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Simulation of the wave-absorbing model of a carbonyl iron/silver-coated core–shell structure

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Abstract. The microwave-absorbing performances of carbonyl iron powder/silver core–shell composite particles are studied on the basis of the electromagnetic scattering theory and the energy conservation law. In addition, a calculation method for reflection loss of the carbonyl iron powder/silver core–shell composite particles with microwave is proposed. The calculated reflection loss of the carbonyl iron powder/silver core–shell composite particles is compared with the experimental results. The findings show that the trend of reflection loss of the carbonyl iron powder/silver composite particles can be predicted which can subsequently provide a relevant reference for future experiment and calculation of the absorbing mechanism of electromagnetic wave-microscopic carbonyl iron powder/silver core–shell composite particles.

Keywords. Carbonyl iron powder/silver nucleus; wave loss; magnetic permeability.

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1. Introduction

To overcome the characteristic limitations, such as corrosion, oxidation and other instability shortcomings [1], of single-component nanocrystalline materials, a core–shell structure with unique physical and chemical properties is introduced. Its inner core and shell are connected with some physical and chemical effects [2,3], and the advantages of using this set-up are widely known in magnetism, biomedicine, optics, catalysis and many other fields. Silver, copper, nickel and other metals have high conductivity and good electromagnetic shielding effect, but their densities are high. Silver has excellent conductivity and chemical stability and thus can be used as a shell structure [4,5]. Carbonyl iron oxide absorbents have high permeability and are frequently utilised, but they have poor conductivity and stability. Thus, they can only be used as a wrapped nuclear structure. Combining the two materials into a shell–core structure improves conductivity and permeability, and subsequently, increased stability and improved absorptivity.

To study the absorbing properties of carbonyl iron/silver-coated core–shell structures, scholars focussed on the preparation and macroscopic aspects of the wave-absorbing mechanism. The silver-coated carbonyl iron powders were prepared using the electroless plating method [6]. The characterisations derived from XRD, SEM and EDX showed a significant improvement in the oxidation resistance and the obtained shielding effectiveness was better than –32 dB in the frequency range of 100 kHz–1.5 GHz [6]. Wang *et al* [7] prepared carbonyl iron powder/silver core–shell composite particles using liquid chemical reduction technology. By using these composite particles as a shielding filler, they prepared a new type of electromagnetic shielding rubber material with broadband and high-efficiency capabilities. Then, the effect of electromagnetic properties of the shielding fillers on the shielding effectiveness of the electromagnetic shielding rubber materials was also investigated. However, microwave absorption properties of carbonyl iron/silver core–shell composite particles still need further study.

The microwave-absorbing properties of carbonyl iron powder/silver core–shell composite particles were investigated earlier based on the scattering theory and the energy conservation law of electromagnetic waves.

2. Absorption model

The carbonyl iron powder/silver core–shell composite particles are dispersed on rubber at 40% volume fraction. The distribution of the individual particles in the rubber matrix is shown in figure 1. Every core–shell particle renders itself as its own centre and occupies a cubic space of length l with the inner radius of its shell kernel a and the outer radius b. When the plane electromagnetic wave is perpendicularly incident on the space occupied by the particles (figure 2), the expressions of the electric field intensity and magnetic field intensity are as follows [8]:

$$\begin{cases} E_i = E_{i0}\mathrm{e}^{-\mathrm{i}(kz-wt)}, \\ H_i = H_{i0}\mathrm{e}^{-\mathrm{i}(kz-wt)}. \end{cases} \tag{1}$$

The electromagnetic wave is propagated along the z-direction. The carbonyl iron powder/silver core–shell composite particles generate electric and magnetic dipole moments while the electromagnetic waves are radiated. The electric field strength E_{cs} and the magnetic field strength H_{cs} of the carbonyl iron/silver-coated core–shell structures are as follows:

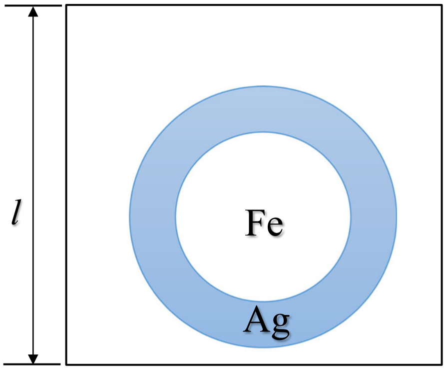

Figure 1. Schematic diagram of a filled single carbonyl iron powder/silver core–shell composite particle.

$$\begin{cases} E_{\mathrm{cs}} = \alpha E_i, \\ H_{\mathrm{cs}} = \alpha H_i, \end{cases} \tag{2}$$

where α is the attenuation constant.

The electric dipole moment p and the magnetic dipole moment m of a particle are [9,10] as follows:

$$\begin{cases} p = \varepsilon_m(\varepsilon_{\mathrm{cs}} - 1)V_{\mathrm{cs}}E_{\mathrm{cs}}, \\ m = \mu_m(\mu_{\mathrm{cs}} - 1)V_{\mathrm{cs}}H_{\mathrm{cs}}, \end{cases} \tag{3}$$

where $V_{\mathrm{cs}} = \frac{4}{3}\pi b^3$.

From eqs (1)–(3), the total dipole moment and magnetic dipole moment of a particle can be obtained as

$$\begin{cases} p = \dfrac{4\pi}{3}b^3\varepsilon_m(\varepsilon_{\mathrm{cs}} - 1)\alpha E_{i0}\mathrm{e}^{-\mathrm{i}(kz-wt)}\hat{x}, \\ m = \dfrac{4\pi}{3}b^3\mu_m(\mu_{\mathrm{cs}} - 1)\alpha H_{i0}\mathrm{e}^{-\mathrm{i}(kz-wt)}\hat{y}. \end{cases} \tag{4}$$

The equivalent dielectric constant and permeability of the carbonyl iron powder/silver core–shell composite particles can be obtained as follows [11,12]:

$$\begin{cases} \varepsilon_{\mathrm{cs}} = \dfrac{\frac{\varepsilon_2}{\varepsilon_1}\left(1+2\frac{\varepsilon_2}{\varepsilon_1}\right)+2\frac{a^3}{b^3}\frac{\varepsilon_2}{\varepsilon_1}\left(1-\frac{\varepsilon_2}{\varepsilon_1}\right)}{\left(1+2\frac{\varepsilon_2}{\varepsilon_1}\right)-\frac{a^3}{b^3}\left(1-\frac{\varepsilon_2}{\varepsilon_1}\right)}\varepsilon_1, \\ \mu_{\mathrm{cs}} = \dfrac{\frac{\mu_2}{\mu_1}\left(1+2\frac{\mu_2}{\mu_1}\right)+2\frac{a^3}{b^3}\frac{\mu_2}{\mu_1}\left(1-\frac{\mu_2}{\mu_1}\right)}{\left(1+2\frac{\mu_2}{\mu_1}\right)-\frac{a^3}{b^3}\left(1-\frac{\mu_2}{\mu_1}\right)}\mu_1, \end{cases} \tag{5}$$

where the angular frequency of the wave is $\omega = 2\pi f$, a is the radius of the carbonyl iron particles, b is the radius of the carbonyl iron powder/silver core–shell composite particles, ε_m and μ_m are the dielectric constant and permeability of the matrix, respectively, ε_1 and μ_1 are the dielectric constant and permeability of the carbonyl iron particles, respectively; ε_2 and μ_2 are the permittivity and permeability of the silver particles, respectively

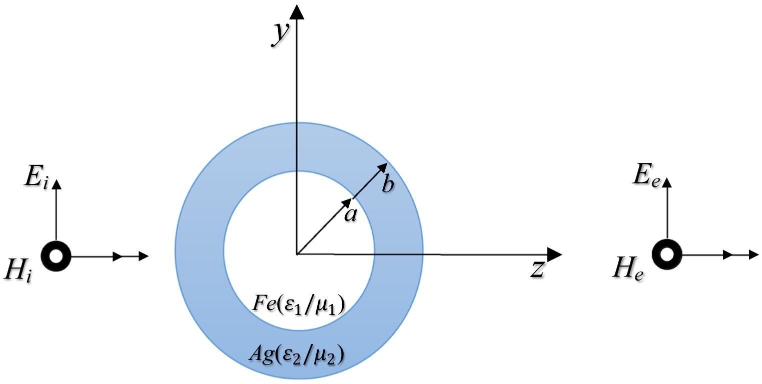

Figure 2. Planar incident wave and ejection wave of the core–shell structure.

and $\varepsilon_{\mathrm{cs}}$ and μ_{cs} are the equivalent dielectric constant and the equivalent permeability of the carbonyl iron/silver core–shell composite particles, respectively.

On the basis of the radiation of the oscillating electric dipole moment [10],

$$A = -\frac{\mu_m}{4\pi r}\mathrm{e}^{-\mathrm{i}kr}\,\dot{p}, \tag{6}$$

$$B = \nabla \times A = -\frac{\mathrm{i}\mu_m k}{4\pi r}\mathrm{e}^{-\mathrm{i}kr}\,\hat{e_r} \times \dot{p}. \tag{7}$$

From eqs (4) and (7), the following can be obtained:

$$\begin{cases} B_{\mathrm{rad}} = \dfrac{\sqrt{\varepsilon_m}}{3c^3 r} b^3 \left[\omega^2(\varepsilon'_{\mathrm{cs}} - 1) + \dfrac{\sigma}{\varepsilon_0}\right] \\ \qquad \times \alpha E_{i0}\mathrm{e}^{-\mathrm{i}(kz+kr-wt)} \sin\theta e_\phi, \\ H_{\mathrm{rad}} = \dfrac{1}{3c^2 r} b^3 \left[\omega^2(\varepsilon'_{\mathrm{cs}} - 1) + \dfrac{\sigma}{\varepsilon_0}\right] \\ \qquad \times \alpha E_{i0}\mathrm{e}^{-\mathrm{i}(kz+kr-wt)} \sin\theta e_\theta. \end{cases} \tag{8}$$

Similarly, on the basis of the magnetic dipole radiation [10],

$$A' = -\frac{\mathrm{i}k\mu_m}{4\pi r}\mathrm{e}^{-\mathrm{i}kr} e_r \times m, \tag{9}$$

$$B' = \nabla \times A' = -\frac{\mu_m \mathrm{e}^{-\mathrm{i}kr}}{4\pi c^2 r}(\ddot{m} \times e_r) \times e_r. \tag{10}$$

From eqs (9) and (10), the following can be obtained:

$$\begin{cases} B'_{\mathrm{rad}} = \dfrac{\mu_m^2}{3c^2 r} b^3 \left[\omega^2(\mu'_{\mathrm{cs}} - 1) + \dfrac{\sigma}{\varepsilon_0}\right] \\ \qquad \times \alpha H_{i0}\mathrm{e}^{-\mathrm{i}(kz+kr-wt)} \sin\theta e_\theta, \\ H'_{\mathrm{rad}} = \dfrac{\mu_m^2}{3cr} b^3 \left[\omega^2(\mu'_{\mathrm{cs}} - 1) + \dfrac{\sigma}{\varepsilon_0}\right] \\ \qquad \times \alpha H_{i0}\mathrm{e}^{-\mathrm{i}(kz+kr-wt)} \sin\theta e_\phi, \end{cases} \tag{11}$$

where ε_0 and μ_0 are respectively the dielectric constant and permeability of vacuum, $\varepsilon'_{\mathrm{cs}}$ and μ'_{cs} are respectively the real part of the relative permittivity and the relative permeability of carbonyl iron powder/silver core–shell composite particles, $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$ represents the characteristic impedance of the vacuum, c is the speed of light in vacuum, σ is the conductivity of carbonyl iron powder/silver core–shell composite particles, θ is the angle between the propagation direction of the radiation wave and the x-axis and $\mu_m \approx 1.0$ represents the relative permeability of the non-ferromagnetic material [13].

Given that the diameter of the carbonyl iron powder/silver core–shell composite particle is much smaller than the wavelength, the diffraction effect can be ignored. The outgoing wave that passes through the nanocarbonyl iron/silver core–shell composite particles can be regarded as a plane wave, and the electric field strength and the magnetic field intensity are expressed as

$$\begin{cases} E_e = E_{e0}\mathrm{e}^{-\mathrm{i}(kz-wt)}, \\ H_e = H_{e0}\mathrm{e}^{-\mathrm{i}(kz-wt)}. \end{cases} \tag{12}$$

The cube with side length l (figure 1) based on the energy conservation law of the electromagnetic field can be realised [14,15] as follows:

$$\begin{aligned} &\frac{1}{2}\iint_{l^2}(E_e \times H_e^*)\mathrm{d}S \\ &\quad = \frac{1}{2}\iint_{l^2}(E_i \times H_i^*)\mathrm{d}S - \frac{1}{2}\oiint(E_{\mathrm{rad}} \times H_{\mathrm{rad}}^*)\mathrm{d}S \\ &\qquad - \frac{1}{2}\oiint(E'_{\mathrm{rad}} \times H_{\mathrm{rad}}^{*\prime})\mathrm{d}S \\ &\qquad - \frac{1}{2}\iiint_{V_m}\left(E_i\frac{\partial(\varepsilon_0\varepsilon_m E_i^*)}{\partial t} + H_i\frac{\partial(\mu_0\mu_m H_i^*)}{\partial t}\right)\mathrm{d}V \\ &\qquad - \frac{1}{2}\iiint_{V_{\mathrm{cs}}}\left(E_{\mathrm{cs}}\frac{\partial(\varepsilon_0\varepsilon_{\mathrm{cs}} E_{\mathrm{cs}}^*)}{\partial t} + H_{\mathrm{cs}}\frac{\partial(\mu_0\mu_{\mathrm{cs}} H_{\mathrm{cs}}^*)}{\partial t}\right)\mathrm{d}V. \end{aligned} \tag{13}$$

The left-hand side of eq. (13) shows the average energy flux of the outgoing wave. The first term on the right-hand side is the average energy flux of the incident wave, the second term is the average energy flux of an electric dipole wave passing through the cube surface, the third term is the average energy flux of the magnetic dipole radiation passing through the cube surface, the fourth term is the consumption rate of electromagnetic energy in the matrix, the value of which is 0 because of the lossless medium and the fifth term is the average value of the electromagnetic energy consumption rate of the carbonyl iron/silver core–shell composite particles.

In eq. (13), the incident and outgoing waves are plane waves, and thus, we can derive [12]

$$\begin{cases} \dfrac{1}{2}\displaystyle\iint_{l^2}(E_i \times H_i^*)\mathrm{d}S = \dfrac{l^2}{2\eta_m}{E_{i0}}^2, \\ \dfrac{1}{2}\displaystyle\iint_{l^2}(E_e \times H_e^*)\mathrm{d}S = \dfrac{l^2}{2\eta_m}{E_{e0}}^2. \end{cases} \tag{14}$$

In eq. (14), the characteristic impedance of the base body can be expressed as $\eta_m = \sqrt{\mu_m/\varepsilon_m}$. If the centre of the carbonyl iron powder/silver core–shell composite particles is regarded as the centre of the sphere, then we consider the enclosure of the cube (figure 1) to have an arbitrary sphere. From eq. (8), the average energy flow of the radiation waves through the cube surface is

$$\begin{aligned} &\frac{1}{2}\oiint(E_{\mathrm{rad}} \times H_{\mathrm{rad}}^*)\mathrm{d}S \\ &\quad = \int_0^{2\pi}\mathrm{d}\varphi\int_0^{\pi}\frac{\sqrt{\varepsilon_m}}{2 \times 3^2 c^5} b^6\left[\omega^2(\varepsilon'_{\mathrm{cs}} - 1) + \frac{\sigma}{\varepsilon_0}\right]^2 \\ &\qquad \alpha^2 E_{i0}^2 \sin^3\theta\,\mathrm{d}\theta \\ &\quad = \frac{4\sqrt{\varepsilon_m} b^6 \pi}{27c^5}\left[\omega^2(\varepsilon'_{\mathrm{cs}} - 1) + \frac{\sigma}{\varepsilon_0}\right]^2 \alpha^2 {E_{i0}}^2. \end{aligned} \tag{15}$$

Similarly, we can derive the average energy flux of the magnetic radiation across the surface of the cube as

$$\frac{1}{2}\oiint (E'_{\mathrm{rad}} \times H^{*\prime}_{\mathrm{rad}})\mathrm{d}S$$
$$= \int_0^{2\pi} \mathrm{d}\varphi \int_0^{\pi} \frac{\mu_m^4}{2 \times 9c^3 r^2} b^6 \left[\omega^2(\mu'_{\mathrm{cs}} - 1) + \frac{\sigma}{\varepsilon_0}\right]^2 \times \alpha^2 H_{i0}^2 \sin^3\theta \mathrm{d}\theta$$
$$= \frac{4\pi\mu_m^4}{27c^3} b^6 \left[\omega^2(\mu'_{\mathrm{cs}} - 1) + \frac{\sigma}{\varepsilon_0}\right]^2 \alpha^2 H_{i0}^2$$
$$= \frac{4\pi\mu_m^3\sqrt{\varepsilon_m\mu_m}}{27c^3} b^6 \left[\omega^2(\mu'_{\mathrm{cs}} - 1) + \frac{\sigma}{\varepsilon_0}\right]^2 \alpha^2 E_{i0}^2. \tag{16}$$

The strength of the electric field that acts on the carbonyl iron/silver core–shell composite particles is proportional to that of the incident wave, and the attenuation constatnt is α. We can derive the average value of electromagnetic loss in a carbonyl iron powder/silver core–shell composite particle [12] as follows:

$$\frac{1}{2}\iiint_{V_{\mathrm{cs}}} \left(E_{\mathrm{cs}} \frac{\partial(\varepsilon_0\varepsilon_{\mathrm{cs}}E^*_{\mathrm{cs}})}{\partial t} + H_{\mathrm{cs}} \frac{\partial(\mu_0\mu_{\mathrm{cs}}H^*_{\mathrm{cs}})}{\partial t}\right)\mathrm{d}V$$
$$= \frac{2}{3}\pi b^3 \sigma \alpha^2 E_{i0}^2. \tag{17}$$

Subsequently, eqs (14)–(17) are substituted into eq. (13):

$$\beta = \frac{E_{e0}}{E_{i0}}$$
$$= \sqrt{1 - f_V^{2/3}\left(\frac{4\pi}{3}\right)^{1/3} b\eta_m\alpha^2 \left\{\frac{2\sqrt{\varepsilon_m}b^3}{9c^3}\left[\frac{1}{c^2}\left[\omega^2(\varepsilon'_{\mathrm{cs}} - 1) + \frac{\sigma}{\varepsilon_0}\right]^2 + \mu_m^{3.5}\left[\omega^2(\mu'_{\mathrm{cs}} - 1) + \frac{\sigma}{\varepsilon_0}\right]^2\right] + \sigma\right\}}. \tag{18}$$

composite material is the same. Therefore, we can obtain the recursion formula of the amplitude of the incident electric field and the radio field of every layer:

$$E_{e0,j} = \beta E_{i0,j} \quad (j = 1, 2, \ldots, 2n), \tag{19}$$

where $E_{i0,j}$, $E_{e0,j}$ are the amplitudes of the incident wave and the outgoing wave at layer j. The relationship of these two waves between the adjacent layers is

$$E_{i0,j} = E_{e0,j-1} \quad (j = 1, 2, \ldots, 2n), \tag{20}$$

where $2n = 2d/l$, in which d is the thickness of the composite material.

According to the theory of electromagnetic waves, the reflected and transmitted waves are generated when the plane electromagnetic waves are perpendicularly incident on the upper surface of the composite material. The electromagnetic fields on the composite surface can be expressed as [7]

$$\begin{cases} E_{\mathrm{inc}} = E_{\mathrm{inc}0}\mathrm{e}^{\mathrm{i}wt}\hat{x}, \\ H_{\mathrm{inc}} = (H_{\mathrm{inc}0}/\eta_0)\mathrm{e}^{\mathrm{i}wt}\hat{y}, \\ E_{\mathrm{ref}} = -E_{\mathrm{ref}0}\mathrm{e}^{\mathrm{i}wt}\hat{x}, \\ H_{\mathrm{ref}} = -(H_{\mathrm{ref}0}/\eta_0)\mathrm{e}^{\mathrm{i}wt}\hat{y}. \end{cases} \tag{21}$$

The transmitted wave that enters the composite is reflected by the metal matrix at the lower surface. Then, the transmitted wave returns to the upper surface. The amplitude is expressed as

$$\beta^{2n}E_{\mathrm{tra}0} = \beta^{2d/l}E_{\mathrm{tra}0}. \tag{22}$$

In eq. (18), the percentage of the carbonyl iron powder/silver core–shell composite particles in the matrix is $f_V = 4\pi b^3/3l^3$ and the decay constant [16] is

$$\alpha = \frac{3\varepsilon_m/(\varepsilon'_{\mathrm{cs}} + 2\varepsilon_m)}{1 + 1.62 f_V(\varepsilon'_{\mathrm{cs}} - 1)/(\pi\varepsilon_m)}.$$

Given that the size of the entire carbonyl iron/silver core–shell composite particle is much smaller than that of the incident wavelength, all particles in the *xy*-plane have the same intensity as that of the electric field. Therefore, eq. (18) is suitable for nanometre particle layers. When the microwave passes through the nanocomposite, a scattering response is produced at the particle–matrix interface and a resulting decay of energy occurs. According to eq. (18), the electric field amplitude attenuation ratios of every layer of the nanometre

Therefore, the electromagnetic field at the upper surface of the transmitted wave is as follows [17]:

$$\begin{cases} E_{\mathrm{tra}} = E_{\mathrm{tra}0}\left[\mathrm{e}^{\mathrm{i}wt} - \beta^{2d/l}\mathrm{e}^{-\mathrm{i}(2k_M d - wt)}\right]\hat{x}, \\ H_{\mathrm{tra}} = E_{\mathrm{tra}0}/\eta_M\left[\mathrm{e}^{\mathrm{i}wt} - \beta^{2d/l}\mathrm{e}^{-\mathrm{i}(2k_M d - wt)}\right]\hat{y}, \end{cases} \tag{23}$$

where the wave number of the composite is represented by $k_M = w\sqrt{\varepsilon_m\mu_m}$, while the wave impedance of the composite is denoted by $\eta_M = \omega\sqrt{\mu_m/\varepsilon_m}$.

On the basis of the boundary conditions and the tangential components of the electric and magnetic field strengths of the incident wave, both the reflected wave and the transmitted wave are continuous at the upper surface of the composite material [17]:

$$\begin{cases} E_{\mathrm{inc}0} - E_{\mathrm{ref}0} = E_{\mathrm{tra}0}\left[1 - \beta^{2d/l}\mathrm{e}^{-\mathrm{i}2k_M d}\right], \\ H_{\mathrm{inc}0} + H_{\mathrm{ref}0} = H_{\mathrm{tra}0}\left[1 + \beta^{2d/l}\mathrm{e}^{-\mathrm{i}2k_M d}\right]. \end{cases} \tag{24}$$

The formula of the power reflection coefficient of the composite materials can then be obtained as

$$\Gamma_p = 20\log\left|\frac{E_{\mathrm{ref}0}}{E_{\mathrm{inc}0}}\right| = 20\log\left|\frac{(\eta_0-\eta_M)+(\eta_0+\eta_M)\beta^{2d/l}\mathrm{e}^{-\mathrm{i}2k_M d}}{(\eta_0+\eta_M)+(\eta_0-\eta_M)\beta^{2d/l}\mathrm{e}^{-\mathrm{i}2k_M d}}\right|, \tag{25}$$

where d is the thickness of the composite.

3. Calculation and experimental results

Wang *et al* [7] have prepared carbonyl iron powder/silver core–shell composite particles using liquid chemical reduction technology. By using composite particles as the shielding filler, they prepared a new type of electromagnetic shielding rubber material with broadband and high efficiency. In the present study, the effect of electromagnetic properties of the shielding fillers on the shielding effectiveness of the electromagnetic shielding rubber materials is investigated. The SEM results show that the surface of the particles is smooth, the size is $a < 5\ \mu$m, and the thickness of the coated silver shell b is 50–100 nm. The prepared carbonyl iron powder/silver core–shell composite particles are filled into the rubber at a volume fraction of $fv = 40\%$ to realise a thickness of 10 mm, and the complex permeability is tested by Agilent 8714B. The real part of the relative permeability μ' and the imaginary part μ'' of the carbonyl iron powder/silver core–shell composite particles are shown in figure 3.

The relative dielectric constant of the rubber is $\varepsilon_m = 2.3$–4.0 [18], the resistivity of the carbonyl iron/silver core–shell composite particles is $2.18\times10^{-3}\,\Omega\cdot\mathrm{cm}$ [7] and the dielectric constant of the metal is not greater than 10 [19]. The calculated frequency range is 0.2–1.4 GHz, and eqs (18) and (25) are used to calculate the reflection loss Γ_p (figure 4).

The calculated and experimental results are compared and analysed. The analytical result shows that the calculated result of the absorption loss is in good agreement with the experimental result. The particle size in the calculation process has a statistical value and thus presents a certain difference with the actual value resulting in a calculation error. However, this study, to a certain extent, can effectively predict the reflection absorption loss of carbonyl iron/silver core–shell composite particles, and this offered prediction capability implies the theoretical reference significance.

Wang *et al* [7] applied the Schelkunoff electromagnetic shielding theory to calculate the absorption and reflection losses of carbonyl iron powder/silver core–shell composite particles. The absorption loss formula is $A = -0.131t\sqrt{f\mu_{\mathrm{r}}\sigma_{\mathrm{r}}}$ and the reflection loss formula is $R = -168.1 + 10\log(f\mu_{\mathrm{r}}/\sigma_{\mathrm{r}})$, where t is the thickness of the material, f is the electromagnetic frequency, σ_{r} is the relative conductivity of the material and μ_{r} is the relative permeability of the material. However, the experimental values in the literature only considered the influence of material thickness, electromagnetic wave frequency, relative conductivity and relative permeability. In this study, the carbonyl iron/silver-coated microwave absorption mechanism of the shell structure of the nuclear material considered several factors, such as material thickness, electromagnetic wave frequency, relative conductivity, relative permittivity, relative permeability, particle size and

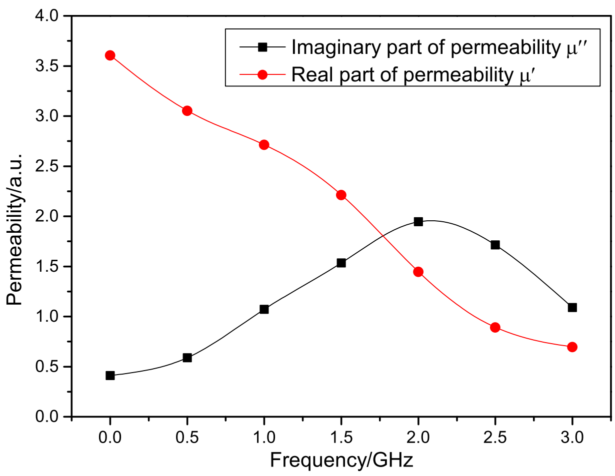

Figure 3. Real part of the permeability μ' and the imaginary part of the permeability μ'' of the carbonyl iron powder/silver core–shell composite particles [7].

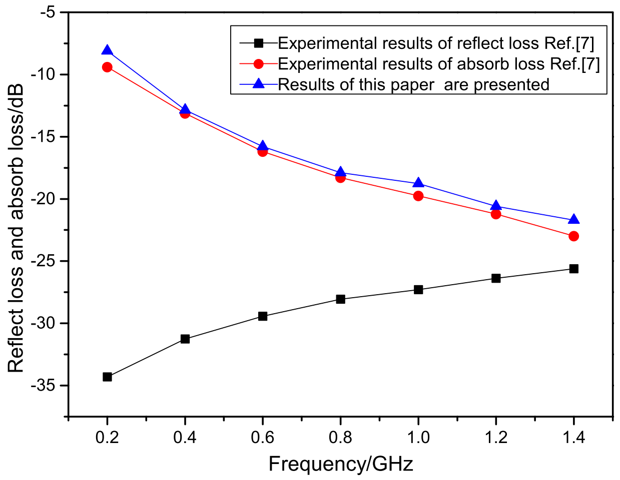

Figure 4. Experimental [7] and calculation results of the reflection loss and absorption loss of carbonyl iron powder/silver core–shell composite particles.

concentration, among others. Thus, the explanation of the mechanism and the overall result of the present study are likely to be more objective than the previous works.

4. Conclusion and outlook

In studying the absorbing properties of carbonyl iron/silver-coated shell structures, previous scholars have focussed on the macroproperties and preparatory mechanisms of wave absorption. By referring to their previous work, an algorithm is proposed for calculating the microscopic reflection loss of the carbonyl iron powder/silver core–shell composite particles based on the electromagnetic scattering theory and the energy conservation law. The calculated results of the present study are compared with the results obtained by Wang *et al* [7], and the reasons for the relative error are analysed.

The calculation method of the present work can effectively predict the trends of electromagnetic wave-absorbing losses of carbonyl iron powder/silver core–shell composite particles. It is important for explaining the microcosmic mechanism of microwave absorption and providing a useful calculation method for reflection loss of carbonyl iron/silver core–shell composite particles in the future, which could reduce the blindness of the experiment.

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