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Research Progress on Carbon-Based Microwave Absorbing Materials: From Composition Design to Multi-Scale Structural Engineering

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Abstract: ***With the rapid advancement of fifth-generation (5G) wireless communication and radar detection technologies, electromagnetic radiation pollution has become a critical threat to the safe operation of electronic equipment, information security, and even human health. Therefore, developing high-performance microwave absorbing materials is of great military and civilian significance. Carbon-based materials, owing to their unique advantages including low density, strong dielectric loss, excellent chemical stability, and highly tunable structural and electromagnetic parameters, show enormous potential in the field of microwave absorption. This article systematically reviews the latest research progress in carbon-based microwave absorbing materials. First, the fundamental principles of electromagnetic wave absorption are elucidated from the perspectives of impedance matching and attenuation mechanisms. Second, the design strategies and absorption performance of various carbon-based absorbers, such as graphene, carbon nanotubes, and biomass-derived carbon, are systematically introduced according to material type. Third, from the perspective of multiscale structural engineering, the regulatory effects of macroscopic structural designs, including aerogels, metamaterials, and bio-inspired structures, on microwave absorption performance are analyzed. Finally, the key challenges currently faced by carbon-based microwave absorbing materials are summarized, and future development trends are discussed, including green preparation, low-frequency absorption, and novel material systems with multi-physics field responsiveness.***

Keywords: Carbon-based materials; Microwave absorption; Impedance matching; Structural design; Multifunctional integration.

1. INTRODUCTION

With the rapid popularization of wireless communication technologies such as 5G and the Internet of Things, electromagnetic radiation pollution has become increasingly serious, becoming the fourth largest pollution after air, water, and noise. In the civilian field, electromagnetic interference can cause malfunctions in precision instruments, deterioration in communication quality, failure of medical equipment, and even pose a potential threat to human health. In the military field, microwave absorbing materials can effectively reduce the radar cross section (RCS) of a target and are a key technology for achieving radar stealth of weapon platforms, directly related to battlefield survivability and penetration capability. Therefore, the development of high-performance microwave absorbing materials is of great strategic significance for ensuring the safe operation of electronic systems, maintaining public health, and improving the stealth performance of defense equipment. Carbon-based materials, with their advantages of being lightweight and having adjustable electromagnetic parameters, have become a research hotspot in this field [1–5].

Carbon-based materials, including graphene [6–8], carbon nanotubes [9–11], and biomass-derived carbon [12,13], have shown significant advantages over traditional ferrite and metal powder absorbing materials in the field of microwave absorption due to their unique physicochemical properties. First, carbon-based materials have ultra-low density, which can significantly reduce the added weight of the absorbing coating and meet the stringent requirements for lightweighting in aerospace and portable electronic devices. Second, their conductivity can be flexibly controlled over a wide range from insulator to conductor. Through carbonization temperature, heteroatom doping, and defect engineering, impedance matching can be precisely optimized and various dielectric loss mechanisms such as conductivity loss, dipole polarization, interface polarization, and multiple reflections and scattering can be excited to achieve efficient electromagnetic wave attenuation [14]. In addition, carbon-based materials have excellent chemical durability and remain stable in complex environments such as acid, alkali, salt spray, and humid heat. They are easy to combine with organic resins, magnetic metals, or ceramics to construct multifunctional integrated absorbing structures. Meanwhile, its microstructure can be designed at multiple levels from the molecular scale to the macro scale, such as porous carbon, carbon aerogel, honeycomb structure, etc., which provides a rich space for regulation to simultaneously take into account impedance matching and attenuation ability [15]. In addition, biomass-derived carbon and other materials are widely available, inexpensive and sustainable, making carbon-based materials one of the most promising high-performance microwave absorbing material systems [16].

This paper systematically reviews the latest research progress of carbon-based materials in the field of microwave absorption. The paper is divided into five parts: Chapter 2 elucidates the fundamental theories of electromagnetic wave absorption, including absorption performance evaluation parameters, impedance matching principles, and major attenuation mechanisms such as conductivity loss and polarization loss; Chapter 3 systematically introduces the design strategies and performance of typical carbon-based microwave absorbing materials according to material type, covering graphene, carbon nanotubes, and biomass-derived carbon; Chapter 4 discusses the role of microscopic, mesoscopic, and macroscopic structural design in regulating microwave absorption performance from the perspective of multi-scale structural engineering; Chapter 5 summarizes the current key challenges and looks forward to future development directions such as green preparation, low-frequency absorption, and new material systems with multi-physics response.

2. FUNDAMENTAL THEORY OF ELECTROMAGNETIC WAVE ABSORPTION

2.1 Evaluation Parameters for Absorption Performance

The core indicators for evaluating the microwave absorption performance of carbon-based materials mainly include reflection loss, effective absorption bandwidth, and impedance matching. Reflection loss (RL) characterizes the material's ability to absorb vertically incident electromagnetic waves. It is usually calculated based on transmission line theory using the complex permittivity and complex permeability. A more negative value indicates stronger absorption. In practical applications, an RL ≤ -10 dB, corresponding to over 90% energy absorption, is generally considered the engineering standard for effective absorption. Effective absorption bandwidth (EAB) is defined as the frequency range covered by RL ≤ -10 dB. Broadband absorption capability is an important parameter for evaluating the practical value of microwave absorbing materials, especially in the 2–18 GHz radar band where the widest possible EAB is sought. Impedance matching describes the degree of coordination between the material surface and free space in electromagnetic wave transmission. When the normalized input impedance of the material is close to 1 (i.e., Zin / Z0 ≈ 1), electromagnetic waves can penetrate the material to the maximum extent possible without being reflected, which is a prerequisite for efficient absorption. In addition, the maximum reflection loss value (RL_{min}) and its corresponding frequency, matching thickness, and other parameters are also commonly used to comprehensively evaluate microwave absorption performance. The above indicators are interrelated. Ideal absorbing materials need to achieve strong attenuation capabilities on the basis of good impedance matching, so as to achieve the goals of low reflection loss and wide effective absorption bandwidth [17–19].

2.2 Impedance Matching Principle

Whether electromagnetic waves can effectively enter the interior of an absorbing material rather than being reflected at the surface depends on the degree of impedance matching between the material and free space. According to transmission line theory, when an electromagnetic wave is normally incident on the surface of a single-layer absorbing material, its reflection coefficient is determined by the normalized input impedance Z_{in} of the materia: $Z = \frac{Z_{in}}{Z_0} = \left|\sqrt{\frac{\mu_r}{\varepsilon_r}} tanh\left[j\left(\frac{2\pi fd}{c}\right)\sqrt{\mu_r\varepsilon_r}\right]\right|$, where $\varepsilon = \varepsilon' - j\varepsilon''$ and $\mu = \mu' - j\mu''$ are the complex permeability and complex permittivity of the material, respectively, f is the frequency, d is the thickness, and c is the speed of light. Ideal impedance matching requires normalization to a free-space wave impedance of 377 Ω, at which point almost all electromagnetic waves penetrate the material's interior. However, most carbon-based materials only have dielectric losses and lack magnetic losses, with ε_r being much larger than μ_r, leading to severe impedance mismatch and the reflection of a large amount of electromagnetic waves. Therefore, common strategies for improving the impedance matching of carbon-based materials include: introducing magnetic components (such as Fe, Co, Ni, and their alloys or oxides) to increase ε_r and bring it closer to μ_r; constructing porous or hierarchical structures to reduce the effective permittivity; or using gradient design to allow the impedance to gradually transition from the surface to the interior. Only when electromagnetic waves can efficiently enter the interior of a material can subsequent attenuation mechanisms such as conductivity loss, polarization loss, and multiple reflections play a full role. It is evident that impedance matching is a prerequisite for achieving efficient microwave absorption, and a reasonable match between dielectric constant and permeability is the core principle for the design of microwave absorbing materials [20–22].

2.3 Attenuation Mechanism

2.3.1 Conductivity Loss

The formation of conductive networks and the regulation of conductivity are among the core mechanisms for electromagnetic wave energy dissipation in carbon-based materials. When carbon-based materials interconnect to form a three-dimensional conductive network within the matrix, incident electromagnetic waves drive the free carriers in the network to undergo collective oscillation and directional migration, generating a conduction current. This current converts electromagnetic energy into heat energy through the Joule effect on the material's resistance, thus achieving energy dissipation. The strength of the conductivity loss directly depends on the material's conductivity σ. According to classical electromagnetic theory, the dielectric loss tangent of a material is $\tan \delta_\varepsilon = \sigma/(\omega\varepsilon_0\varepsilon_r)$. At a given frequency ω, the higher the conductivity, the greater the dielectric loss. However, excessively high conductivity can exacerbate the skin effect, causing electromagnetic waves to propagate only on the material's surface and unable to penetrate the interior. Simultaneously, it causes the material's input impedance to deviate significantly from its free-space impedance, resulting in substantial reflection of electromagnetic waves at the surface. Therefore, the rational regulation of conductivity is crucial. Ideal carbon-based microwave absorbing materials need to control their conductivity within a moderate range of 10^{-2}–10^{2} S/m to ensure sufficient conductivity loss while maintaining good impedance matching. Common conductivity control strategies include: adjusting the carbonization temperature, where high-temperature graphitization can increase conductivity, while low-temperature treatment retains defects to reduce conductivity; introducing heteroatoms such as N, B, and P to alter the local electronic structure; controlling the filler content close to the percolation threshold to construct a discontinuous conductive network; and combining carbon materials with low-conductivity components. In addition, the microstructure of the conductive network has a significant impact on conductivity loss efficiency: line-to-line contacts of one-dimensional carbon nanotubes, face-to-face overlaps of two-dimensional graphene, and continuous framework structures of three-dimensional aerogels can all form highly efficient conductive pathways. By optimizing the connectivity and conductivity level of the conductive network, an optimal balance can be achieved between conductivity loss and impedance matching, thereby maximizing electromagnetic wave absorption performance [23,24].

2.3.2 Polarization Loss

Polarization loss is another important mechanism for the dissipation of electromagnetic wave energy in carbon-based microwave absorbing materials, mainly including dipole polarization, interfacial polarization, and defect-induced polarization. Dipole polarization originates from the orientation relaxation process of intrinsic or induced electric dipoles within the material in an alternating electric field. Carbon materials often contain oxygen-containing functional groups such as –OH and –COOH, residual hydrogen, or heteroatoms such as N, B, S, and P. These atoms with significantly different electronegativity form dipole centers with the carbon framework, undergoing rotation and rearrangement under the influence of an external electric field, converting electromagnetic energy into thermal energy. Interfacial polarization occurs at the interfaces of components with different electrical conductivities or dielectric constants, such as graphene/magnetic particle interfaces, carbon/polymer interfaces, or carbon/air interfaces. Due to the difference in conductivity between different phases, free charge carriers accumulate at the interface to form space charge, generating a macroscopic dipole moment and inducing dielectric relaxation. In porous carbon or hierarchical structures, abundant solid-gas interfaces further enhance the interfacial polarization effect. Defect-induced polarization is caused by the uneven distribution of local charge due to intrinsic defects such as vacancies, edge dislocations, and topological defects in the carbon lattice, forming local dipoles that undergo relaxation loss under an external electric field. In particular, polarization centers can be introduced into the perfect six-membered ring of graphene through heteroatomic doping. Due to the difference in electronegativity and atomic radius between the doped atoms and carbon atoms, the original charge symmetry is destroyed, generating a large number of local dipole moments. Different doping types of pyridine N, pyrrole N, and graphitic N can synergistically generate multiple polarization relaxation processes, thereby achieving efficient polarization loss over a wide frequency band. Therefore, through defect engineering and heteroatomic doping design, the polarization loss capability of carbon-based materials can be significantly enhanced, and synergistic attenuation of multiple polarization mechanisms can be achieved, which is an effective way to improve microwave absorption performance [25–27].

2.3.3 Multiple Reflections and Scattering

Porous and hierarchical structures are key design strategies for achieving multiple reflections and scattering losses in carbon-based microwave absorbing materials. When electromagnetic waves enter the interior of materials with abundant pores, cavities, or interlayer gaps, repeated reflections and scattering occur between the pore walls and the carbon skeleton, significantly extending the effective propagation path of the electromagnetic waves within the material. Each reflection and scattering process is accompanied by energy dissipation, and the cumulative effect greatly improves the overall absorption efficiency. Specifically, the coexistence of micropores, mesopores, and macropores at multiple levels constitutes a complex physical space, causing electromagnetic waves to continuously change their propagation direction as they cross pores of different scales, increasing the frequency of interaction with the carbon walls. Furthermore, hierarchical structures such as three-dimensional interconnected networks, dendritic morphologies, and layered stacking can further induce diffuse reflection of electromagnetic waves, disrupting their directional propagation mode and causing them to reflect back and forth within the material. This multiple reflection and scattering mechanism not only extends the effective operating distance but also provides more opportunities for other attenuation mechanisms, with each reflection prompting the electromagnetic waves to re-interact with the carbon surface, defects, and heterogeneous interfaces. Therefore, constructing porous/hierarchical structures through ice template method, foaming method, template sacrifice method, etc. can significantly improve the energy dissipation efficiency of electromagnetic waves without significantly increasing the material density, which is an important means to realize lightweight and efficient microwave absorbing materials [28–30].

2.3.4 Interference Cancellation

Interference loss, based on the principle of quarter-wavelength destructive interference, is an important auxiliary attenuation mechanism in carbon-based absorbing materials. When an electromagnetic wave is incident perpendicularly on the surface of an absorbing material, part of the wave is reflected at the surface, while the other part is transmitted into the material and reflected again at the interface of the underlying metal backing plate. If the material thickness *d* is exactly an odd multiple of the wavelength of the electromagnetic wave in the medium, i.e., *d* = (2n+1) λ_m / 4, the phase difference between the surface reflected wave and the bottom reflected wave is π. They undergo destructive interference, causing the total reflected wave amplitude to cancel each other out, thus enhancing the absorption effect. In hierarchical porous structures, this interference loss mechanism is significantly enhanced. On the one hand, the hierarchical porosity creates multiple reflection interfaces within the material, forming a multi-layered interference system. Each interface contributes to destructive interference, and the cumulative effect broadens the effective absorption bandwidth. On the other hand, the hierarchical structure causes the electromagnetic wave to undergo multiple reflections and transmissions within the material, increasing the equivalent optical path. This allows the interference conditions, originally only applicable to a single thickness, to be approximately satisfied across multiple thickness regions, thereby maintaining a low reflectivity over a wider frequency range. Furthermore, the effective dielectric constant of porous carbon materials can be controlled by adjusting the porosity, thereby regulating the quarter-wavelength matching thickness and enabling interference loss to work synergistically with mechanisms such as conductivity loss and polarization loss [31,32]. Therefore, by rationally designing hierarchical porous structures, the utilization of quarter-wavelength destructive interference can be maximized, achieving lightweight, broadband, and efficient absorption.

3. TYPICAL CARBON-BASED MICROWAVE ABSORBING MATERIALS

3.1 Graphene-based Microwave Absorbing Materials

3.1.1 Absorption Characteristics and Limitations of Intrinsic Graphene

Intrinsic graphene has inherent advantages such as high conductivity, large specific surface area and ultra-low density, and theoretically has the potential to be a lightweight microwave absorbing material [33]. However, its actual microwave absorption performance is severely restricted. On the one hand, the dielectric constant of graphene is too high, especially the real part of the complex dielectric constant is large, while its complex permeability is close to 1, resulting in the normalized input impedance of the material being much less than 1, and the impedance matching with free space is extremely poor. This causes most incident electromagnetic waves to be directly reflected on the surface of graphene rather than being dissipated inside. On the other hand, intrinsic graphene relies only on conductivity loss and dipole polarization for energy attenuation, lacking magnetic loss and rich interface polarization and other synergistic mechanisms, and the single loss path is difficult to achieve efficient absorption. The above defects together result in the weak absorption intensity and narrow effective absorption bandwidth of intrinsic graphene, which cannot meet the comprehensive requirements of "thin, light, wide and strong" in practical applications. Therefore, it is necessary to functionalize intrinsic graphene through composite modification, structural design or defect engineering to overcome the bottleneck of impedance mismatch and single loss mechanism.

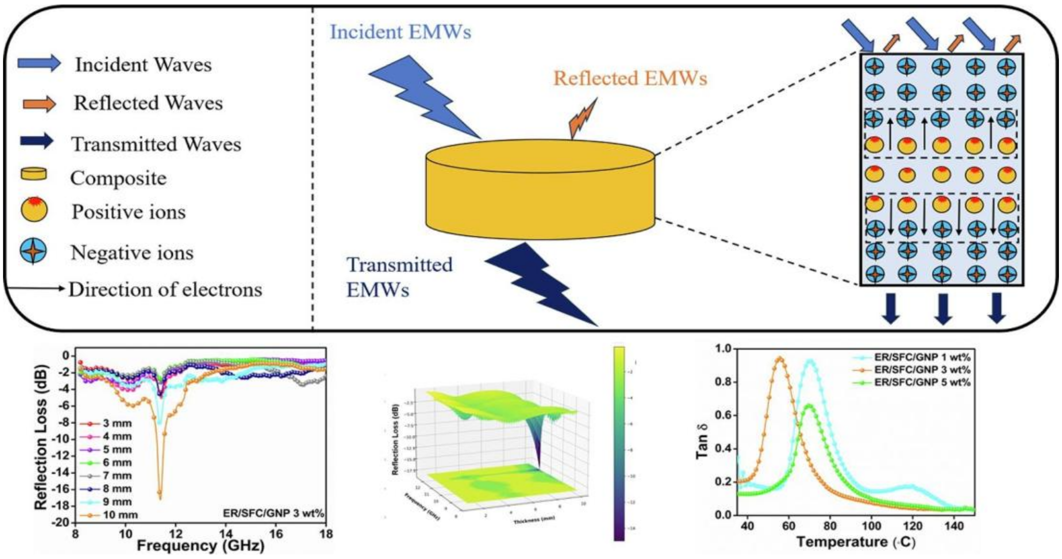

Figure 1: Graphical Abstract: Engineering multifunctionality graphene-based nanocomposites with epoxy-silane functionalized cardanol for next-generation microwave absorber [33]

3.1.2 Heteroatom Doping Strategy

To overcome the limitations of intrinsic graphene's impedance mismatch and singular loss mechanism, heteroatomic doping has proven to be an effective control method. Recent strategies involving the integration of single metal atoms into the graphene lattice via nitrogen atom coordination assistance can significantly modulate the material's conductivity and dielectric dispersion characteristics, thereby simultaneously optimizing impedance matching and introducing multiple loss mechanisms. The strong coordination between nitrogen atoms and metal atoms stably anchors the metal atoms within the carbon framework, forming atomically dispersed metal -N active centers. These centers not only enhance dipole polarization and defect-induced polarization as polarization centers but also introduce magnetic losses through the magnetic contribution of metal atoms, achieving synergistic attenuation of dielectric and magnetic losses. Simultaneously, the precise control of graphene's electronic structure through single-atom doping can moderately reduce the effective dielectric constant, improving impedance matching with free space. Thanks to these synergistic effects of multiple mechanisms, this type of material exhibits excellent microwave absorption performance even with extremely low filler content. For example, 3DPG-NH3-Fe achieved a minimum reflection loss of -56.35 dB and an effective absorption bandwidth of 4.45 GHz with a filler load of only 3 wt.% and a thickness of only 1.4 mm, which surpasses most reported graphene-based electromagnetic microwave absorbing materials. This demonstrates the unique advantage of the atomic doping strategy in low-filler systems [34]. This strategy provides a new approach for designing lightweight, efficient, and broadband graphene-based microwave absorbing materials.

3.1.3 Composite Design and Interface Engineering

Besides atomic-scale doping strategies, another effective way to improve the intrinsic microwave absorption performance of graphene is to combine it with magnetic components such as FeNi alloys [16,35] and Fe3O4 [36] or dielectric components such as conductive polymers [37] and MXene [38] through composite design and interface engineering at the nanoscale. On the one hand, the introduction of magnetic components can add a magnetic loss mechanism to the graphene system that originally relied solely on dielectric loss. At the same time, the permeability of the magnetic components increases the complex permeability of the material, which helps to make the normalized input impedance approach 1, thereby alleviating the impedance mismatch problem caused by the excessively high dielectric constant of graphene. On the other hand, the rich heterogeneous interface formed between graphene and the second phase will induce a strong interface polarization effect, further enhancing the dielectric loss capability. In addition, the embedding of second-phase nanoparticles can suppress the recombination of graphene sheets, maintain a high specific surface area and abundant edge defects, and provide more active sites for dipole polarization. By controlling the composite method, component ratio, and microstructure, an optimal balance can be achieved between dielectric loss and magnetic loss, impedance matching and attenuation capability. Therefore, composite design and interface engineering provide a broad and flexible design space for developing high-performance graphene-based microwave absorbing materials.

3.2 Carbon Nanotube-based Microwave Absorbing Materials

3.2.1 Intrinsic Absorption Characteristics of CNTs

Carbon nanotubes (CNTs) have extremely high aspect ratios and excellent conductivity, which endows them with strong intrinsic dielectric loss capabilities. The high aspect ratio makes it easy for CNTs to overlap in the matrix to form a three-dimensional conductive network. When electromagnetic waves are incident, they drive π electrons in the tube to migrate along the axis, resulting in strong conductivity loss. At the same time, defects in the CNT tube wall, residual functional groups, and contact interfaces between tubes can induce dipole polarization and interface polarization, further contributing to dielectric loss. However, similar to graphene, intrinsic CNTs also face the limitations of poor impedance matching and a single loss mechanism. The excessively high dielectric constant causes most electromagnetic waves to be reflected on the surface, and there is a lack of magnetic loss synergy, resulting in limited absorption performance when used alone. Therefore, it is usually necessary to perform composite modification or structural design on CNTs to fully utilize their dielectric loss potential while improving impedance matching [39].

3.2.2 Component optimization and microstructure design

To overcome the limitations of poor impedance matching and a single loss mechanism in intrinsic carbon nanotubes (CNTs), researchers have conducted systematic optimization designs from two dimensions: component selection and microstructure control. Regarding component selection, CNTs are often combined with magnetic components (Fe, Co, Ni and their alloys or oxides), conductive polymers (PANI, PPy), or dielectric ceramics (SiC, MXene) to introduce magnetic losses or enhance interfacial polarization, while simultaneously adjusting the effective dielectric constant to improve impedance matching. For example, CNT/Fe_3O_4 composites exhibit both electrical and magnetic losses, achieving broadband absorption with relatively low filler content. In terms of microstructure control, the design of hierarchical, porous, and hollow structures has become a research hotspot. Hierarchical structures utilize the synergistic effect of carbon materials with different dimensions to construct multiple conductive networks and abundant heterogeneous interfaces, effectively broadening the absorption bandwidth. Porous structures are prepared using ice-templating or foaming methods; the three-dimensional interconnected open-pore system not only reduces the effective dielectric constant of the material to optimize impedance matching but also introduces multiple reflection and scattering paths, significantly enhancing the energy dissipation efficiency of electromagnetic waves. Hollow structures utilize the cavity resonance effect to prolong the electromagnetic wave interaction time, while the hollow shell can provide additional interfacial polarization sites. The above structural designs are often carried out in conjunction with composition optimization. By precisely controlling the CNT content, pore size and heterojunction density, efficient absorption with a reflection loss of less than -10 dB can be achieved over a wide frequency band [40,41].

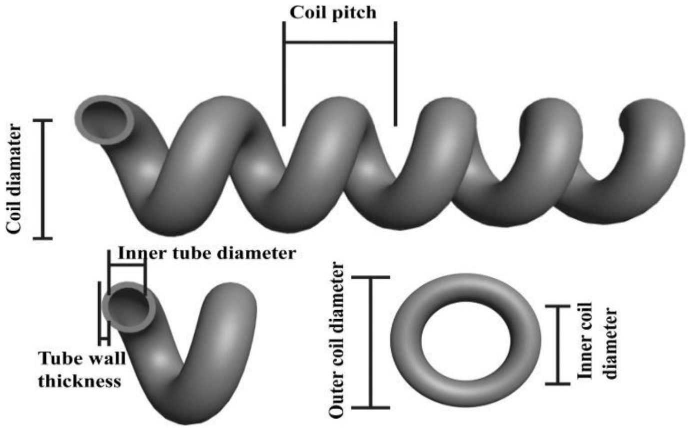

Figure 2: The structure diagram types of coiled carbon nanotubes [40]

3.2.3 CNT/fiber composite microwave absorbing material

Fiber materials are widely used in the field of composite materials due to their light weight, softness, high strength and large specific surface area. In recent years, they have also received more and more attention in the field of microwave absorbing materials. Using carbon nanotubes to modify the surface of fibers or doping them in bulk can significantly improve the electromagnetic wave absorption capacity of fiber-based microwave absorbing materials. At present, the preparation process of CNT modified fiber microwave absorbing materials mainly includes three strategies. The matrix/solution blending method directly disperses CNTs in polymer solutions or melts and obtains CNT modified fibers by wet spinning or electrospinning. For example, by using electrospinning-carbonization process to introduce magnetic metal nanoparticles and CNTs into carbon nanofibers at the same time, a three-dimensional core-shell structure nanofiber network can be formed. The optimized sample achieves a minimum reflection loss of -69.2 dB at 16.2 GHz and the effective absorption bandwidth is extended to 7.31 GHz [42]. The fiber surface growth/grafting method directly grows or grafts CNTs on the fiber surface through chemical vapor deposition (CVD) or hydrothermal synthesis. One-dimensional ultralight magnetic CNT spiral/chiral porous carbon fibers were sustainably prepared by catalytic self-deposition method, exhibiting excellent absorption performance in a wide temperature range of 700–800 °C. After growing Co particles and CNTs on the surface of SiC fibers, the sample achieved a minimum reflection loss of -70.22 dB at 11.21 GHz and an effective absorption bandwidth of 6.03 GHz at a thickness of 1.71 mm, covering the entire Ku band [43]. Core- shell structured CNT@Ni-CNT fibers were prepared by coaxial wet spinning. Ni coating significantly improved impedance matching, and the inner gradient conductive network effectively promoted the entry of electromagnetic waves, achieving an electromagnetic shielding performance of 20.07 dB and a strain sensitivity of 81.58 % [44]. Macro-CNT aggregate intercalation method introduced macro-CNT aggregates into the fiber interlayer to construct a three-dimensional interconnected conductive network. Using polypropylene fiber as a precursor, graded hollow porous carbon fiber was prepared by regulating the sulfuric acid treatment time. The autocatalytic effect of Fe in high-temperature carbonization was used to realize the synchronous growth of CNT on the surface and inside of HPCF. The composite material achieved a minimum reflection loss of -54.03 dB at a thickness of 1.9 mm and an effective absorption bandwidth of 6.04 GHz at a thickness of 1.8 mm, covering the entire Ku band [45]. The dispersion uniformity of CNT, the interfacial bonding strength between the fiber and the matrix, and the cost control of large-scale production are the main challenges currently facing CNT modified fiber absorbing materials to practical applications. In the future, while increasing production, it is necessary to optimize the materials and structure for practical applications and establish relevant standards.

Table 1: Summary of Performance of CNT/fiber composite absorbing materials

Materials	Frequency	RL min/EMI SE	EAB	Ref
Ni–CNT/CNFs(7)	16.2 GHz	-69.2 dB	7.31 GHz	[42]
SiC@Co/CNT-30%	11.21 GHz	-70.22 dB	6.03 GHz	[43]
CNT20@Ni-CNT60 fibers	-	20.07 dB	-	[44]
CNTs@ HPCFs-1	11.37–15.45 GHz	-54.03 dB	6.04 GHz	[45]

3.3 Biomass -derived Carbon-based Microwave Absorbing Materials

3.3.1 Advantages and characteristics of biomass carbon sources

Biomass-derived carbon uses abundant plant, animal and microbial remains in nature as precursors, and has outstanding advantages such as abundant resources, low cost, renewable sources and easy large-scale production. Compared with artificially synthesized carbon materials such as graphene and carbon nanotubes, the preparation of biomass carbon does not require complex and expensive chemical vapor deposition equipment, and can be obtained by high-temperature carbonization, which significantly reduces production costs. More importantly, biomass has formed a unique and precise natural porous structure in the long-term evolution process. These structures are preserved after carbonization, providing an ideal carbon skeleton for high-performance microwave absorbing materials. Natural multi-level channels help to reduce the effective dielectric constant to improve impedance matching, while extending the transmission path of electromagnetic waves and triggering multiple reflections and scattering. In addition, biomass itself is rich in heteroatoms such as O, N, and S. After carbonization, some heteroatoms remain in the carbon skeleton to form defects and polarization centers, further enhancing dielectric loss capability [46]. Therefore, biomass-derived carbon has comprehensive advantages such as low density, low cost, inheritable structure and self-doping, and is an important way to realize the preparation of green, efficient and large-scale microwave absorbing materials.

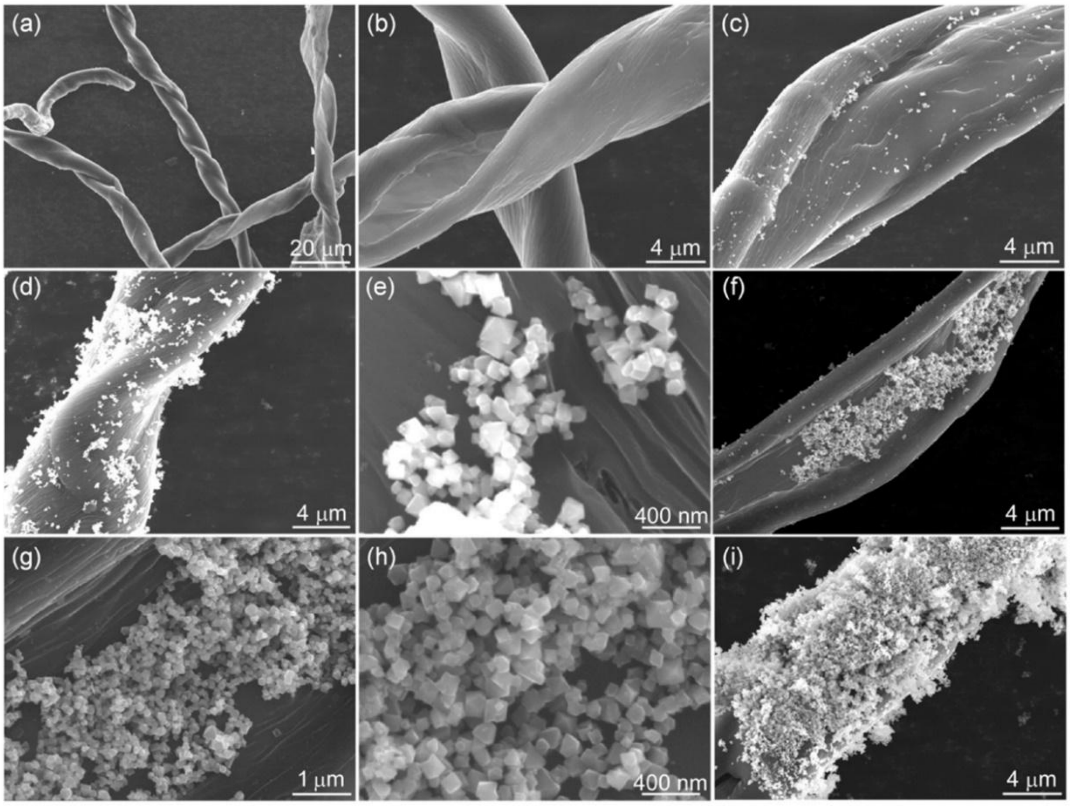

Figure 3: SEM images of the synthesized samples: (a,b) CCF, (c) NiFe2O4/CCF-1, (d,e) NiFe2O4/CCF-2, (fh) NiFe2O4/CCF-3, and (i) NiFe2O4/CCF-4 [46].

3.3.2 Removal valve

Using plant tissues such as wood, straw, cotton fiber, fruit shell, and corn stalk as precursors, and utilizing their inherent vascular bundle structure or cell wall network, the natural hierarchical porous morphology can be preserved after carbonization. By further constructing porous structures (such as KOH activation to create pores) and introducing magnetic components (Fe_3O_4, Ni, $CoFe_2O_4$, etc.) or conductive fillers (CNT, graphene, etc.), the synergistic absorption of dielectric loss and magnetic loss can be achieved. For example, after lignin removal and Fe^{3+} impregnation, lignocarbon can be carbonized to obtain Fe/Fe_3O_4 loaded hierarchical porous carbon, which exhibits excellent broadband absorption performance at low filling amounts [47]. Using chitosan, proteins (such as gelatin and silk fibroin), feathers, and animal bones as precursors, these materials are naturally rich in nitrogen (amide groups in proteins and amino groups in chitosan). After activation with metal salts (such as $FeCl_3$, $Co(NO_3)_2$, and $ZnCl_2$) and high-temperature carbonization, honeycomb or foam-like carbon frameworks rich in N/O heteroatom doping can be obtained. During carbonization, the metal salts act as activators for etching and pore creation, and can also be reduced to magnetic metal nanoparticles, uniformly anchored in the carbon matrix. Heteroatom doping enhances dipole polarization and defect-induced polarization, while magnetic particles contribute magnetic loss, synergistically improving microwave absorption performance. Using mycelia (fungal filamentous networks), bacterial cellulose, yeast, and other microorganisms as templates or precursors, biomass precursors with a three-dimensional interconnected network structure can be obtained through cultivation. After carbonization, low-density, high-porosity, and structurally tunable carbon materials are obtained. Bacterial cellulose is composed of interwoven nanofibers that, upon carbonization, form a three-dimensional nano-carbon network with a high specific surface area and rich in oxygen-containing functional groups. The mycelium retains its filamentous branching structure after carbonization, constructing macroscopic porous carbon blocks. This type of material can achieve an ideal lightweight microwave absorbing structure without additional pore-forming agents and can be further composited with magnetic nanoparticles to enhance its attenuation capabilities.

4. MULTI-SCALE STRUCTURAL DESIGN STRATEGIES

4.1 Microscale

4.1.1 Element Doping

At the microscale, heteroatom doping is an effective means of controlling the electrical properties and polarization loss of carbon materials. Introducing heteroatoms such as N, B, S, and P into the carbon framework can break the charge symmetry distribution of intrinsic carbon materials, generate local dipole moments, and thus enhance dipole polarization loss. At the same time, the introduction of heteroatoms will change the band structure and carrier concentration of carbon materials, and achieve fine adjustment of conductivity. Excessive conductivity can easily lead to impedance mismatch. Moderate doping can reduce the effective dielectric constant and improve the electromagnetic wave penetration capability [48]. Taking nitrogen doping as an example, nitrogen with different configurations produces different charge distributions in the carbon lattice, which can trigger multiple polarization relaxation processes and broaden the effective absorption bandwidth [49]. Boron doping, due to the electron-deficient characteristics of boron atoms, can induce the formation of positive charge centers in the carbon framework and enhance polarization response [50]. Sulfur doping, due to the large atomic radius of sulfur atoms, will introduce out-of-plane distortion and structural defects in the carbon layer, further enriching the polarization sites [51]. By controlling the type, concentration, and method of dopant, the dielectric constant and polarization loss can be adjusted as needed over a wide frequency range, providing a flexible micro-control tool for the design of high-performance carbon-based microwave absorbing materials.

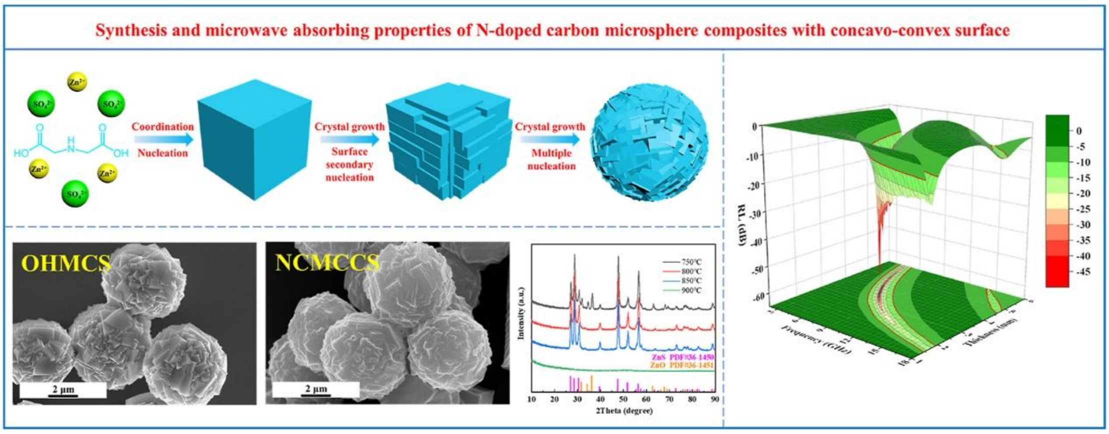

Figure 4: Morphology characterization and microwave absorption performance plots of nitrogen doping [49]

4.1.2 Interface Engineering

Interface engineering significantly enhances the polarization loss and scattering effect of carbon-based microwave absorbing materials by constructing heterogeneous interfaces and introducing microstructural defects. Heterogeneous interface construction involves combining carbon materials with dielectric or magnetic components such as metal oxides, sulfides, MXene, and conductive polymers, forming numerous interfaces between different phases. Due to the differences in conductivity and dielectric constant among the phases, free carriers accumulate at the interfaces under an alternating electric field, generating space charge polarization, also known as Maxwell-Wagner polarization, whose relaxation process efficiently dissipates electromagnetic energy. Furthermore, multilayer or multi-component interface designs, such as core-shell structures and sandwich structures, can generate multiple interface polarizations, broadening the effective absorption bandwidth. Defect engineering intentionally introduces microstructural defects such as vacancies, edge dislocations, topological defects, or residual functional groups into the carbon lattice. These defects disrupt the periodic charge distribution of the carbon framework, forming localized dipoles that undergo orientation relaxation under an external electric field, enhancing dipole polarization loss. Simultaneously, defect sites can act as scattering centers for electromagnetic waves, causing diffuse reflection of incident waves and extending the propagation path. By controlling the type and density of defects, such as adjusting the carbonization temperature, acid oxidation treatment, and plasma etching, the synergistic optimization of polarization loss and scattering loss can be achieved. Interface engineering and defect engineering often work together. The heterogeneous interface is often accompanied by lattice mismatch and dangling bonds, which further enrich the defect density. The two work together to promote the efficient attenuation of electromagnetic wave energy [52,53].

4.2 Mesoscale

At the mesoscale, from tens of nanometers to micrometers, structural units such as MXene, MOF, and heterogeneous continuous fibers can be constructed through in-situ multi-level assembly strategies, which can effectively enhance the conductivity and interfacial loss of carbon-based microwave absorbing materials. MXene, such as $Ti_3C_2T_x$, has high conductivity and abundant surface functional groups. Its two-dimensional nanosheets can be stacked into layered, wrinkled, or aerogel-like structures at the mesoscale through self-assembly or template method, forming an efficient conductive network. At the same time, the interlayer gaps and surface end groups provide a large number of interfacial polarization sites [54]. Metal-organic frameworks (MOFs) are formed by the periodic coordination of metal nodes and organic ligands. Their mesoscale morphology, such as dodecahedrons, cubes, and nanorods, can be precisely controlled by adjusting the synthesis conditions. After in-situ carbonization, the porous carbon derived from MOF can retain its original morphology and form a composite structure of metal and carbon. Metal nanoparticles are uniformly embedded in the carbon matrix, generating abundant metal-carbon interfaces and enhancing interfacial polarization. At the same time, the three-dimensional interconnected porous structure is beneficial to conductivity loss and multiple reflections. Heterogeneous continuous fibers, such as composites of carbon fibers and CNTs, or composites of carbon fibers and MOF-derived carbons, construct gradient conductive or gradient dielectric structures from the inside out at the mesoscale by in-situ growth or coating of other functional components on the fiber surface. This hierarchical assembly not only improves the overall conductivity and forms a continuous conductive path, but also introduces multi-level heterogeneous interfaces, such as fiber-coating interfaces and coating-air interfaces, significantly enhancing interfacial polarization losses. Mesoscale in-situ multi-level assembly connects microscopic chemical composition with macroscopic structural performance, serving as a key bridge for achieving synergistic optimization of conductivity and dielectric loss in carbon-based microwave absorbing materials.

4.3 Macroscale

4.3.1 Aerogel Structure

Carbon-based aerogels are a class of macroscopic microwave absorbing materials with three-dimensional interconnected conductive networks and diverse porous microstructures. Their ultra-low density, continuous conductive skeleton and rich pore features can effectively reduce the effective dielectric constant, thereby optimizing impedance matching. At the same time, they can efficiently dissipate electromagnetic wave energy through the synergistic effect of multiple loss mechanisms such as conductivity loss, polarization loss and multiple reflection and scattering. According to different preparation paths, the construction strategies of carbon-based aerogels are mainly divided into three categories. The first category is the hard template method, which uses natural biomass such as wood, cotton or polymer foam such as melamine foam as a sacrificial skeleton. After carbonization, the template is removed to obtain porous carbon- based aerogels [55]. The second category is the soft template method, which mainly uses isotropic or directional freeze-drying technology to control the orientation and size of the pores by controlling the growth direction of ice crystals, forming a layered or honeycomb structure [56]. The third category is the non-template method, which includes electrospinning combined with carbonization and three-dimensional printing technology, which can realize the precise design of the macroscopic shape and microscopic pores of aerogels [57]. The above methods each have their own advantages and can be flexibly selected or combined according to the requirements of the target microwave absorption performance, providing a wealth of technical paths for the development of lightweight, efficient, and structurally controllable carbon-based microwave absorbing materials.

4.3.2 Metamaterial Structures

Metamaterials can effectively broaden the absorption bandwidth by exciting resonance effects in specific frequency bands through periodic structural design. Unlike traditional absorbing materials that rely on intrinsic electromagnetic parameters, the electromagnetic response of metamaterials mainly comes from their subwavelength scale artificial structural units. By precisely designing the shape, size and arrangement of the units, special electromagnetic properties such as negative permittivity and negative permeability can be achieved in the target frequency band, thereby generating strong resonant absorption [58]. This design not only breaks through the bottleneck of bandwidth limitation of traditional absorbing materials, but also maintains the advantages of lightweight and tunable carbon-based materials, providing a new idea for the development of broadband and efficient absorbing structures.

4.3.3 Bionic Structure

Inspired by nature, biomimetic structural design has shown unique advantages in the optimization of wave absorption performance. In nature, organisms have evolved over a long period of time to form a variety of efficient energy manipulation structures, such as the multi-level papillae on the surface of lotus leaves, the periodic scales of butterfly wings, the spiral stacking of mantis shrimp claws, and the hexagonal lightweight structure of honeycomb. By introducing these topological features into the design of carbon-based wave-absorbing materials, impedance matching optimization, multiple reflection enhancement and broadband absorption can be achieved simultaneously. The effectiveness of biomimetic structures depends not only on the shape and size of the structural units, but also on the accurate reproduction of natural forms by the fabrication process. Therefore, structural selection and process design need to be coordinated and controlled: on the one hand, select appropriate biological prototypes and abstract key geometric parameters according to the electromagnetic wave characteristics of the target frequency band; on the other hand, use advanced manufacturing technologies such as template method, three-dimensional printing or ice template to achieve the shape-preserving construction of biomimetic structures. Only through the deep integration of structure and process can the potential of biomimetic design in electromagnetic wave absorption be fully realized [59].

4.3.4 Honeycomb and Sandwich Structures

The design of sandwich honeycomb structures and surface metastructures enables carbon-based absorbing materials to possess both excellent electromagnetic wave absorption performance and superior mechanical load-bearing capacity. Sandwich honeycomb structures typically consist of two high-strength panels on the top and bottom, with a honeycomb core layer in between. The unique hexagonal periodic lattice of the honeycomb core layer not only significantly reduces material density but also provides excellent compressive and bending resistance. There are two main ways to incorporate absorption functionality into this structure: one is to directly fabricate the honeycomb core layer using carbon-based composite materials, utilizing the multiple reflections of electromagnetic waves and dielectric loss through the pore walls to achieve absorption; the other is to embed absorbing fillers such as graphene, carbon nanotubes, or magnetic particles into the honeycomb core layer or panels. Surface metastructures, on the other hand, involve designing subwavelength-scale periodic or quasi-periodic patterns on the material surface, such as mushroom-shaped, pyramidal, or grid-like structures. These metastructures can modulate the equivalent electromagnetic parameters of the surface, improve impedance matching, and broaden the absorption bandwidth through local resonance and diffraction effects. More importantly, surface metastructures can act as a protective layer against external forces and environmental erosion. By integrating sandwich honeycomb with surface metastructure, the material can achieve absorption performance with reflection loss of less than -10 dB over a wide frequency range, while meeting the requirements of lightweighting and structural load-bearing in aerospace, high-speed train and other fields. This synergistic design strategy of structure and function provides an effective way to develop multifunctional composite materials with both wave absorption and mechanical properties [60].

5. CHALLENGES AND OUTLOOK

5.1 Major Challenges Currently Faced

Despite significant progress in the research of carbon-based microwave absorbing materials, several key challenges remain before practical applications. First, the contradiction between the single loss mechanism of carbon-based materials and impedance matching has not been fundamentally resolved. Pure carbon materials primarily rely on dielectric loss, lacking magnetic loss, and excessively high dielectric constants can easily lead to severe impedance mismatch. Even with composite modification, achieving both low reflection loss and a wide effective absorption bandwidth across a broad frequency range remains challenging. Second, efficient absorption in the low-frequency band remains a bottleneck. This band has longer wavelengths, placing more stringent requirements on the dielectric constant and thickness of the material. However, carbon-based materials often exhibit insufficient dielectric dispersion characteristics at low frequencies, resulting in a significant decrease in absorption performance, making it difficult to meet the practical needs of radar stealth and communication anti-jamming. Third, the difficulty of large-scale fabrication and cost control are prominent issues. High-performance carbon-based materials at the laboratory level often rely on complex synthesis routes (such as MOF templates, CVD growth, freeze-drying, etc.), resulting in poor batch stability, low yield, and high energy consumption. During the scaling-up from gram-level laboratory to kilogram-level or even ton-level industrial applications, uncontrollable changes in microstructure and absorption performance are likely to occur. Finally, the complexity of multifunctional synergistic design is increasingly evident. Practical applications often require microwave absorbing materials to possess multiple functions simultaneously, including lightweight, mechanical load-bearing capacity, thermal management, corrosion resistance, and self-healing. However, the requirements for material structure and composition may conflict between these different functions (e.g., high conductivity is beneficial for microwave absorption but detrimental to infrared stealth). Achieving synergistic compatibility of multiple functions through multi-scale structural design, rather than mutual constraints, is a current research challenge. These challenges are interconnected and require collaborative efforts at multiple levels, including fundamental theory, materials processing, and system integration.

5.2 Future Development Direction

5.2.1 Green and efficient preparation

In terms of green and efficient preparation, developing milder, lower-energy-consumption biomass activation and modification processes is key to promoting the development of low-cost, sustainable microwave absorption technology. Traditional biomass carbonization often requires high-temperature treatment and uses highly corrosive activators such as KOH and H_3PO_4, which not only consumes a lot of energy but also generates a large amount of waste liquid and gas. Future research should focus on developing environmentally friendly activation strategies, such as using low-corrosive salts like calcium chloride and potassium carbonate as mild activators, or utilizing the gases and water vapor generated by the pyrolysis of biomass itself to achieve self-activation. Low-temperature hydrothermal carbonization combined with subsequent short-time pyrolysis can obtain oxygen-rich functional group carbon precursors at lower temperatures, reducing energy input. Microwave-assisted pyrolysis technology can achieve rapid bulk phase heating, significantly shortening processing time and reducing energy consumption. In addition, using industrial waste such as distiller's grains, pharmaceutical residues, and sludge as carbon sources, and developing recyclable reaction media such as eutectic solvents, can further reduce raw material costs and environmental burden. By integrating and optimizing these green processes, it is hoped that large-scale, low-cost, and environmentally friendly preparation of high-performance carbon-based microwave absorbing materials can be achieved, thus promoting microwave absorbing technology from laboratory research to practical applications.

5.2.2 Low-frequency broadband absorption

Highly efficient low-frequency absorption in the S-band and C-band is an urgent need in radar stealth and communication anti-jamming fields. Long-range early warning radars and some ground reconnaissance radars operate in the S/C bands, and achieving stealth in this band can significantly improve the survivability of weapon platforms. Simultaneously, some frequency bands of 5G and future 6G communications also fall within this range, making low-frequency absorbing materials crucial for suppressing electromagnetic interference between base stations and terminals. However, carbon-based materials face significant challenges in the low-frequency region: according to transmission line theory, achieving low-frequency absorption requires large material thickness or extremely high dielectric constants, but the dielectric dispersion characteristics of conventional carbon materials at low frequencies typically exhibit a high real part and a low imaginary part, leading to poor impedance matching and insufficient attenuation. To overcome this bottleneck, future research can focus on the following directions: First, constructing carbon/magnetic composite systems with strong magnetic loss, utilizing the natural resonance of magnetic components to supplement attenuation capabilities in the low-frequency region; second, designing hierarchical structures with long-range ordered conductive networks, such as three-dimensional graphene foams or carbon nanotube arrays, to extend the interaction time between electromagnetic waves and materials; third, employing metamaterials or frequency-selective surface design to excite magnetic dipole resonance through subwavelength artificial structures, achieving strong low-frequency absorption under subthickness conditions; and fourth, developing novel carbon-based nanocomposite materials with high dielectric imaginary parts and smooth low-frequency dispersion. The comprehensive application of these strategies is expected to break through the low-frequency absorption bottleneck, realizing thin, lightweight, wide-band, and strong carbon-based low-frequency absorbing materials.

5.2.3 New Material Systems with Multiphysics Response

The future development of carbon-based microwave absorbing materials will transcend the single function of electromagnetic wave absorption, evolving towards multi-physics response and multi-functional integration. By integrating microwave absorption with functions such as thermal management, mechanical enhancement, and sensing actuation into the same material system, the stringent requirements for comprehensive material performance in complex applications such as aerospace, wearable electronics, and smart skins can be met. Regarding the integration of microwave absorption and thermal management, porous carbon skeletons with high thermal conductivity channels can be designed to quickly dissipate heat while absorbing electromagnetic waves, preventing localized overheating. Conversely, low thermal conductivity carbon aerogels can be used to achieve integrated microwave absorption and thermal insulation for stealth protection in high-temperature environments. Regarding the integration of microwave absorption and mechanical enhancement, by constructing continuous fiber-reinforced carbon-based composite materials or biomimetic layered structures, the tensile strength, modulus, and fracture toughness of the material can be significantly improved while ensuring broadband absorption, achieving structural-functional integration. Furthermore, combining microwave absorption with intelligent response characteristics such as self-sensing and self-actuation can lead to the development of intelligent microwave absorbing materials that can actively adjust their absorption performance according to the external electromagnetic environment. The key to achieving these multi-physics responses lies in the multi-scale synergistic design of materials: controlling electronic structure and polarization properties at the atomic scale, constructing heterogeneous interfaces and conductive networks at the nanoscale, and designing mechanical support frameworks and thermal transport paths at the macroscale. Through cross-scale integrated design, the synergistic compatibility and optimal performance of multiple functions such as wave absorption, thermal management, and mechanics are ultimately achieved.

REFERENCES

[1] D. Ma, T.R. Lee, Meeting a Rising Need of Electromagnetic Interference Shielding with Nanomaterials, ACS Appl. Nano Mater. 7 (2024) 2414–2416. https://doi.org/10.1021/acsanm.3c06009.
[2] Y. Bai, B. Xie, H. Li, R. Tian, Q. Zhang, Mechanical properties and electromagnetic absorption characteristics of foam Cement-based absorbing materials, Construction and Building Materials 330 (2022) 127221. https://doi.org/10.1016/j.conbuildmat.2022.127221.
[3] C. Guan, S. Su, B. Wang, J. Zhong, J. Chen, F. Sun, L. Zhan, Electromagnetic stealth technology: A review of wave-absorbing structures, Materials & Design 253 (2025) 113891. https://doi.org/10.1016/j.matdes.2025.113891.
[4] X. Zeng, X. Cheng, R. Yu, G.D. Stucky, Electromagnetic microwave absorption theory and recent achievements in microwave absorbers, Carbon 168 (2020) 606–623. https://doi.org/10.1016/j.carbon.2020.07.028.
[5] K. Tian, Y. Huang, J. Wang, C. Zhang, R. Shu, Z. Chen, X. Liu, Y. Li, L. Xu, Carbon cloth based flexible electromagnetic wave absorbing materials loaded with Co3O4 array and tunable electromagnetic wave absorption performance, Journal of Colloid and Interface Science 649 (2023) 675–684. https://doi.org/10.1016/j.jcis.2023.06.131.
[6] Y. Liu, S. Hao, H. Wu, S. Cai, J. Xie, Efficient preparation of high-frequency wave-absorbing SiC/graphene composite powder, Journal of Materials Science: Materials in Electronics 37 (2026) 235. https://doi.org/10.1007/s10854-026-16654-w.
[7] M. Ling, F. Wu, P. Liu, Q. Zhang, B. Zhang, Fabrication of Graphdiyne/Graphene Composite Microsphere with Wrinkled Surface via Ultrasonic Spray Compounding and its Microwave Absorption Properties, Small 19 (2023) 2205925. https://doi.org/10.1002/smll.202205925.
[8] C. Liu, J. Lin, N. Wu, C. Weng, M. Han, W. Liu, J. Liu, Z. Zeng, Perspectives for electromagnetic wave absorption with graphene, Carbon 223 (2024) 119017. https://doi.org/10.1016/j.carbon.2024.119017.
[9] X. Chen, H. Liu, D. Hu, H. Liu, W. Ma, Recent advances in carbon nanotubes-based microwave absorbing composites, Ceramics International 47 (2021) 23749–23761. https://doi.org/10.1016/j.ceramint.2021.05.219.
[10] Z.G. Sun, X.J. Qiao, X. Wan, Q.G. Ren, W.C. Li, S.Z. Zhang, X.D. Guo, The synthesis and microwave absorbing properties of MWCNTs and MWCNTs/ferromagnet composites, Applied Physics A 122 (2016) 87. https://doi.org/10.1007/s00339-016-9598-5.
[11] C. Mingdong, Y. Huangzhong, J. Xiaohua, L. Yigang, Optimization on microwave absorbing properties of carbon nanotubes and magnetic oxide composite materials, Applied Surface Science 434 (2018) 1321–1326. https://doi.org/10.1016/j.apsusc.2017.11.107.
[12] Y. Chen, R. Qiang, Y. Shao, J. Qiu, Q. Ma, X. Yang, R. Xue, B. Chen, S. Feng, Y. Ding, Biomass-derived Fe/C composites for broadband electromagnetic wave response, Journal of Alloys and Compounds 968 (2023) 171952. https://doi.org/10.1016/j.jallcom.2023.171952.
[13] X. Lin, Y. Zhou, J. Hong, X. Wei, B. Liu, C.-C. Wang, Facile preparation of ZIF-8/ZIF-67-derived biomass carbon composites for highly efficient electromagnetic wave absorption, Chinese Chemical Letters 35 (2024) 109835. https://doi.org/10.1016/j.cclet.2024.109835.
[14] J. Jing, Y. Xiong, S. Shi, H. Pei, Y. Chen, P. Lambin, Facile fabrication of lightweight porous FDM-Printed polyethylene/graphene nanocomposites with enhanced interfacial strength for electromagnetic interference shielding, Composites Science and Technology 207 (2021) 108732. https://doi.org/10.1016/j.compscitech.2021.108732.

[15] Y. Shi, B. Liang, H. Gao, R. Zhao, Q. Dong, T. Li, Y. Ma, W. Gao, J. Zhang, J. Gu, S. Melhi, M. Shalash, Z.M. El-Bahy, Z. Guo, Research progress on spherical carbon-based electromagnetic wave absorbing composites, Carbon 227 (2024) 119244. https://doi.org/10.1016/j.carbon.2024.119244.

[16] Y. Wang, X. Zhou, H. Gu, S. Yang, X. Long, S. Zhai, Q. Sun, Preparation and properties of starch-based carbon aerogel/FeCoNi composite wave-absorbing materials, RSC Adv. 16 (2026) 15609–15625. https://doi.org/10.1039/D6RA00299D.

[17] F. Luo, D. Liu, T. Cao, H. Cheng, J. Kuang, Y. Deng, W. Xie, Study on broadband microwave absorbing performance of gradient porous structure, Advanced Composites and Hybrid Materials 4 (2021) 591–601. https://doi.org/10.1007/s42114-021-00275-4.

[18] J. Zhao, J. Zhang, L. Wang, S. Lyu, W. Ye, B.B. Xu, H. Qiu, L. Chen, J. Gu, Fabrication and investigation on ternary heterogeneous MWCNT@TiO2-C fillers and their silicone rubber wave-absorbing composites, Composites Part A: Applied Science and Manufacturing 129 (2020) 105714. https://doi.org/10.1016/j.compositesa.2019.105714.

[19] J. Wang, Y. Huyan, Z. Yang, A. Zhang, Q. Zhang, B. Zhang, Tubular carbon nanofibers: Synthesis, characterization and applications in microwave absorption, Carbon 152 (2019) 255–266. https://doi.org/10.1016/j.carbon.2019.06.048.

[20] X. Wang, Z. Du, M. Hou, Z. Ding, C. Jiang, X. Huang, J. Yue, Approximate solution of impedance matching for nonmagnetic homogeneous absorbing materials, The European Physical Journal Special Topics 231 (2022) 4213–4220. https://doi.org/10.1140/epjs/s11734-022-00570-1.

[21] C. Liu, Y. Tong, C. Liu, H. Sun, Q. Hu, S. Wu, Y. Zhao, J. Li, X. Guo, Y. Feng, Impedance matching optimization mechanism of SiBCN(Ni) absorbing fibers with Ni as catalyst, Ceramics International 50 (2024) 15965–15975. https://doi.org/10.1016/j.ceramint.2024.02.076.

[22] Y. Feng, T. Li, K. Ge, X. Wang, G. Wen, J. Ye, L. Xia, Impedance matching strategy boost excellent wave absorption performance of zinc-Aluminosilicate cladded short carbon fiber core-sheath structure, Materials Research Bulletin 153 (2022) 111872. https://doi.org/10.1016/j.materresbull.2022.111872.

[23] Y. He, X. Li, D. Liu, W. Fu, Q. Su, B. Zhong, L. Xia, X. Huang, Tuning N-doping to balance conductivity and polarization relaxation: A strategy for converting SiO2 from an electromagnetic wave-transmitting to absorbing material, Applied Surface Science 639 (2023) 158151. https://doi.org/10.1016/j.apsusc.2023.158151.

[24] Z. Ye, R. Luo, L. Wang, H. Yang, Z. Ye, J. Wang, X. Dong, X. Yang, J. Huang, Effects of high-temperature pre-oxidation treatment on the wave-absorbing properties of SiC fibers, Ceramics International 51 (2025) 20755–20764. https://doi.org/10.1016/j.ceramint.2025.02.242.

[25] Y. Zhao, Z. Lin, L. Huang, Z. Meng, H. Yu, X. Kou, Z. Zou, P. Huang, Y. Wang, D. Xi, P. Yin, G. Su, Z. Fan, Z. Su, D. Xu, L. Pan, L. Xu, Simultaneous optimization of conduction and polarization losses in CNT@NiCo compounds for superior electromagnetic wave absorption, Journal of Materials Science & Technology 166 (2023) 34–46. https://doi.org/10.1016/j.jmst.2023.04.045.

[26] J. Lu, X. Zhang, X. Yan, D. Liu, L. Wang, Y. Wang, X. Huang, G. Wen, Sodium citrate-induced generation of multi-interfacial embroidered spherical SnO2 for augmented electromagnetic wave absorption, J. Mater. Chem. C 11 (2023) 4855–4866. https://doi.org/10.1039/D3TC00229B.

[27] L. Yuan, W. Zhao, Y. Miao, C. Wang, A. Cui, Z. Tian, T. Wang, A. Meng, M. Zhang, Z. Li, Constructing core-shell carbon fiber/polypyrrole/CoFe2O4 nanocomposite with optimized conductive loss and polarization loss toward efficient electromagnetic absorption, Advanced Composites and Hybrid Materials 7 (2024) 70. https://doi.org/10.1007/s42114-024-00864-z.

[28] S. Wei, X. Wang, B. Wang, Y. Wang, Y. Liang, Z. Liu, H. Zhang, Q. Xu, H. Mou, Constructing and optimizing epoxy resin-based carbon Nanotube/Barium ferrite microwave absorbing coating system, Materials Research Bulletin 179 (2024) 112928. https://doi.org/10.1016/j.materresbull.2024.112928.

[29] Y. Zeng, L. Long, J. Yu, Y. Li, Y. Li, W. Zhou, High-efficiency electromagnetic wave absorption of lightweight Nb2O5/CNTs/polyimide with excellent thermal insulation and compression resistance integration, Composites Science and Technology 250 (2024) 110531. https://doi.org/10.1016/j.compscitech.2024.110531.

[30] Z. Zhong, B. Zhang, J. Ye, Y. Ren, F. Ye, Tailorable microwave absorption properties of macro-porous core@shell structured SiC@Ti3SiC2 via molten salt shielded synthesis (MS3) method in air, Journal of Alloys and Compounds 927 (2022) 167046. https://doi.org/10.1016/j.jallcom.2022.167046.

[31] J. Zhang, P. Wang, G. Wang, B. Duan, T. Wang, F. Li, Investigation on the absorption performance by separated electromagnetic waves reflected from different interfaces of absorber, Journal of Magnetism and Magnetic Materials 498 (2020) 166096. https://doi.org/10.1016/j.jmmm.2019.166096.

[32] H.T. Yudistira, K. Kananda, The Preliminary Microwave Metamaterial Absorber Based on Ring-Shaped for Stealth Technology, IOP Conference Series: Earth and Environmental Science 1209 (2023) 012028. https://doi.org/10.1088/1755-1315/1209/1/012028.

[33] M. Sathish Kumar, A. Joseph, K.C. James Raju, R. Jayavel, Engineering multifunctionality graphene-based nanocomposites with epoxy-silane functionalized cardanol for next-generation microwave absorber, Journal of Colloid and Interface Science 678 (2025) 407–420. https://doi.org/10.1016/j.jcis.2024.08.193.

[34] X. Guo, Q. Wei, P. Zhang, P.K. Shen, Z.Q. Tian, 3D Porous Graphene with Atomic Fe Coordinated by Pyrrole-N Dopants for Efficient Electromagnetic Wave Absorption with Low Filler Loading and Thin Thickness, Small 21 (2025) 2501189. https://doi.org/10.1002/smll.202501189.

[35] Z. Liu, B. Wang, S. Wei, W. Huang, Y. Wang, Y. Liang, X. Wang, Z. Yang, Controlled self-assembled FeNi alloy/graphene foam composite for lightweight and broadband microwave absorption, J. Mater. Chem. C 13 (2025) 17662–17673. https://doi.org/10.1039/D5TC02072G.

[36] Y. Shi, X. Gao, J. Qiu, Synthesis and strengthened microwave absorption properties of three-dimensional porous Fe3O4/graphene composite foam, Ceramics International 45 (2019) 3126–3132. https://doi.org/10.1016/j.ceramint.2018.10.212.

[37] J. Yan, Y. Huang, X. Chen, C. Wei, Conducting polymers-NiFe2O4 coated on reduced graphene oxide sheets as electromagnetic (EM) wave absorption materials, Synthetic Metals 221 (2016) 291–298. https://doi.org/10.1016/j.synthmet.2016.09.018.

[38] D. Lei, C. Liu, C. Dong, S. Wang, P. Zhang, Y. Li, J. Liu, Y. Dong, C. Zhou, Reduced Graphene Oxide/MXene/FeCoC Nanocomposite Aerogels Derived from Metal–Organic Frameworks toward Efficient Microwave Absorption, ACS Appl. Nano Mater. 7 (2024) 230–242. https://doi.org/10.1021/acsanm.3c04301.

[39] K. Zhang, X. Chen, X. Gao, L. Chen, S. Ma, C. Xie, X. Zhang, W. Lu, Preparation and microwave absorption properties of carbon nanotubes/iron oxide/polypyrrole/carbon composites, Synthetic Metals 260 (2020) 116282. https://doi.org/10.1016/j.synthmet.2019.116282.

[40] J. Feng, Y. Wang, Y. Hou, J. Li, L. Li, Synthesis and microwave absorption properties of coiled carbon nanotubes/CoFe2O4 composites, Ceramics International 42 (2016) 17814–17821. https://doi.org/10.1016/j.ceramint.2016.08.110.

[41] Q. Yang, L. Liu, D. Hui, M. Chipara, Microstructure, electrical conductivity and microwave absorption properties of γ-FeNi decorated carbon nanotube composites, Composites Part B: Engineering 87 (2016) 256–262. https://doi.org/10.1016/j.compositesb.2015.09.056.

[42] Y. Wang, Y. Liu, S. Yuan, H. Huang, Z. Wu, L. Xu, Y. Zhao, Optimizing electromagnetic wave absorption in electrospun carbon-based fibers through dielectric and magnetic component modulation, Inorg. Chem. Front. 12 (2025) 786–800. https://doi.org/10.1039/D4QI02776K.

[43] Z. Zhao, Z. Ma, Z. Ding, Y. Liu, M. Zhang, C. Jiang, Synergistic effect and heterointerface engineering of cobalt/carbon nanotubes enhancing electromagnetic wave absorbing properties of silicon carbide fibers, Nano Research 17 (2024) 8479–8486. https://doi.org/10.1007/s12274-024-6780-5.

[44] Y. Shao, L. Zou, Y. Chen, L. Wang, L. Song, H. Xu, P. Yang, Core-sheath structured CNT@Ni-CNT fiber-based multifunctional fabric with high-sensitivity, wide-range strain sensing, and enhanced electromagnetic shielding absorption, Chemical Engineering Journal 512 (2025) 162358. https://doi.org/10.1016/j.cej.2025.162358.

[45] M. Yang, Y. Deng, M. Zhang, S. Zhou, C. Liu, X. Jian, Y. Chen, Simple preparation of 1D hierarchical magnetic CNTs/hollow porous macroscopic carbon fiber composites for efficient microwave absorption, J. Mater. Chem. A 12 (2024) 24682–24693. https://doi.org/10.1039/D4TA03562C.

[46] W. Li, F. Guo, Y. Zhao, Y. Liu, A Sustainable and Low-Cost Route to Design NiFe2O4 Nanoparticles/Biomass-Based Carbon Fibers with Broadband Microwave Absorption, Nanomaterials 12 (2022) 4063. https://doi.org/10.3390/nano12224063.

[47] Z. Lou, Q. Wang, W. Sun, J. Liu, H. Yan, H. Han, H. Bian, Y. Li, Regulating lignin content to obtain excellent bamboo-derived electromagnetic wave absorber with thermal stability, Chemical Engineering Journal 430 (2022) 133178. https://doi.org/10.1016/j.cej.2021.133178.

[48] S. Zhang, J. Zheng, X. Liang, D. Lan, L. Niu, X. Zhao, Z. Zhao, S. Zhang, G. Wu, X. Li, Phosphorus-Driven Heteroatom Doping in Mesoporous Carbon Hollow Platelets Enables Efficient Electromagnetic Wave Absorption, Small 21 (2025) e09237. https://doi.org/10.1002/smll.202509237.

[49] J. Wang, J. Ren, Q. Li, Y. Liu, Q. Zhang, B. Zhang, Synthesis and microwave absorbing properties of N-doped carbon microsphere composites with concavo-convex surface, Carbon 184 (2021) 195–206. https://doi.org/10.1016/j.carbon.2021.08.021.

[50] M. Ding, Y. Liu, X. Lu, Y. Li, W. Tang, Boron doped diamond films: A microwave attenuation material with high thermal conductivity, Applied Physics Letters 114 (2019) 162901. https://doi.org/10.1063/1.5083079.

[51] Q. Pang, Z. Zhou, K. Cao, Z. Chen, Y. Zhang, X. Yang, W. Ye, C. Zheng, Y. Yang, R. Zhao, W. Xue, Eco-friendly N/S-doped synthesis of armor-like carbon fibers from waste wipes for broadband microwave absorption, Surfaces and Interfaces 72 (2025) 107334. https://doi.org/10.1016/j.surfin.2025.107334.

[52] M. Qin, Q. Ye, X. Cai, J. Cai, H. Wu, Interface engineering by redox reaction on ferrites to prepare efficient electromagnetic wave absorbers, Journal of Materials Science & Technology 188 (2024) 1–10. https://doi.org/10.1016/j.jmst.2023.10.065.

[53] Z. Zhao, Z. Ma, Z. Ding, Y. Liu, M. Zhang, C. Jiang, Synergistic effect and heterointerface engineering of cobalt/carbon nanotubes enhancing electromagnetic wave absorbing properties of silicon carbide fibers, Nano Research 17 (2024) 8479–8486. https://doi.org/10.1007/s12274-024-6780-5.

[54] X. Wang, C. Zhao, C. Li, Y. Liu, S. Sun, Q. Yu, B. Yu, M. Cai, F. Zhou, Progress in MXene-based materials for microwave absorption, Journal of Materials Science & Technology 180 (2024) 207–225. https://doi.org/10.1016/j.jmst.2023.08.064.

[55] W. Chu, K. Wang, S. Liu, Y. Chen, H. Li, H. Liu, Tailorable effective microwave absorption bandwidth of chitosan-derived carbon-based aerogel under different compression, Materials Research Bulletin 177 (2024) 112857. https://doi.org/10.1016/j.materresbull.2024.112857.

[56] T. Huang, Z. Wu, J. Lin, Q. Yu, D. Tan, L. Li, A Facile Freeze-Drying Strategy To Prepare Hierarchically Porous Co/C Foams with Excellent Microwave Absorption Performance, ACS Appl. Electron. Mater. 1 (2019) 2541–2550. https://doi.org/10.1021/acsaelm.9b00565.

[57] B. Li, J. Qiao, Y. Liu, H. Tian, W. Liu, Q. Wu, Z. Wang, J. Liu, Z. Zeng, Research on Electromagnetic Wave Absorption Based on Electrospinning Technology†, Chinese Journal of Chemistry 42 (2024) 777–789. https://doi.org/10.1002/cjoc.202300577.

[58] Y. Yang, X. Shi, Q. Zhou, G. Deng, W. Li, C. Li, T. Yang, L. Yin, Structural design and electromagnetic wave absorbing performance optimization of lightweight foam cement-based metamaterials, Construction and Building Materials 438 (2024) 137191. https://doi.org/10.1016/j.conbuildmat.2024.137191.

[59] S. Wu, X. Xu, D. Li, Multifunctional layered absorbing structures with ultra-wideband absorption derived from bio-inspired microwave absorbers, Applied Materials Today 45 (2025) 102796. https://doi.org/10.1016/j.apmt.2025.102796.

[60] Y. Zhao, Y. Shan, G. Ji, Y. Sun, W. Shi, M. Li, Enhanced Microwave-Absorbing Property of Honeycomb Sandwich Structure with a Significant Interface Effect, Materials 15 (2022) 5741. https://doi.org/10.3390/ma15165741.