MICROWAVE ABSORPTION PERFORMANCE SIMULATION OF A FACILE YET UNEXPECTEDLY EFFECTIVE MICROWAVE ABSORPTION COMPOSITE MATERIAL

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ABSTRACT

The microwave absorption performance of a facile yet effective electromagnetic wave absorption composite material was simulated with an Ansoft software called high frequency structure simulator (HFSS) in the frequency range of 2-18GHz. The investigated electromagnetic wave absorption composite material model is made up of a honeycomb structure plate covered by composite material plates with low reflectivity on the top and high reflectivity for microwave at the bottom respectively. Dielectric spherical shells with the complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) and complex permeability ($\mu = \mu' - j\mu''$) measured form a novel graphene-based material were arranged in a close-packed face centered cubic lattice structure and filled into the periodically arranged holes in a continuous honeycomb shaped plate to form a hierarchical periodic structure. With periodic boundary conditions and a floquet port excitation, the composite model reveals excellent microwave absorbing capability with both strong absorption and a maximum absorption frequency bandwidth. In particular, for the simulated composite model with the thickness of a few millimeters the reflection loss (RL) reaches a maximum value of -51.65dB at 16.7GHz and the optimized effective absorption bandwidth (RL < -10dB) covers 5.5-18GHz. The enhanced microwave absorption performance of the composite model was attributed to the multiple reflection effect of the close-packed spherical shells, high intrinsic dielectric loss of the graphene-based dielectric and the improved overall impedance matching with free space arising from the hierarchical periodic structure. With the fantastic microwave absorption performance the investigated composite model may be a promising microwave absorbent candidate, which is in urgent need to deal with the serious electromagnetic wave interference pollution.

1 INTRODUCTION

Novel high efficient and light weight microwave wave absorption material has drawn much attention owing to the electromagnetic interference arising from the extensive utilization of electronic device and communication facilities [1-4]. In the past decades, research interests have been focused on the fabrication of dielectric loss materials such as carbon materials [5-7], and magnetic loss materials, for instance carbonyl iron, ferrite[8,9]. Wang et al fabricated a graphene-Fe3O4 nanohybrids by depositing β-FeOOH crystals with diameter of 3-5nmon the surface of the graphene sheets, followed by annealing under Ar flow, which reduce β-FeOOH to Fe_3O_4. The Fe_3O_4 nanoparticles with a diameter of about 25 nm were uniformly dispersed over the surface of the graphene sheets. The nanohybrids exhibited significantly increased electromagnetic absorption properties owing to high surface areas, interfacial polarizations, and good separation of magnetic nanoparticles. The maximum reflection loss was up to -40.36 dB for G–Fe_3O_4 nanohybrids with a thickness of 5.0 mm. Feng et.al decorated reduced graphene oxide (RGO) with ZnO nanocrystals, which has a strong absorption (maximum reflection loss of -54.2 dB), broad effective absorption bandwidth (6.7 GHz) and small thickness (2.4 mm) [10]. Yang et.al obtained a hierarchical architecture by fabricate NiO nanorings on

SiC through a facile two-step method. The architecture demonstrates multirelaxation and possesses high-efficient absorption. The reflection loss exceeds −40 dB and the bandwidth covers 85% of X band (approximately −20 dB) [11]. However these strategies fail to meet the demand of broad absorption frequency band, high absorption capacity, low density, good thermal stability and anti-oxidation capability, which are very much expected for high- performance practical microwave absorbents. As is known, properties of materials generally depend upon their component and more importantly micro-structure and macro-structure as well. Which inspires us proper macro/microstructure designing of conventional microwave absorbent has the potential for the fabrication of efficient yet broad band microwave absorption materials. Sun et al achieved a dendrite-like ferrite micro-structure with phase transformation from dendritic α-Fe_2O_3 to Fe_3O_4, Fe by partial and full reduction ,and γ-Fe_2O_3 by a reduction–oxidation process, exhibit excellent microwave absorbability in low or middle frequency (2-9GHz)[12]. Qiang et.al prepared a novel Fe/C nanocomposite through an in situ controlled high-temperature pyrolysis of a metal–organic framework, Prussian blue. A best microwave absorption performance is obtained at the pyrolysis temperature of 650 ℃[13]. As for marocstructure design of microwave absorbent, periodic frequency selective surfaces are conventional hotspot for structural microwave absorbent. Most of them has a impressive maximum absorption, however the effective band width usual very narrow. Hierarchical structures combines micro and macro structure, deal to synergistic effect these kinds of structures usual have exciting performances, for example hysteresis, self-cleaning effect, and low or middle frequency absorption [12]. For design of a effective yet with broad band width microwave absorption material/structure, it's a much more promising strategy to come up with hierarchical structures.

In this work, we designed a hierarchical structure by combine hollow spherical shells which is close-packed in a face-centered like structure and a periodically arranged continuous hexagonal honeycomb plate. The microwave absorption property is simulated with high frequency structure simulator (HFSS) a Ansoft software widely used in electronic and microwave device simulation. With periodic boundary conditions and a floquet port excitation, the composite model reveals excellent microwave absorption properties with strong absorption and wide absorption band. In particular, for the simulated composite model with the thickness of a few millimeters the reflection loss (RL) reached a minimum of -51.6dB at 16.7GHz and the optimized effective absorption bandwidth (RL < -10dB) reaches 12.4GHz (5.6-18GHz). The enhanced microwave absorption performance of the composite model was attributed to the multiple reflection effect of the close-packed spherical shells, high intrinsic dielectric loss of the carbon-based dielectric and the improved entire impedance matching arise from the hierarchical periodic structure.

2 METHOD

2.1 Model configuration

The simulated hierarchical structure model composed of a periodic macro hexagonal honeycomb structure plate made of aramid fiber paper and epoxy resin composite, 10mm in thickness and the periodically arranged holes with a diameter of 5mm, as shown in figure 1(a), which is in extensive utilization as Lightweight Load bearing structure, the hexagonal holes in the honeycomb structure are filled up with hollow spherical shells with a typical external diameter of 2mm, and a typical internal radius (r_{in}) to external radius (r_{ex}) ratio of R=0.8~0.99, which is close-packed in a face-centered cubic like structure as shown in figure 1 (b). A typical microwave absorption cell is displayed in figure1(c). Considering the working conditions of the microwave absorption materials, a high reflection layer is need to simulate the raw metallic surfaces. Under the hierarchical structure model, an aluminum plate with thickness of 4mm is placed at the bottom of the hierarchical structure model (shown in figure1(c), gray in colour). A overall view of the hierarchical structure is shown in figure 1 (d), the theoretically scale for simulation is infinite, but for the sake of convenience a 300mmx300mm representative is displayed.

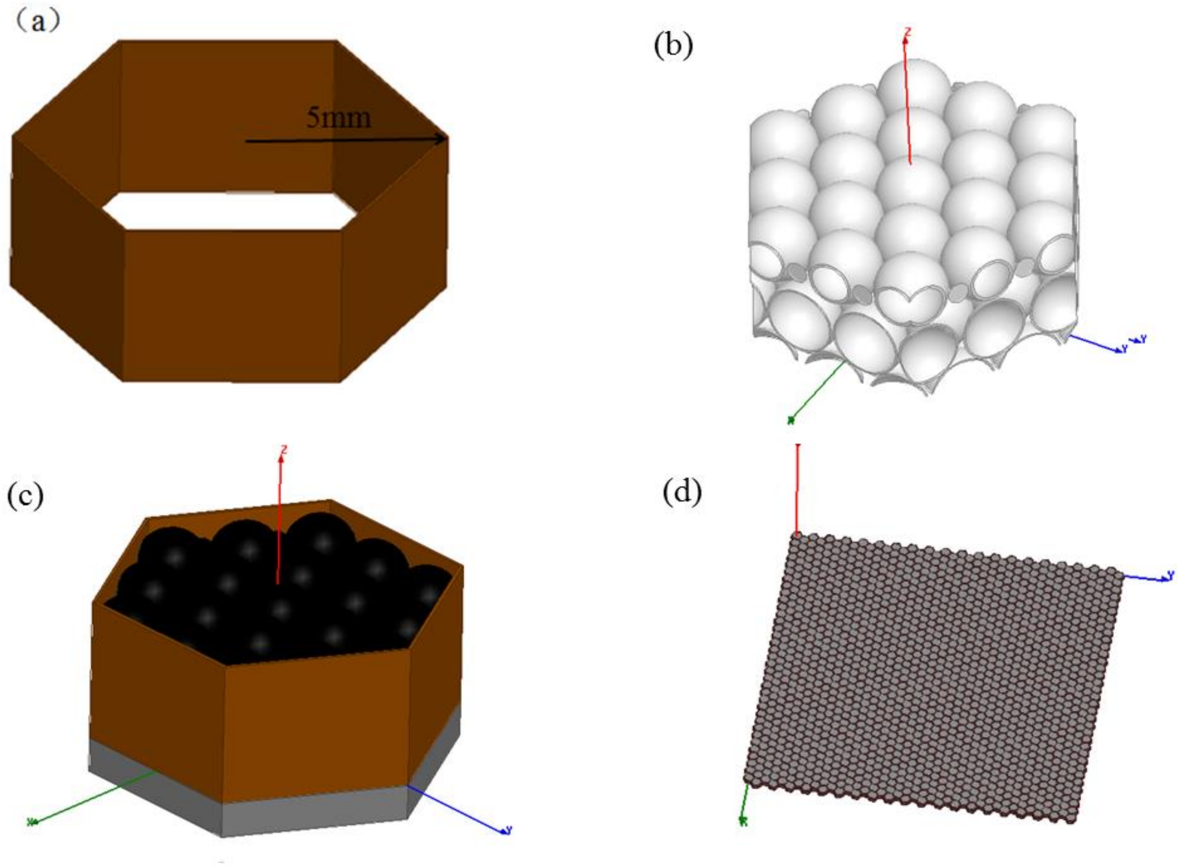

Figure 1: configuration of the hierarchical structure: (a) a typical empty hole of the periodical macro hexagonal honeycomb structure, (b) hollow spherical shells close-packed in a face-central cubic like structure, (c) A typical microwave absorption cell, (d) A overall view of the hierarchical structure

2.2 Simulation detail

For the electromagnetic wave reflection simulation of hierarchical structure model, some more material parameters are needed, Complex permittivity, complex permeability and the electrical conductivity of the composite hexagonal honeycomb structure plate and more importantly of the hollow spherical shells are the most essential parameters. Material properties of the composite hexagonal honeycomb structure plate is assigned from the material library of HFSS. The real part of the permittivity is approximately 3.6, and the dielectric loss tangent has a number of 0. As for magnetic properties, the real part of the permeability is assigned as 1, and the magnetic loss tangent is set as 0. As for the hollow spherical shells, the material is an graphene-based absorbent synthesised by us. Samples for the complex permittivity and permeability measurement were prepared by loading the absorbent in paraffin wax with a weight fraction of 30 wt.%. which is pressed into toroidal shape with outer diameter of 7.0 mm, inner diameter of 3.0 mm, and thickness of 3.0 mm. An Agilen vector network analyzer is used for the measurement of the electromagnetic parameters.

For the reflection loss simulation of the hierarchical structure in the frequency range of 2-18GHz, proper solving conditions are given. As the macro hexagonal honeycomb is a typical periodic structure, 3 pairs master-slave boundary conditions is sited (figure 2(a)). In this way we can get the reflection loss of an infinite panel by simply calculate the result of a single MW absorption cell (only one of the holes in the hexagonal honeycomb structure). To match up with the master-slave boundary conditions Floquet port excitation, which is specially useful for the simulation of periodic structures , are assigned to the upper and bottom surfaces of the air box , as shown in figure 2(b), which is 50mm high and covering the hierarchical structure. Default mesh operation is used. For the analysis of process, frequency sweep range from 2GHz to 18GHz is added and the central solution frequency is set to be 10GHz.

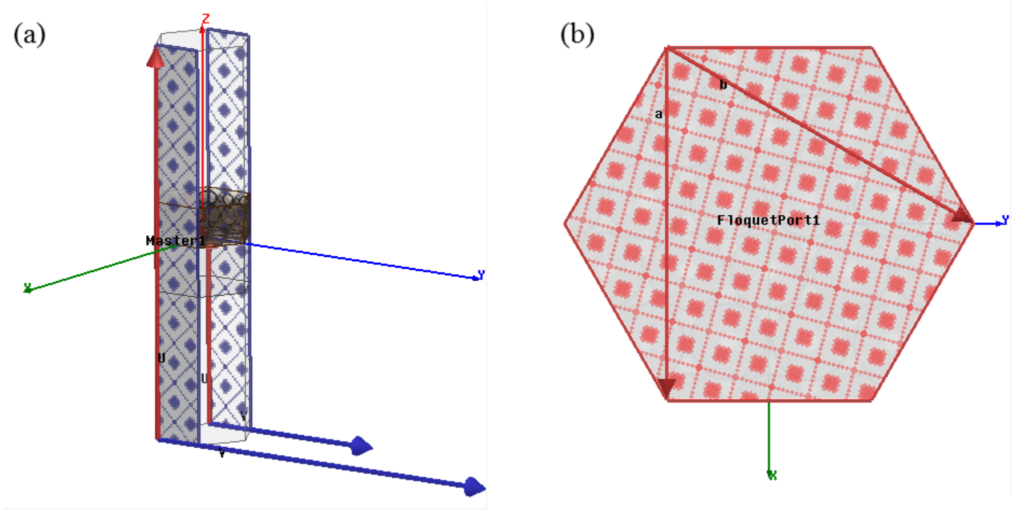

Figure 2: solving conditions for the the hierarchical structure model, (a) typical master-slave boundary conditions surrounding the model, (b) Floquet port excitation on the top and bottom surfaces.

3 RESULT AND DISCUSSION

3.1 Complex permittivity and permeability of the graphene-based absorbent

The result for the complex permittivity, permeability and loss tangent of the graphene-based absorbent is shown in figure 3. As it shows in figure 3(a) the graphene-based absorbent has a very large complex permittivity, whose real part is approximately 10-55, monotonic decrease in the frequency range of 2-18GHz, the imaginary part first increase from 31.2 at 2GHz to a peak value of 39.9 at 6.72GHz, then monotonic decrease to 21.9 at 18GHz.

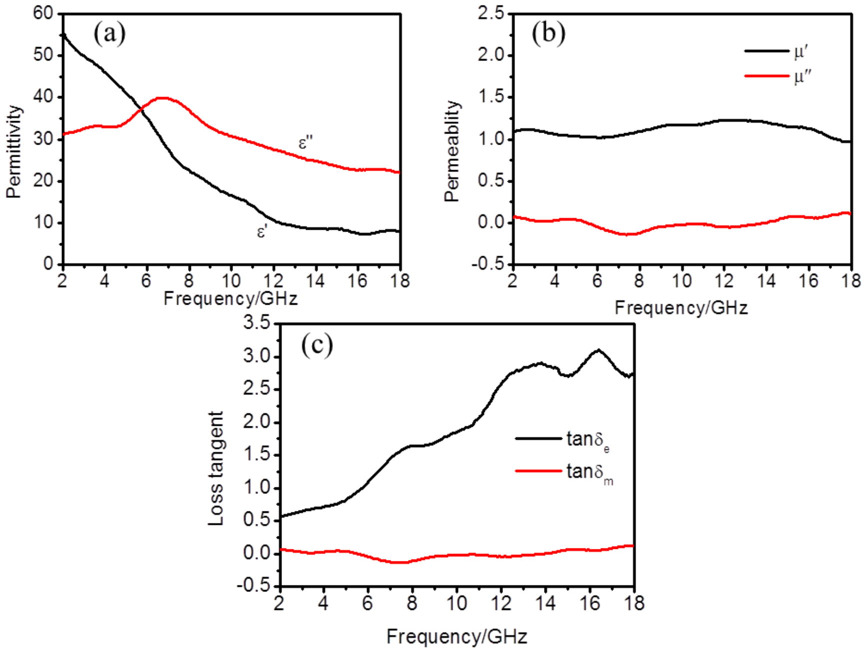

Figure 3: real and image part of (a) complex permittivity, (b) permeability and (c) loss tangent of the graphene-based absorbent

As the imaginary part reveals the dielectric loss of the electromagnetic energy, the peak at 6.8GHz means the graphene-based absorbent has a very strong energy dissipation effect at 6.8GHz. The real and imaginary part of the complex permeability are small and almost constant in the investigated frequency range, as the absorbent is nonmagnetic, the real part has a very narrow fluctuation range of 1.0-1.2, and imaginary part ranges from -0.13-0.07,which also reveals there is no magnetic loss in the MW absorbent.

3.2 Reflection loss results and optimization

With the complex permittivity, permeability and loss tangent of the graphene-based absorbent the hollow spheres in the hexagonal honeycomb structure becomes a very efficient MW absorption structure. The reflection loss simulation of the hierarchical structure in 2-18GHz is carried out with HFSS when the internal radius (r_{in}) to external radius (r_{ex}) ratio R is set to be 0.95 and the external radius ranging from 2.5mm, 3mm and 4mm. The result is shown in figure 4.

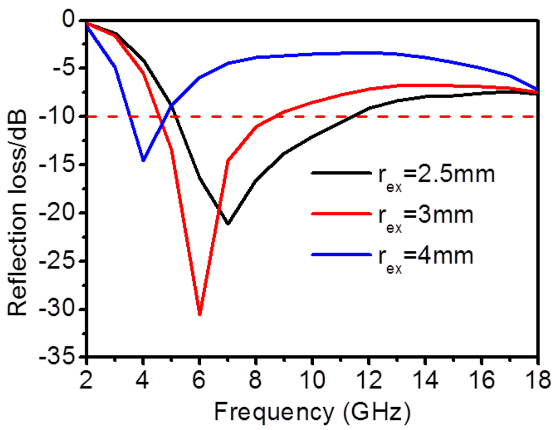

Figure 4: reflection loss of the hierarchical structure with R=0.95 and external radius ranging from 2.5mm to 4mm of the hollow spheres

With the external radius varies from 2.5mm to 4mm the effective absorption band width becomes narrower and narrower. When r_{ex}=2.5mm the hierarchical structure has a effective absorption band width of 5.8GHz (from5.6GHz to 11.4GHz). As r_{ex} increases to 3mm the frequency range in which reflection loss is under -10dB decrease to 4.1GHz (4.2GHz-8.3GHz). When r_{ex} is set to be 4mm, the effective absorption band width further reduces to 1.6GHz (3.5GHz-5.1GHz). Meanwhile the maximum absorption intensity first increase from -21.1dB for 2.5mm to -30.6 dB for 3mm. But as the external radius continuously increase to 4mm the maximum absorption intensity decrease to -14.5dB. It reveals that a smaller external radius is favourable for a better MW absorption performance (a broader effective absorption band width mostly).

As we know the impedance match between air and MW materials is a crucial factor for the reflection loss performance. When the hierarchical structure is divided into two layer with different R, and different density as a result, it forms a gradient structure which is favourable to improve the impedance match condition.

Inspired by the gradient structure, with r_{ex}=2.5mm we divided the hollow spheres into two layers with equal thickness (5mm) , the top and bottom layers are given different R, R_T and R_B respectively. a bigger R_T means less absorbent in the upper layer which is expected to be favourable to give a better impedance match. Meanwhile R_B should have a smaller value which means the under layer has more graphene based MW absorbent. As the low density upper layer increase the transmission of microwave into the MW absorption structure, more graphene based MW absorbent in the under layer means more electromagnetic energy can be dissipate. R_T were first set to 0.95 and R_B is swept in the range of 0.1-0.99. The result is shown in figure 5(a), it reveals that when R_B =0.8-0.95 it has a broader effective absorption band range. Further sweep in 0.8-0.95 show a when R_B =0.860, the broadest band width reaches10.6GHz (51.GHz-8GHz , 10.3GHz- 18GHz), as shown in figure 5(b) . When R_B is set to be 0.860, we further swept the R_T in 0.1-0.99. The result shows when R_T =0.95-0.99 the hierarchical structure has the best microwave absorption performance, which is consistent with the theoretical prediction. As shown in figure 5(d) and (e) the R_T is further swept in 0.95-0.99, a best reflection loss performance is achieve when R_T =0.967.The optimized reflection loss performance with the optimized configuration of R_B =0.86 and R_T =0.967 is shown in figure 5(f) , a 12.5GHz effective absorption band width (5.5GHz-18GHz) and a -51.65 maximum absorption at 16.7GHz is obtained.

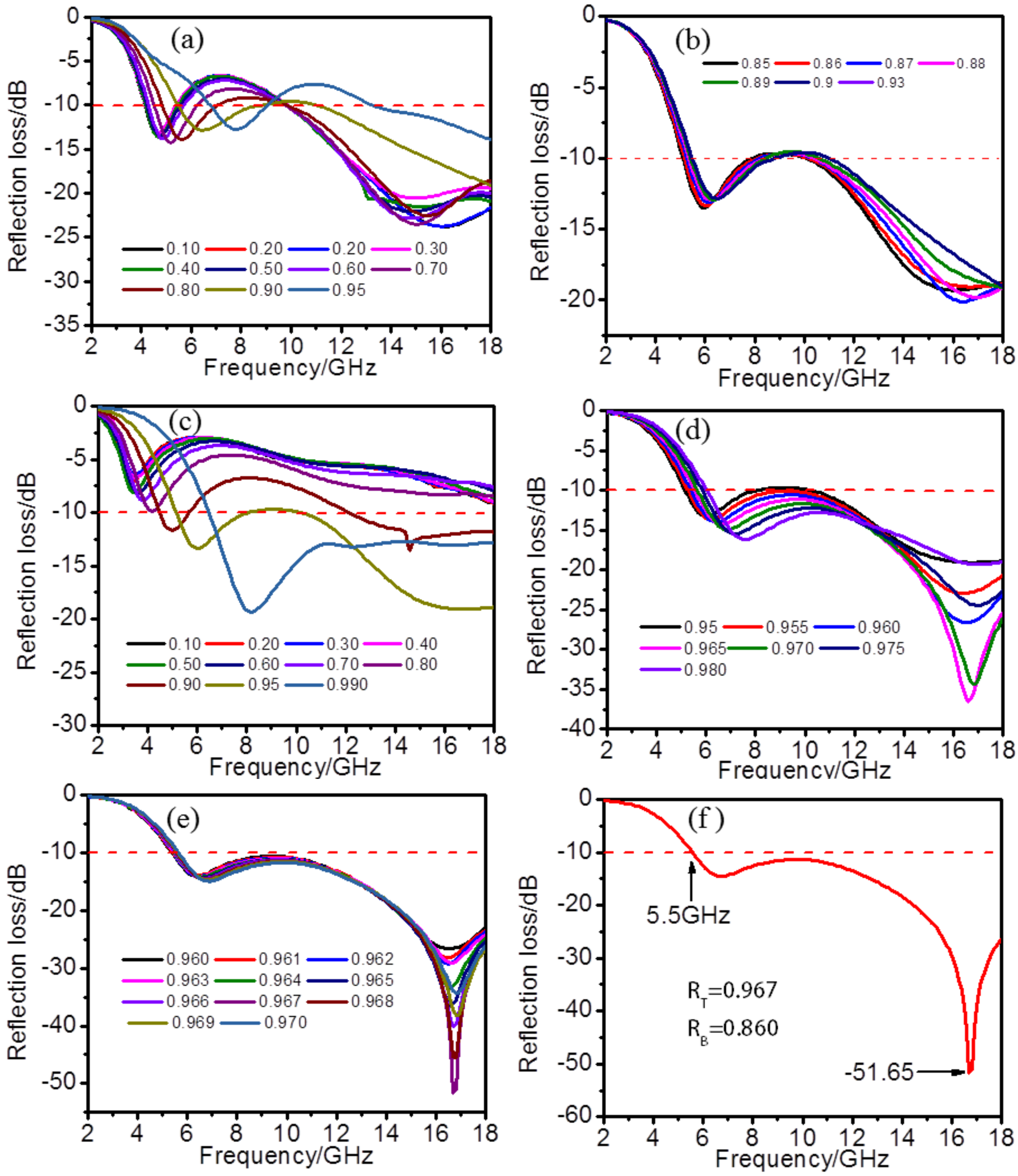

Figure 5: reflection loss of the hierarchical structure with optimized R_B (a), (b), (c) and R_T (d), (e) and the optimized reflection loss performance of the hierarchical structure with R_{T}=0.967 and R_{B}=0.860

The excellent MW absorption performance of the hierarchical structure can be attribute to the impedance modulation effect of the hexagonal honeycomb structure and the double-layer gradient structure and the excellent microwave absorbing capacity of the close-packed hollow spherical shells which is made of highly efficient graphene-based microwave absorbent as well. The close-packed hollow spherical shells were divided into hexagonal bulks with the scale of a few millimetres by the hexagonal honeycomb structure, which is very helpful for reducing the overall electrical conductivity of the hierarchical structure. As a result the effective permittivity of the hierarchical structure decreased, which will certainly improve the impedance match condition of the whole structure. The double-layer gradient structure of the hexagonal bulks is also beneficial for mitigate impedance mismatch between air and the hierarchical structure, so that transmission of the microwave at the interface can be dramatically improved. When the microwave transmitted into the hierarchical structure, it will be multi-reflected in the close-packed hollow spherical shells, which will dramatically increase the effective enlarge the optical path length in the hierarchical structure. Therefor more electromagnetic energy can be dissipated, which will certainly leading to a much lower reflection of the microwave energy.

4 CONCLUSIONS

The microwave absorption performance of a periodical hierarchical microwave absorption structure is simulated with an Ansoft software called high frequency structure simulator (HFSS) in the frequency range of 2-18GHz. The hierarchical microwave absorption structure consist of a periodical hexagonal honeycomb structure, which is filled with hollow spherical shells arranged in a close-packed face-centered cubic lattice structure. With external radius of the hollow spherical shells decrease from 4mm to 2.5mm the effective absorption band width were enlarged from 1.6GHz (3.5GHz-5.1GHz) to 5.8GHz (5.6GHz - 11.4GHz), Meanwhile the maximum absorption intensity first increase from -14.5dB for 4mm to -30.6 dB for 3mm, then decrease to -21.1dB for 2.5mm. A double-layer density gradient structure is introduced to the hierarchical microwave absorption structure, With the optimized internal radius (r_{in}) to external radius (r_{ex}) ratio R_T=0.967 and R_B=0.860, the hierarchical microwave absorption structure exhibits a 12.4GHz effective absorption band width (5.6GHz-18GHz) and a -51.6 maximum absorption at 16.7GHz. The excellent MW absorption performance of the hierarchical structure is mainly attribute to the impedance modulation effect of the hexagonal honeycomb structure as well as the double-layer gradient structure and the excellent microwave absorbing capacity of the close-packed hollow spherical shells which has the complex permittivity, permeability and loss tangent of a highly efficient graphene-based microwave absorbent.

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