Design of a Thin Broadband Metamaterial Absorber Based on Resistance Frequency Selective Surface

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Abstract ─ A thin broadband metamaterial absorber with Resistive Frequency Selective Surface (RFSS) is presented. The absorber maintains a good performance over a broad operating frequency band with low profile. It is designed by a class of periodic artificial electromagnetic structures and the unit cell of the proposed absorber is composed of resistively loaded square loops with different sizes. By combining multiple resonant square loops (MRSL) of different geometries on a single layer structure, the absorption spectrum is greatly expanded. Simulation results show that the absorption coefficient is greater than 85% from 7.9GHz to 18.9GHz, while the thickness of the whole structure is 0.1λ (the free space wavelength) at the lowest operation frequency. A prototype was fabricated and measured in an anechoic chamber to validate the proposed design method. Favorable agreement among the full-wave simulation result and measurement result was achieved.

Index Terms ─ Broadband absorber, multiple resonant, resistive frequency selective surface.

I. INTRODUCTION

A lot of effort has been devoted in the last decades by technology research to realizing materials with absorb electromagnetic wave properties. One of the challenges at present is to improve the operation bandwidth of a structure at a lower profile so that a wider application. The dilemma of attaining both thin thickness and wide bandwidth on metal backed magnetodielectric absorbers simultaneously has been illustrated by the Razanov limitation [1]:

$$\Delta\lambda=\left(\lambda_{\max}-\lambda_{\min}\right)<\frac{2\pi^2\sum_i \mu_{s,i}^{'} d_i}{\left|\ln p_0\right|}\ , \tag{1}$$

where d_i, $\mu_{s,i}^{'}$ are the thickness and the static permeability of ith layer of the multilayer slab. These materials are conventionally characterized by the thickness d_i and by the largest value of module of the voltage reflection coefficient ρ_0 within the operating waveband. There is an optimal bandwidth-thickness ratio (Δλ/t), because the absorption bandwidth (Δλ) is proportional to the effective total thickness ($t=\sum \mu_{s,i}^{'} d_i$). Hence, it is always a challenge for designers to develop technologies to approach this optimal ratio on microwave planar absorbers [2].

Based on the new properties of metamaterial, the metamaterial absorbers (MMA) are widely concerned by many researchers, especially in the optical band and microwave band. The first perfect MMA based on the theory of electromagnetic resonance was proposed by Landy et al. in 2008 [3]. However, owing to the facts that the absorber design principle is based on resonant properties, it inherently limits the absorption to a narrow spectrum. Since then, researchers proposed a variety of MMA that polarization-insensitive and wide incidence angle characteristics, but the absorption frequency spectrum is still narrow [4-9].

In order to achieve broadband absorption performance, the general method is to obtain multi-resonant modes by multi-scaled patterns or fractal structures [10-14]. To a certain extent, the spectrum of broadband absorption has improved, however, the multiple absorption spectra are discretely distributed.

To obtain continuous broadband absorption, several other bandwidth enhancement approaches including the lumped elements loading technology and the multi-layer resistive frequency selection surface (RFSS) absorber [15-18] are proposed. However, these methods have several limitations for the practical application, owing to the increased unit dimension, overall thickness of the absorber, and fabrication difficulty, which are not convenient for many practical applications. Therefore, the design of the low profile with the simple resonance structure, broadband absorption, and high absorption ratio becomes particularly urgent.

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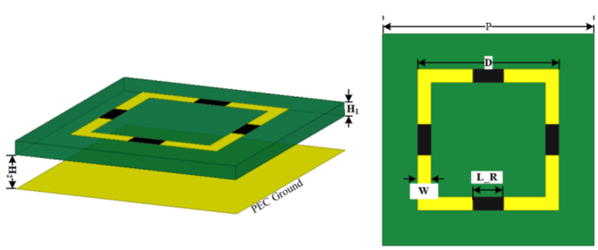
In this paper, a new multiple resonant broadband absorber is studied and presented, which consists of multi-sizes square loops in periodic. The design of the square loop structure based on the theory of resistive frequency selective surface. Simulation results of single and multiple resonances structure are presented, which allow a detailed explanation of the multi-resonant mechanism of the wideband absorber. By rationally designing the size of the multi-resonant square loops and appropriately optimizing the combined structure, continuous multi-resonance point absorption can be generated, which greatly expands the operation spectrum range of the microwave planar absorbers. The absorption coefficient of full-wave HFSS simulation is compared to verify the validation. Using this multi-resonant method, the multi-resonant planar absorbing structure is designed. This letter gives a brief introduction of the multi-resonant square loop absorber design method, which could be used in the wideband absorber design for RCS reduction application of the wideband antenna.

II. ABSORBER DESIGN

A. Single resonant square loop structure

A unit cell of the single resonant square loop (SRSL) absorber based on Resistive Frequency selective surface FSS is shown in Fig. 1. It consists of three layers: surface metal layer, dielectric layer and the PEC ground plane. Between the substrate and the ground plane, an air gap or a foam layer is usually applied to modify the resonant frequency band. Four resistors which can absorb the resonant power are welded in the middle of each edge. Such unit cell can be arranged in periodic to make up a resonant structure that have frequency selective characteristic, based on the theory of frequency selective surface FSS.

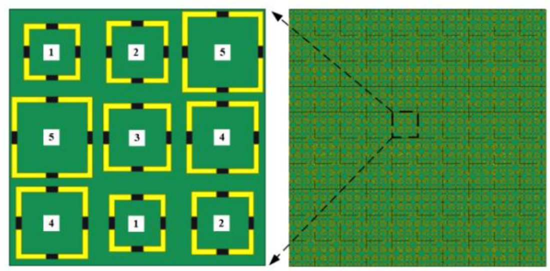


(a) (b)

Fig. 1. The structure of a SRSL: (a) 3D view and (b) top view.

B. Multi-resonant square loop structure

The schematic of the proposed Multi-resonant square loop (MRSL) absorber is shown in Fig. 2. As seen from Fig. 2 (a), the MRSL absorber is built up arranging the single square loops in a periodic structure and each unit cell has nine square loops which in five different sizes. Particularly, every square loop is welded with chip resistors of same resistance in the middle of each edge. Figure 2 (b) presents the 10×10 periodic structure model of the MRSL absorber. All the square loops are printed on a FR-4 substrate with the relative permittivity of 4.4 and thickness of 0.8mm.



(a) (b)

Fig. 2. The proposed MRSL absorber: (a) a view of the unit cell in periodic structure model, and (b) a 10×10 periodic structure model.

Comparing with the single resonant square loop structure, the perimeter of the square loops at different positions are variable with five sizes, but the distance between any two adjacent square loop and the height of the air layer are remained. This change can connect the independent resonance points to produce a wideband frequency response.

III. SMULATION RESULTS

The unit cell was simulated by the electromagnetic full-wave simulator Ansys HFSS. Simulation schematic of parameters is given in Fig. 3. In the simulation, the unit cell placed in a waveguide, where each side of the waveguide is excited by a Floquet port. Master and slave boundaries are applied to the lateral walls of the waveguide to numerically realize an infinite array.

The absorption coefficient of the unit cell, $A(\omega)$, was computed as follows:

$$A(\omega)=1\text{-}R(\omega)-T(\omega), \tag{2}$$

$$R(\omega)=|S_{11}|^2, \tag{3}$$

$$T(\omega)=|S_{21}|^2. \tag{4}$$

Where $A(\omega)$ is absorption coefficient. $R(\omega)$ and $T(\omega)$ represent reflection coefficient and transmission coefficient, respectively. The transmission coefficient $T(\omega)$ is zero, due to the presence of the PEC ground plane. According to (2), (3), (4), absorption coefficient can be easily calculated.

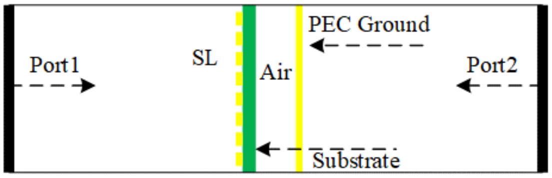


Fig. 3. Simulation schematic of the Floquet periodic boundary condition.

A. Simulation results of SRSL structure

The absorptivity of SRSL absorber is related to the distance (H_2) between the substrate and the ground plane. Besides, the value of the loaded resistance will affect the absorptivity [19]. This article focuses on how to implement a broadband absorber at a lower profile. Therefore, the following parameters are unchanged: P=13.8mm, W=0.88mm, L_R=2mm, H_1=0.8mm, H_2=2.0mm. To obtain a better absorptivity, the absorption characteristics of different resistances loaded with different size square loops have been studied.

Five different sizes of the meta square loop of SRSL absorbers unit cell at the same height were analyzed. The simulated optimal absorption ratio of the different SRSL absorbers are shown in Fig. 4. It can be seen that five different SRSL units have five discretely absorption spectrums. Obviously, single resonant square loop structure has narrowband absorption spectral characteristics. It will get a continuous broadband absorption bandwidth if they work simultaneously in one plane.

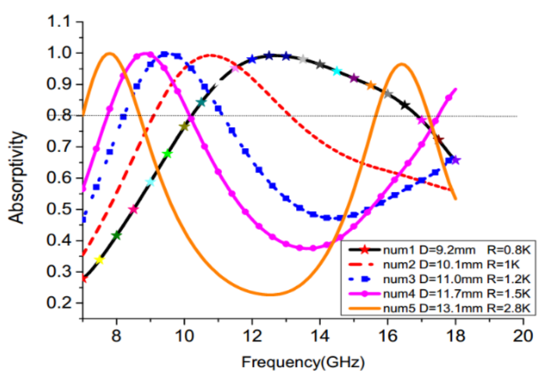


Fig. 4. The simulated absorptivity of the SRSL absorbers with different sizes meta square loops.

B. Simulation results of MRSL structure

The Broadband absorber is designed according to the ideas in the previous section. Generally speaking, multiple absorption spectra are discretely distributed unless the SRSL size was properly designed and the composite structure array was properly selected. Continuous multiple resonance absorption greatly expands the operating spectral range of a single layer structure.

The single resonant square loops in the previous section are selected to combine into different multi-resonant square loop structures. The metal square loops of different sizes have been numbered in Fig. 2, Fig. 7 and Fig. 8. The optimized parameters of the five SRSL are given in the Table 1. Other parameters remain unchanged.

Table 1: The optimized parameters of the five SSL absorber

SLL	D (mm)	R (ohm)	SLL	D (mm)	R (ohm)
#1	9.2	0.8K	#2	10.1	1K
#3	11.0	1.2K	#4	11.7	1.5K
#5	13.1	2.8K			

Four different multi-resonant structure unit cells are proposed in Fig. 5 to verify that different combinations of the MRSL can affect the absorption performance. The divergence is that different loops are placed in different positions, which will change the coupling capacitance between the square loops. In Fig. 5 (a), there is only one square loop No. 3 that placed in the middle of the cell, and the other square rings appear randomly in different positions twice. According to this rule, the intermediate unit cell is replaced in Figs. 5 (b), (c) and (d). These unit cells are used to simulate infinite periodic arrays in master-slave boundary conditions

The absorptivity of the different form MRSL absorbers are shown in Fig. 6. Simulation results show that the multi-form of arrangement and compositions have a great influence on the absorptivity performance, especially, the middle absorption spectrum decreased. In Fig. 6 (a), the absorptivity of b, c, and d is less than 0.8 in the middle spectrum. However, the absorption curve of a is above 0.8 from 12 GHz to 16 GHz, indicating an excellent absorption performance. Figure 6 (b) reveals the best absorptivity curve in Fig. 6 (a). It is clear that the efficient absorptivity of the best MRSL absorber in the four proposed absorbers is above 85% from 7.9 GHz to 18.9 GHz for the normal incident electromagnetic waves. Especially, the X-band and Ku-band are completely covered. Comparing the four MRSL unit cells with different arrangement, the structure shown in Fig. 8 (a) is the best combination.

The electric field distribution of the MRSL absorber unit cell is also studied, as it can help us analyze the information about the way and location of electromagnetic energy absorption. In Fig. 7, the surface electric field distributions are present at different frequencies, which correspond to the multiple absorption peaks. It can be seen that the electric field is mainly concentrated on the largest square loop when it is excited with a low frequency electromagnetic wave. As the frequency moves toward a high frequency, the electric field shift to other rings regularly. At the highest frequency, the electric field is mainly concentrated on the minimum square loops. Because of the coupling between the square loops, the electric field may distribute over multiple square loops of similar size occasionally. Most of the resonant energy of square loops is absorbed by the resistor, indicating that the proposed MRSL Structure has broadband electromagnetic wave absorption capacity.

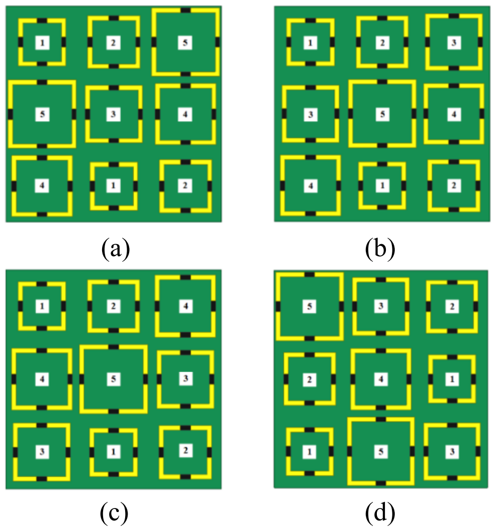


Fig. 5. The unit cell of four different MRSL absorbers.

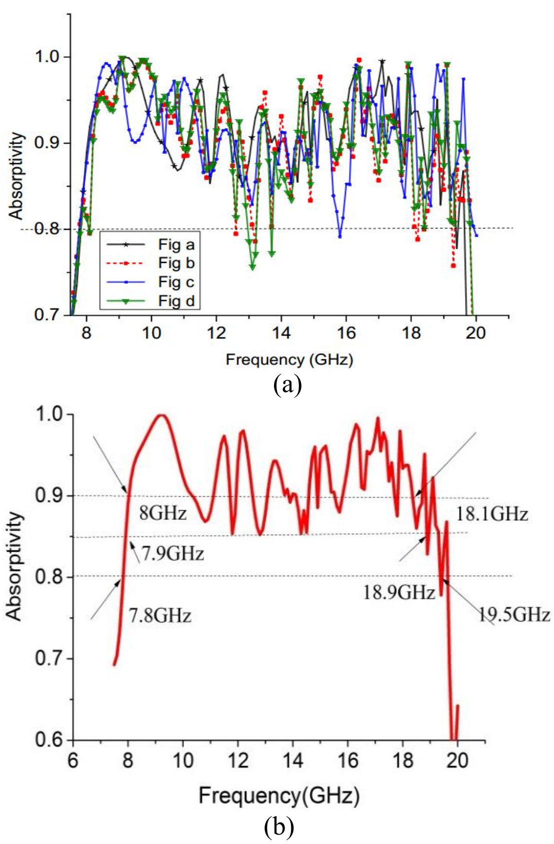


Fig. 6. (a)Simulation results of the proposed four MRSL absorbers, and (b) the best curve of Fig. (a).

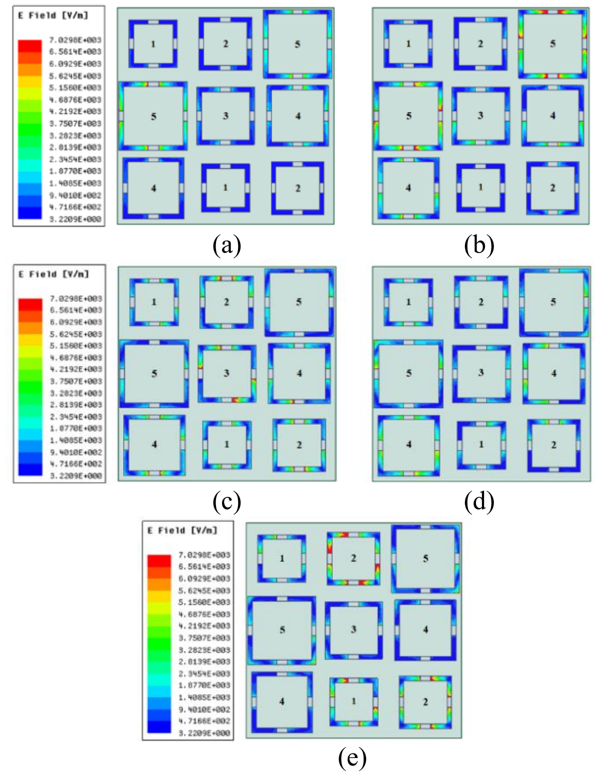


Fig. 7 The electric field distribution of the MRSL absorber unit cell: (a) at 8GHz, (b) at 9.5GHz, (c) at 10.5GHz, (d) at 11.5GHz, and (e) at 14GHz.

IV. EXPERIMENT RESULTS AND ANALYSIS

To validate the proposed design, a prototype has been fabricated on FR4 sheet using PCB technique. The overall size of the sample is 414 mm× 414 mm, where 10 × 10 unit cells are printed. Figure 8 (a) shows the photograph of the prototype and Fig. 8 (b) shows the prototype under test.

The characterization of the sample is achieved by a free space measure method to measure the reflectivity at normal incidence electromagnetic wave. In the experiment, one pair of horn antennas are connected to the vector network analyzer which works in the range of 1-40 GHz. The horn antenna used works in the range of 6-18 GHz.

The simulation and measurement results of the prototype are shown in Fig. 9. It can be seen that the absorption rate of both is above 80%. The difference between them is that the simulation result is smooth, but the test curve is a jittery curve. Overall, the trend of test results is consistent with the simulation result. The measurement method is shown in the Fig. 10. The receiving antenna receives electromagnetic wave scattered by the transmitting antenna and a bit of electromagnetic wave reflected by the absorber. In addition, machining errors and test system errors are not considered in the simulation. These changes, which differ from the simulation, may cause small fluctuations in the absorption rate during testing.

(a) (b)

Fig. 8. (a) Photograph of the fabricated absorber, and (b) prototype under test.

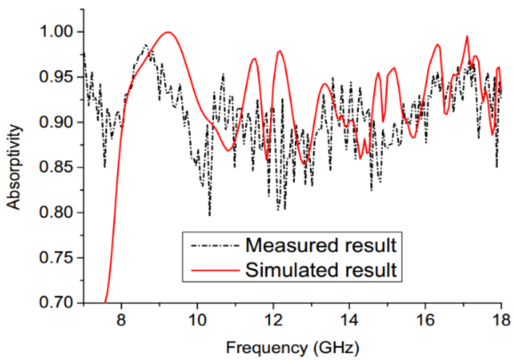


Fig. 9. Simulated and measured results for normal incidence.

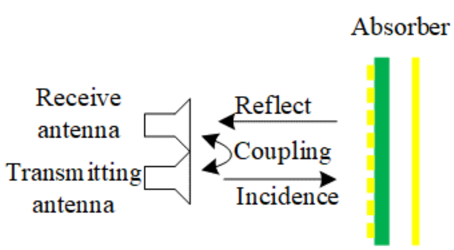


Fig. 10. Measurement method of the prototype.

V. CONCLUSION

Design of thin and broadband metamaterial absorber with Resistive Frequency Selective Surface (RFSS) has been presented. The structure has connected multiple isolate resonant frequency band to a continuous broadband due to the use of MRSL structure. However, the proposed absorber has a thin thickness of only 2.8 mm. Two prototypes have been fabricated using printed circuit board technology to highlight the simplicity of the fabrication for such kind of structures. The simulated and measured results exhibit a broadband absorption frequency band above 85% from 7.9GHz to 18.9GHz. Some future work may be interested in polarization insensitive performance and tunable frequency selective absorber.

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