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A Broadband Metamaterial Absorber Using Fractal Tree Structure

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Abstract—A novel broadband absorber using the fractal tree structure is presented in this paper, which consists of three metallic layers separated by two dielectric substrates. Five metallic vias connect these three layers which make the whole structure like a two order fractal tree. Simulated and measured results show that this absorber can provide a high absorptivity level from 4.98 to 12.58 GHz, equivalent to a relative absorption bandwidth about 87%. Further investigations show that this wideband absorption can be attributed to the multi-eigenmodes and lower quality factor of the fractal tree structure.

1. INTRODUCTION

A wide variety of metamaterial absorbers have been investigated in the past years. Among them, a simple design is to use Salisbury screen [1, 2] which consists of a resistive sheet located at a quarter-wavelength above a PEC back dielectric slab. One advantage of Salisbury screen is its simplicity, whereas the main disadvantages are the relatively narrow bandwidth and large thickness. Another popular method is to use high impedance surfaces (HISs) to construct ultra-thin absorbers [3]. In this case, the HIS structure works as artificial magnetic conductor. The lumped resistances are welded between the patches of HIS to form resistive sheet, and the quarter-wavelength distance between the lossy layer and the reflector is not necessary any more. So these HIS designs can be seen as derived from Salisbury screen, but their drawback is still the inherent difficult way of realizing the wide band absorptivity.

Recently, lots of suggestions have been presented about metamaterial absorber design to achieve multi-band or wide-band absorption [4–7]. As we know, fractal structures commonly present some special features, such as self-similarity and self-affinity, not shared by common Euclidean shapes. One of the most promising applications for these properties is to design multi-band or broadband antennas [8–10]. This innovative methodology can also be used in the radar absorber design. In this work, we propose a novel absorber using a planar fractal tree structure which can operate at a wideband frequency. Its -10 dB bandwidth is from 4.98 to 12.58 GHz with an acceptable thickness of 0.12λ at center frequency. In addition, this design also has the merits of wide-angle and polarization-insensitive absorption performance.

2. THE FRACTAL TREE ABSORBER

Figure 1 shows a unit cell of the proposed fractal tree absorber. It is composed of three metallic layers separated by two FR4 dielectric substrates with $\varepsilon_r = 4.4$ and loss tangent of 0.02. As the traditional HIS design, the bottom layer of this structure is still set by the metallic ground plane, while the top and middle layers consist of metallic crosses which can be seen as tree branches. Five metallic vias connect these three metallic layers, which can be seen as the tree trunks. Four chip resistors are inserted between the adjacent crosses in the top layer with resistance $R = 220\,\Omega$ for enhancement of the Ohmic loss.

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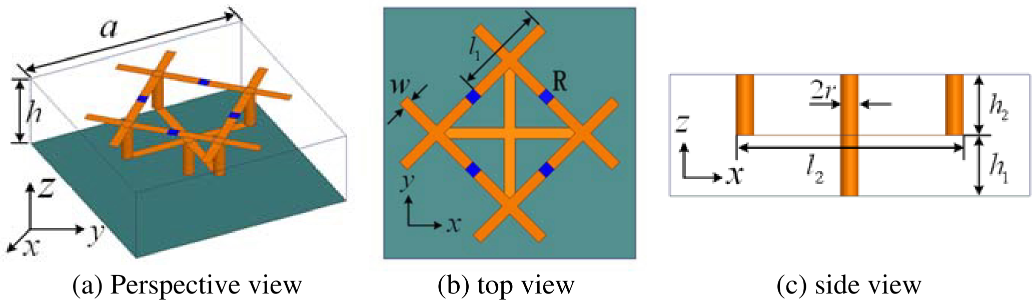


Figure 1. Geometry of the proposed absorber unit cell with structure parameters are $a = 12$, $h = 4h_1 = h_2 = 2$, $w = 0.5$, $l_1 = 4.4$, $l_2 = 7r = 0.3$ (unit: mm).

A full-wave simulation was performed by using the High Frequency Structure Simulator (HFSS) based on finite element analysis. The periodic boundary conditions and Floquet port were utilized to simulate the infinite periodic cells. The absorptivity was calculated by using the equation $A = 1 - |S_{11}|^2$ since the absorber is blocked off by metallic ground plane.

Figure 2 gives the frequency responses under different polarizations for normal incidence. It can be observed that the simulated absorptivity exceeds 90% from 4.98 GHz to 12.58 GHz, equivalent to a relative absorption bandwidth about 87%. Total 4 mm thickness of this absorber only equates 0.12λ for the center frequency 8.78 GHz. Moreover, due to the unit cell's symmetry, we can also see that absorptivity is nearly unchanged for different polarization angles from 0° to 90° in 30° steps.

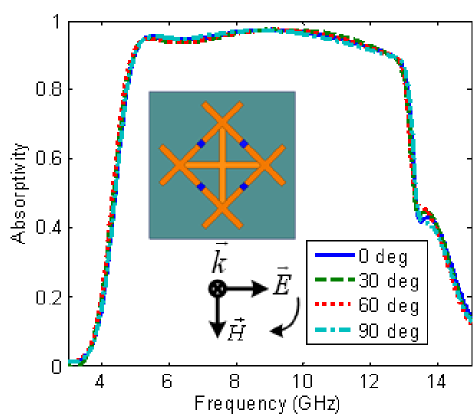
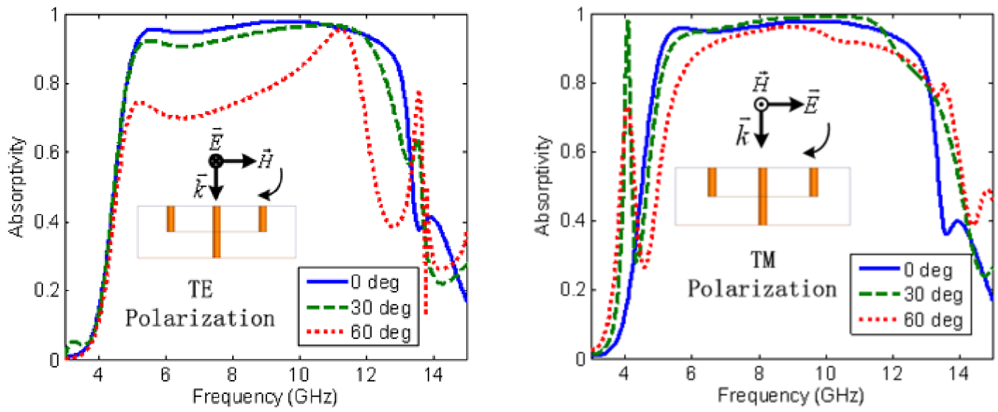


Figure 2. Simulated absorption for different polarization angles for the normal incidence.

The behaviors of the absorber for oblique incidence are reported in Fig. 3. It can be seen that the absorption of this structure maintains a high and stable absorptivity level up to 30 degrees both for TE and TM polarizations, but it starts to deteriorate at 60 degrees, especially for TE polarization.

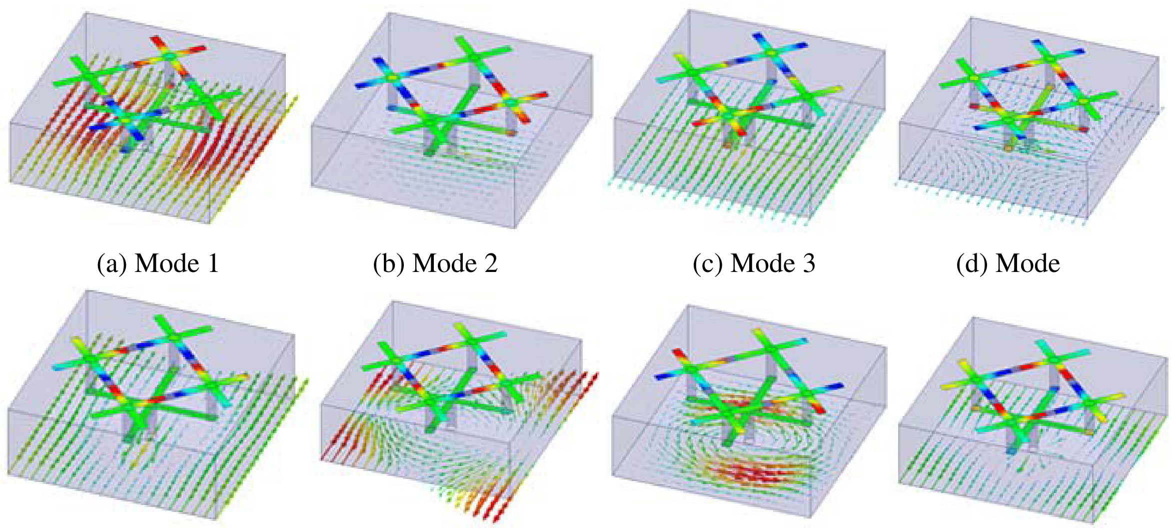
3. MODES ANALYSIS OF ABSORPTION

The resonant mode analysis can be used to gain insight into the absorption behavior. In this section, the resonant modes of the absorber are investigated by setting the perfect electric conductor (PEC) boundaries in x, z direction sides and the perfect magnetic conductor (PMC) boundaries in y direction sides. So the calculation model can be seen as a lossy cavity, and the eigenmodes can be calculated by HFSS. The distribution of the electric field z component on metallic cross and surface current on the ground plane are plotted in Fig. 4. These different field and current distributions denote different resonant modes for the cavity. As shown in Fig. 4 and Table 1, there are total eight modes with different



(a) (b)

Figure 3. Simulated absorption for different oblique incidence angles, (a) for TE polarization, (b) for TM polarization.



(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode

(e) Mode 5 (f) Mode 6 (g) Mode 7 (h) Mode 8

Figure 4. Simulated distribution of the electric field z component on the metallic cross and surface current on the ground plane for different eigenmodes.

Table 1. The resonance frequency and quality factor of these eigenmodes.

Mode	1	2	3	4
f (GHz)	5.13	5.91	7.76	9.18
Q	3.1	1.58	3.46	9.68

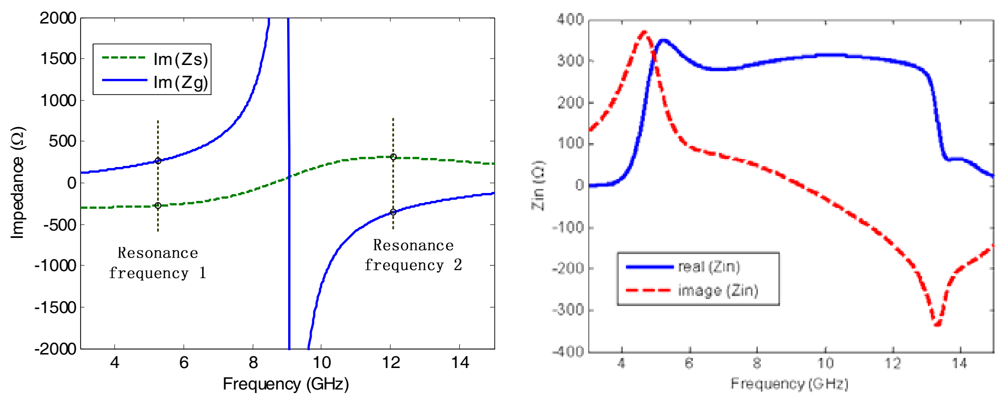
Mode	5	6	7	8
f (GHz)	9.88	10.55	11.5	12.17
Q	2.4	1.51	18.6	2.1

resonant frequencies and quality factors in the absorption band. Obviously, these modes all have lower quality factors which mean a high power loss in the cavity.

As well known, the impedance of a HIS absorber can be presented as a parallel connection between the surface metallic patch impedance Z_s and surface impedance of the grounded dielectric slab Z_g [11]. When impedance Z_g and the imaginary part of Z_s assume the same value, the parallel circuit resonates, and the impedance of the whole structure Z_{in} becomes purely real, and when it matches the free space impedance η_0, the incoming signal can all propagate into the absorber without any reflection. For example, in Fig. 5(a) the impedance of the grounded dielectric substrate, computed analytically, and the impedance of the fractal tree patch, computed by retrieving full wave data, are reported. Obviously, at the center of the operating band, about 8.78 GHz in our design, the substrate thickness 4 mm is equal to about $\lambda/4$ acting as a high-impedance wall. These circumstances allow the structure working as a conventional Salisbury screen. At the higher frequency range, the dielectric substrate behaves as capacitance when its thickness becomes thicker than a quarter wavelength. Meanwhile, the metallic patch behaves as an inductance. When this inductive impedance equals the imaginary part of capacitive impedance, a parallel resonance between the patch and the substrate can be generated. As shown in Fig. 5(a), this resonance named resonance frequency 2, which is equal to about 12.58 GHz, determines the upper frequency boundary of our absorber. Similarly, at the lower frequency range, a parallel resonance named resonance frequency 1 determines the lower frequency boundary about 4.98 GHz. In Fig. 5(b), the real and imaginary parts of the input impedance of the absorber, calculated using the Nicolson-Ross-Weir (NRW) approach described in [12, 13], are shown. We can see that in the absorption band, the structure's surface impedance matches the free space impedance, which guarantees the broadband absorption.

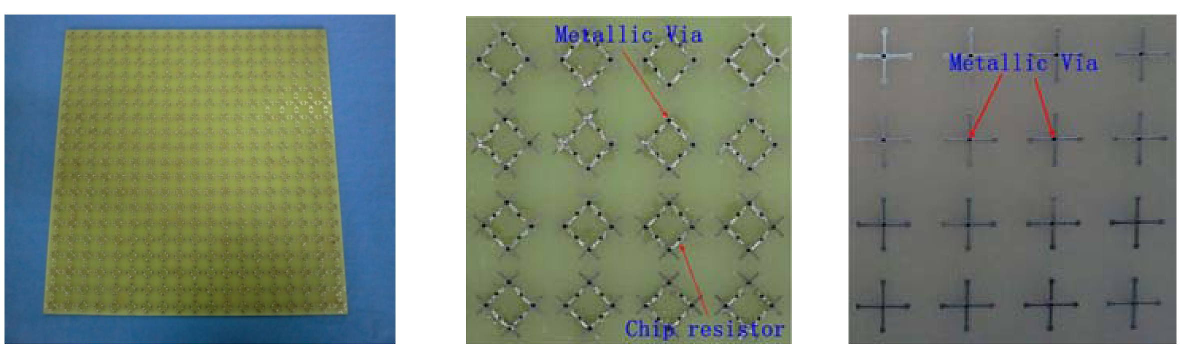
4. FABRICAITON AND MEASUREMENT

For experiment, an absorber sample consisting of 19×19 arrays was fabricated which resulted in a $228 \times 228\,\text{mm}^2$ absorption screen as shown in Fig. 6. Measurement was performed in a microwave



(a) (b)

Figure 5. Calculated effective surface impedance of (a) Z_s, Z_g and (b) Z_{in}.



(a) (b) (c)

Figure 6. (a) Photo of the fabricated 19×19 fractal tree absorber and (b) zoom in the top layer and (c) middle layer.

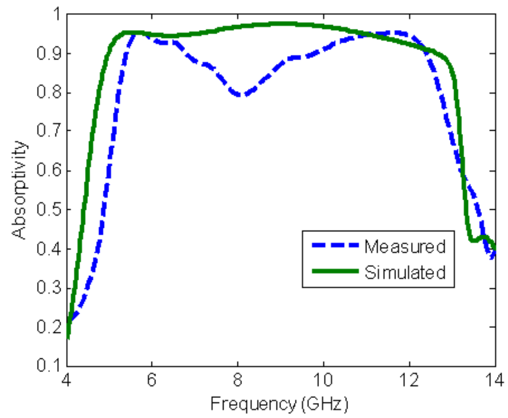


Figure 7. Simulated and measured absorptivity of the 19 × 19 absorber array.

anechoic chamber by using two horn antennas aligned closely and focused on the sample. By replacing the sample with a same size metallic surface for calibration of the reflection, the absorptivity was measured as shown in Fig. 7. Although there exists an obvious deviation compared with the simulated one, the absorber is still with a wide bandwidth and acceptable absorption level which exceeds 80% from 5.23 GHz to 12.76 GHz. The main reason for this deviation can be attributed to the fabrication and measurement errors.

5. CONCLUSIONS

A novel broadband absorber using the fractal tree array is presented in this paper. Simulated and measured results show that this metamaterial absorber has a wide-band, wide-angle, and polarization-insensitive absorption, which can provide 90% absorptivity from 4.98 GHz to 12.58 GHz, equivalent to a relative absorb bandwidth about 87%. The thickness of this absorber is only 0.12λ at the center frequency 8.78 GHz. Further investigations show that this broadband property can mainly be attributed to the multi-eigenmodes and lower quality factor of the fractal tree structure. The eight closer eigen-frequencies and the wide-band impedance matching condition both result in the broadband absorption.

ACKNOWLEDGMENT

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