of the magnetic material

terial is a kind of polymer composites filled with carbonyl iron and Co_2Z ferrite. Complex permittivity ε_r^* can be calculated by $\varepsilon_r^* = \varepsilon_r' - \varepsilon_r''$, and complex permeability μ_r^* can be calculated by $\mu_r^* = \mu_r' - \mu_r''$. Because of the high real permittivity and real permeability at the low-frequency band, the magnetic material features an absorption band in low frequency. When we place a metal ground plane at the back of the magnetic material, the whole structure can be regarded as a simple absorber. The characteristic impedance of the absorber is influenced by complex permittivity, complex permeability and thickness. This magnetic material absorbs electromagnetic waves over a wide range of frequencies, especially at a lower frequency. As a result, this character facilitates designing low-frequency and miniaturized absorbers.

2 Simulation Results

We simulate and compare the absorbers with and without a magnetic material layer (the total thickness of the two absorbers remains equal). The results are shown in Fig.3, where E layer is the electrical loss layer, M layer is the magnetic loss layer, and the vertical coordinate S is the scattering parameter and used to reflect the electromagnetic characteristics. With the addition of a magnetic material layer, the absorption of the absorber is improved overall. If there is a need for further design, magnetic materials can be introduced to enhance the effect once the electrical loss effect from miniaturized structure or structure with thickness limitation is not satisfactory. Fig.4 shows the simulation result of the proposed absorber for different polarizations, where TE and TM represent the two polarization directions of electromagnetic waves and their electric vectors are in different directions. The absorber has a dual-polarization structure. The two bands with 90% absorption are from 1.35 GHz to 2.24 GHz and from 10.37 GHz to 12.37 GHz respectively with a wide-band space between them. As mentioned, the highest frequency, 12.37 GHz, is about 9.16 times the lowest frequency. The good performance of the lower absorption band is mainly caused by the magnetic material. Except for the magnetic loss, the 2.5D meander-line closed-loop loaded with resistors also consumes a lot of energy. The higher absorption band is due to the coupling resonance among the eight sets of meander-line and the one between the meander-line and adjacent cells. Because the change in the electrical loss structure does not affect magnetic loss, the design of the electrical loss structure is relatively free, which leads to an easier design of dual or even multi-band absorbers as well as adjustment of the band space.

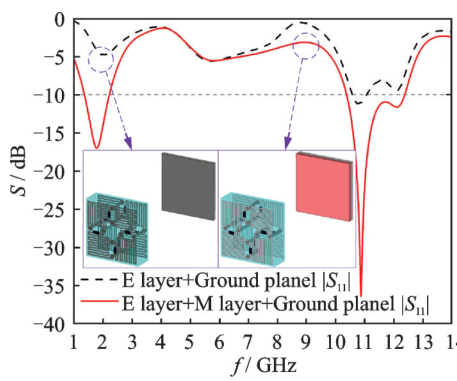


Fig.3 Comparison between two absorbers

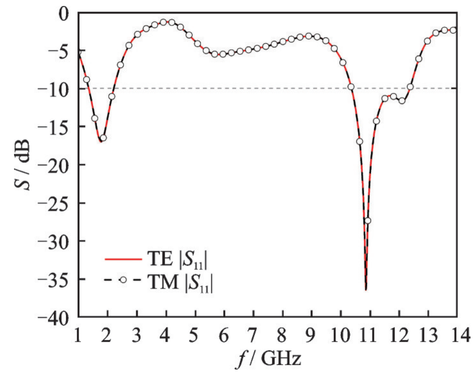


Fig.4 Simulation result of the proposed absorber for different polarizations

Due to the compactness of this model, there is some parasitic capacitance. These cause some absorption between the two absorption bands. Fig.5(a) shows the surface current distribution of 1.79 GHz, which is the resonance point of the lower absorption band. The current flows through the whole 2.5D meader-line loop. We consider the path of the whole loop is divided into several shorter paths at high frequency. The surface current distributions of 10.88 GHz and 12.14 GHz are shown in Figs.5(b, c), respectively. The distribution of current is denser on the metal strips close to adjacent cells of adjacent meander-line regions, which indicates coupling

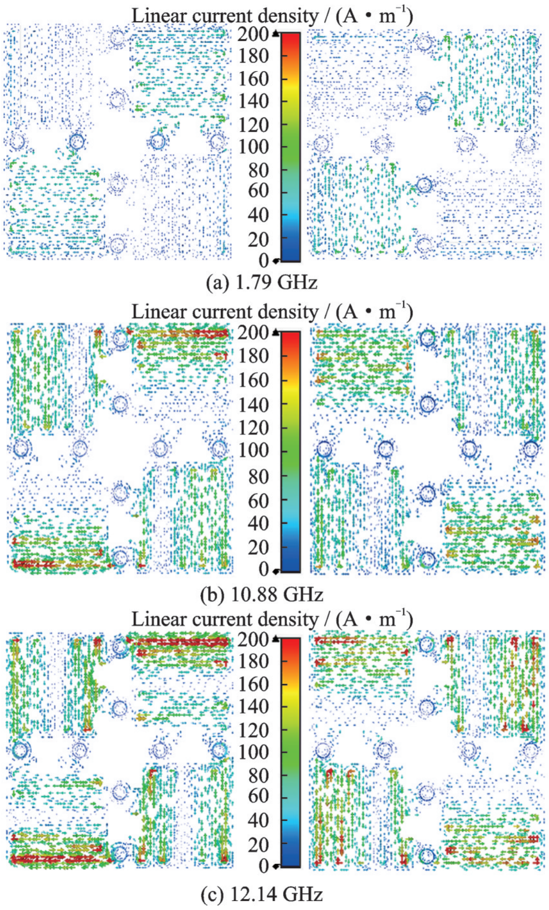


Fig.5 Surface current distributions on both sides of the electrical loss layer for TE polarization

generation. As shown in Fig.6(a), when we move the position of the central vias by changing the value of a, the S curve at higher absorption band changes. When a decreases, the distance between the vias and the meander-line becomes farther, then the coupling resonance at the lower absorption peak is weakened. In Fig.6(b), when l changes, both the parasitic capacitance on the surface of the loss layer and the equivalent inductance of the meander-line change accordingly. This causes two absorption peaks to move towards the high frequency. By changing the structure of the electrical loss layer, the position and bandwidth of the second absorption band produced by electrical loss can be designed independently to some extent.

Fig.7 shows the effect of the thickness variation of the dielectric substrate and magnetic material. We choose F4B as the substrate because it is cheap and easy to process, and it is also a commonly used material for FSS structure. As shown in

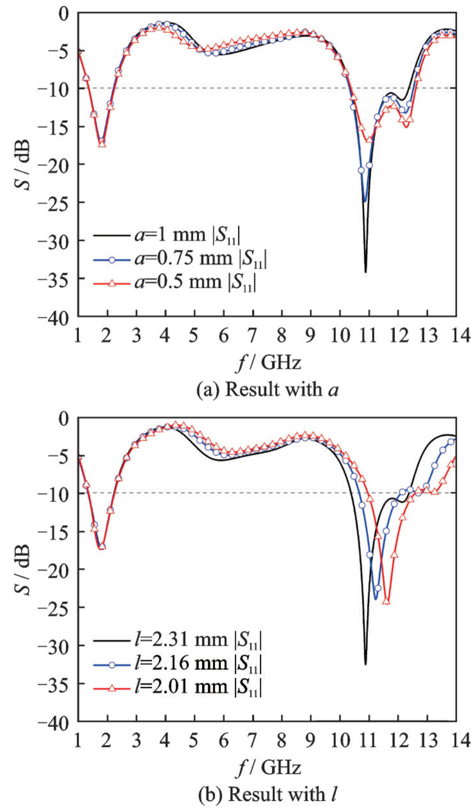


Fig.6 Simulation results of the proposed absorber with parameters a and l

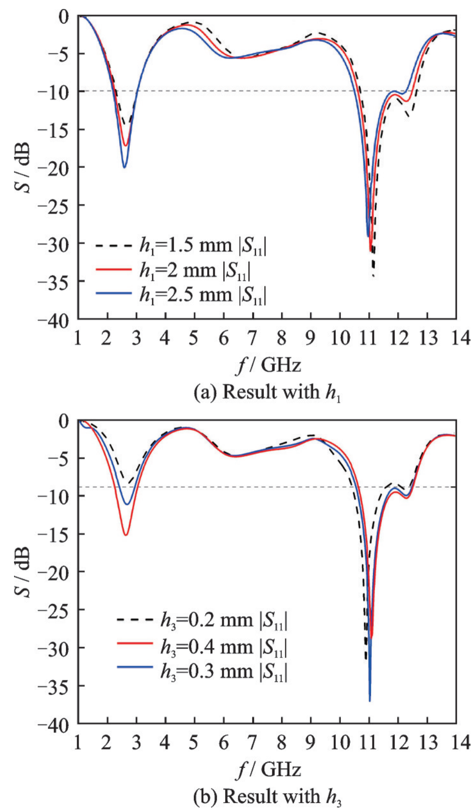


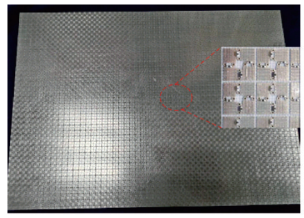
Fig.7 Simulation results of the proposed absorber with parameters h_1 and h_3

Fig.7(a), when h_1 decreases, the low-frequency absorption bandwidth and the absorption rate decrease. Although the low-frequency absorbing effect is enhanced when h_1 increases, the high frequency absorbing effect is weakened, and the space between the two absorption bands becomes smaller. In Fig.7(b), the simulation result shows that the absorption effect deteriorates with the decrease of the thickness of the magnetic material layer. Due to the limitation of process technology, the maximum thickness of this single layer magnetic material is 0.4 mm. The air layer is used for impedance matching. If the thickness of the air layer is changed, electromagnetic waves are not able to enter the inside of the absorber, which will lead to a poor absorption effect.

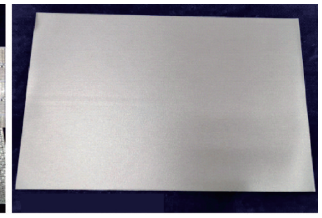
3 Experimental Results

According to the above-mentioned design and magnetic material, we apply the standard print-circuit-board techniques and fabricate a 219.78 mm× 308.88 mm absorber shown in Fig.8(a). As for the air layer, we introduce PMI foam to support the electrical loss layer with relative permittivity of 1, as same as free space. Besides, the thickness of the foam is 15.5 mm. Therefore, the foam could act as an air layer. Fig.8(b) shows a thin magnetic material layer. The experiment is carried out in a microwave anechoic chamber, as shown in Fig.8(c). A pair of horn antennas that connect a vector network analyzer is placed in the front of the absorber sample, so as to measure the reflectivity. We also measure copper plate of the same size to obtain the difference of reflection between the absorber and the copper plate. The difference represents the absorption.

Fig.9 demonstrates the experimental result of the proposed absorber. Considering that the dimensions of the sample are not equal in the x and y directions, we measure it only at one polarization direction which corresponds to the longer side of the sample to make its performance closer to a periodic situation. We can compare the curves with simulated ones. The measured result is in good agreement with the simulation. Table 1 shows the comparison of simulated and measured results. The absorption bands below −10 dB range from 1.66 GHz to 2.16 GHz and from 9.77 GHz to 13.02 GHz. Wide space is between these two absorption bands. Frequency excursion and some differences between the two results may come from fabrication tolerances of the sample and PMI foam. Finally, we compare the performance of this absorber with one of some previously presented absorbers. Results are given in Table 2.



(a) Proposed absorber sample



(b) Magnetic material layer

(c) Experimental environment

Fig.8 Photographs of absorber sample, magnetic layer and experimental environment

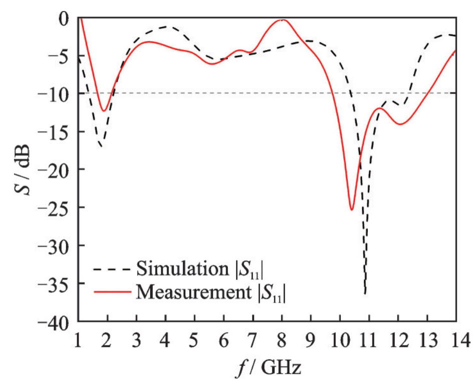


Fig.9 Experimental result of the dual-band metamaterial absorber for TE polarization

Table 1 Comparison of simulated and measured results

Performance	Single or dual	Bandwidth/GHz	Relative bandwidth/%	f_H/f_L
Simulated result	Dual	1.35—2.24, 10.37—12.37	49.58, 17.59	9.16
Measured result	Dual	1.66—2.16, 9.77—13.02	26.18, 28.52	7.84

Note: f_H is the highest frequency of absorption band and f_L the lowest one.

Table 2 Performance comparison of the proposed absorber with previously presented absorbers

Absorber	Single or dual	Bandwidth/GHz	Relative bandwidth/%	Periodic length per λ	f_H/f_L	Thickness/mm
Ref.[10]	Single	11.4—20.0	54.78	0.190	1.75	26.6
Ref.[11]	Single	8.3—11.3	30.61	0.260	1.36	2.0
Ref.[13]	Dual	1.3—4.1, 7.2—10	103.7, 32.56	0.270	7.69	21.0
Ref.[15]	Single	4—15	115.79	0.290	3.75	2.3
Ref.[21]	Single	6.7—11.6	82.46	0.340	2.40	1.6
This paper	Dual	1.35—2.24, 10.37—12.37	49.58, 17.59	0.035	9.16	17.9

Note: Periodic length per λ is equal to the unit side length divided by the wavelength.

The proposed absorber has advantages in terms of thickness compared with both the absorber that uses electrical loss and the dual-band absorber. It also has good unit miniaturization and wide spacing characteristics.

4 Conclusions

In this work, a wide-spaced and dual-band metamaterial absorber using magnetic material is well studied. The proposed absorber is composed of two parts: The electrical loss part and the magnetic loss part. For miniaturization and multiple resonant frequencies, we employ a 2.5D closed meander-line loop which can maximize the length of the current path. When this loop is divided into short paths by lumped resistors under the high frequency, we can obtain the second absorption band. In order to strengthen the absorption effect, we introduce a thin layer of magnetic material. Finally, dual absorption bands range from 1.35 GHz to 2.24 GHz and from 10.37 GHz to 12.37 GHz. Experimental results show a good characteristic of absorption and have a good agreement with the full-wave simulation one. This wide-spaced and dual-band absorber could play a role in stealth technology for the broadband antenna.

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Author contributions Miss **DENG Junyu** designed the study, conducted the simulation, experiment and analysis, interpreted the result, and wrote the manuscript. Prof. **LIU Shaobin** contributed to the background and model of the study. Mr. **LI Wei** contributed to the data and discussion of the study. Mr. **WU Chen** provided assistance for experiment. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Huangqun)

一种基于2.5D频率选择表面和磁材料的宽间隔双频带超材料吸波器

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摘要：提出一种宽间隔双频带超材料吸波器（双频带为1.35～2.24 GHz和10.37～12.37 GHz），将2种损耗结合起来消耗电磁能量，从而获得更好的双频吸收效果。在吸波器电损耗层中，介质基板的两面都印有弯折线结构，并且与电阻串联。考虑到小型化的需求，本文用8个金属过孔将这些弯折线连接起来形成一个2.5D结构，单元的尺寸为5.94 mm×5.94 mm，该尺寸在低频吸波带的中间频率处为0.035λ。在吸波器磁损耗层中，0.4 mm厚的磁材料层应用于金属平板上。此外，本文给出了磁材料的复数介电常数和磁导率。最后本文制作了吸波器原型，并得到了与全波模拟结果相吻合的测量结果。

关键词：超材料吸波器；双频带；频率选择表面；磁材料