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Carbon Nanotube-Based Microwave Absorbing Materials: Research Progress on Mechanisms, Composite Systems, and Structural Design

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Abstract: ***With the rapid development of electronic information technology, electromagnetic pollution is becoming increasingly serious, and the demand for high-performance microwave absorbing materials in radar stealth and civilian electromagnetic protection is becoming more and more urgent. Carbon nanotubes (CNTs) have become a research hotspot for next-generation microwave absorbing materials due to their unique advantages such as lightweight, high conductivity, tunable dielectric properties, rich polarization loss mechanisms, and ease of composite formation. This paper systematically reviews the latest research progress of CNTs-based microwave absorbing materials. First, the absorption mechanism of CNTs is elucidated, including dielectric loss, conductivity loss, interfacial polarization, and magnetic loss introduced by magnetic modification. The control of absorption performance by structural parameters such as tube diameter, aspect ratio, degree of graphitization, defect doping, and surface functionalization is analyzed. Then, composite systems of CNTs with polymers, magnetic metals, metal oxides, and two-dimensional materials such as MXene and graphene are introduced, and the roles of one-dimensional core-shell structures, three-dimensional network structures, and hierarchical multi-scale structure designs in optimizing impedance matching and enhancing multi-loss synergy are discussed. Finally, the challenges currently faced by CNTs, such as dispersion uniformity, preparation cost, and large-scale production, are analyzed, and future development directions such as intelligent tunable absorbing materials, machine learning-aided design, and green synthesis are discussed. This review aims to provide a systematic reference for the rational design and practical application of high-performance CNT-based microwave absorbing materials.***

Keywords: Carbon nanotubes, Microwave absorption, Electromagnetic loss, Composite materials, Structural design, Impedance matching**.**

1. Introduction

Background of Electromagnetic Pollution and Advantages of Carbon Nanotube (CNT) Absorbing Materials. With the rapid development of modern electronic information technology and the widespread deployment of wireless communication, radar systems, smart terminals and high-power electrical equipment, electromagnetic radiation problems are becoming increasingly serious. This not only causes electromagnetic interference between devices, leading to malfunctions of precision instruments and system paralysis, but also poses a potential threat to human health. Therefore, the development of high-performance microwave absorbing materials has become an urgent need in the fields of national defense security and civilian health [1–5]. CNTs have shown great potential in this field due to their unique structural advantages: they have low density, excellent and tunable conductivity, and the complex permittivity can be precisely controlled by adjusting the tube diameter, chirality and graphitization degree; their abundant defects and functional groups on the surface can induce strong dipole polarization relaxation, and the heterogeneous interface formed after being combined with polymers or magnetic particles can also generate significant interfacial polarization loss; when the filling content exceeds the percolation threshold, CNTs can build a three-dimensional conductive network in the matrix, causing electromagnetic waves to be repeatedly reflected and scattered between tubes, extending the action path; helical CNTs can even generate eddy current loss by utilizing the chiral structure. Furthermore, CNTs are easy to load with magnetic nanoparticles such as iron, cobalt, and nickel, achieving synergistic absorption of dielectric and magnetic losses. This allows for wideband and high-efficiency microwave absorption performance at low filler ratios, while significantly reducing material density and thickness, and meeting diverse application requirements such as flexible wearables and integrated stealth structures. Therefore, CNTs are considered important candidates for next-generation lightweight, wideband, and strong-absorbing microwave materials. Since the discovery of CNTs' excellent electromagnetic properties, research on them as microwave absorbing materials has rapidly progressed from exploring the performance of single components to the design of multi-component composite systems and sophisticated structures. Early studies mainly focused on the influence of the diameter, length, and graphitization degree of pure CNTs on dielectric loss, but found that single CNTs often had limited absorption bandwidth due to poor impedance matching and a lack of magnetic loss mechanisms. To address this issue, researchers have turned to combining CNTs with magnetic metals or ferrites, utilizing the synergistic effect of dielectric and magnetic losses to significantly improve absorption intensity and broaden the effective bandwidth. Among these, CNT composites loaded with iron, cobalt, nickel, and their oxides have become the mainstream system [6–10]. In recent years, with a deeper understanding of interface polarization and multiple reflection mechanisms, the design of three-dimensional network structures, hierarchical porous structures, and heterogeneous interfaces between CNTs and two-dimensional materials such as graphene and MXene has received widespread attention. These structures can optimize impedance gradients and enhance electromagnetic wave dissipation paths. At the same time, lightweighting and broadbanding have become core objectives, and significant progress has been made in achieving efficient absorption at low filler ratios and extending the absorption frequency band to the S-band and Ku-band. Driven by applications, flexible absorbing fabrics, corrosion-resistant coatings, and radar-infrared compatible stealth materials are also gradually emerging. Currently, CNT absorbing materials are continuously developing towards integrated structure and function, intelligent controllability, and machine learning-assisted optimization. However, how to achieve low-cost large-scale preparation and maintain performance stability remains a key challenge restricting practical applications [11–13].

This paper aims to systematically review the latest research progress of CNTs-based microwave absorbing materials, comprehensively discussing absorption mechanisms, performance tuning, composite material systems and structural design, application prospects, and future challenges, providing a reference for the rational design and engineering application of high-performance CNTs absorbing materials. The paper is divided into four chapters: Chapter 1 is the introduction, outlining the background of electromagnetic pollution and the unique advantages of CNTs absorbing materials, and summarizing the current research status; Chapter 2 focuses on the microwave absorption mechanism and performance tuning of CNTs, covering impedance matching theory, dielectric loss and magnetic loss mechanisms, and the influence of structural parameters and surface functionalization on absorption performance; Chapter 3 introduces CNTs-based absorbing composite material systems and structural design, including composite strategies with polymers, magnetic metals, metal oxides, and two-dimensional materials, as well as one-dimensional core-shell structures, three-dimensional network structures, and hierarchical multi-scale designs, and discusses impedance matching optimization and multi-loss synergistic strategies; Chapter 4 analyzes the current challenges such as dispersion, cost, and large-scale fabrication, and looks forward to future development directions such as intelligent tunable materials and machine learning-aided design, finally giving conclusions.

2. Microwave Absorption Mechanism and Performance Regulation of Carbon Nanotubes

2.1 Theoretical Basis of Microwave Absorption

The theoretical basis of microwave absorption mainly covers three aspects: impedance matching, transmission line theory, and reflection loss evaluation. Impedance matching refers to the fact that the equivalent complex impedance of the absorbing material is equal to or as close as possible to the free space impedance, thereby minimizing the reflection of electromagnetic waves on the material surface and allowing the incident wave to enter the material smoothly. According to the impedance matching condition, the normalized input impedance of the material should approach 1, which requires reasonable control of the ratio of complex permittivity to complex permeability. Transmission line theory regards the absorbing material as a transmission line with a metal backplate at the end, and is used to calculate the total reflection behavior of electromagnetic waves after multiple reflections and transmissions inside the material. Under this theoretical framework, the input impedance of the material can be described by its characteristic impedance and propagation constant, and then the theoretical expression of reflection loss can be derived. Reflection loss is the core indicator for evaluating the performance of absorbing materials, usually expressed in dB. The more negative the value, the stronger the absorption capacity of the material for electromagnetic waves. When the reflection loss is less than -10 dB, it means that more than 90% of the incident electromagnetic waves are absorbed. This frequency band is called the effective absorption bandwidth (EAB) [14–18]. Using the three theoretical tools mentioned above, we can systematically analyze the intrinsic relationship between the electromagnetic parameters of absorbing materials and their absorbing performance, providing theoretical guidance for material design and optimization.

2.2 Wave Absorption Mechanism of Carbon Nanotubes

The absorption mechanisms of CNTs mainly include dielectric loss, conductivity loss, polarization loss, multiple reflections, and magnetic loss introduced during magnetic modification [19–21]. Dielectric loss originates from the polarization relaxation process generated by CNTs in an applied alternating electromagnetic field, including dipole polarization caused by defects in the carbon nanotubes themselves and surface functional groups, as well as interfacial polarization at the interface between the tube and the matrix. These polarization processes lag behind the change in electric field, thus converting electromagnetic energy into thermal energy. Conductivity loss depends on the three-dimensional conductive network formed by CNTs. When the filling content exceeds the percolation threshold, free electrons migrate in the conductive network and collide with the lattice to generate Joule heat, efficiently dissipating electromagnetic wave energy. Polarization loss can be regarded as an important component of dielectric loss. Among them, dipole polarization mainly comes from structural defects, dangling bonds, and oxygen-containing functional groups on the surface of CNTs, while interfacial polarization occurs at the heterogeneous interface between CNTs and polymer matrix or different components [22–24]. Multiple reflection loss mechanisms refer to the multiple reflections and scattering that occur between carbon nanotubes, between the tube wall and the matrix, and in the three-dimensional network structure after electromagnetic waves enter CNTs-based materials. This significantly prolongs the path of electromagnetic waves and increases the probability of energy dissipation [25,26]. In addition, when CNTs are loaded with magnetic nanoparticles such as iron, cobalt, and nickel, the materials acquire significant magnetic loss capabilities, including natural resonance, exchange resonance, and eddy current loss. These magnetic loss mechanisms work synergistically with the aforementioned dielectric loss mechanisms to simultaneously optimize impedance matching and attenuation constant, achieving broadband and efficient absorption [27,28].

2.3 Structural Parameters and Performance Regulation of Carbon Nanotubes

The structural parameters of carbon nanotubes (CNTs) have a decisive influence on their microwave absorption performance, mainly including tube diameter, aspect ratio, degree of graphitization, defects and doping, and surface functionalization. Tube diameter directly affects the conductivity and dielectric response of CNTs. Smaller diameters are beneficial for enhancing quantum confinement effects and polarization losses, but excessively thin carbon nanotubes may weaken conductive losses due to decreased conductivity. Therefore, there exists an optimal tube diameter range to achieve a balance between impedance matching and loss capability. The aspect ratio affects the dispersion state of CNTs in the matrix and the efficiency of conductive network construction. High aspect ratio carbon nanotubes are more likely to form percolation conductive pathways at low filler ratios, thereby enhancing conductive losses and multiple reflections. However, excessively long carbon nanotubes are prone to aggregation, which needs to be controlled through process optimization. The degree of graphitization determines the order of sp^2 hybrid carbon atoms in CNTs. Highly graphitized CNTs have good conductivity and strong conductivity loss, but excessive graphitization will reduce defect density and weaken dipole polarization loss. Appropriately reducing the degree of graphitization can introduce more structural defects and enhance polarization relaxation, but conductivity will decrease accordingly. Therefore, it is necessary to adjust according to the target frequency band. Defects and doping are effective means to control the electromagnetic parameters of CNTs. By doping with elements such as nitrogen and boron or artificially introducing lattice defects, local states and dipole centers can be generated on the surface of CNTs, which can significantly enhance dipole polarization loss. At the same time, doping can also adjust the Fermi level and improve impedance matching characteristics. Surface functionalization usually introduces oxygen-containing functional groups such as carboxyl and hydroxyl groups on the surface of CNTs through acid oxidation treatment. These polar groups generate dipole orientation polarization in an applied alternating electromagnetic field, contributing additional dielectric loss. At the same time, functionalization can also improve the dispersion of CNTs in the polymer matrix and enhance the interfacial polarization effect [29–32]. The above structural parameters are interconnected and work together, and through system control, the microwave absorption performance of CNTs can be precisely designed.

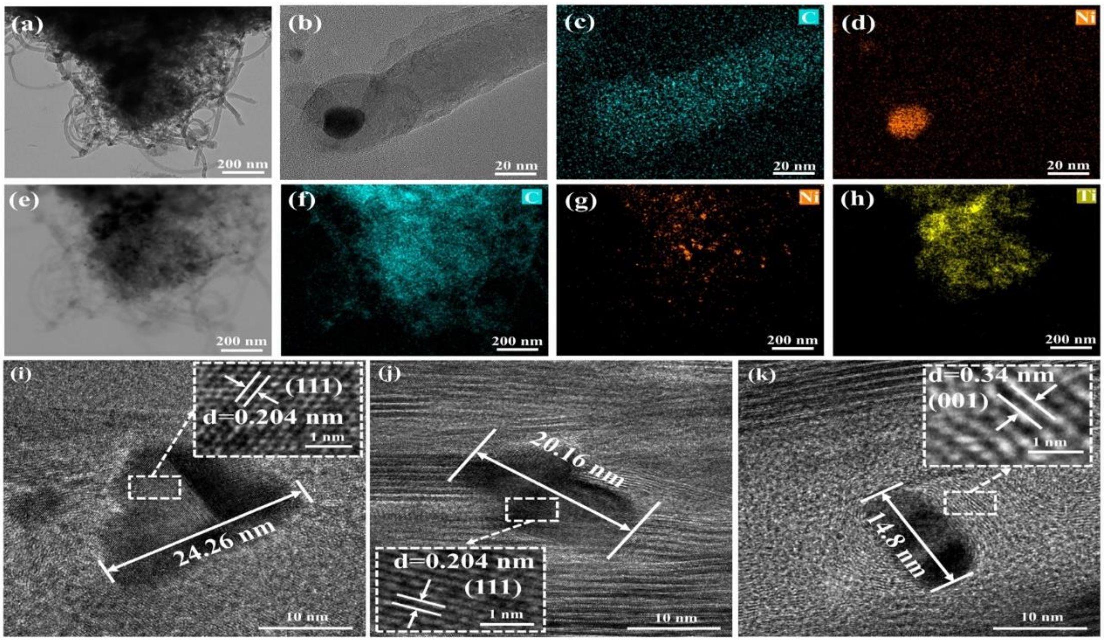

Figure 1: TEM images of (a) 2-Ni-MWCNTs/Ti3C2Tx. (b–d) HRTEM images of CNTs/Ni and corresponding elemental mapping of C and Ni. (e–h) STEM images of 2-Ni-MWCNTs/Ti3C2Tx and corresponding elemental images of C, Ti and Ni. HRTEM images of (i) 2-Ni-MWCNTs/Ti3C2Tx, (j) 1.5-Ni-MWCNTs/Ti3C2Tx, (k) 1-Ni-MWCNTs/Ti3C2Tx [31]

2.4 Key Performance Influencing Factors

Filler ratio, thickness, and dispersion are key factors affecting the actual performance of CNTs absorbing materials. The filler ratio refers to the mass or volume fraction of CNTs in the composite material, directly determining the overall dielectric constant and the formation state of the conductive network. When the filler ratio is low, CNTs are isolated, making it difficult to form continuous conductive paths, resulting in weak conductive loss and multiple reflection effects, leading to poor absorption performance. As the filler ratio increases above the percolation threshold, a three-dimensional conductive network gradually forms, significantly enhancing dielectric loss. However, an excessively high filler ratio leads to excessive conductivity, severely deteriorating impedance matching, and most electromagnetic waves are reflected at the material surface, failing to penetrate the interior, thus reducing absorption efficiency. Therefore, there exists an optimal filler ratio range within which sufficient loss capability can be obtained while maintaining good impedance matching. Thickness is an important parameter determining the absorption peak position and EAB. According to the quarter-wavelength matching condition, when the material thickness is equal to an odd multiple of one-quarter of the wavelength of the incident electromagnetic wave inside the material, the incident and reflected waves produce destructive phase interference at the material surface, thereby achieving maximum absorption at a specific frequency. By rationally designing the thickness, the absorption peak can be tuned to the target frequency band. At the same time, increasing the thickness usually helps low-frequency absorption, but excessively thick materials do not meet the requirements of lightweighting. Dispersion reflects the degree of uniform distribution of CNTs in the matrix. Good dispersion can give full play to the loss capacity of each CNT, form a uniform conductive network and increase the effective heterostructure interface, thereby enhancing polarization loss and multiple reflections; conversely, severe aggregation of CNTs leads to excessively high conductivity in some areas and insufficient conductivity in other areas, resulting in impedance mismatch and a significant decrease in absorption performance. Surface functionalization modification or optimized composite process can effectively improve dispersion, thereby improving the overall absorption performance [33–37]. The above three factors are interdependent and need to be comprehensively considered and optimized in practical material design.

3. Carbon Nanotube-based Microwave Absorbing Composite Material System and Structural Design

3.1 Carbon Nanotube-based Composite Systems

Combining CNTs with different functional materials is an important way to improve microwave absorption performance, and various composite systems have been developed. In CNT-polymer composite systems, CNTs are dispersed in matrices such as epoxy resin, paraffin, or polyvinylidene fluoride, utilizing the low dielectric properties of polymers to improve impedance matching, while CNTs provide conductive and polarization losses. However, a single dielectric loss mechanism is often insufficient to achieve the goal of wide-band, strong absorption. Combining CNTs with magnetic components, two-dimensional MXene materials, or MOF-derived carbon materials can introduce multiple synergistic loss mechanisms such as magnetic loss and interfacial polarization, thereby significantly improving microwave absorption performance. In CNT-magnetic component composite systems, the introduction of magnetic materials not only brings magnetic loss but also adjusts the dielectric constant to improve impedance matching. For example, in the NiZn -based ferrite/CNTs composite material prepared by solid-state reaction, different metal ion doping can effectively control the microwave absorption performance. The Cu^{2+} doped sample achieved a minimum reflection loss of −46.32 dB at a thickness of 1.4 mm [38]. Yuan et al. prepared a VSe$_2$ /CNTs/ Fe$_3$O$_4$ ternary composite material with a variety of unique three-dimensional self-assembled structures such as starfruit, bitter melon, and peony by a two-step hydrothermal combined with a one-step carbothermal reduction method. Utilizing the ternary synergistic effect between the conductivity and polarization loss of CNTs, the polarization loss of the multi-level heterogeneous interface constructed by VSe$_2$ and Fe$_3$O$_4$ and the magnetic loss of Fe$_3$O$_4$, a minimum reflection loss of −50.96 dB was achieved at a thickness of 1.8 mm, and an effective absorption bandwidth of 4.93 GHz was obtained at a thickness of 2.0 mm [39]. Combining CNTs with MXene can solve the problems of easy stacking and poor impedance matching of MXene: CoPC/ CNTs@MXene hybrid adopts a strategy combining MOF derivation and electrostatic self-assembly, introduces 0D CoPC particles and 1D CNTs between 2D MXene layers to construct a multidimensional hierarchical structure. Its excellent absorption performance is attributed to the synergistic effect of interface polarization and magnetic loss. The resulting material achieves an effective absorption bandwidth of 5.6 GHz and a minimum reflection loss of −54.2 dB with a thickness of 1.8 mm [40]. In addition, using metal-organic frameworks (MOF) as precursors, magnetic nanoparticles such as Co and Ni are generated in situ on the surface of CNTs through a pyrolysis autocatalytic process. Composite materials with hierarchical porous structures and multiple heterogeneous interfaces can be prepared. With a low filling amount of only 5 wt %, a reflection loss of −51.56 dB and an effective absorption bandwidth of 6.88 GHz are obtained [41]. Similarly, the composite of CNTs with metals/metal oxides can utilize numerous heterogeneous interfaces to generate strong interfacial polarization and dipole polarization, further enhancing dielectric loss capability. In summary, CNT-based composite systems are developing from single-component to multi-component, multi-dimensional, and multi-interface synergy. By precisely controlling the spatial configuration and interfacial structure of each component, it is expected to achieve the controllable fabrication of lightweight, broadband, and strong absorbing microwave materials.

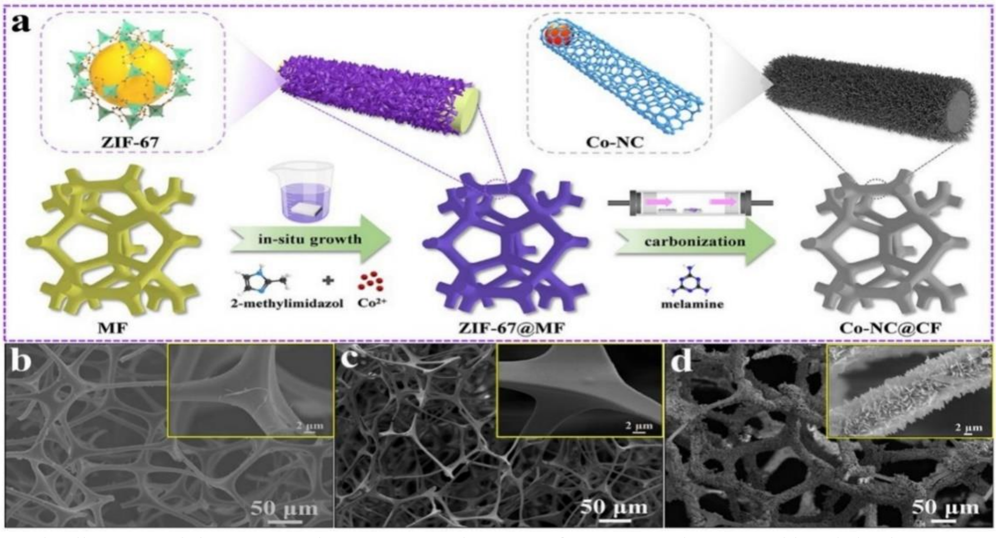

Figure 2: a Schematic diagram of the preparation process of Co-NC@CF. SEM images of b original MF, c NaOH treated MF, and d ZIF-67@MF [41]

Table 1: Performance Comparison of Carbon Nanotube-Based Composite Materials

Materials	Frequency	RL $_{min}$	EAB	Ref
$Ni_{0.4}Zn_{0.4}Me_{0.2}Fe_{1.94}Cr_{0.01}O_4$/CNT	16 GHz	−46.32 dB	4.3 GHz	[38]
VSe_2/CNTs/Fe_3O_4	11.21 GHz	−50.96 dB	4.93 GHz	[39]
CCM-20	5.56 GHz	− 54.2 dB	5.6 GHz	[40]
Co-NC@CF-800	14.96 GHz	−51.56 dB	6.88 GHz	[41]

3.2 One-dimensional (Core-shell Structure, Pod-like), Three-dimensional Network, Hierarchical Multi-scale Structural Design

In the structural design strategy of CNTs-based microwave absorbing materials, one-dimensional core-shell structure, pod-like structure, three-dimensional network structure and hierarchical multi-scale structure have been proven to be effective ways to improve microwave absorption performance. One-dimensional core-shell structure uses CNTs as the core and uniformly coats magnetic metal, metal oxide or conductive polymer as the shell on its surface. This structure can not only utilize the strong interfacial polarization loss generated at the core-shell interface, but also introduce additional magnetic loss or dielectric loss through the shell material. At the same time, the shell has the effect of regulating the overall impedance matching. For example, CNT/ Fe_3O_4 @C composite material was prepared by scalable chemical vapor deposition method. By utilizing the synergistic dissipation effect of the core-shell structure and the excellent conductivity loss of the carbon nanotube skeleton, a minimum reflection loss of −50.1 dB and an effective absorption bandwidth of 4.6 GHz were achieved at 9.7 GHz [42]. Another example is the synthesis of PPy / TiO_2 (np)/CNT nanocomposites with core-shell structure by chemical oxidative polymerization. In X-band testing, the sample with a thickness of 3 mm achieved the lowest reflection loss of −51.11 dB at 8.64 GHz [43]. The pod-like structure refers to the special configuration in which magnetic metal nanoparticles are encapsulated in the inner cavity of CNTs, similar to peas in a pod. On the one hand, the shell of CNTs protects the internal magnetic particles and prevents them from agglomerating. On the other hand, the close contact between the nanoparticles and the inner wall of CNTs generates strong interfacial polarization and local electromagnetic field enhancement effects. For example, using hollow Fe_2O_3 particles as catalysts, core-shell Fe/carbon nanotube hybrid materials were prepared by chemical vapor deposition without hydrogen reduction. The minimum reflection loss of −40.15 dB was achieved at 17.15 GHz with a thickness of 1.5 mm, and the reflection loss of less than −20 dB was obtained in the full frequency band of 1–18 GHz within the thickness range of 1.3–10.0 mm, demonstrating a simple and environmentally friendly high-performance thin-layer lightweight absorbing material preparation method [44]. Cobalt-filled carbon nanotube composite materials were prepared by a simple and efficient wet chemical method. The maximum reflection loss was measured to be −39.32 dB in the frequency band of 2–18 GHz, corresponding to an absorption bandwidth of 3.47 GHz below −10 dB. It was also found that the maximum reflection loss peak shifted to lower frequencies as the matching thickness increased [45].

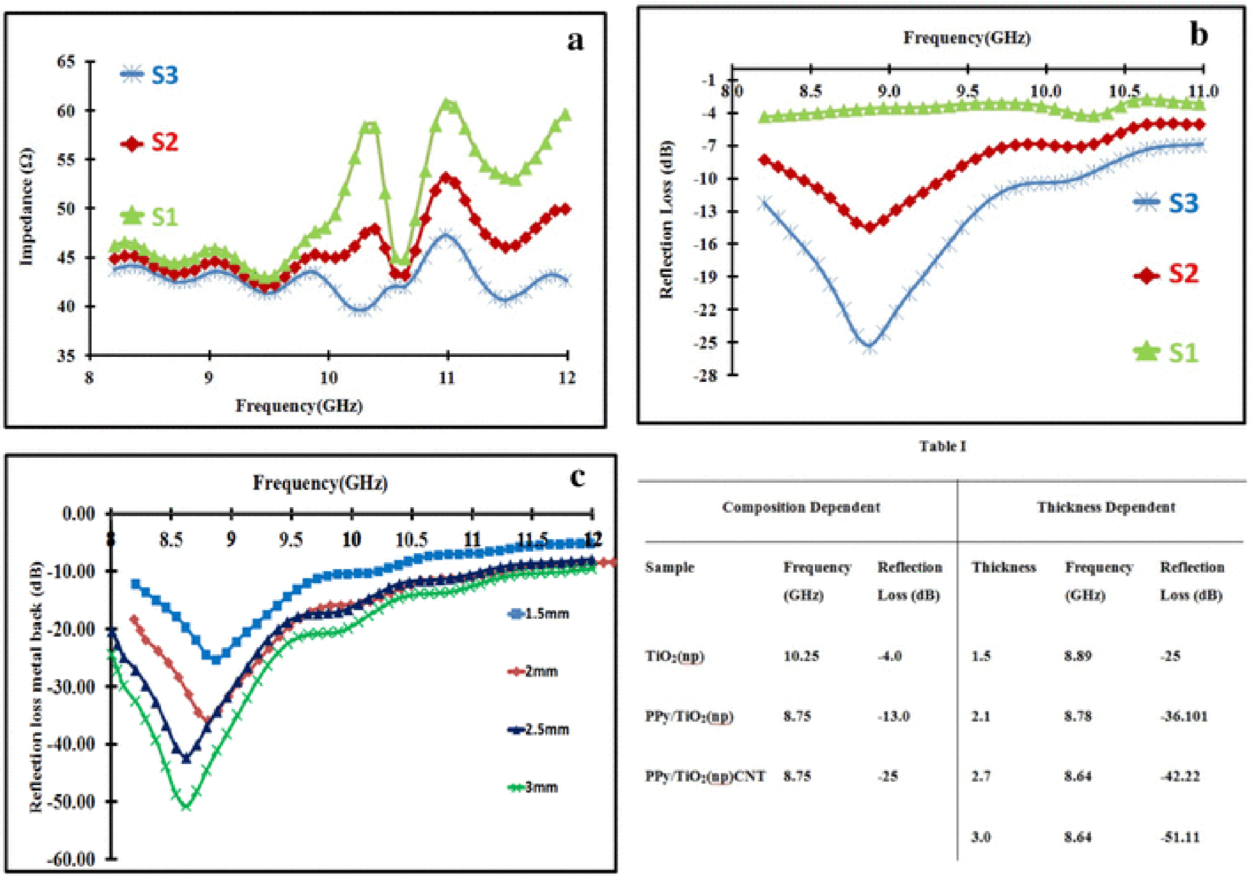

Table I

Composition Dependent			Thickness Dependent		
Sample	Frequency (GHz)	Reflection Loss (dB)	Thickness	Frequency (GHz)	Reflection Loss (dB)
TiO_2(np)	10.25	-4.0	1.5	8.89	-25
PPy/TiO_2(np)	8.75	-13.0	2.1	8.78	-36.101
PPy/TiO_2(np)CNT	8.75	-25	2.7	8.64	-42.22
			3.0	8.64	-51.11

Figure 3: shows the variation of a impedance, b reflection loss and c reflection loss with thickness variation, with frequency [43]

Three-dimensional network structures are constructed by assembling CNTs into macroscopic bodies such as aerogels, foams or sponges to form a continuous three-dimensional conductive network. This structure has low density, high porosity and abundant porous channels. After electromagnetic waves enter the network, they undergo multiple reflections, scattering and transmissions, which significantly prolongs the action path. At the same time, a large number of pore walls and CNTs intersections become polarization loss centers, which effectively enhances energy dissipation. For example, the ultralight copolymer aerogel prepared by lyophilizing CNTs modified with silane coupling agent and constructing a three-dimensional network hydrogel achieved a minimum reflection loss of −54.8 dB and an effective absorption bandwidth of 4.13 GHz at a thickness of 1.15 mm [46]. The ultralight multi-walled carbon nanotube /graphene composite foam prepared by a simple solvothermal method achieved an effective absorption bandwidth covering 16 GHz in the full frequency band of 2–18 GHz, with a minimum reflection loss of −39.5 dB and a specific absorption performance of up to 12243 dB cm^2 g^{-1} [47].

Hierarchical multi-scale structural design integrates zero-dimensional magnetic nanoparticles, one-dimensional CNTs, two-dimensional sheet materials and three-dimensional porous frameworks across scales, realizing the synergistic effect of multi-level loss mechanisms from micro to macro. MXene and metal-organic frameworks are assembled into an intertwined one-dimensional heterostructure and a three-dimensional cross-linked network is constructed. The prepared composite material achieves a minimum reflection loss of −51.6 dB and an effective absorption bandwidth of 4.5 GHz at a thickness of 1.6 mm [48]. The above structural design significantly improves the comprehensive performance of CNTs - based microwave absorbing materials through fine control of geometric morphology and multi-scale synergistic effect.

3.3 Synergistic Strategy of Impedance Matching Optimization and Multi-Loss Mechanisms

Impedance matching optimization and multi-loss mechanism synergistic strategy are the core of achieving efficient broadband absorption of carbon nanotube-based absorbing materials. Impedance matching requires the ratio of the complex permittivity to the complex permeability of the material to be as close as possible to the free space impedance. For carbon nanotube materials with dielectric loss as the main component, excessively high conductivity often leads to impedance matching deterioration, so it is necessary to optimize it through structural design and composition control. Commonly used impedance matching optimization strategies include controlling the carbon nanotube filling content to balance the permittivity, constructing gradient structures or layered structures to achieve impedance gradient, introducing porous structures to reduce the effective permittivity, and composite magnetic components to increase permeability and thus narrow the gap with the permittivity. For example, a double-layer gradient absorber was designed, with epoxy resin as the matrix and carbon nanotubes and their hybrid with graphene oxide as absorbers to prepare composite foam. By combining foam layers of different thicknesses and filler contents, a reflection loss peak of −40 dB and an effective absorption bandwidth of 11.5 GHz (6.5–18 GHz) were achieved in a 2.6 mm + 1.3 mm double-layer structure [49]. Another example is the preparation of flexible PVDF-MWCNT foam with 88.9% porosity by solvent method, which achieved a reflection loss of −26.5 dB and a high shielding efficiency of 78.46 dB at 9.96 GHz, showing electromagnetic interference shielding characteristics dominated by absorption [50].

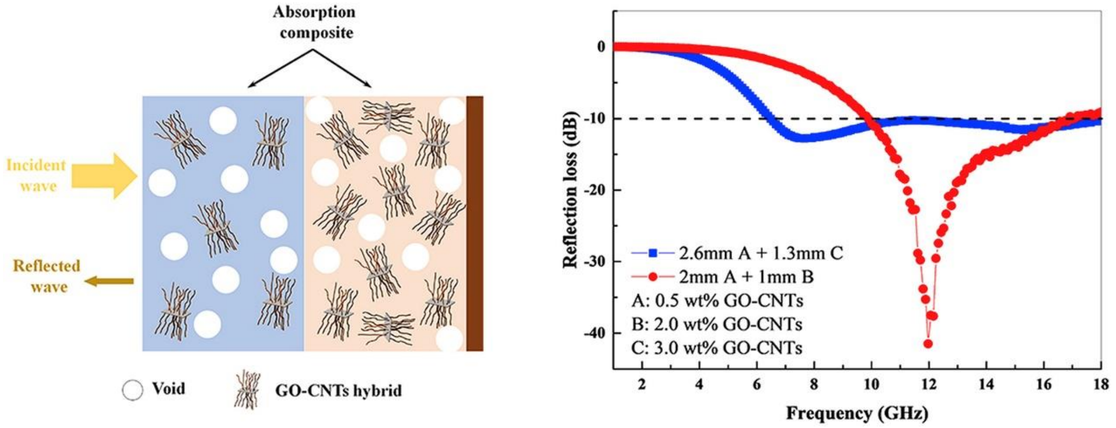

Figure 4: Graphical abstract of GO-CNTs hybrids reinforced epoxy composites with porous structure as microwave absorbers [49]

The multi-loss mechanism synergistic strategy aims to integrate multiple energy dissipation pathways such as dielectric loss, conductive loss, polarization loss, multiple reflection loss and magnetic loss into the same material system, overcoming the limitation that loss capacity and impedance matching are difficult to achieve under a single mechanism. Typical synergistic designs include magnetic-dielectric synergy between carbon nanotubes and magnetic nanoparticles, interfacial polarization synergy between carbon nanotubes and two-dimensional materials, and multi-loss synergy of multi-component hierarchical structures. In terms of magnetic-dielectric synergy, Fe_3O_4 modified carbon nanotubes achieve RL min of −52.8 dB at a filling amount of 20 wt % [51]. In terms of interfacial polarization synergy, 3D MXene -CNTs/Ni constructed after introducing Ni achieves RL min of −56.4 dB at 2.4 mm [52]. In terms of hierarchical structure synergy, the one-dimensional micro-nano hybrid scale hierarchical porous carbon architecture based on MOF derivatives significantly enhances dielectric loss through a uniform carbon nanotube interconnection network. The minimum reflection loss reaches −55.3 dB at a thickness of 1.71 mm, and the effective absorption bandwidth is 5.5 GHz at a thickness of 1.82 mm [53]. The above design combines impedance matching optimization with multi-loss mechanism synergy, which is an effective way to break through the performance bottleneck of CNTs-based absorbing materials.

4. Challenges and Prospects

4.1 Current Challenges

Currently, CNT-based absorbing materials face four major challenges: dispersion uniformity, cost, large-scale preparation, and multi-spectral compatibility. Regarding dispersion, CNTs are prone to aggregation due to strong van der Waals forces and high aspect ratios, leading to uneven conductive networks, deteriorated impedance matching, and weakened loss mechanisms. In terms of cost, the synthesis of high-quality CNTs requires expensive catalysts and post-processing, resulting in prices far exceeding those of ferrites and carbon black, making it difficult to meet the low-cost requirements for civilian applications. Regarding large-scale preparation, while laboratory performance is excellent, poor tube diameter, aspect ratio, and batch stability in kilogram-scale production significantly reduce actual absorption performance. Regarding multi-spectral compatibility, it is difficult to simultaneously achieve high infrared emissivity and radar absorption with CNTs; introducing low-emissivity coatings disrupts impedance matching, and the coupling mechanism is unclear, lacking a multi-physics model. These challenges are interconnected and require multi-level collaborative efforts.

4.2 Future Directions

Future directions mainly include four aspects: intelligent tunable absorbing materials, machine learning-aided design, green synthesis, and theoretical models. Intelligent tunable absorbing materials achieve on-demand adjustment of absorption performance by dynamically controlling the dielectric constant and impedance matching under external field excitation, through the composite of carbon nanotubes with conductive polymers or phase change materials. Machine learning-aided design utilizes algorithms such as neural networks to establish predictive models of synthesis parameters and electromagnetic properties, enabling rapid screening of optimal material formulations and shortening the R&D cycle. Green synthesis advocates replacing fossil carbon sources with biomass carbon sources, combined with low-temperature plasma or microwave-assisted chemical vapor deposition processes, to reduce energy consumption and avoid heavy metal pollution. In terms of theoretical models, it is necessary to develop cross-scale multiphysics coupling models, combining first-principles calculations, molecular dynamics simulations, and finite element electromagnetic simulations to provide theoretical support for the rational design of carbon nanotube absorbing materials.

4.3 Conclusion

Carbon nanotubes (CNTs) have become important candidates for next-generation microwave absorbing materials due to their lightweight, high conductivity, tunable dielectric properties, and rich polarization loss mechanisms. This paper systematically reviews the research progress of CNT-based absorbing materials in terms of absorption mechanism, performance regulation, composite systems, and structural design. The synergistic optimization of impedance matching and attenuation capability is key to achieving efficient broadband absorption. Electromagnetic parameters can be effectively adjusted by controlling the diameter, aspect ratio, graphitization degree, defect doping, and surface functionalization of CNTs. Combining CNTs with polymers, magnetic metals, metal oxides, and two-dimensional materials such as MXene and graphene can introduce magnetic loss and interfacial polarization loss, overcoming the limitations of a single dielectric loss mechanism. One-dimensional core-shell structures, pod-like structures, three-dimensional network structures, and hierarchical multi-scale structural designs significantly enhance multiple reflections and interfacial polarization effects, further improving absorption performance. Despite current challenges in terms of dispersion uniformity, preparation cost, large-scale production, and multi-spectral compatibility, emerging directions such as intelligent tunable absorbing materials, machine learning-aided design, green synthesis processes, and cross-scale theoretical models offer feasible paths to overcome existing bottlenecks.

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