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A frequency selective surface loaded two-layer composite for tunable microwave absorption

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Abstract
To obtain tunable microwave absorption, a strategy of constructing a frequency selective surface (FSS) on a two-layer composite is proposed. The designed FSS loaded two-layer composite is composed of a FSS constructed by evenly spaced circular copper sheet, an impedance matching layer that EP layer serves as a good impedance matching layer with increased microwave absorption. Both simulation and experiments indicate that the SiO2/EP layer serves as a good impedance matching layer with increased microwave absorption efficiency. By analyzing the distributions of electric field, magnetic field as well as the power loss, the strong resonance should be attributed to the enhanced incident microwave caused by FSS.

1. Introduction

Microwave absorbing materials/structures are widely used to decrease electric magnetic pollution in electronic industry or in daily life [1–4]. However, there applications are currently inhibited by lacking tuning capabilities, as well as limited working bandwidth [5–7]. Thus constructing tunable microwave absorbing materials/structures with broadband microwave absorption is a major concern.

According to the designing principle of a well-performed microwave absorbing materials/structures [8–10], the absorption efficiency of materials is determined by two factors: (1) the impedance matching between the absorbing materials and the free space, which affects the electromagnetic reflection at the surface; (2) the strong electromagnetic loss induced by the absorbing material, which would result in the power attenuation. Thus, introducing the impedance matching layer is necessary to improve the microwave absorbing efficiency [11–14]. It is well established that the microwave absorbing efficiency could be characterized as a function of frequency and the resonance peaks of the absorbing materials. Because resonance peaks can be tuned by the thickness of the absorbing materials, the frequency dependent absorbing performance can be tailored by the thickness. However, most absorbing devices have particular geometrical features, which requires specific thickness of the absorbing materials, therefore simply changing the thickness is not a reasonable solution to the tuning of the frequency dependent absorption.

Metamaterials are artificial materials with rationally designed sub-wavelength structures, which can be designed to adjust the performance of electromagnetic waves [15]. Metal frequency selective surface (FSS) has been widely used to design microwave absorbing structures, since the microwave absorption performance can be easily controlled by adjusting the dimension parameters of the FSS [16–19]. Thus, introducing FSS is believed to be another efficient way to influence the interaction between microwave and absorbing materials and tailor the resonance peaks of the absorbing materials without changing the thickness.

In this study, evenly spaced circular copper sheets are designed as FSS on the surface of a two-layer structure composed of a SiO2 fiber reinforced epoxy resin (EP) composite (SiO2f/EP) and a SiO2 fiber reinforced EP composite using carbon nanowires (CNWs) as the interphase (CNWs-SiO2f/EP), to tune and improve microwave absorption. The designed FSS loaded two-layer composite is manufactured and the microwave
absorbing property is characterized and verified by simulation results. In addition, the microwave absorbing mechanism is discussed by analyzing the electromagnetic resonance between microwave and the absorbing structure.

In this paper, firstly, the microwave absorption of the lossy layer, the CNWs-SiO$_2$/EP composite, was characterized. Secondly, the microwave absorbing property of the two-layer composite (the lossy layer with the impedance match layer, CNWs-SiO$_2$/EP and SiO$_2$/EP) was investigated. Thirdly, the microwave absorbing property of the FSS loaded two-layer composite was studied both experimentally and numerically.

### 2. Experimental and simulation method

#### 2.1. Material fabrication

Figure 1 shows the schematic of FSS loaded two-layer composite and its preparation process. Figure 2 shows the schematic of a unit cell in the designed FSS loaded two-layer composite. The FSS loaded two-layer composite is formed by adding a FSS on a two-layer composite. Firstly, a lossy layer (CNWs-SiO$_2$/EP) with CNWs (6 wt%) as the interphase between SiO$_2$ fiber and EP matrix was fabricated. The CNWs (diameter, 20~50 nm) were prepared by chemical vapor infiltration (CVD) at 700 °C using C$_2$H$_4$ as carbon source and Ni as catalyst. Secondly, a SiO$_2$ fiber reinforced EP matrix composite (SiO$_2$/EP) was prepared as the impedance matching layer to cover the lossy layer. Thirdly, circular copper sheets, the FSS, with a diameter of 5.0 mm and thickness of 0.2 mm were machined and evenly distributed on top of the SiO$_2$/EP. It is worth noting that the FSS loaded two-layer composite is polarization insensitive, for the material we prepared has 90° rotational symmetry.

#### 2.2. Characterization

The permittivity of the CNWs-SiO$_2$/EP and SiO$_2$/EP composites were determined by a vector network analyzer (VNA, MS4644A; Japan) in two sub wavebands of X band (8.2~12.4 GHz) and Ku band (12.4~18 GHz), using a 22.86 mm × 10.16 mm rectangular waveguide and a 15.80 mm × 7.9 mm rectangular waveguide, respectively. The reflection loss curves of the fabricated three-layer composites with dimensions of 180 mm × 180 mm × h were measured by free space method. In measurement, the reflection from a pure metal plate with the same size as that of the fabricated composites was used for normalization.

#### 2.3. Simulations and calculations

Numerical simulations were performed using the finite integration technique (CST Microwave Studio). Boundary conditions were applied in the x and y directions with magnetic field and electric field, respectively. A wave-guide port was used to generate transverse electromagnetic plane waves perpendicularly to the sample plane, which got through along the −z direction. The absorption could be calculated as $A(\omega) = 1 - T(\omega) - R(\omega)$, where $R(\omega) = |S_{11}|^2$ and $T(\omega) = |S_{21}|^2$ are the reflectance and transmittance obtained from the frequency-dependent complex S-parameter, respectively. Here, the backside is grounded by metallic plane, the equivalent
transmittance \((S_{21})\) is zero. Thus, the absorption can be reduced as \(A(\omega) = 1 - R(\omega)\). In detail, \(S_{12} = S_{21} = 0\), \(S_{11} = S_{22} = RL\) (When S-parameters are converted to dB).

The reflection loss (RL) for a single layer of flat absorbing material backed by a conductive metal plate can be calculated as [20]:

\[
RL = 20 \log_{10} \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right|
\]

(1)

\[
Z_{in} = Z_0 \sqrt{\mu/\varepsilon} \ \tanh \left[ \frac{2\pi}{c} \sqrt{\mu\varepsilon} fd \right]
\]

(2)

where \(Z_0 = (\mu_0/\varepsilon_0)^{1/2}\) is the characteristic impedance of free space, \(Z_{in}\) is the normalized input impedance of the absorbing material, \(\varepsilon\) and \(\mu\) are the relative complex permittivity and permeability, respectively, \(f\) is the frequency of microwave, \(d\) is the layer thickness of the absorbing material, and \(c\) represents the speed of light in the free space. For dielectric material in this work, the RL is calculated from relative complex permittivity, frequency and thickness.

### 3. Results and discussion

#### 3.1. Microwave absorption of the CNWs-SiO\(_2\)/EP composite

The complex permittivity of CNWs-SiO\(_2\)/EP composite in the frequency range of 8.2 ~ 18 GHz are shown in figure 3(a). The real part \((\varepsilon')\) and imaginary part \((\varepsilon'')\) of the complex permittivity decrease significantly with frequency increase and exhibit excellent frequency dispersion effect, which imply the polarization charge inside the material have a significant hysteresis effect when moving in alternating electromagnetic field. Enhanced hysteresis effect increases electromagnetic loss, so it has the potential for broadband microwave absorption [21].

The RL of the fabricated CNWs-SiO\(_2\)/EP composite is calculated via equations1–2 for different thicknesses and frequencies, and the results are plotted in figure 3(b). The minimum RL is larger than \(-7\) dB when the thickness changes from 0 to 6.0 mm, indicating that the CNWs-SiO\(_2\)/EP composite has relatively poor microwave absorbing properties. This weak microwave absorption is attributed to the mismatched impedance between the CNWs-SiO\(_2\)/EP and the free space, which results from the large complex permittivity of the CNWs-SiO\(_2\)/EP.

#### 3.2. Microwave absorption of the two-layer composite (CNWs-SiO\(_2\)/EP and SiO\(_2\)/EP)

In order to improve the microwave absorption of the CNWs-SiO\(_2\)/EP composite, a SiO\(_2\)/EP composite with a dielectric constant of \(\varepsilon = 4.7(1-j0.025)\), which is similar to the dielectric constant of porous EP Matrix, is introduced on the CNWs-SiO\(_2\)/EP layer as the impedance matching layer. Due to the impedance match afforded by SiO\(_2\)/EP, more microwave incidents get into the material and are consumed by the CNWs-SiO\(_2\)/EP layer, resulting in higher microwave absorption efficiency.
Figure 4 shows the simulated microwave absorption of the two-layer composite (CNWs-SiO$_2$/EP and SiO$_2$/EP) with different SiO$_2$/EP thicknesses ($d_2$) but same CNWs-SiO$_2$/EP thickness ($d_1 = 2.8$ mm). When $d_2 = 0$, the simulated RL of two-layer composite is consistent with the calculated results as shown in figure 3(b). When $d_2$ changes from 1.5 to 2.5 mm, the RL of the two-layer composite largely decreased in the frequency range from 8.2 to 18 GHz compared with $d_2 = 0$. Therefore, introducing the impedance layer can significantly improve the microwave absorption. It is worth noting that as $d_2$ increases from 1.5 to 2.5 mm, the resonance peaks move to lower frequencies. At the resonance frequency, the product of angular frequency and relaxation time is 1\[^2\]. Therefore, as $d_2$ (the thickness of the impedance matching layer) increases, the angular frequency decreases, indicating increased relaxation time. The increase of relaxation time enhances the hysteresis effect of the polarization charge inside the material, which improves microwave absorption efficiency at low frequency.

When $d_2 = 2.0$ mm, the simulated two-layer composite shows a maximum RL of $-7.3$ dB and minimum RL of $-24.3$ dB as shown in figure 4(a). The measured RL curves of the fabricated two-layer composites with different $d_1$ are shown in figure 4(b). The measured RL shows that more than 90% of the microwave is absorbed in the frequency range of 9.7 to 15.5 GHz with $d_2 = 2.0$ mm. The measured results in figure 4(b) of the two-layer composites are consistent with the simulated RL curves in figure 4(a), which indicates the simulation results are confirmed by experiments.

3.3. The FSS loaded two-layer composite

Figure 5(a) shows the RL curves of the FSS loaded two-layer composites when $d_1 = 2.8$ mm and $d_2 = 2.0$ mm with different periods $p$. For the FSS layer, with increasing $p$, the resonance peaks move to higher frequencies, which means shorter relaxation time \[^2\] and weaker polarization charge hysteresis. Thus it is easier to achieve excellent microwave absorption efficiency at high frequencies.
Without FSS, the resonance peak is located at 13.5 GHz with \( RL \) of \(-24.3\) dB. It can be concluded that such two-layer composite with FSS can be used to regulate absorption performance of microwave absorbing structure for practical application. Figure 5(b) shows the measured and simulated \( RL \) of FSS loaded two-layer composite when \( p = 15 \) mm. The experimental curve is in a good agreement with the simulation result when taking into account of the roughness in the fabrication process as well as the errors in the experimental measurement (the free space method has a test error of 5\%).

Figure 6 demonstrates the distributions of the electric field and magnetic field at absorption peak frequency 11.2 GHz, which is analyzed to investigate the underlying physical mechanism of microwave absorbing with or without FSS, compared with the microwave absorption without FSS, a strong coupling of electric fields and magnetic field emerges at the location of FSS for the FSS loaded two-layer composite. This indicates the energy of incident electromagnetic wave can be consumed by the FSS resonance elements\[23, 24\]. Furthermore, the distributions of power loss density are shown in figure 7. The FSS loaded two-layer composite exhibits enhanced power loss than the two-layer composite without FSS. This is attributed to the enhanced incident electromagnetic wave caused by FSS.

According to the transmission lines theory, the proposed FSS loaded two-layer composite can be treated as the equivalent circuit model which consists of inductance and capacitance. Thus, the impedance of the FSS loaded two-layer composite, which corresponds to the inductance and capacitance of the equivalent circuit, can
be tailored by changing the structural parameters (period, diameter of each unit) of FSS [24]. Table 1 shows the representative RL data in this work.

### 4. Conclusions

A FSS loaded two-layer composite is proposed by introducing FSS (evenly distributed circular copper sheets) on a two-layer composite that comprises a lossy layer (CNWs-SiO₂f/EP) and an impedance matching layer (SiO₂f/EP). The CNWs-SiO₂f/EP layer exhibits a significant frequency dispersion effect, leading to a high loss of microwave energy. The SiO₂f/EP layer affords a good impedance match with free space. The FSS has been found to be able to effectively tailor the resonance peaks. The designed FSS loaded two-layer composite shows enhanced microwave absorption with frequency dependent absorbing curves that can be tuned by simply changing the dimension parameters of the FSS. This frequency tuning mechanism can be applied for designing tunable absorbing devices with a set thickness.

### Data availability statement

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

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