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The origin of reflection loss peaks in the double-layer electromagnetic wave absorber

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ABSTRACT

We investigated the origin of reflection loss (RL) peaks of Co_2Z particle composite (t mm)/fake-shaped carbonyl iron (CI) particle composite (1.5 mm) double-layer absorbers backed by a perfect conductor in 0.1–18 GHz. The RL peak frequency in the low frequency region remains unvariable and the RL peak in the high frequency region moves to lower frequency with the increase of Co_2Z particle composite thickness. The investigation results indicated that the two RL peaks come from the quarter-wavelength cancellation at the interface from Co_2Z particle composite to CI particle composite and the interface from air to Co_2Z particle composite, respectively.

1. Introduction

Electromagnetic wave absorber with high absorption performance attracts much more attention due to the serious electromagnetic interference with the development of electron and information techniques [1,2]. Due to that strong absorption and broad frequency band are required for the high performance, new type of materials and structure design are proposed [3–6]. Among them, the double-layer absorber consisting of an outer layer and inner layer has been considered to have better absorption properties compared with a single-layer absorber [6,7]. In previous reports on double-layer absorbers, most of work only paid attention to the phenomena of broad band and the effect of outer layer which enables more electromagnetic wave to enter the absorber [8,9]. As we know, the formation mechanism of the RL peak is significant for us to design absorbers with specific purpose. For the single-layer absorber including magnetic particle filler, reports have shown that the RL peak frequency is determined by the quarter-wavelength cancellation condition and moves toward lower frequency with the thickness increasing [10,11]. However, there are no studies on the formation mechanism of RL peaks in the double-layer absorber. In this paper, the Co_2Z particle composite was used as an outer layer due to the closed value of permeability and permittivity, which enables more electromagnetic wave energy to enter the composite [12]. The flake-shaped CI particle composite was used as an inner layer because the high values of permeability and permittivity are useful to design a thin absorber [13,14]. Both the outer and inner layers consist of magnetic fillers because the magnetic particle composites are believed to attenuate the electromagnetic energy more effectively and make the absorber thinner [15]. We investigated the RL peaks of the double-layer absorber made by the above-mentioned composites through direct measurements and theoretical analysis and give the explanation for the origin of RL peaks.

2. Preparation and characterization

The magnetic particles in the composite are Co_2Z particles and flake-shaped CI particles, which were fabricated in our laboratory. Their SEM photographs are shown in Fig. 1(a) and (b). The matrix of the composite was paraffin. The double-layer absorber used for measurement consists of Co_2Z particle composite and the flake-shaped CI particle composite with the thickness of 1.5 mm and volume concentration of 35% for each layer, as shown in Fig. 2. Here, the interface A denotes the area between air and Co_2Z particle composite, the interface B denotes the area between Co_2Z particle composite and CI particle composite, and the interface C denotes the area between CI particle composite and the perfect conductor. When we measure the absorption properties, the electromagnetic wave is incident normally from the front of Co_2Z particle composite and the double-layer absorber is backed by a perfect conductor.

The absorber has a toroidal shape with an outer diameter of 7.00 mm and an inner diameter of 3.04 mm. An Agilent PNA E8363B vector network analyzer in the range of 0.1–18 GHz was used to measure permeability and permittivity dependence of frequency and the absorbing properties. As we know, the reflection coefficient S_{11} parameter represents the fraction of the power

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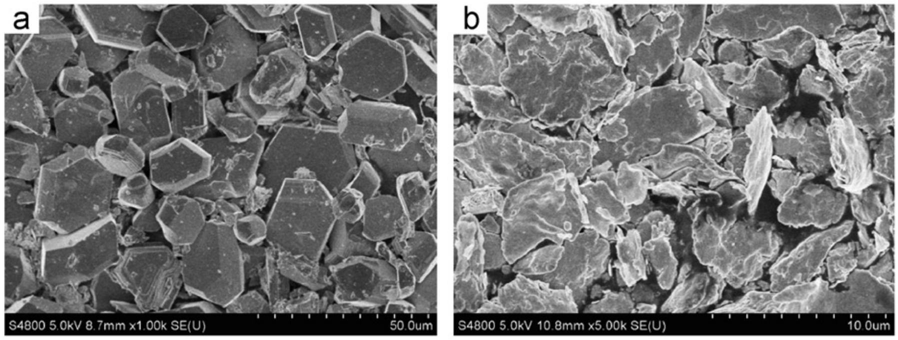

Fig. 1. SEM photographs of (a) Co_2Z particles and (b) flake-shaped CI particles.

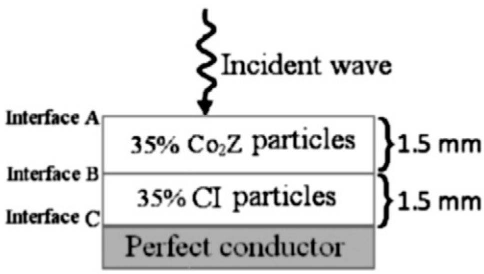

Fig. 2. The sketch of the double-layer absorber.

of electromagnetic wave reflected by a sample. In this work, the absorbing properties of the absorber were characterized by the $S_{11\ \text{short}}$ parameter measured from a short transmission port method in which the double-layer absorber was backed by a perfect conductor [13].

3. Results and discussion

Fig. 3 shows the complex permeability and permittivity of Co_2Z and flake-shaped CI particle/paraffin composite with the 35% volume concentration. Their hysteresis loops are shown as the inset in Fig. 3(b) and (d). The coercivities of Co_2Z and flake-shaped CI particles composites are all very small, indicating the soft magnetic properties. For the Co_2Z particle composite, both the permeability and permittivity are small. The closed value of them enables more electromagnetic wave energy to enter the composite. For the flake-shaped CI particle composite, the permeability and permittivity are all larger than those of Co_2Z particle composite, and the permittivity is much larger than the permeability. The high ratio of permittivity to permeability results in the serious reflection when the electromagnetic wave arrives at the interface of the composite from air. Therefore, the flake-shaped CI particle composite was used as an inner layer in the double-layer absorber design.

Fig. 4 shows the electromagnetic wave absorption properties ($S_{11\ \text{short}}$) for the double-layer absorber shown in Fig. 2. In the $S_{11\ \text{short}}$ curve, there is a strong absorption peak in the low frequency region and the peak position locates at 2.68 GHz. To compare with the direct measurement result, the RL was also calculated using the theoretical formula of a double-layer absorber backed by a perfect conductor [16]:

$$\mathrm{RL} = 20\log|(Z_{in}-Z_0)/(Z_{in}+Z_0)|,$$
$$Z_{in} = \frac{Z_2(Z_1+Z_2\tanh(j(2\pi f d_2/c)\sqrt{\mu_2\varepsilon_2}))}{Z_2+Z_1\tanh(j(2\pi f d_2/c)\sqrt{\mu_2\varepsilon_2})},$$

where Z_0 is the impendence of air, Z_1 and Z_2 are the characteristic impendence of CI particle composite and Co_2Z particle composite and they are determined by the permeability and permittivity of their corresponding composites. The calculated result is shown in Fig. 4, labeled as $S_{\text{calculation}}$. We can see the RL curves from the direct measurement and theoretical calculation agree well each other. This result proves that the theoretical model is suitable to investigate the absorption properties of a double-layer absorber.

Since the theoretical model is suitable, the absorption properties of the double-layer absorber with other thicknesses can be achieved by changing the thickness of Co_2Z particle composite or CI particle composite. Here, the thickness of CI particle composite was fixed at 1.5 mm and the thickness of Co_2Z particle composite was varied from 0 to 5 mm. Their absorption properties were calculated and partial results were exhibited in Fig. 5(a). When the thickness of Co_2Z particle composite is 0, the RL curve represents the absorption properties of a single CI particle composite absorber, and there is a strong RL peak at about 2.68 GHz. As the thickness of the Co_2Z particle composite increases, the peak becomes stronger; however, we are amazed to find that the peak frequency position remains unvariable. Even the thickness increases to 5 mm, the peak position still locates at about 2.68 GHz. The result revealed that the RL peak frequency is not related with the thickness of Co_2Z particle composite. This phenomenon is quite different from that of a single-layer absorber in which the RL peak frequency is determined by the quarter-wavelength cancellation condition: $f_m = c/4t_m\sqrt{|u_r\varepsilon_r|}$, where t_m and f_m are the matching thickness and peak frequency, c is the velocity of light. The RL peak frequency moves toward lower frequency with the absorber thickness increasing.

From the above results, the RL peak frequency seemed to be only related with the CI particle composite. Fig. 5(a) has shown the RL peak frequency of a single CI particle composite absorber ($t=0$) with a thickness of 1.5 mm locates at 2.68 GHz. The quarter-wavelength dependence of frequency for the single CI particle composite according to its permeability and permittivity is shown in Fig. 5(b). When the thickness is 1.5 mm, the peak frequency agrees well with the quarter-wavelength cancellation condition. According to the previous study [17], for a single-layer absorber the strong RL peak originates from the cancellation of two electromagnetic waves at front interface of the absorber. The two waves are the reflection wave which is partially reflected at the front interface of the absorber when the electromagnetic wave is incident normally to the absorber and the emerging wave which is reflected by the perfect conductor and then out of the absorber. Since the thickness of CI particle composite in the double-layer absorber has been fixed at 1.5 mm, and the peak frequency remains unvariable with the increase in the Co_2Z particle composite, we deduced that the RL peak frequency is only determined by the quarter-wavelength cancellation condition of the CI particle composite. The RL peak originates from the cancellation of two electromagnetic waves at interface B shown in Fig. 2. The incident electromagnetic wave is partially reflected when it arrives at the interface B because the permeability and permittivity of CI particle composite are much larger than those of Co_2Z particle