Enhanced microwave absorption properties and mechanism of core/shell structured magnetic nanoparticles/carbon-based nanohybrids

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Abstract: An efficient scheme was designed to selectively synthesize different categories of core/shell structured magnetic nanoparticles/carbon-based nanohybrids such as Fe₃O₄/C and Fe/helical carbon nanotubes (HCNTs) through the decomposition of acetylene directly over Fe₂O₃ nanotubes by controlling the pyrolysis temperature. The measured electromagnetic parameters indicated that the Fe/HCNT nanohybrids exhibited enhanced microwave absorption properties, which may be related to their special structures. The optimum reflection loss (RL) could reach -47.1 dB at 17.39 GHz with a matching thickness of 1.39 mm. The absorption bandwidth with the RL values below -20 dB was up to 11.59 GHz. Moreover, based on the obtained results, the possible enhanced EM absorption mechanisms were also discussed in details. The results show the excellent microwave absorption materials with lightweight, strong absorption and wide absorption frequency band may be realized in these nanohybrids.

Keywords: Core/shell structured nanohybrids; Fe/helical carbon nanotubes; Microwave absorption properties; electromagnetic absorption mechanisms

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1. Introduction

Microwave absorbing materials (MAMs), which can dissipate electromagnetic (EM) wave by converting EM energy into thermal energy, have attracted more and more attention due to serious EM pollution caused by the rapidly extensive application of wireless equipment, radar systems and local area networks, etc [1-3]. For MAMs, the reflection and attenuation properties are mainly determined by the balance between the complex permittivity ($\epsilon_r = \epsilon' - j\epsilon''$) and permeability ($\mu_r = \mu' - j\mu''$). It is well known that the reflection loss (RL), return coefficient (Γ) and attenuation constant (α) are defined by the following equations [4,5]:

$$RL = 20 \lg |\Gamma| \quad (1)$$

$$\Gamma = (Z_{in}/Z_0 - 1)/(Z_{in}/Z_0 + 1) \quad (2)$$

$$Z_{in} = Z_0 (\mu_r / \epsilon_r)^{1/2} \tanh(\gamma d) \quad (3)$$

$$\gamma = j\omega(\mu_r \epsilon_r)^{1/2} = \alpha + j\beta \quad (4)$$

$$\alpha = \frac{\sqrt{2}\pi f}{c} \sqrt{(\mu''\epsilon'' - \mu'\epsilon') + \sqrt{(\mu''\epsilon'' - \mu'\epsilon')^2 + (\epsilon'\mu'' + \epsilon''\mu')^2}} \quad (5)$$

$$\mu_r = \mu' - j\mu'' \quad (6)$$

$$\epsilon_r = \epsilon' - j\epsilon'' \quad (7)$$

Where f is the frequency of EM wave, d is the thickness of an absorber, c is the velocity of light and Z_{in} is the input impedance of absorber. It is well known that the return coefficient of an ideal absorber should be zero, which means that it must fulfill the optimal impedance matching condition: $Z_0 = Z_{in}$. However, it is difficult to meet this condition on the single dielectric or magnetic loss materials due to their mismatch in the values of μ_r and ϵ_r [6-12]. Therefore, considerable attention has been paid to develop high efficiency MAMs with light weight, low

thickness, wide absorption frequency range, strong absorption capability, and good antioxidation properties in the past years [13-18].

Among these MAMs, core/shell structured magnetic nanoparticles/carbon-based nanohybrids have received an increasing attention owing to their unique interfacial and synergistic effects [19-24]. For example, Kim and Che et al. synthesized core/shell Fe/carbon nanotubes (CNTs), and proved their excellent microwave absorption capabilities, respectively [25,26]. Terada et al. reported that the as-synthesized $\text{Fe}_3\text{C}/\text{C}$ had an excellent EM wave absorption capability in the range of 0.9-9.0 GHz [27]. Narayanan et al. found that Ni-filled CNTs could exhibit an enhanced microwave absorption property in the S band [28]. And other nanohybrids such as Ni/C [29], Co/C [30], $\text{Fe}_3\text{O}_4/\text{Fe}/\text{C}$ [31], Fe-carbon nanofibers [32], $\text{Li}_{0.32}\text{Zn}_{0.26}\text{Cu}_{0.1}\text{Fe}_{2.32}\text{O}_4/\text{CNTs}$ [33], Fe_3O_4 or Ni/carbon nanocoils [34], Fe/CNTs, Co/CNTs, and Ni/CNTs [35-41] were also demonstrated to have excellent microwave absorption performances. However, these core/shell structured carbon-based nanohybrids still suffer from some problems such as low efficiency of encapsulation, large thickness of absorber, optimal RL usually above -40 dB, and so on. Moreover, their enhanced microwave absorbing mechanisms were seldom discussed.

The aim of this work was to synthesize high encapsulation efficiency of magnetic nanoparticles/carbon-based nanohybrids and investigate their microwave absorption properties and mechanisms. Herein, we proposed a simple and efficient scheme to synthesize different categories of core/shell structured magnetic nanoparticles/carbon-based nanohybrids. Moreover, based on the measured complex permittivity and permeability, the microwave absorbing properties and mechanisms of the obtained nanohybrids were discussed in details.

2. Experimental

2.1. *Synthesis of Fe₂O₃ nanotubes and magnetic nanoparticles/carbon-based nanohybrids.*

Same to the method reported previously [42,43], Fe₂O₃ nanotubes were synthesized by hydrothermal method firstly. Then, the as-obtained Fe₂O₃ nanotubes were used as catalyst for catalytic decomposition of acetylene at 400, 500 and 600 °C, respectively. After cooling to room temperature (RT), different categories of magnetic nanoparticles/carbon-based nanohybrids could be obtained. For easy description, the products generated at 400, 500 and 600 °C were denoted hereinafter as C-400, C-500 and C-600, respectively.

2.2. *Characterization*

The samples were examined on an X-ray powder diffractometer (XRD) at RT for phase identification using CuK α radiation (model D/Max-RA, Rigaku). Raman spectroscopic investigations were performed using a Jobin-Yvon Labram HR800 instrument with 514.5 nm Ar⁺ laser excitation. The morphology of samples was examined using a transmission electron microscope (TEM) (model JEM-2000EX, operated at an accelerating voltage of 80 kV), and field emission scanning electron microscope (FE-SEM) (model FEI Sirion 200, operated at accelerating voltages of 5 kV). For microwave measurement, the as-prepared samples (30 wt%) were mixed with paraffin, respectively. The complex permittivity and permeability of composite were measured in frequency range of 0.5-18 GHz over an Agilent E8363B vector network analyzer.

3. Results and discussions

3.1. Phases, microstructures and possible formation mechanism of core/shell structured nanohybrids.

Figure 1 shows XRD patterns of the obtained catalyst and as-synthesized samples. As shown in Figure 1a, the diffraction peaks located at 24.1, 33.2, 35.6, 40.9, 49.5, 54.1 and 57.6° can be assigned to (012), (104), (110), (113), (024), (116) and (018) crystal planes of Fe₂O₃ (JCPDS No.86-0550), and no impurities such as FeOOH or Fe₃O₄ are detected. The result indicates that the used catalyst is single phase of Fe₂O₃. Figure 1b presents the XRD pattern of C-400. As indicated by the symbols in Figure 1b, all the diffraction peaks correspond to the hexagonal phase of graphite (JCPDS No.75-1621), cubic phase of Fe₃O₄ (JCPDS No.85-1436), orthorhombic phase of Fe₃C (JCPDS No.77-0255) and cubic phase of α -Fe (JCPDS No.06-0696), respectively. The XRD patterns of C-500 and C-600 (as shown in Figures 1c and d) indicate that all the labeled peaks can be indexed to the phases of graphite (JCPDS No.75-1621), Fe₃C (JCPDS No.77-0255) and α -Fe (JCPDS No.06-0696), respectively. The graphitic properties of the obtained samples can also be confirmed further by Raman spectrum [42]. As shown in Figure 1e, two peaks at ca. 1358 cm⁻¹ (D band) and 1599 cm⁻¹ (G band) can be observed clearly. As pointed out by the previous works [43-45], the D band is due to breathing-like modes of hexagonal carbon rings, which is related to existed defects in the graphitic structure. While the G band is ascribed to a doubly degenerate (in-plane transverse-optical (iTO) and longitudinal optical (LO)) phonon mode (E_{2g} symmetry) at the center of the Brillouin zone (Γ point). The Raman results indicate the graphitic properties of samples. In general, one can find that the pyrolysis temperature has a great impact on the phase and composition of the obtained samples. The iron oxides (Fe₂O₃ as well as Fe₃O₄) will be

converted into Fe_3C and $\alpha\text{-Fe}$ completely through the reduction reaction with the increasing temperature.

The images of catalyst and as-synthesized nanohybrids are shown in Figure 2. As shown in Figure 2a, it can be seen that the catalysts used here are Fe_2O_3 nanotubes with uniform size. Figure 2b presents a typical TEM image of C-400. Based on the phase of C-400 (as shown in Figure 1b), one can find that core/shell structured $\text{Fe}_3\text{O}_4/\text{C}$ can be synthesized in large quantities after the reduction of acetylene at a relatively low temperature ($\sim 400^\circ\text{C}$). The TEM images of C-500 and C-600 are shown in Figures 2c and d, respectively. It can be observed obviously that the two samples exhibit a similar morphology. Combined with the aforementioned XRD results of C-500 and C-600 (as shown in Figures 1c and d), core/shell structured Fe/helical carbon nanotubes (HCNTs) are the majority in the obtained samples. Therefore, as revealed before [46], different categories of core/shell structured magnetic nanoparticles/carbon-based nanohybrids such as $\text{Fe}_3\text{O}_4/\text{C}$ and Fe/HCNTs can be synthesized selectively by controlling the pyrolysis temperature. In order to investigate the experimental reliability, the designed experiments were repeated three times. As shown in Table 1, the detailed TEM investigations indicated that the experiments showed an excellent reproducibility.

Based on the aim of designed experiments and the obtained results, one can find that the phase, composition and morphology of the obtained samples can be regulated by the pyrolysis temperature. And the possible formation mechanism of core/shell structured $\text{Fe}_3\text{O}_4/\text{C}$ and Fe/HCNTs can be explained by the following reactions:

Among these reactions, reaction (1) is an incomplete reduction reaction between C_2H_2 and Fe_2O_3 , which mainly occurs at the relatively low temperature. And reaction (2) is a full reduction process, which will happen at the relatively high temperature. Through the aforementioned reactions, the elemental Fe can form through the reduction of Fe_2O_3 by C_2H_2 , and Fe particle is easily carbonized to generate Fe_3C [reaction (3)]. It is well known that the formation of Fe_3C is very crucial to the catalytic growth of core/shell carbon-based nanohybrids [47]. In our experiment, along with the reactions (2) and (3), the incomplete reaction (1) should be the main chemical reaction process at 400 °C. And the reduction reaction will happen fully when the temperature is enhanced greatly (~ 500 °C). Therefore, the formation of Fe_3O_4 /carbon nanohybrids should be the result of the incomplete reduction reaction at 400 °C and the full reduction reaction between C_2H_2 and Fe_2O_3 can result in the growth of Fe/HCNT nanohybrids. Moreover, according to the obtained results and models for CNM growth [48,49], the formation mechanism of Fe_3O_4 /carbon and Fe/HCNT nanohybrids are given in Figure 3. The possible pathways to grow core/shell structured nanohybrids are in the following: (1) the reduction reaction between Fe_2O_3 and C_2H_2 to form carbon atoms; (2) the dissolution and diffusion of carbon atom around the catalyst; (3) the incomplete reduction reaction between Fe_2O_3 and C_2H_2 at the relatively low temperature (~ 400 °C) to form Fe_3O_4 /C nanohybrids; (4) the full reduction reaction at the much higher temperature (500 and 600 °C) results in the formation of Fe/HCNT nanohybrids. Generally, compared to the previously reported schemes for the synthesis of core/shell structured carbon-based nanohybrids through the process of chemical vapor decomposition [50-52], our proposed project should be much more effective due to the uninterrupted reduction reaction and growth processes between the catalyst and carbon source.

3.2. EM and microwave absorption properties of the obtained nanohybrids.

Figure 4 displays the EM parameters of the wax composites containing 30 wt% of the obtained core/shell structured nanohybrids. Figures 4a and b show the complex permittivity of C-400, C-500 and C-600. With the frequency increasing from 0.5 to 18 GHz, the ϵ' and ϵ'' values of C-400 decrease from 34.3 to 7.4, and 50.8 to 6.5, respectively. Besides some fluctuations in the whole frequency range, the ϵ' and ϵ'' values of C-500 and C-600 also exhibit a fall trend. Moreover, the complex permittivity of C-400 is evidently higher than those of C-500 and C-600, and the discrepancy in the complex permittivity of C-500 and C-600 is very small. It is well known that the dielectric properties of magnetic particles/carbon-based nanohybrids are mainly determined by carbon materials. In our experiment, layers of carbon could form over Fe_2O_3 nanotubes at 400 °C, and HCNs could be obtained at 500 and 600 °C. Therefore, we think that this disparity in the values of the obtained complex permittivity should be related to the different categories of carbon materials in the obtained carbon-based hybrids. Figures 4c and d present the complex permeability of C-400, C-500 and C-600. One can find that all the obtained nanohybrids exhibit a relatively low permeability, which may be due to their low magnetizations and slow saturation processes [46]. Similar results were also observed previously over other metal nanocomposites [53,54]. Moreover, as shown in Figure 4d, the μ'' values of C-600 exhibit several resonance peaks at ca. 11.5 and 16.0 GHz, which can be ascribed to the natural resonance as reported elsewhere [55].

According to the equations (1)-(3), the RL of the obtained nanohybrids could be obtained and shown in Figure 5. As shown in Figure 5a, one can find that the minimal RL value of C-400 is ca. -16.7 dB at 17.21 GHz with a matching thickness of 1.46 mm. And the RL values below -10 dB, which indicates 90% of EM wave energy is

attenuated by the absorber, can be obtained in the frequency range of 8.64-18.0 GHz. Figure 5b shows that the optimal RL value of C-500 is ca. -43.4 dB at 8.52 GHz with the matching thickness of 2.71 mm, and the absorption bandwidth with RL values less than -20 dB (99% of EM wave energy absorption) can be obtained in the frequency range of 6.67-9.17 and 15.83-18.0 GHz. As shown in Figure 5c, it can be seen that the minimal RL value of C-600 is ca. -47.1 dB at 17.39 GHz with the matching thickness of 1.39 mm, and the absorption bandwidth with RL values less than -20 dB is 10.59 GHz (from 7.41 to 18.0 GHz). Generally, as shown in Table 2, the microwave absorption performance of the obtained samples is as follows: C-400<C-500<C-600. Moreover, compared to the representative microwave absorption properties of magnetic carbon-based nanohybrids [58-61], the obtained nanohybrids here exhibit enhanced microwave absorption properties even with the low weight content in the matrix. In other words, the obtained Fe/HCNTs can be used as the lightweight and excellent MAMs alternative to these previously reported EM absorption materials. Moreover, it is well known that the microwave absorption will result in the generation of heat within the sample. In order to study the experimental repeatability, the morphology and phase of C-600 were characterized again after the EM irradiation. The results indicated that no obvious difference in the morphology and phase was detected between the raw and irradiated C-600, which implying that the effect of generated heat on the morphology, phase and microwave absorption properties can be ignored. The negligible effect of generated heat should be ascribed to the good protection of α -Fe by Fe_3C and HCNTs, good chemical stability and thermal conductivity of HCNTs.

3.3. Possible enhanced absorption mechanism of the obtained nanohybrids.

In order to analyze the possible enhanced microwave absorbing mechanism, the dielectric and magnetic loss properties, attenuation constant and impedance matching of the obtained nanohybrids were investigated in details. As shown in Figure 6, one can find that all the obtained samples exhibit much larger values of $\tan \delta_E$ than those of $\tan \delta_m$, which implying that the RL is mainly due to dielectric loss. Moreover, the dielectric loss performance of the samples presents the following tendency: C-400>C-600>C-500. Based on the previous results (as shown in Figures 2 and 4), the disparities in dielectric loss should be related to the different structures of carbon. Moreover, compared to other core/shell structured nanohybrids reported elsewhere [58,62], the obtained nanohybrids display an excellent mutual compensation between dielectric loss and magnetic loss. Generally speaking, the obtained C-600 shows the best compensation while C-400 exhibits the worst one among the obtained nanohybrids, and this effective compensation is very beneficial to enhance their microwave absorbing capabilities [63]. Combined with the obtained results, one can find that the compensation is related to not only the core/shell structure but also the phase and morphology. C-500 and C-600 exhibit the better compensation between dielectric loss and magnetic loss should be related to the tube structure of HCNTs and good ferromagnetic property of α -Fe at RT.

As reported by the previous works, the improved microwave absorption capabilities of MAMs mainly result from their attenuation constant α and impedance matching [16,62]. In order to understand the enhanced microwave absorption properties, the α values and impedance matching ratio of the obtained nanohybrids were obtained. According to equation (5), the α values of the obtained nanohybrids were obtained and shown in Figure 7a. It can be seen that the obtained Fe₃O₄/carbon (C-400)

exhibits much larger α values than those of Fe/HCNTs (C-500 and C-600). However, as shown in Figure 7b, compared to C-400, the obtained C-500 and C-600 present much better impedance matching properties. As aforementioned results in Figures 4a and b, the obtained C-400 exhibits much higher values of ϵ'' , which worsening the impedance matching ratio. Therefore, the effective offsetting the drawbacks between attenuation constant and impedance matching can improve their microwave absorption capabilities effectively.

Based on the recent mechanisms for the enhanced microwave absorption properties of MAMs, two models were tried to interpret the enhanced EM absorption properties of the obtained nanohybrids [5,13]. The first one is zero reflection, according to the EM wave theory, the relationship $\mu_r = \epsilon_r$ should be satisfied. However, as shown in Figure 4, all the obtained samples exhibit much higher values of permittivity than their permeability. Therefore, the model cannot be used to explain the obtained results. The other model is geometrical effect, which occurs when the incident and reflected waves in the material are out of phase 180° at the particular thickness. This effect is strongly dependent on the following equation [5]:

$$d = n\lambda_m / 4 \quad (n = 1, 3, 5, \dots) \quad (8)$$

Where $\lambda_m = \frac{c}{f_m \sqrt{|\mu_r| |\epsilon_r|}}$. According to the obtained values of RL, f_m , μ_r and ϵ_r , the data of thickness (d) can be obtained. As shown in Table 3, one can find that the calculated thickness d is not absolutely equal to the true matching thickness d_m . However, it is also observed clearly that the disparity between d and d_m is decreasing, and the d values of C-600 are very close to those of d_m . Therefore, the geometric effect cannot account for the excellent EM absorption properties of the obtained nanohybrids completely.

According to Cole-Cole dispersion laws, the Debye relaxation process can be reflected in the plot of ϵ' versus ϵ'' . Each semicircle corresponds to one Debye relaxation process, and the enhanced Debye relaxation process induced by the interfaces can contribute to the improved EM absorbing capability [61,64]. Based on the permittivity of the obtained samples, the $\epsilon' - \epsilon''$ plots of C-400 and C-600 are shown in Figure 8. One can find that the obtained C-600 has much more semicircles than that of C-400, which indicating that the interface polarization also plays an important role in the enhanced microwave absorption properties. Generally, similar to the recently reported mechanisms [65-67], because of the tube structure, good ferromagnetic properties of α -Fe and core/shell structured nanohybrids, the obtained C-500 and C-600 here exhibit the excellent mutual compensation between dielectric loss and magnetic loss, the effective offsetting the drawbacks between attenuation constant and impedance matching, the partial geometric effect and interface polarization, which can favor the enhanced attenuation of EM wave.

4. Conclusions

In summary, we proposed an efficient scheme to synthesize core/shell structured magnetic nanoparticles/carbon-based nanohybrids through the decomposition of acetylene directly over Fe_2O_3 nanotubes. And different categories of core/shell structured nanohybrids such as $\text{Fe}_3\text{O}_4/\text{C}$, Fe/HCNTs could be synthesized selectively by increasing the pyrolysis temperature from 400 to 600 °C. The investigations indicated that the microwave absorption capabilities of the obtained nanohybrids enhanced gradually with the increasing pyrolysis temperature, which may be related to their special structure and synergetic effect. The optimal RL could be up to -47.1 dB with the matching thickness of 1.39 mm. Moreover, the possible formation and

enhanced EM absorption mechanisms of core/shell structured nanohybrids were discussed in details. The improved EM absorption capabilities could be attributed to the excellent mutual compensation between dielectric loss and magnetic loss, the effective offsetting the drawbacks between attenuation constant and impedance matching, the partial geometric effect and enhanced interface polarization. The obtained results indicated the as-synthesized Fe/HCNT nanohybrids may be a promising light-weight and high performance MAMs.

Acknowledgments

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Figure Captions

Figure 1. XRD patterns of (a) catalyst, (b) C-400, (c) C-500, (d) C-600; and (e) Raman spectrum of C-400 and C-600.

Figure 2. (a) FE-SEM image of catalyst, and TEM images of (b) C-400, (c) C-500, (d) C-600, respectively.

Figure 3. Schematic diagram for the formation mechanism of magnetic nanoparticles/carbon-based nanohybrids.

Figure 4. (a) the real and (b) imaginary parts of permittivity, (c) real and (d) imaginary parts of permeability of the obtained nanohybrids.

Figure 5. The reflection losses of (a) C-400, (b) C-500 and (c) C-600, respectively.

Figure 6. Loss tangent as a function of frequency for (a) C-400, (b) C-500, and (c) C-600, respectively.

Figure 7. (a) Attenuation constant, and (b) impedance matching ratio versus frequency for the obtained nanohybrids.

Figure 8. Cole-Cole semicircles of the obtained C-400 and C-600.

Table 1. Effects of pyrolysis temperature of acetylene on products

Temperature (°C)	Product	Species as revealed by TEM studied	Efficiency of encapsulation
400	C-400	$\text{Fe}_3\text{O}_4@\text{C}$	98%
			93%
			97%
500	C-500	$\text{Fe}@\text{HCNTs}$	97%
			93%
			94%
600	C-600	$\text{Fe}@\text{HCNTs}$	91%
			95%
			94%

Table 2. Summary of representative microwave absorption properties reported in recent papers.

Sample	C	Optimal RL value (dB)	d_m (mm) (RL<-20 dB)	Frequency range (GHz) (RL<-20 dB)	Reference
ZnO/Fe@Fe ₃ O ₄ /G ^b	20	-38.4	2.5-5.0	5.9-15.2	18 ₍₂₀₁₂₎
Ni/CNTs	60	-37	3.77-6.56	1.83-3.07	38 ₍₂₀₁₁₎
Fe/CNTs	60	-39	3.36-5.57	2.04-3.47	38 ₍₂₀₁₁₎
Fe ₃ O ₄ /C	55	-27.9	1.5-5	4.5-6.5	42 ₍₂₀₁₁₎
Fe ₃ O ₄ /ZnO	50	-30	2-4	4.5-15.5	56 ₍₂₀₁₀₎
Fe ₃ O ₄ /TiO ₂	50	-20.6	5	17.28	57 ₍₂₀₁₀₎
Ni/G	60	-17.8	-	-	58 ₍₂₀₁₂₎
Fe/G ^c	40	-45	1.5-4.0	5.0-17.8	59 ₍₂₀₁₃₎
Fe/CNTs	30	-40.15	1.5-8.0	2.0-17.9	60 ₍₂₀₁₅₎
Fe@MnO ₂ -G ^d	50	-17.5	-	-	61 ₍₂₀₁₅₎
Fe ₃ O ₄ /C (C-400)	30	-16.7	-	-	This work
Fe/HCNTs (C-500)	30	-43.4	1.29-1.46, 2.50-3.03	6.67-9.17, 15.83-18.0	This work
Fe/HCNTs (C-600)	30	-47.1	1.28-2.98	7.41-18.0	This work

^aC denotes the added amounts of the absorbents in the paraffin composites.

^bZnO/Fe@Fe₃O₄/graphene

^cFe/graphene

^dFe@MnO₂-graphene

Table 3. RL values of the obtained nanohybrids at the different matching thickness (d_m) and the calculated thickness (d) in terms of geometrical effect.

Sample	d_m/mm	RL/dB	f_m/mm	d/mm
C-400	1.5	-16.65	16.95	1.32
	2.0	-13.69	11.79	1.79
	2.5	-10.81	9.34	2.15
C-500	1.5	-20.28	15.83	1.37
	2.0	-15.54	11.44	1.87
	2.5	-19.96	9.17	2.29
C-600	1.5	-37.12	15.11	1.46
	2.0	-39.54	11.18	1.92
	2.5	-38.55	8.73	2.41

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<p>Enhanced microwave absorption properties and mechanism of core/shell structured magnetic nanoparticles/carbon-based nanohybrids</p>	<p>In the article, core/shell $\text{Fe}_3\text{O}_4/\text{C}$, Fe/helical carbon nanotubes were synthesized selectively. The results indicated that the optimum reflection loss (RL) could reach -47.1 dB at 17.39 GHz with a matching thickness of 1.39 mm. The absorption bandwidth with the RL below -20 dB was up to 11.59 GHz. Moreover, based on the</p>
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