Design of An Ultra-Thin and Broadband Absorption Materials For Middle-Temperature Applications

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Abstract

A radar absorbing material (RAM) is designed based on the magnetic ceramic and frequency selective surface (FSS). The phase composition and micromorphology were characterized, respectively. The complex permittivity and complex permeability of magnetic ceramic were tested and studied from 25 °C to 500 °C temperature. Based on the experimental and simulation results, the changes of reflection loss along with the structure parameters of RAM are analyzed at 500 °C. The relationship of reflection loss varies with temperature are studied. The analytical results show that the absorption property of the RAM increases with the increase of temperature. An optimal absorption of RAM is obtained at 500°C. When the thickness of RAM is 1.5 mm, the reflection loss lower than -10 dB can be obtained in the frequency range from 8.2 ~ 16 GHz. More than 90% microwave energy can be consumed in the RAM which may be applied in the high temperature environment.

1. Introduction

With the development of radar detection technology, the survival ability of aircraft or other weapons and equipment are facing a great threat in the war. In order to improve the survivability of weapons and equipment, stealth technology as a means to effectively reduce the radar cross section (RCS) of weapons and equipment, has been highly valued by military powers in the world [1-3]. Generally, stealth technology can be divided into two types: structural stealth technology and absorbing material technology. Radar absorbing materials (RAM) play an auxiliary role in the stealth for the shape structure, which can absorb the incident electromagnetic wave and convert it into other forms of energy attenuation. The RAM must have the characteristics of "thin", "wide", "light" and "strong" [4-8]. In addition, restricted by the working environment of aviation weapon components, it is necessary to develop new RAM which can adapt to the high temperature environment. For traditional RAM, their absorbing properties mainly depend on the adjustment of the content of absorbers [9-11]. At present, the absorbents used to study the absorption properties of magnetic coatings include: metallic iron powder, ferrite, hydroxy iron, iron wire fiber and other magnetic materials. The absorption of electromagnetic wave mainly depends on the magnetic polarization effects such as hysteresis loss, eddy current loss, domain wall resonance, aftereffect loss and residual loss [12-15]. The absorbents used in dielectric absorbing coating include graphite powder, carbon nanotube, carbon fiber, calcium titanate, magnesium titanate, barium titanate, spinel, zinc oxide and other dielectric materials. The dielectric loss is mainly caused by electric conductivity, ion transition, ion vibration and ion deformation, etc. [16-20].

In recent years, RAM composed of absorbing material and frequency selective surface (FSS), which are highly valued by many researchers due to their unique electromagnetic resonance coupling characteristics. The researches show that the transmission and reflection characteristics of electromagnetic wave can be effectively controlled by changing the shape, size and period of the FSS, which can not only be used to improve the electromagnetic properties of antennas and microwave devices, but also provide a new technical way for the development of new absorbing materials [21-23]. At present, most of researches on the properties of RAM are focused on the room temperature. The

researches on electromagnetic coupling of the FSS at high temperature is few. It makes the absorption performance of RAM difficult to control and affect the research progress of RAM [24-27].

In this work, the effects of structural parameters of FSS on the absorption performance of RAM are studied, the researches on electromagnetic coupling of RAM at high temperature environment are studied. The change of energy loss density of RAM is analyzed at different temperatures.

2. Design And Experiment

Fig. 1 shows the structure schematic diagram of RAM. The structure is divided into three parts. The upper part is FSS layer which composes of periodic structure metal patches, the middle part is magnetic ceramic layer synthesized through using Aluminum Oxide (chemical formula Al_2O_3 , purity 99.9%) and Lanthanum Strontium Cobaltite (chemical formula LaSrCoO_3 , purity 99.9%) powders with the mass ratio of 1:1. The magnetic ceramic used in this work is provided by Shaanxi Huaqin Technology Co., Ltd, Xi'an, China. The lower part is metal plate, the FSS pattern is printed on a metal backed magnetic ceramic substrate. As shown in Fig. 1, the radius of the circular patches is a . The period length of circular periodic structure patches is C . The thickness of the dielectric layer is t . The thickness of the FSS layer is t_0 . The RAM is simulated and studied using the commercial software CST Microwave Studio based on electromagnetic parameters of magnetic ceramic [28-30]. The geometry and size of the unit cell is optimized by numerical simulation to obtain a good microwave absorption performance. The initial parameters dimensions of the absorber are $C = 10\text{mm}$, $a = 2\text{mm}$ and $t = 2\text{mm}$, $t_0 = 0.01\text{mm}$.

The phases of the magnetic ceramic were characterized through X-ray diffraction (XRD, D/MAX2500 diffractometer, Japan). The surface morphology of the magnetic ceramic was characterized by scanning electron microscopy (SEM, Model JSM-6360, Japan) [31-32]. The electromagnetic parameters (complex permittivity and complex permeability) of were measured through using a vector network analyzer (Agilent Technologies E8362B PNA, USA).

3. Results And Discussion

Fig. 2 (a) ~ Fig. 2 (b) exhibits the X-ray diffraction (XRD) patterns and Scanning electron microscope (SEM) photographs of magnetic ceramic layer, respectively. In Fig. 2 (a), it is observed that the magnetic ceramic layer contains two phases of Al_2O_3 and LaSrCoO_3 . From Fig. 2 (b), it is observed that the magnetic ceramic has higher density and a few pores.

Fig. 3 shows the measured electromagnetic parameters of magnetic ceramic in the frequency range of 8.2 ~ 12.4 GHz under the tempurate of 25 °C to 500 °C. Fig. 3. (a) ~ (d) are the real parts and imaginary parts of the complex permittivity and the complex permeability, respectively. It is observed that both the complex permittivity and complex permeability of the ceramic increase with the increase of temperature. The complex permittivity and the complex permeability will directly affect the electromagnetic wave loss of the materials. The bigger of the complex permittivity and complex permeability, the greater loss [33-35].

Thus, the changes of dielectric constant and magnetic permeability may affect the electromagnetic absorption properties of materials.

Fig. 4 shows the reflection loss of the RAM versus frequency for different C . The influences of period length C of the FSS on reflection loss (RL) of the RAM are calculated based on electromagnetic parameters of magnetic ceramic at 500°C, while the other parameters remain unchanged. The RL is an effective evaluation standard of the microwave absorbance capacity of metal backed slabs of material, and low RL corresponds to high absorption. From the results in Fig. 4, an absorption peak is observed between the frequency of the 8.2 GHz and 12.4 GHz (X-band). The position of absorption peak shifts to high frequency and the intensity of absorption peaks decreased with the increase of C . When the period length C is equal to 10 mm, the reflection loss less than -10 dB can be obtained in the frequency range from 8.5 ~ 10.4 GHz and the minimum value of the reflection loss is -15 dB. Therefore, the optimal period length may be about 10 mm.

Fig. 5 shows the influences of radius a of the FSS on the reflection loss of absorber while the other parameters are unchanged. As shown in Fig. 5, an resonance absorption peak appears at different frequencies with variable a . The results show that the minimum reflection loss of the designed RAM first decreases and then increases with the increase of radius a , while the reflection loss increases gradually in the frequency range from 15 GHz to 18 GHz. When the radius length a is equal to 2 mm, the minimum reflection loss is -16 dB, the absorption band-width with reflection loss less than -10 dB is the largest. Therefore, the optimal radius of the FSS patch may be about 2 mm.

Fig. 6 shows the effects of ceramic layer thickness t on the absorbing properties of RAM while the other parameters remain unchanged. The results show that the resonance absorption peak increased firstly and then decreased with the increase of thickness t . The frequency of the absorption peak moves to the low-frequency region and the absorption bandwidth below -5 dB also increases gradually. Therefore, the absorption of all peaks of absorbing materials are enhanced with increasing thickness t . When the ceramic thickness t is equal to 2 mm, the absorption bandwidth with reflection loss below -10 dB is the largest in the X-band. When the thickness t is equal to 1.6 mm, the minimum value of the reflection loss is -19 dB at about 12.5 GHz. Therefore, the optimal thickness may be about 1.6 mm.

In order to make the absorbing performance of RAM the best, the genetic algorithm is employed to solve the optimization problem. According to the above research results, the initial values are redesigned as follows: $C = 10$ mm, $a = 2$ mm, $t = 1.6$ mm. Fig. 7 shows the optimized reflection loss results of RAM under the temperature from 25 °C to 500 °C. From Fig. 7, it is observed that the reflection loss of the RAM below -5 dB can be obtained in Ku-band under the temperature from 25 °C to 500 °C. As the temperature increases from 25 °C to 500 °C, the reflection loss of the RAM gradually decreases, the absorption peak gradually moves to the low frequency. When the temperature is 500 °C, the reflection loss below -10 dB can be obtained in the whole X-band. The reflection loss curve of RAM shows a double absorption peak structure in the frequency range of 8.2 ~18 GHz, the absorption frequency peaks are located at 9 GHz and 13.2 GHz, respectively. The minimum value of reflection loss is -39 dB at 13.2 GHz. Thus, a broad

bandwidth is obtained with a reflectance lower than - 10 dB in the frequency range from 8 ~16 GHz which cover the entire X-band. More than 90% microwave energy can be consumed in the RAM which can fill the requirement of practical application. The optimal structural parameters are as follows: $C = 10.31$ mm, $a = 1.59$ mm and $t = 1.50$ mm.

In order to further study the absorption mechanism with different temperature of the designed RAM, the volume power loss density distribution of RAM are given in Fig. 8 under different temperatures. From Fig. 8, it is observed that the power loss density of the RAM increases as the temperature increases from 25 °C to 500 °C. Power loss density is directly related to the absorption efficiency of the RAM. The bigger of the loss, the greater absorption efficiency [36, 37]. Thus, this result is consistent with the results in Fig. 3. and Fig. 7. When the temperature was raised between 25 °C and 200 °C, the loss is mainly caused by the FSS layer, as shown in Fig. 8 (a) ~ (c). As the temperature was raised between 300 °C and 500 °C, the complex permittivity and the complex permeability of ceramic layer increase gradually, the loss is mainly caused by the FSS and ceramic layer, as shown in Fig. 8 (d) ~ (f). Thus, two absorption peaks are very strong when the temperatures are 300°C, 400 °C and 500 °C, as show in Fig. 7. So, the concept of resonant coupling is realized using the FSS layer and magnetic ceramic for wide-band absorption.

Conclusions

In summary, a new ultra-thin and wide-band radar absorbing material is designed based on magnetic ceramic layer and FSS structure. The temperature and frequency corresponding laws of the complex permittivity and the complex permeability of magnetic ceramic in the frequency of X-band (8.2 ~ 12.4 GHz) and Ku-band (12.4 ~18 GHz) are analyzed in the temperature range of 25 ~ 500 °C. The structure parameters of FSS and ceramic thickness are studied. Results indicate that the complex permittivity and the complex permeability of magnetic ceramic gradually increase and the reflectivity of absorber decrease with the increase of temperature. The improvement of electromagnetic absorption performance comes from the continuous strengthening of resonance coupling in FSS and magnetic ceramic at high temperature. When the temperature is 500 °C, the reflectivity of the RAM less than - 10 dB can be obtained in the 8.2 -16 GHz band.

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Figures

Figure 1

Structure diagram of radar absorbing material with FSS. The circular radius is a and the period length is C , the thickness of dielectric ceramic is t . (a) Top view, (b) Side view.

Figure 2

(a) X-ray diffraction patterns of magnetic ceramic. (b) Surface topography of magnetic ceramic.

Figure 3

(a) Real part and (b) Imaginary part of the complex permittivity of ceramic layer. (c) Real part and (d) Imaginary part of the complex permeability of ceramic layer.

Figure 4

Simulated reflection loss of the RAM versus frequency for different C, $a = 2\text{ mm}$, $t = 2\text{ mm}$.

Figure 5

Simulated reflection loss of the RAM versus frequency for different a . $C = 10\text{ mm}$, $t = 2\text{ mm}$;

Figure 6

Simulated reflection loss of the RAM versus frequency for different t . $C = 10\text{ mm}$, $a = 2\text{ mm}$;

Figure 7

Optimized reflection loss results of RAM versus frequency for different temperature.

Figure 8

The volume power loss density distribution of RAM at different temperatures. (a) 25 °C, (b) 100 °C, (c) 200 °C, (d) 300 °C, (e) 400 °C, (f) 500 °C.