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A two-layer dielectric absorber covering a wide frequency range

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Abstract

A two-layer dielectric absorber for use as high temperature radar wave-absorbing material was developed by hot-pressing nanometer SiC and LAS glass-ceramic. The complex permittivity of the hot-pressed LAS glass-ceramic and SiC/LAS composite was investigated at 8.2–12.4 GHz. Results show that the real and imaginary parts of the permittivities of the SiC/LAS composites greatly increase as the content of the nanometer SiC powders increases. Based on the test results, a two-layer ceramic absorber, composed of LAS layer and SiC/LAS layer, covering a wide frequency range was designed and prepared. Its reflectivity at 8.2–12.4 GHz is less than −6 dB.

Keywords: C. Dielectric properties; D. SiC; Glass-ceramic; Reflectivity

1. Introduction

In response to the need for effective electromagnetic absorbent to operate in wide bands at high temperature, more and more attention has been paid toward tailoring dielectric materials because of their relatively stable complex permittivity from room temperature to high temperature. Compared to magnetic materials, however, dielectric absorbers perform in a much narrower frequency range. In order to broaden the operation bandwidth of dielectric absorbers, a two-layer absorbent is developed, in which one layer acts as a low-impedance resonator and the other as the impedance transformer layer [1]. The reported results show that, an absorber covering a wider frequency ranger could be obtained through the combination of absorbent layers.

In this paper, a series of low-impedance resonator layer and impedance transformer layer with different complex permittivity were developed and the dielectric properties of the layers were explored. Based on the work, one two-layer absorber covering wide frequency range was designed and prepared.

2. Experiments

2.1. Specimen preparation

The impedance transformer layer, LAS glass-ceramic, was hot-pressed using LAS glass powder. The glass was prepared from analytical grade reagents of SiO_2, Al_2O_3 and Li_2CO_3 in a mol ratio of 4:1:1.

The low-impedance resonator layer, SiC/LAS composite, was prepared using nanometer SiC powder and the LAS glass powder. The nanometer SiC powder synthesized by laser pyrolysis of HMDS ($((CH_3)_3Si)_2NH$) is characterized by high dielectric dissipation.

2.2. Measurement

The samples of the impedance transformer layer and resonator layer were machined into a plate with the size of 10.16 mm × 22.86 mm × 2 mm and put into the brass holder (10.16 mm × 22.86 mm) to measure the complex permeability and permittivity, which was based on the measurements of the reflection and transmission module between 8.2 and 12.4 GHz, in the fundamental wave-guide mode TE10. After calibrated with short circuit and blank holder, reflection and transmission coefficients were obtained with the help of an automated

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measuring system (HP8510B network analyzer). Both the real and imaginary parts of the permittivity and permeability were then calculated after measurement. For a dielectric material ($\mu' = 1$, $\mu'' = 0$) the relative error varies between 1% (pure dielectric) and 10% (highly conductive materials).

Measurement of microwave radiation reflection was carried out on sample with the surface area of 18 cm × 18 cm using a Hewlett-Packard 8510B Network Analyzer. The reflection measurement was obtained with the sample backed with an aluminium plate.

3. Results and discussion

3.1. Material permittivity

Fig. 1 shows the complex permittivity of the impedance transformer layer LAS glass-ceramic in the X band. The permittivity of the measured sample is $\varepsilon_r = \varepsilon_r' - j\varepsilon'' = 7.5 - j0.16$ and it keeps constant in the tested frequency range of 8.2–12.4 GHz.

Due to the difficulty in direct test of nanometer SiC powder permittivity, this was mixed with molten paraffin and then cast into standard copper clamp to measure the permittivity of the mixture. Fig. 2 shows the complex permittivity of the mixture of the nanometer SiC powder and paraffin.

For this mixture, both the real part and the imaginary part of permittivity slightly decrease with the increase of frequency. The real part decreases from 5.17 at 8.2 GHz to 4.72 at 12.4 GHz, and the imaginary part from 2.95 at 8.2 GHz to 2.47 at 1 GHz.

The permittivity of the paraffin in this frequency range is known and keeps constant (the real part is 2.56 and imaginary part is nearly zero) and the volume fraction of the nanometer SiC in the mixture is very low, so the permittivity of the nanometer SiC could be obtained according to Polder-van Santen equation 1 [3].

$$\varepsilon_e = \varepsilon + \frac{\sum_{i=1}^{3} f[\varepsilon_e + N_i(\varepsilon_e - \varepsilon)](\varepsilon_s - \varepsilon)/3[\varepsilon_e + N_i(\varepsilon_s - \varepsilon_e)]}{1 - \sum_{i=1}^{3} fN_i(\varepsilon_s - \varepsilon)/3[\varepsilon_e + N_i(\varepsilon_s - \varepsilon_e)]} \quad (1.1)$$

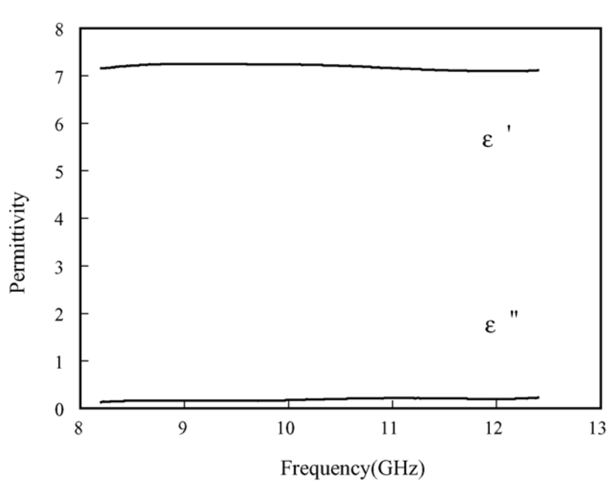

Fig. 1. Permittivity vs. frequency of the LAS glass-ceramic.

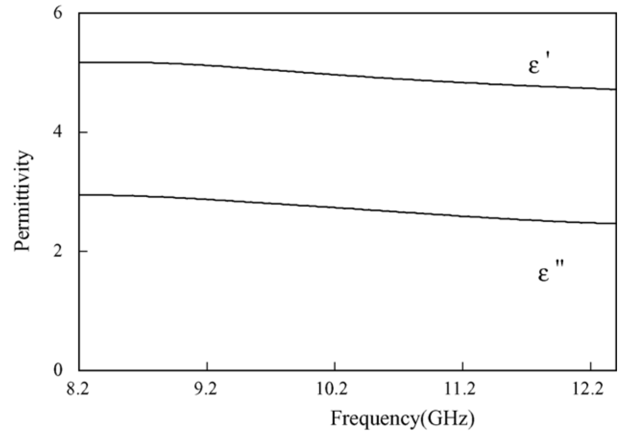

Fig. 2. Permittivity of a mixture of 7 wt.% SiC + 93 wt.% paraffin.

where the ε, ε_s and ε_e are permittivity of matrix, dispersed phase and mixture, respectively; f is the volume fraction of the dispersed phase; N_i is the factor of shape depolarization. For needle particles, $N_1 = 1/2$, $N_2 = 1/2$, $N_3 = 0$; for plate particles, $N_1 = 1$, $N_2 = 0$, $N_3 = 0$; for spherical particles, $N_1 = 1/3$, $N_2 = 1/3$, $N_3 = 1/3$. In our previous work [4], TEM microphotograph revealed that the as-received nanometer SiC particles are needle-shaped, so $N_1 = 1/2$, $N_2 = 1/2$, $N_3 = 0$ were taken into Eq. (1.1). If the pores existing in the mixture are neglectable, Eq. (1.1) could be directly used to calculate the permittivity of the nanometer SiC according to the permittivity of the mixture and that of the paraffin. From the above measured data, the calculated permittivity of the nanometer SiC is $\varepsilon_r = \varepsilon_r' - j\varepsilon'' = 235 - j277$ at 9.375 GHz.

LAS glass powder was mixed with 3, 5, 7 and 10 wt.% SiC nanometer powders and the mixtures were hot-pressed at 1080 °C for 30 min at 15 MPa using a graphite die operating in a nitrogen atmosphere. Fig. 3 shows the permittivities of the sintered samples at 9.375 GHz as a function of the contents of nanometer SiC powders.

As shown in Fig. 3, the real and imaginary parts of the permittivities of the samples greatly increase as the content of

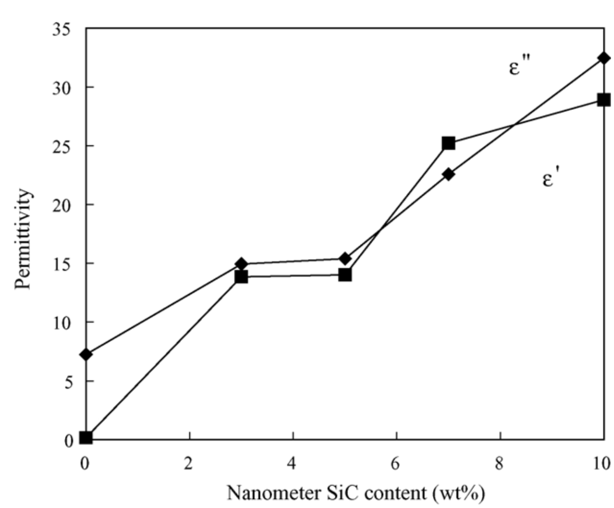

Fig. 3. Relationship between the permittivity of SiC/LAS at 9.375 GHz and the nanometer SiC contents.

the nanometer SiC powders increases. The real part increases from 14.93 to 32.45 when the contents of the nanometer SiC powders increase from 3 to 10 wt.%, and accordingly, the imaginary part increases from 13.85 to 28.9. It indicates that the permittivities of the samples are dominated to a great extent by the amounts of nanometer SiC powders.

3.2. Broad band absorbent with two-layer construction

To obtain a broadband electromagnetic wave absorber as thin as possible, a two-layer structure was adopted. According to Eq. (1.2) [2], thickness of each layer could be calculated using the complex permittivities of LAS glass-ceramic and SiC/LAS composites.

$$R = 20\log_{10}|\Gamma| = \frac{[(\sqrt{\mu_1/\varepsilon_1}\tanh(\gamma_1 d_1) + \sqrt{\mu_2/\varepsilon_2}\tanh(\gamma_2 d_d))/(\sqrt{\mu_1\varepsilon_2/\mu_2\varepsilon_1}\tanh(\gamma_1 d_1)\tanh(\gamma_2 d_2)+1)] - 1}{[(\sqrt{\mu_1/\varepsilon_1}\tanh(\gamma_1 d_1) + \sqrt{\mu_2/\varepsilon_2}\tanh(\gamma_2 d_d))/(\sqrt{\mu_1\varepsilon_2/\mu_2\varepsilon_1}\tanh(\gamma_1 d_1)\tanh(\gamma_2 d_2)+1)] + 1} \quad (1.2)$$

where $\gamma = \mathrm{j}(2\pi f/c)\sqrt{\mu\varepsilon}$, d is the thickness of impedance layer and absorbing layer.

Fig. 4 is the calculated reflectivity of 3 mm thick two-layer structure absorber. Curves 1–3 show the variations of reflectivity in function of the frequency of the permittivity of the absorbing layer when the permittivity of the impedance transfer layer is fixed. It indicates that a low reflectivity can be obtained if the permittivity of the absorbing layer is low. Compared with the wave impedance of the impedance transfer layer, the wave impedance of the absorbing layer is lower. The wave impedance of the absorbing layer 1 is the highest among the three absorbing layers, so a best wave impedance match is achieved between the impedance transfer layer and the absorbing layer 1 and a low reflectivity is expected [3].

Fig. 5 is also a calculated reflectivity of 3 mm thick two-layer structure absorber. Curves 1–3 show the variations of reflectivity of the absorber with the permittivity of the impedance transfer layer while the permittivity of the absorbing layer is fixed. It indicates that if the ceramic with the lowest permittivity is used as an impedance transfer layer, the lowest reflectivity can be obtained. Because the wave impedance of the impedance transfer layer best matches with the that of the air, the lowest reflectivity is expected when impedance transfer layer 1 and the absorbing layer is combined into an absorber [3].

Figs. 4 and 5 show that a low reflectivity can be obtained through permittivity and thickness variation of impedance transfer layer and absorbing layer. The desired permittivity of impedance transfer layer and absorbing layer can be achieved by selecting and sintering materials with different permittivity. Fig. 3 is an example of the case by sintering LAS and nanometer SiC powder.

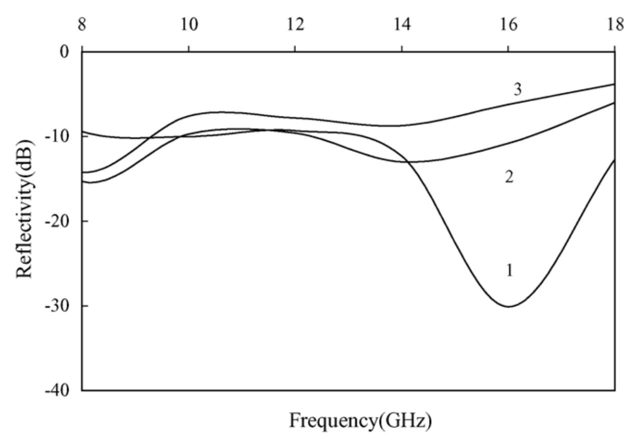

Fig. 5. Calculation of effect of permittivity of impedance transfer layer on reflectivity of two-layer absorber (absorbing layer ε = 32 − j35; curve 1 for impedance transfer layer ε = 7.2 − j0.2; curve 2 for impedance transfer layer ε = 10 − j0.2; curve 3 for impedance transfer layer ε = 12.5 − j0.2).

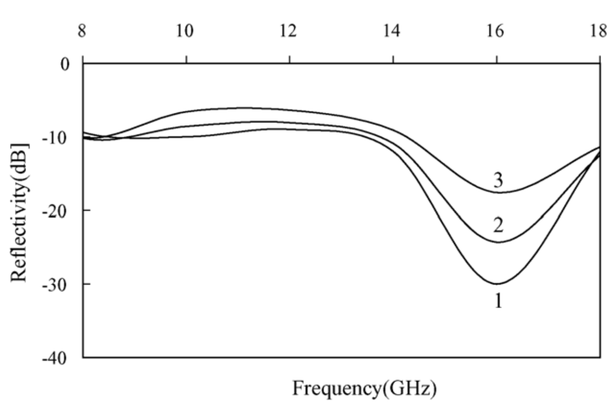

Fig. 4. Calculation of effect of permittivity of absorbing layer on reflectivity of two-layer absorber (impedance transfer layer: ε = 7.2 − j0.2; curve 1 for absorbing layer ε = 32 − j35; curve 2 for absorbing layer ε = 37 − j40; curve 3 for absorbing layer ε = 42 − j45).

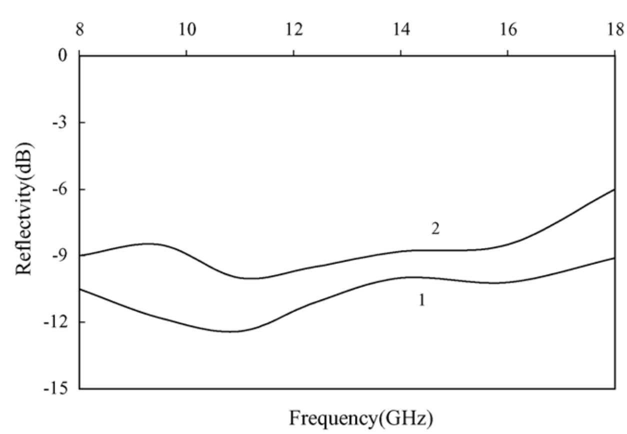

Fig. 6. Optimized and measured curves of two-layer absorber curve 1 is optimized reflectivity; curve 2 is measured reflectivity.

Curve 1 in Fig. 6 is an optimized reflectivity of two-layer structure absorber by Eq. (2) according to the permittivities of LAS glass-ceramic and SiC/LAS composites. Curve 2 in Fig. 6 is the measured reflectivity.

We could see that some difference exists between optimized and measured curves. It may be caused by errors in permittivity and reflectivity measurement and by absorber preparation.

4. Conclusions

The real and imaginary parts of the permittivities of the SiC/LAS greatly increase as the content of the nanometer SiC powders increases. Different permittivity of SiC/LAS could be obtained by varying the content of SiC in the SiC/LAS. This is essential for the design of the two-layer structure absorber with a fixed thickness. The absorber shows a good microwave absorption at 8–18 GHz. Although the designed and measured reflectivity curves are alike somewhat, there are still some difference between them, which may be attributed to errors in permittivity, reflectivity measurements.

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