Optimization Design and Simulation of Light Broadband Multilayer Composite Absorber

Ping-an Yang (✉ yangpa@cqupt.edu.cn)

Chongqing University of Posts and Telecommunications <https://orcid.org/0000-0002-8072-8506>

Yuxuan Huang

Chongqing University of Posts and Telecommunications

Rui Li

Chongqing University of Posts and Telecommunications

Yang Sun

Chongqing University of Posts and Telecommunications

Xin Huang

Chongqing University of Posts and Telecommunications

Mengjie Shou

Chongqing University of Posts and Telecommunications

Xiaojie Wang

Chongqing University of Posts and Telecommunications

Research Article

Keywords: Multilayer plate structure, Genetic algorithm, Finite element simulation, light broadband absorber

Posted Date: May 17th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-493508/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Optimization design and simulation of light broadband multilayer composite absorber

Ping-An Yang¹ · Yuxuan Huang¹ · Rui Li^{1*} · Yang Sun¹ · Xin Huang¹ · Mengjie Shou¹ · Xiaojie Wang^{1,2}

¹ School of Automation, Chongqing University of Posts and Telecommunications, Chongqing 400065, People's Republic of China

² Bio-inspired Robotics and Intelligent Material Laboratory, Institute of Advanced Manufacturing Technology, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Changzhou 213164, People's Republic of China

*lirui@cqupt.edu.cn

Abstract

Multilayer plate structure is an effective way to design the absorbing coating with excellent performance. Based on the analysis of the electromagnetic (EM) absorbing principle of multilayer structure, this paper selects materials with magnetic loss type and resistance loss type to establish the database of EM parameters. Genetic algorithm is used to optimize the design of the multilayer structure. Finally, COMSOL is used for simulation verification. The results show that the multilayer materials prepared by different types of EM loss materials have the characteristics of large absorption bandwidth and strong absorption capacity. When optimizing for different frequency bands and the thickness is limited to 5 mm, the absorption band can be adjusted freely between 5 GHz and 15 GHz by selecting the materials and thickness of each layer, which solves the limitation that a single material only meet the requirements in a specific frequency band. When optimizing for absorption intensity, the minimum reflection loss ($RL_{\min}$) can reach -30.7 dB and the effective absorption bandwidth (EAB) is 3.3 GHz (13.1 GHz -16.4 GHz) achieved with only 2.44 mm. This design method provides the possibility to design multilayer composite materials with high absorption and low reflection in a wider frequency band range.

Keywords Multilayer plate structure · Genetic algorithm · Finite element simulation · light broadband absorber

1 Introduction

In recent years, the use of high-power electronic devices and equipment has been increasing geometrically. Electromagnetic (EM) pollution and harm caused by EM radiation problems has become more and more serious [1,2]. On the one hand, pervasive EM pollution seriously interferes with the normal operation of communication signals and electronic equipment [3]. On the other hand, long-term excessive EM radiation directly threatens human health [4]. EM absorbing materials are an effective way to overcome the above problems [5].

EM absorbing material is a kind of EM functional material that can convert incident EM wave energy into heat energy or other energy and dissipate it [6]. According to the loss mechanism of EM waves, absorbing materials can be divided into dielectric loss type [7], magnetic loss type [8,9] and resistance

loss type [10]. The traditional design of the absorbing body focuses on improving the loss performance of the absorbing material itself [11], while neglecting the optimization of the absorbing structure [12]. The multilayer plate absorbing structure has attracted much attention in recent years because it is easier to achieve impedance matching and its absorption performance is much better than that of the single-layer absorbing structure [13]. Chen Mingxia et al [14] designed a multilayer gradient absorption material with different mass fractions of carbon nanomaterials, and the results showed that its minimum reflection loss ($RL_{\min}$) was -9.5 dB, which improved the absorption performance by 1.5 times compared with the single-layer structure. However, the selection and thickness of each layer material in a multilayer structure directly affect the absorption performance and the width of the absorption band, and the relationship between

the two constraints constitutes a multi-objective optimization problem [15]. Intelligent heuristic algorithm which can search for the optimal solution in the global scope, the characteristics of absorbing materials has become a complex multilayer structure design method of the main [16]. Davide Micheli et al [17] used multi-walled carbon nanotubes with different mass fractions as the database, obtained the arrangement order and angle of multilayer structure through particle swarm optimization algorithm, and measured the minimum RL of -26 dB and the effective absorption bandwidth (EAB, RL < -20 dB) of 2 GHz. Undoubtedly, although the multilayer absorbing structure has better EM absorption performance compared with the single-layer structure, the aforementioned studies all use the same type of loss absorbing material to establish the database for optimization, so the improvement of the absorbing performance is very limited [18].

On this basis, in order to achieve better absorption performance, it is necessary to expand the range of EM parameters through the rich composite material library of absorbing materials with different mechanisms [19]. Ferromagnetic materials have excellent EM absorption properties due to their high saturation magnetization, high Snoke limiting frequency and high relative permeability [20]. At the same time, carbon material not only has high conductivity and EM wave absorption performance, but also has the significant advantage of low density [21]. Therefore, many researchers focus on improving the wave-absorbing performance by combining ferromagnetic materials with carbon materials [22, 23]. For example, Li et al [24] can increase the minimum RL from -22.63 dB before coating to -71.47 dB after coating carbon shell with rose-shaped iron. Thus it can be seen that the absorption materials with different loss types can achieve better absorption performance by combining with each other.

In this paper, three types of loss absorbing materials are used as the material database, including magnetic loss, resistance loss and a combination of the two loss types. The genetic algorithm was selected as the optimization method, and the multilayer plate structure was designed with the minimum RL

and the maximum absorption bandwidth as the optimization objectives. Material databases covering magnetic loss materials as well as resistance loss materials make it possible to optimize absorption performance in the broad band and the combinatorial optimization method can simultaneously use various EM characteristics in the database to search for the global optimal solution to adjust the multilayer structure. Finally, finite element simulation software COMSOL is used to verify the optimization results, and the multilayer EM wave absorption principle is expounded.

2 Material and EM parameter test

2.1 Material

When designing the layered absorbing structure, the diversity of materials determines the richness of the database. This article specifically selected the following four materials and substrates to achieve the best optimization results by Taking full advantages of magnetic loss materials and dielectric loss materials: CIP, purchased from the BASF corporation($d_{50} = 3-4 \mu\text{m}$); GNP, purchased from the XFNANO corporation (diameter around $5-10 \mu\text{m}$, thickness around $3-10 \text{ nm}$); MWCNT, purchased from TIMENANO corporation (diameter around $10-20 \text{ nm}$, purity 90%); NPCNT, purchased from TIMENANO corporation (diameter around 50 nm , length around $10 \mu\text{m}$); Paraffin wax is adopted as an adhesive substrate was purchased from FUSHUN PETROCHEMICAL corporation.

Fig. 1 SEM images: (a) CIP zoom 5k $\times$ (1 μm scale), (b) GNP zoom 5k $\times$ (1 μm scale), (c) MWCNT zoom 20k $\times$ (200nm scale), (d) NPCNT zoom 20k $\times$ (200nm scale)

Scanning electron microscope (SEM) analysis has been widely adopted in the laboratory using VEGA TESCAN SEM model. In particular, in Fig.1, SEM images of CIP (a), GNP (b), MWCNT (c), NPCNT (d) are shown. CIP and GNP are zoomed 5 k time for observing clearly. MWCNT and NPCNT are zoomed 20 k time. It depends on the respective diameter.

2.2 Manufacturing and Testing

Table 1 Coding of materials in the database

Layer Material	Mass Ratio	Material Code
CIP	30%	1
	45%	2
	60%	3
	75%	4
GNP	1%	5
	2%	6
	3%	7
	4%	8
MWCNT	0.5%	9
	1%	10
	1.5%	11
NPCNT	2%	12
	1%	13
	2%	14
	3%	15
	4%	16

To test the EM parameters, the materials with different contents are dispersed into paraffin and pressed into a coaxial ring with an

outer diameter of 7.00mm, inner diameter of 3.04mm and a thickness of 3mm. The specific composition and number of samples are shown in Table I. The numbers of these materials are related to the decoding of the optimization results. The EM parameters of the coaxial samples were measured by the coaxial network test with vector network analyzer Angilent 8722ES in the range of 2 GHz-18 GHz.

It can be seen from Fig. 2 (a, d) that ε' and μ'' of CIP are significantly larger than those of the other three, indicating that CIP has a higher degree of polarization and magnetic loss ability. At the same time, it can be seen from Fig. 2 (b) that ε'' of the four materials presents the same trend, and there are many vibration peaks on the curve [26]. In addition, it can be seen from Fig. 2 (c), The real part of the permeability of CIP decreases rapidly in the test frequency band, while the change amplitude of the other three materials is relatively stable.

Therefore, referring to the structural characteristics of multilayer composite absorbers [27], CIP can be used to provide strong EM absorption capacity, while GNP, MWCNT and NPCNT may be used as impedance matching layers to promote more EM waves into the absorber.

Fig. 2 Real and imaginary part of CIP, GNP, MWCNT, NPCNT relative permittivity and permeability

3 Model

3.1 Physical Model of Multilayer Absorption Material

The absorption characteristics of EM waves in multilayer materials are mainly related to the material properties and the thickness of each layer. According to the principle of EM wave propagation in the medium [28], an excellent absorption material must satisfy two conditions: Firstly, EM waves can be maximally made into the material to reduce the directly reflection when EM waves reach the surface of the material. It is required to fully consider the impedance matching between the absorption material and the free space when designing the material. Secondly, when the EM wave enters the inside of the material, it is necessary to make the material absorb or attenuate the incident EM wave effectively, which is mainly determined by the attenuation characteristics of the material. These two conditions make the design of the matching layer particularly important when designing the structure. The latter layer is adopted as the absorption layer to achieve maximum absorption of the material. A schematic diagram of the structure of the multilayer material is shown in Fig. 3. As can be seen that, the first layer is in contact with the perfect electrical conductor (PEC) layer, and the outermost layer is in contact with air. The parameters, ε_{ri} , μ_{ri} and d_i respectively present the complex permittivity, complex permeability and thickness of the i_{th} layer. Z_i is the wave impedance at the interface between the i_{th} layer and the $i + 1_{th}$ layer, E_i is the incident wave and E_o is the reflected wave.

Fig. 3 Multilayer absorption material physical model

3.2 Numerical Model

If a beam of unit amplitude EM waves is incident perpendicularly on the surface of the n th layer of material. According to the transmission

line impedance conversion equation of Kraus [29], the wave impedance of the i_{th} layer is

$$Z_i = \eta_i \frac{Z_{i-1} + \eta_i \tanh(\gamma_i d_i)}{\eta_i + Z_{i-1} \tanh(\gamma_i d_i)} \quad (1)$$

Where $\gamma_i = j\omega\sqrt{\mu_i \varepsilon_i}$, is the propagation constant of the i_{th} layer material, ε_i and μ_i is the complex permittivity and complex permeability of the i_{th} layer. $\eta_i = \sqrt{\mu_{ri}/\varepsilon_{ri}} \cdot \sqrt{\mu_0/\varepsilon_0}$, is the intrinsic impedance of the i_{th} layer material, d_i is the thickness of the i_{th} layer material. Then the calculation formula of the RL of the multilayer absorption material can be expressed as

$$R_{dB} = 20 \lg \left(\frac{Z_n - Z_0}{Z_n + Z_0} \right) \quad (2)$$

Where Z_0 is the characteristic impedance of air, its value is 377Ω , $Z_i = \eta_i \tanh(\gamma_i d_i)$.

According to the analysis, we hope that the thickness and total thickness of each layer should under the appropriate range, so the constraint is

$$\sum_{i=1}^n d_i \leq D \text{ and } d_i < D - \sum_{j=1}^{i-1} d_j \quad (3)$$

Where D is the total thickness of the multilayer absorption material. The objective function obtained by aiming at the best absorption loss and the widest absorption band is

$$f = k_1 f_1 + k_2 f_2 \quad (4)$$

with

$$f_1 = \max[\max(M_i)] \text{ and } f_2 = \max(|RL_{dB}(i)|)$$

Where i is the part of consecutive points in the given frequency band that are greater than the absorption loss threshold R_{min} , k_i is the number of

consecutive points in part i , $M_i = \sum_{j=1}^{k_i} m_{ij}$ is the total number of the i_{th} segment, and m_{ij} is whether the j_{th} point of the i_{th} segment, k_1 and k_2 are the share factors.

3.3 FEM Finite Element Model

In order to analyze the propagation and absorption properties of EM waves in absorption materials systematically, COMSOL Multiphysics are adopted for numerical simulation calculations. The calculation method is derived from the radar cross section (RCS) method in the GJB2038-94 "Radar Absorption Material Reflectivity Test Method" adopted in the experiment, that is, the EM wave is incident on the plane of the

absorption material and the plane of the good conductor, which is from the same direction and the same power under the given wavelength and polarization conditions. The ratio of the specular power of the two results is the ratio of the reflectivity of the material to the EM wave.

$$R = 10 \lg(P_1/P_0) \quad (5)$$

Where R is the reflectivity of the absorption material; P_0 is the echo power as a function of frequency measured by measuring the frequency domain response of the metal plate when it is incident normally; P_1 is the normal incidence of the absorption material plate by measuring the same size. The frequency domain response is obtained by its echo power as a function of frequency. The smaller R is, the better the absorbing effect of the absorbing material is.

Fig. 4 (a) Three-dimensional EM shielding model, **(b)** mesh of the five-layered EM shielding structure

Fig. 4 (a) shows the 3D EM shielding model created by COMSOL. Material EM parameter properties of the material layer are derived from the EM parameter database determined by the experiment. The bottom of the absorber has a thin highly conductive layer to block any noise from outside, which is modeled as a perfect electric conductor (PEC). The model domain immediately outside of the material is filled with air. Perfectly matched layers (PMLs) above the air at the top of the unit cell absorb higher order modes generated by the periodic structure-if there are any- as well as the upward traveling excited mode from the source port. The PMLs attenuate the field in the direction perpendicular to the PML boundary. A port boundary condition is placed on the interior boundary of the PMLs, adjacent to the air domain. The interior port boundaries with PML backing require the slit condition. The port orientation is specified to define the inward direction for the S-parameter calculation. Since higher order diffraction modes are not of particular interest in

this paper, the combination of domain-backed type slit port and PMLs is adopted instead of adding a diffraction order port for each diffraction order and polarization. The periodic boundary condition requires identical surface meshes on pairing boundaries. An identical surface mesh can be created by using the copy face operation from one boundary to another boundary.

Fig. 4 (b) shows the meshing results of the five-layer absorption structure. Mesh growth was optimized by setting suitable parameters to assure high reliability in the EM analysis: the greatest size of mesh elements was set to $\lambda_{\min} / 10$, where $\lambda_{\min} = 3 \cdot 10^8 / f_{\max} \cong 1.67 \text{ cm}$ is the lowest wavelength in the frequency range investigated, while the smallest size is around 10^{-7} m .

4 Result and Discussion

4.1 Frequency Band Optimization

Due to the diversity of the type selection of the absorbing fillers in each layer of the multilayer composite structure, which covers a wide range of EM parameters, there is a lot of room for optimization of its performance. Combined with the layer number and thickness setting of traditional multilayer plate absorbing structure, the thickness is limited to 5 mm and the number of layers is 5. The genetic algorithm is selected for the combinatorial optimization algorithm. The initial population is set to 100, the maximum propagation algebra is set to 100, the mutation probability is set to 0.1, and the gene recombination probability is set to 0.9. In order to achieve tunable absorption of EM waves in different frequency bands, the optimal step size is set as 2 GHz, and the widest absorption bandwidth and maximum reflection loss are taken as the optimization objectives in each step size to solve the construction scheme of multilayer composite structure.

Table 2 shows the optimization results of different types of materials in the 5 GHz-7 GHz frequency band. Since the GNPs and NPCNT have no obvious absorbing properties, only the hybrid, CIP and MWCNT multilayer composite structures are discussed. It can be seen from Table 2 that the total thickness of each material type is limited to about 5mm.

For hybrid materials, 1 wt.% MWCNT is used as the top impedance matching layer, and

CIP with high mass fraction is used as the absorption layer, which occupies a large proportion of thickness. For single type materials, the layers adjacent to air are occupied by the materials with the minimum mass fraction, because the ability of absorbing EM waves gradually decreases with the decrease of MWCNT content, But the permeability of EM wave is gradually improved, so it is more suitable as impedance matching layer.

Table 2 Material and thickness optimized results of Hybrid materials, CIP, and MWCNT in the range of 5 GHz-7 GHz

	Material	Thickness (mm)	Total thickness (mm)
Hybrid	(Free space)	0.11	4.98
	MWCNT 1%	0.15	
	NPCNT 2%	0.58	
	CIP 75%	3.54	
	MWCNT 1%	0.6	
CIP	(Free space)	0.02	4.88
	CIP 30%	0.19	
	CIP 30%	0.13	
	CIP 60%	4.1	
	CIP 75%	0.44	
MWCNT	(Free space)	0.13	4.99
	MWCNT 0.5%	0.01	
	MWCNT 1%	0.2	
	MWCNT 0.5%	1.45	
	MWCNT 1%	3.2	

Fig. 5 displays the optimization results of hybrid, CIP and MWCNT in the range of 5 GHz-7 GHz. It can be seen from the figure that the RL of hybrid is less than -10 dB in the range of 5 GHz-7 GHz, and the $RL_{\min}$ is -18.7 dB. CIP is less than -10 dB in the bandwidth of 0.9 GHz, and the $RL_{\min}$ is only -10.5 dB. MWCNT is less than -10 dB in the bandwidth of 0.5 GHz, and the $RL_{\min}$ is -15.1 dB. The results show that the hybrid material is better than the single material in bandwidth and $RL_{\min}$.

In Fig. 6, optimization of 5 layers of absorption materials in each frequency band with the genetic algorithm is shown. Hybrid materials can achieve better results in all frequency bands except in the range of 2 GHz-5 GHz and 15 GHz-18 GHz. In contrast, CIP has optimized results in the range of 5 GHz-7 GHz, 7 GHz-9 GHz, 13 GHz-15 GHz, and a result is found in the 5 GHz-7

GHz using MWCNT. While NPCNT and GNP showed no results in each frequency band. This demonstrates the advantages of hybrid materials from another angle, it can meet our various frequency band need, and has excellent absorbing effect. The single type of material can only meet the requirements on a fixed frequency band, and the optimization effect is not good, and even some materials cannot obtain the optimization result in the entire frequency band.

Fig. 5 Optimization results of Hybrid materials, CIP, and MWCNT in the range of 5 GHz-7 GHz

Fig. 6 Optimization of 5 layers of absorption materials in each frequency band by genetic algorithm

The CIP, GNP, MWCNT, NPCNT complex permittivity and complex permeability value distribution map (see Fig. 7) was given to interpret the results. Firstly, hybrid materials can adopt the EM parameters of all materials, which makes it possible to obtain optimal results in various frequency bands. Secondly, CIP has the widest EM parameter distribution, so it can meet the objective function in multiple frequency bands. Thirdly, MWCNT can get the optimal solution in a fixed frequency band because of its good magnetic loss characteristics. Finally, EM

parameters of GNP and NPCNT do not change much with the increase of the content, and the

values are closer and smaller, so they cannot obtain the optimal solution in each frequency band.

Fig. 7 Distribution of complex permittivity and complex permeability values of CIP, GNP, MWCNT, NPCNT, the numbers in the figure correspond to the material database table

4.2 Absorption Intensity Optimization

After the above experiment, the material selection and the corresponding thickness of the multilayer plate absorbing structure are optimized in any 2 GHz frequency band from 2 GHz-18 GHz in the hybrid material library. The results show that the absorption performance of the multilayer composite absorbing structure can be adjusted within 5 GHz-15 GHz after the optimization, so as to realize the light, broadband and tunable multilayer plate absorbing structure.

However, the constraints of limited thickness and piecewise optimization limit the structure to pursue lower reflection loss and smaller structure quality. Therefore, based on the original genetic algorithm, taking 2 GHz-18 GHz as the conditional frequency band, taking the minimum RL as the optimization objective, and lifting the 5 mm thickness limit, the parameters of multilayer plate absorbing structure are optimized again.

Table 3 shows the optimized results of the mixed materials in the whole frequency band. The GNPs in contact with air are 4 wt.%, followed by CIP and GNPs alternately, which is basically consistent with the results of the frequency band optimization. Firstly, GNPs have weak absorption capacity for EM waves, which are close to the EM parameters of air, so they are adjacent to air as impedance matching layer, 75 wt.% CIP has a large EM wave absorption capacity. As an

absorption layer, it is placed in the middle layer or the bottom layer. The former can ensure that the EM wave can enter into the material as much as possible, and the latter can ensure that the EM wave can be absorbed to the maximum extent. The two complement each other, and finally achieve a better absorption effect.

Table 3 Optimized material and thickness setting of each layer of hybrid material in full frequency band

Material	Thickness (mm)	Total thickness(mm)
(Free space)	0.05	2.44
GNP 4%		
CIP 30%	0.54	
GNP 2%	0.1	
CIP 75%	0.75	
CIP 75%	1	

Table 4 shows the comparison between the optimization results of the model and those reported in the literature in the full frequency range. It can be clearly seen from the table that the optimal material thickness obtained by using the hybrid material is only 2.44 mm. The RL_{min} is -30.7 dB, and the EAB is 3.3 GHz. In comparison, the minimum RL of reference [31] is -29.5 dB, but its thickness is also increased by nearly ten times. The comprehensive performance is better than the optimization results, which fully show the advantages of using mixed materials as a material database.

Table 4 Comparison of absorption properties of multilayer material

Source	Material adopted	Thickness (mm)	Minimum RL (dB)	Optimal bandwidth (<-20 dB, GHz)
Literature [14]	CNT/SiO ₂	5	-9.5	—
Literature [17]	MWCNT	8.9	-26	2
Literature [15]	MWCNT, CNF, GNPs, PANI	9.4	-26	1.8
Literature [30]	MWCNT	10	-25	3
Literature [31]	MWCNT, SWCNT, CNF	21	-29.5	3.6
This article	CIP, GNPs, MWCNT, NPCNT	2.44	-30.7	3.3

4.3 Simulation Verification and Analysis

Fig. 7 shows the comparison between the theoretical calculation and model simulation results in COMSOL. It can be seen from the figure that except for the deviation at individual points, the variation trend of the simulation values and the theoretical values in other frequency bands are basically consistent, so the simulation model established in this paper is reliable. On this basis, the transmission process of EM wave in multilayer plate absorbing structure is further analysed.

Fig. 7 RL theory and simulation results of multilayer material

In Fig. 8, the optimization results of using hybrid materials in the whole frequency band are simulated by COMSOL at 9 GHz and 15 GHz. Fig. 8 (a, b) shows the electric field distribution (unit: V / M) of EM loss in the material, in which the white arrow represents the direction and intensity of the electric field. By comparing the electric field distribution diagrams of 9 GHz and 15 GHz, it can be seen that the impedance matching is better at 15 GHz, which has greater EM capacity. At 9 GHz, due to the low impedance matching, there is a large reflection, which weakens the material's ability to absorb EM waves. Therefore, from the electric field distribution, it

can be seen that the absorption of material performance at 9 GHz is less than 15 GHz.

By observing the change of EM loss density (unit: W / m^3) in Fig. 8 (c, d), we can understand how the multilayer absorption structure work. The first three layers in the multilayer structure have little difference, but the EM loss density changes greatly from the fourth layer. At 15 GHz, with the increase of distance, the EM wave loss increases sharply. When passing through the last layer, a large number of EM waves will be lost. At 9 GHz, the EM loss density increases sharply. Although the initial loss is large, the loss of the fourth intermediate layer decreases gradually, and the loss of the last layer has little effect. Therefore, the ability of absorbing EM wave of the multilayer plate structure is particularly prominent at 15 GHz, but weaker at 9 GHz.

Fig. 8 Simulation: optimized result by adopting hybrid material

(a, c) electric field(V/m) and EM power loss density (W/m^3) at 9 GHz,
(b, d) electric field(V/m) and EM power loss density (W/m^3) at 15 GHz

5 Conclusion

Based on the analysis of the principle of EM wave absorption of multilayer plate structure, the

possibility of using genetic algorithm to optimize a multilayer structure is proposed. The specific implementation includes theory, numerical calculation and simulation analysis, from the selection of material library to the optimization design of multilayer structure, and finally combined with COMSOL for simulation analysis and verification. The results show that the multilayer plate materials with different loss types have the characteristics of large absorption bandwidth and strong absorption capacity. The minimum RL value of the layered material is -30.7dB, the absorption bandwidth is 3.3 GHz, and the thickness is only 2.4 mm. The thickness constraint of 5mm and the number of 5 layers not only have excellent absorbing effect in limited space, but also can greatly save the cost in the engineering sense, which has high theoretical and practical significance. In addition, the multilayer plate structure can meet the optimization requirements of a variety of frequency bands. Although there is no optimization result in the range of 2 GHz-5 GHz and 15 GHz-18 GHz in this paper, which is also the direction of further optimization in the future, the limitation that a single material can only meet the absorption requirements of a specific frequency band can be solved well by using hybrid materials, which is mainly because the hybrid materials have a wide range of EM parameters. Therefore, it is feasible to use hybrid materials to design multilayer composite absorbing materials with high absorption, low reflection and large bandwidth.

Acknowledgments This study was funded by National Natural Science Foundation of China (grant number: 61901073, 52075063), Special Key Project of Technological Innovation and Application Development in Chongqing (grant number: cstc2019jscx-fxydX0085). The authors are grateful for the helpful comments of the reviewers and editor to improve the paper.

References

1. Yang, D., Yin, Y., Zhang, Z.-K., Li, D.-C., Cao, Y.: Wide-angle microwave absorption properties of multilayer metamaterial fabricated by 3D printing. *Mater. Lett.* **281**, 128571 (2020). <https://doi.org/10.1016/j.matlet.2020.128571>
2. Yang, P.-A., Yu, M., Fu, J., Wang, L.-R.: Synthesis and microwave absorption properties of hierarchical Fe micro-sphere assembly by nano-plates. *J. Alloy. Compd.* **721**, 449-455 (2017). <https://doi.org/10.1016/j.jallcom.2017.05.296>
3. Li, Y., Sun, L., Xu, F., Wang, S.-S., Peng, Q.-Y., Yang, Z.-Y., He, X.-D., Li, Y.-B.: Electromagnetic and acoustic double-shielding graphene-based metastructures. *Nanoscale* **11**, 1692-1699 (2019). <https://doi.org/10.1039/C8NR06143B>
4. Kowall, B., Breckenkamp, J., Heyer, K., Berg-Beckhoff, G.: German wide cross sectional survey on health impacts of electromagnetic fields in the view of general practitioners. *Int. J. Public Health* **55**, 507-512 (2010). <https://doi.org/10.1007/s00038-009-0110-2>
5. Wei, H.-Y., Zhang, Z.-P., Hussain, G., Zhou, L.-S., Li, Q., Ken Ostrikov, K.: Techniques to enhance magnetic permeability in microwave absorbing materials. *Applied Materials Today* **19**, 100596 (2020). <https://doi.org/10.1016/j.apmt.2020.100596>
6. Cheng, Y.-H., Tan, M.-Y., Hu, P., Zhang, X.-H., Sun, B.-Q., Yan, L.-W., Zhou, S.-B., Han, W.-B.: Strong and thermostable SiC nanowires/graphene aerogel with enhanced hydrophobicity and electromagnetic wave absorption property. *Appl. Surf. Sci.* **448**, 138-144 (2018). <https://doi.org/10.1016/j.apsusc.2018.04.132>
7. Yue, L.-Q., Zhong, B., Xia, L., Zhang, T., Yu, Y.-L., Huang, X.-X.: Three-dimensional network-like structure formed by silicon coated carbon nanotubes for enhanced microwave absorption. *J. Colloid Interf. Sci.* **582**, 177-186 (2021). <https://doi.org/10.1016/j.jcis.2020.08.024>
8. Shi, Y.-P., Zhang, M.-M., Zhang, X.-F., Zhang, L., Zhang, Y.-H., Jiang, Z.-Y., Si, H.-X., Gong, C.-H.: Achieving excellent metallic magnet-based absorbers by regulating the eddy current effect. *J. Appl. Phys.* **126**, 105109 (2019). <https://doi.org/10.1063/1.5109538>
9. Wang, L., Qiu, H., Liang, C.-B., Song, P., Han, Y.-X., Han, Y.-X., Gu, J.-W., Kong, J., Pan, D., Guo, Z.-H.: Electromagnetic interference shielding MWCNT-Fe₃O₄@Ag/epoxy nanocomposites with satisfactory thermal conductivity and high thermal stability. *Carbon* **141**, 506-514 (2019). <https://doi.org/10.1016/j.carbon.2018.10.003>
10. Dai, J.-J., Yang, H.-B., Wen, B., Zhou, H.-W., Wang, L., Lin, Y.: Flower-like MoS₂@Bi₂Fe₄O₉ microspheres with hierarchical structure as electromagnetic wave absorber. *Appl. Surf. Sci.* **479**, 1226-1235 (2019). <https://doi.org/10.1016/j.apsusc.2019.02.049>
11. Zhao, X., Xu, L.-L., Chen, Q., Peng, Q.-Y., Yang, M.-L., Zhao, W.-Q., Lin, Z.-S., Xu, F., Li, Y.-B., He, X.-D.: Highly Conductive Multifunctional rGO/CNT Hybrid Sponge for Electromagnetic Wave Shielding and Strain Sensor. *Advanced Materials Technologies* **4**, 1900443 (2019). <https://doi.org/10.1002/admt.201900443>
12. Gairola, P., Purohit, L.-P., Gairola, S.-P., Bhardwaj, P., Kaushik, S.: Enhanced electromagnetic absorption in ferrite and tantalum pentoxide based polypyrrole nanocomposite. *Progress in Natural Science: Materials International* **29**, 170-176 (2019). <https://doi.org/10.1016/j.pnsc.2019.03.011>
13. Zhang, X., Ji, G., Liu, W., Zhang, X.-X., Gao, Q.-W., Li, Y.-C., Du, Y.-W.: A novel Co/TiO₂ nanocomposite derived from a metal-organic framework: synthesis and efficient microwave absorption. *J. Mater. Chem. C* **4**, 1860-1870 (2016). <https://doi.org/10.1039/C6TC00248J>
14. Chen, M.-X., Zhu, Y., Pan, Y.-B., Kou, H.-M., Xu, H., Guo, J.-K.: Gradient multilayer structural design of

- CNTs/SiO₂ composites for improving microwave absorbing properties. *Materials & Design* **32**, 3013-3016 (2011). <https://doi.org/10.1016/j.matdes.2010.12.043>
15. Micheli, D., Vricella, A., Pastore, R., Marchetti, M.: Synthesis and electromagnetic characterization of frequency selective radar absorbing materials using carbon nanopowders. *Carbon* **77**, 756-774 (2014). <https://doi.org/10.1016/j.carbon.2014.05.080>
 16. Liu, B., Akinsolu, M.-O., Ali, N., Abd-Alhameed, R.: Efficient global optimisation of microwave antennas based on a parallel surrogate model-assisted evolutionary algorithm. *IET microwaves, antennas & propagation* **13**, 149-155 (2019). <https://doi.org/10.1049/iet-map.2018.5009>
 17. Micheli, D., Apollo, C., Pastore, R., Bueno Morles, R., Laurenzi, S., Marchetti, M.: Nanostructured composite materials for electromagnetic interference shielding applications. *Acta Astronaut.* **69**, 747-757 (2011). <https://doi.org/10.1016/j.actaastro.2011.06.004>
 18. Micheli, D., Pastore, R., Delfini, A., Giusti, A., Vricella, A., Santoni, F., Marchetti, M., Tolochko, O., Vasilyeva, E.: Electromagnetic characterization of advanced nanostructured materials and multilayer design optimization for metrological and low radar observability applications. *Acta Astronaut.* **134**, 33-40 (2017). <https://doi.org/10.1016/j.actaastro.2017.01.044>
 19. Zhao, Y.-T., Liu, L., Jiang, K.-D., Fan, M.-T., Jin, C., Han, J., Wu, W.-H., Tong, G.-X.: Distinctly enhanced permeability and excellent microwave absorption of expanded graphite/Fe₃O₄ nanoring composites. *RSC Adv.* **7**, 11561-11567 (2017). <https://doi.org/10.1039/C7RA00334J>
 20. Yu, M., Yang, P.-A., Fu, J., Liu, S.-Z.: Flower-like carbonyl iron powder modified by nanoflakes: Preparation and microwave absorption properties. *Appl. Phys. Lett.* **106**, 161904 (2015). <https://doi.org/10.1063/1.4919064>
 21. Li, W., Li, C., Lin, L., Wang, Y., Zhang, J.: All-dielectric radar absorbing array metamaterial based on silicon carbide/carbon foam material. *J. Alloy. Compd.* **781**, 883-891 (2019). <https://doi.org/10.1016/j.jallcom.2018.12.010>
 22. Li, Y.-J., Yu, M., Yang, P.-A., Fu, J.: Enhanced Microwave Absorption Property of Fe Nanoparticles Encapsulated within Reduced Graphene Oxide with Different Thicknesses. *Ind. Eng. Chem. Res.* **56**, 8872-8879 (2017). <https://doi.org/10.1021/acs.iecr.7b01732>
 23. Han, D.-D., Xiao, N.-R., Hu, H., Liu, B., Song, G.-X., Yan, H.: A promising broadband and thin microwave absorber based on ternary FeNi@C@polyaniline nanocomposites. *RSC Adv.* **5**, 97944-9795 (2015). <https://doi.org/10.1039/c5ra19816j>
 24. Li, X.-A., Du, D.-X., Wang, C.-S., Wang, H.-Y., Xu, Z.-P.: In situ synthesis of hierarchical rose-like porous Fe@C with enhanced electromagnetic wave absorption. *J. Mater. Chem. C* **6**, 558-567 (2018). <https://doi.org/10.1039/C7TC04897A>
 25. Yu, M., Yang, P.-A., Fu, J., Liu, S.-Z., Qi, S.: Study on the characteristics of magneto-sensitive electromagnetic wave-absorbing properties of magnetorheological elastomers. *Smart Mater. Struct.* **25**, 85046 (2016). <https://doi.org/10.1088/0964-1726/25/8/085046>
 26. Zhao, B.-A., Shao, G., Fan, B.-B., Zhao, W.-Y., Zhang, R.: Facile synthesis and enhanced microwave absorption properties of novel hierarchical heterostructures based on a Ni microsphere - CuO nano-rice core - shell composite. *Phys. Chem. Chem. Phys.* **17**, 6044-6052 (2015). <https://doi.org/10.1039/C4CP05229C>
 27. Yuan, C.-X., Zhou, Z.-X., Zhang, J.-W.-W., Xiang, X.-L., Feng, Y., Sun, H.-G.: Properties of Propagation of Electromagnetic Wave in a Multilayer Radar-Absorbing Structure With Plasma- and Radar-Absorbing Material. *IEEE T. Plasma Sci.* **39**, 1768-1775 (2011). <https://doi.org/10.1109/TPS.2011.2160285>
 28. Liu, Y., Zhang, Y.-C., Zhang, C., Huang, B., Wang, X., Li, Y., Lai, W., Liu, X.: Aligned fluorinated single-walled carbon nanotubes as a transmission channel towards attenuation of broadband electromagnetic waves. *J. Mater. Chem. C* **6**, 9399-9409 (2018). <https://doi.org/10.1039/C8TC02522C>
 29. Huang, B., Yue, J., Wei, Y., Huang, X., Tang, X., Du, Z.: Enhanced microwave absorption properties of carbon nanofibers functionalized by FeCo coatings. *Appl. Surf. Sci.* **483**, 98-105 (2019). <https://doi.org/10.1016/j.apsusc.2019.03.301>
 30. Micheli, D., Apollo, C., Pastore, R., Barbera, D., Morles, R.-B., Marchetti, M., Gradoni, G., Mariani Primiani, V., Moglie, F.: Optimization of Multilayer Shields Made of Composite Nanostructured Materials. *IEEE T. Electromagn. C.* **54**, 60-69 (2012). <https://doi.org/10.1109/TEMTC.2011.2171688>
 31. Micheli, D., Pastore, R., Apollo, C., Marchetti, M., Gradoni, G., Mariani Primiani, V., Moglie, F.: Broadband Electromagnetic Absorbers Using Carbon Nanostructure-Based Composites. *IEEE T. Microw. Theory* **59**, 2633-2646 (2011). <https://doi.org/10.1109/TMTT.2011.2160198>

Figures

Figure 1

SEM images: (a) CIP zoom 5kx (1μm scale), (b) GNP zoom 5kx (1μm scale), (c) MWCNT zoom 20kx (200nm scale), (d) NPCNT zoom 20kx (200nm scale)

Figure 2

Real and imaginary part of CIP, GNP, MWCNT, NPCNT relative permittivity and permeability

Figure 3

Multilayer absorption material physical model

Figure 4

(a) Three-dimensional EM shielding model, (b) mesh of the five-layered EM shielding structure

Figure 5

Optimization results of Hybrid materials, CIP, and MWCNT in the range of 5 GHz-7 GHz

Figure 6

Optimization of 5 layers of absorption materials in each frequency band by genetic algorithm

Figure 7

Distribution of complex permittivity and complex permeability values of CIP, GNP, MWCNT, NPCNT, the numbers in the figure correspond to the material database table

Figure 8

RL theory and simulation results of multilayer material

Figure 9

Simulation: optimized result by adopting hybrid material (a, c) electric field(V/m) and EM power loss density (W/m³) at 9 GHz, (b, d) electric field(V/m) and EM power loss density (W/m³) at 15 GHz