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Design of mesoscopic metacomposites for electromagnetic wave absorption: enhancing performance and gaining mechanistic insights

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Abstract

The increasing issue of electromagnetic pollution necessitates the development of high-efficiency microwave absorbing materials. Traditional composites present challenges due to temperature sensitivity, complicating impedance matching and loss capabilities across varying temperatures. Rather than concentrating on the micro-scale structures and components typical in traditional design strategies, mesoscopic metacomposites have garnered significant attention due to their capacity to enhance microwave absorption and impedance matching through a discrete distribution of subwavelength-scale functional units in the composites. This review focuses on the applications of mesoscopic metacomposites in improving microwave absorbing performance. The discrete arrangement of subwavelength units improves anti-reflection effects and provides significant intrinsic loss capacity, enabling strong attenuation and effective impedance matching. Additionally, mesoscopic metacomposites facilitate controlled reflection and scattering of electromagnetic waves by carefully designing conductivity, dimensions, and spatial configurations. This presents groundbreaking methods for the further enhancement of microwave absorption efficacy. This review aspires to illuminate the pathway toward the development of thin, lightweight, highly efficient microwave absorbing materials with broadband absorption capabilities.

Keywords: Mesoscopic, metacomposites, microwave absorbing materials, dispersion and distribution, multiple reflection-scattering

INTRODUCTION

The rapid development of modern electronic devices and wireless communication technologies has intensified the challenges associated with electromagnetic wave pollution[1,2]. Significant advancements in radar technology have posed challenges to the survivability of advanced aviation weapons, thereby necessitating the development of high-performance microwave absorbing materials (MAMs)[3-5]. As a specialized category of functional materials, MAMs operate by efficiently converting incident electromagnetic wave energy into heat or other forms of energy through mechanisms such as dielectric loss and magnetic loss, while simultaneously suppressing electromagnetic wave reflection to achieve superior absorption performance[6-8]. Traditional MAMs are predominantly classified into two categories: magnetic loss materials and dielectric loss materials. Magnetic loss materials, which include ferrites and carbonyl iron, dissipate electromagnetic wave energy through mechanisms such as hysteresis loss, eddy current loss, and natural resonance phenomena[9-11]. However, these materials face significant limitations including high density and challenging processability[12,13]. Notably, their magnetic properties deteriorate considerably in high-temperature environments due to constraints imposed by the Curie temperature; this limitation renders them inadequate for meeting the demands of complex operational conditions[14,15].

In contrast, dielectric loss materials (e.g., carbon-based materials, conductive polymers, metal oxides) have emerged as prominent research hotspots in recent years owing to their advantages of low density, strong designability, and exceptional high-temperature stability[16-18]. The primary mechanism for attenuating electromagnetic waves involves polarization relaxation loss and conductive loss, and their absorption performance can be optimized through structural design and component regulation[19]. However, dielectric MAMs still encounter two critical challenges: (1) the inherent trade-off between impedance matching and attenuation capability, which hinders simultaneous achievement of robust dielectric loss and robust impedance matching across a wide temperature range[20]; (2) the difficulty in precisely controlling filler dispersion within the matrix leads to inevitable agglomeration and resultant inhomogeneous performance. Therefore, it is imperative to innovate design concepts and develop novel composites that integrate excellent impedance matching with efficient attenuation through multi-component and multi-structural synergistic design. This approach aims to overcome the performance bottlenecks associated with traditional MAMs.

In recent years, bioinspired structures have attracted great attention from researchers[21-24]. In nature, certain flora and fauna have evolved photonics microstructures that facilitate precise manipulation of electromagnetic waves[25]. For instance, the compound eyes of moths exhibit unique anti-reflection properties, which have inspired researchers to develop photonic structures within the visible light spectrum[26-28]. From the fundamental perspective of electromagnetic-wave-matter interaction, optical subwavelength structure presents innovative approaches for designing advanced MAMs. Mesoscopic metacomposites (MSMCs) particularly capitalize on this concept by translating photonics architectures into mesoscopic dimensions, thereby enabling tunable microwave absorption through hierarchical structural engineering[29]. Specifically, MSMCs are composite materials composed of sub-wavelength-scale functional units, where the primary feature is the discrete distribution of functional units within the matrix. Compared to conventional MAMs, the advantages of MSMCs can be primarily attributed to several key factors. Firstly, traditional MAMs, such as carbon nanotubes (CNTs) and graphene, often experience spontaneous aggregation into larger aggregates due to various physical or chemical processes when dispersed in a matrix[30]. This uncontrollable aggregation process results in unstable electromagnetic properties, which ultimately diminishes the reliability of these absorbing materials in practical engineering applications. The absorbers of MSMCs are fabricated into sub-wavelength functional units. The effective dispersion of these functional units facilitates the attainment of stable electromagnetic parameters, thereby enhancing the reliability of the absorbing materials in engineering applications.

Furthermore, traditional absorbing materials primarily achieve electromagnetic wave absorption at high temperatures by decreasing the content of absorbents in composite materials and enhancing the polarization loss capability[31,32]. However, this approach relies on decreasing the loss characteristics of composite materials to achieve impedance matching at elevated temperatures, making it challenging to attain significant electromagnetic wave attenuation. Mesoscopic functional units are discretely distributed within the matrix, allowing charge transfer to occur solely within these functional units. Despite rising temperatures, the conductivity remains relatively unchanged, resulting in a decoupling of conductivity from impedance matching and maintaining excellent impedance matching across a wide temperature spectrum. By converting macroscopic continuous conductive networks into discrete functional units while maintaining intact internal conductive pathways, MSMCs demonstrate superior capabilities for electromagnetic wave dissipation. Consequently, MSMCs exhibit a strong loss capability over a broad temperature range. Secondly, reflection and scattering can prolong the transmission path of electromagnetic waves, thereby promoting attenuation of electromagnetic waves[33,34]. The contribution of reflection and scattering to electromagnetic wave loss capability is insufficient in traditional MAMs[35]. Functional units at sub-wavelength scales exhibit more pronounced reflection and scattering when interacting with electromagnetic waves, and manipulation of electromagnetic wave transmission paths can be achieved by adjusting the scale and arrangement of functional units. The MSMCs establish intricate pathways for electromagnetic wave propagation that enable multiple reflections and scattering among functional units. These interactions effectively extend the path length within the material, resulting in increased energy dissipation during propagation and enhanced microwave absorption performance.

Although MSMCs demonstrate significant application potential, the substantial challenges, particularly fabrication process intricacies, uncertainties in establishing quantitative structure-property relationships, and difficulties associated with large-scale production, have considerably hindered their practical realization. With ongoing advancements in synthesis techniques and a deeper understanding of the interaction mechanisms between electromagnetic waves and matter, it is anticipated that the electromagnetic parameters of these materials can be further optimized. This optimization would facilitate the development of MSMCs characterized by exceptional overall performance, including broad frequency absorption, strong loss characteristics, lightweight architecture, and high temperature resistance. Consequently, this progress will provide essential technical support for electromagnetic compatibility systems, invisibility technology, and electromagnetic pollution control.

This review systematically summarizes the recent advancements in MSMCs, with a focus on construction strategies and mechanisms for enhancing microwave absorption performance. Firstly, we conduct an in-depth analysis of the structural design strategies employed in MSMCs, meticulously examining the correlation between material composition, interfacial characteristics and wave-absorbing performance. Subsequently, we elucidate the mechanisms underlying performance enhancement in MSMCs. This encompasses the controlled dispersion of functional units designed to achieve synergistic impedance matching across a wide range of temperatures, along with innovative attenuation mechanisms enabled by multi-scattering configurations. Ultimately, we delve into the prospective trajectories of development and the promising applications of MSMCs, intricately intertwined with the current landscape of research. Our objective is to furnish theoretical insights and technical references that will serve as a foundation for the design of high-performance MAMs.

STRUCTURAL DESIGN AND MICROWAVE ABSORPTION MECHANISMS OF MESOSCOPIC METACOMPOSITES

Structural design of functional units

MSMCs represent an emerging class of materials that synergistically combine materials science with periodic/aperiodic structural design, whereby dielectric materials are engineered into mesoscopic functional units and discretely distributed within the transparent matrix to achieve excellent microwave absorption performance[36,37]. Especially, mesoscale functional units serve as the core absorptive components; the structure, size, composition, and distribution state within the matrix play a decisive role in the overall absorption performance of the material[38].

In terms of material composition, MSMCs commonly employ materials with high dielectric loss or unique physical and chemical properties as the substrate for functional units[39]. Carbon-based materials exhibit remarkable characteristics including low density, superior dielectric loss properties, outstanding chemical durability, and excellent mechanical performance[40,41]. Most conductive loss absorbing materials primarily consist of carbon-based materials, including graphite, graphene, CNTs, and carbon fibers[42,43]. These materials are further optimized for electromagnetic wave absorption performance through approaches such as nanosizing, surface modification, and composite assembly. For instance, graphite nanosheets (GNs), CNTs, and fumed silica particles enabled the formation of multi-layered composite microspheres. The CNTs bridging adjacent GNs established the fundamental framework, creating a closed conductive network, which not only enhanced electrical conductivity but also significantly improved electromagnetic wave dissipation capacity through polarization relaxation at the interface between the two components[44].

In addition to the carbon-materials described above, conductive carbon-based materials that excel at effectively absorbing electromagnetic waves have emerged. These materials exhibit similar physical and chemical properties to other carbon-based materials, while also possessing multiple electromagnetic wave loss mechanisms. Graphitic carbon nitride (g-C_3N_4) has demonstrated significant potential as a carbon-based electromagnetic wave absorber, owing to its advantageous combination of low density, exceptional stability, and tunable electrical conductivity[45]. g-C_3N_4 has a two-dimensional structure similar to graphene, in which sp^2-carbon nitrogen hybridization produces π-conjugated electronic configurations[46]. The incorporation of heteroatoms leads to conductivity loss and dipole polarization, thereby contributing to its high performance as an electromagnetic wave absorber. MXene material is also a new type of two-dimensional material similar to graphene[47]. MXene demonstrates exceptional absorbing material properties due to its ease of preparation, the straightforward modulation of defects and surface functional groups, and its high conductivity[48]. Furthermore, the expanded interlayer spacing and the incorporation of diverse functional groups enhance the coupling between MXene and other types of absorbing materials, thereby improving the composite performance[49]. The resultant composite absorbent material possesses multiple electromagnetic loss mechanisms, which further contribute to its superior absorption capability.

Metal-organic frameworks (MOFs)-derived carbon-based materials have attracted widespread attention due to high structural tunability, a large specific surface area, and a uniform pore size distribution[50]. Through high-temperature carbonization of MOFs, composite materials with tailored pore structures can be obtained, leading to the formation of numerous defects that further enhance the dissipation of electromagnetic waves[51]. Molybdenum disulfide (MoS_2) is a remarkable two-dimensional transition metal disulfide compound that is gaining recognition as a significant material for microwave absorption due to its dielectric loss absorption properties[52]. The thin layer of MoS_2 enables effective microwave penetration and attenuation. Moreover, its plate-like structure minimizes eddy currents to the greatest extent, facilitating resonance transfer to higher frequencies and broadening the absorption bandwidth[53]. The floral layered configuration of MoS_2 is anticipated to exhibit superior microwave absorption performance as its surface area increases and its structure becomes more intricate[54]. Ceramic materials are another important type of dielectric material. In recent years, high-entropy materials, particularly high-entropy ceramics, have garnered increasing research attention within the scientific community[55]. High-entropy oxides exhibit pronounced stress concentration and lattice distortion due to mismatches in ionic quantities, sizes, and bonding states[56]. These structural characteristics generate defect configurations that are particularly conducive to electromagnetic wave dissipation. For example, in spinel/perovskite high-entropy oxides, around the interface of spinel and perovskite planes, notable stress concentrations and lattice distortions are directly observed, inducing numerous point defects and stacking faults[57]. The two biphasic high-entropy oxides achieve optimized synergistic effects via precisely engineered phase composition control.

From the perspective of structural design, both dimensions and morphology play a pivotal role in tuning microwave absorption characteristics. Currently, the functional units of MSMCs are predominantly classified into microspheres and lamellar films. Microspheres exhibit outstanding advantages in terms of flowability, close packing, dispersibility, and wear resistance. More importantly, the structural size can be easily controlled, offering significant application potential in the preparation of MSMCs[58,59]. Zhao *et al.* prepared graphene aerogel microspheres with outstanding elasticity and specific strength via a wet-spinning technique [Figure 1A][60]. Notably, both horizontally and vertically grouped spheres manifested superelasticity comparable to individual spheres, maintaining excellent shape recoverability even after 1,000 compression cycles at 70% strain[60]. With the continuous exploration and application of microsphere-based materials, various microsphere architectures have been developed, including core-shell microspheres, hollow microspheres, and porous microspheres[61,62]. For instance, Tian *et al.* developed reduced graphene aerogel microspheres with ring-like structure and regular layer spacing via wet spinning combined with chemical reduction method[63]. As shown in Figure 1B, the graphene microspheres displayed a unique chiral helical structure and electromagnetic cross-polarization, as opposed to the disordered porous structure of conventional aerogels. Such structural peculiarities are responsible for the improved impedance matching and electromagnetic wave attenuation.

Apart from the influence of shape, the unit size affects the distribution of functional units in the matrix and the content of fillers, which is very important for the regulation of microwave absorption performance[64]. Cai *et al.* designed polyimide-derived carbon/graphene hybrid aerogel microspheres via a process involving high-pressure spraying, freeze-shaping, freeze-drying, *in-situ* thermal reduction, imidization, and high-temperature thermal decomposition[65]. The as-prepared microspheres exhibited a diameter of only ten micrometers [Figure 1C]. Microspheres exhibited outstanding mechanical properties and could maintain a complete structure in the matrix. Composite materials exhibited strong absorption amplitude and wide absorption frequency range at low filler content and thin thickness, indicating that they are effective candidate materials for ultra-light and high-efficiency electromagnetic wave absorbers[65]. Dielectric ceramic materials exhibit broad application prospects in the field of electromagnetic wave absorption, particularly due to their unique corrosion resistance and high-temperature stability, which ensure reliable performance under complex working conditions[66]. Yang *et al.* synthesized composite TiAlCo ceramic microspheres (composed of TiO_2, Co_3O_4, and Al_2O_3) using spray drying technology[67]. As illustrated in Figure 1D, the microspheres measured approximately 50 μm, with each component maintaining a stable structure.

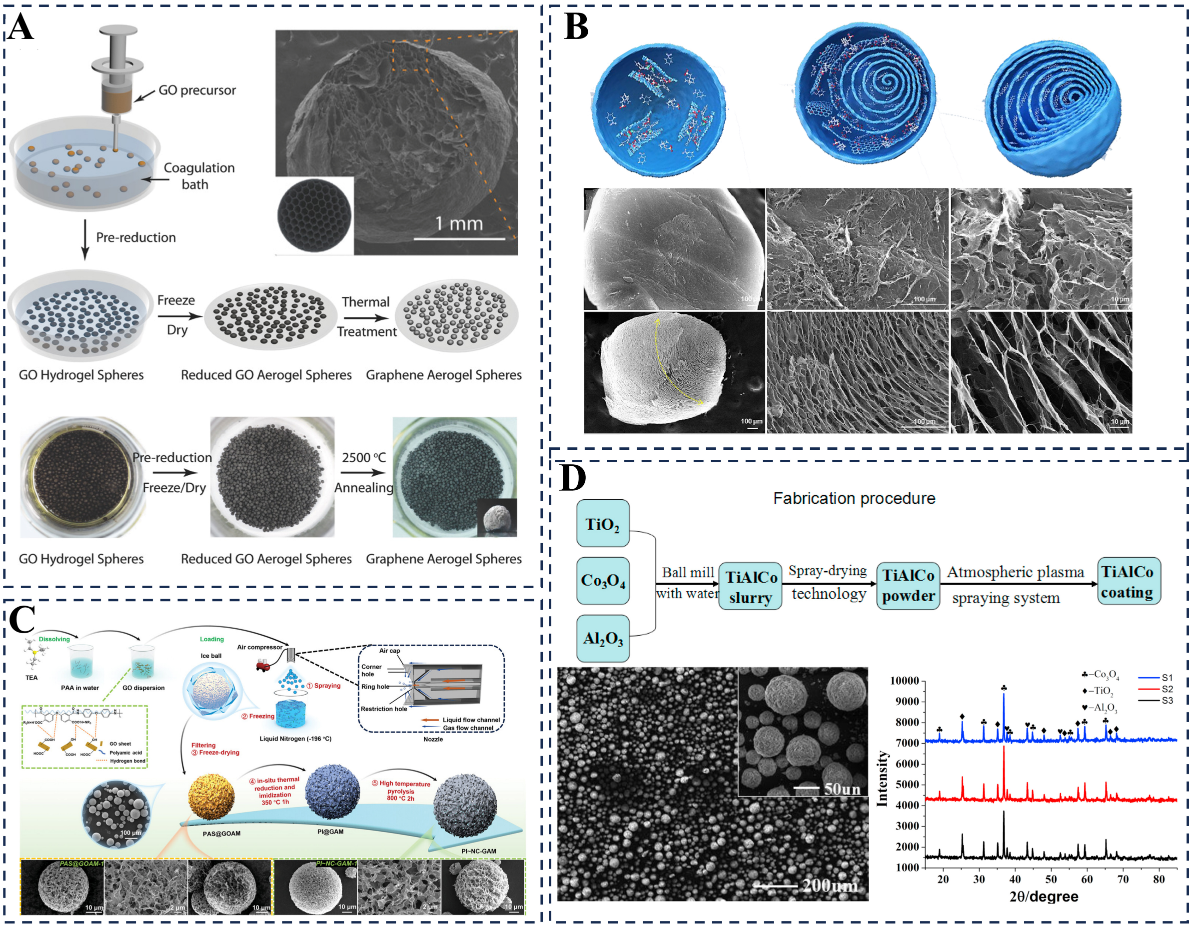

Figure 1. (A) Fabrication of RGO microspheres via wet spinning technique and corresponding SEM image of their internal structure[60]. Copyright 2017, Wiley-VCH GmbH; (B) Structural image of reduced graphene oxide aerogel microspheres exhibiting tree-ring-like structures with ordered interlayer spacing[63]. Copyright 2023, Elsevier; (C) Synthesis process and various images of small-scale carbon/graphene hybrid aerogel microspheres[65]. Copyright 2025, Wiley-VCH GmbH; (D) SEM image and XRD pattern of small-scale TiAlCo ceramic microspheres[67]. Copyright 2016, Elsevier. RGO: Reduced graphene oxide; SEM: scanning electron microscopy; XRD: X-ray powder diffraction.

Benefiting from this characteristic, the composite demonstrated exceptional microwave absorption performance in the X-band. Hollow glass microspheres, characterized by their miniature hollow architecture, demonstrate exceptional microwave absorption capabilities when integrated with high-permittivity dielectric materials, making them a prevalent choice in electromagnetic wave attenuation applications[68,69].

In contrast to microsphere structures, the research on mesoscopic functional units with film structures is still in its infancy, particularly regarding film materials that combine high-loss dielectric materials with low-loss materials to achieve processability and robust mechanical properties[70]. As a typical conductive ceramic material, the flexible titanium nitride (TiN) films have been employed as functional units for constructing MSMCs. The TiN subwavelength scale films could be readily dispersed within the matrix, enabling effective electromagnetic wave attenuation through energy dissipation[71]. The inherent scalability of film dimensions offers distinct advantages in the design of mesoscopic functional units, providing a new perspective for optimizing microwave absorption performance. Block structures with irregular shapes can also function as effective mesoscale units. For instance, Zhao *et al.* developed a high-entropy oxide ceramic material in which a spinel phase is dispersed within a rock salt matrix[72]. By leveraging the significant polarization loss inherent to high-entropy oxides and the spatial distribution of functional units, the resulting composite demonstrates outstanding electromagnetic wave absorption performance[72].

Microwave absorption mechanisms of mesoscopic metacomposites

Dielectric materials primarily exhibit the polarization response and conduction response when subjected to electromagnetic fields. The permittivity ($\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$) characterizes the response behavior of dielectric materials in electromagnetic fields. The real part of the permittivity indicates the ability to store electromagnetic energy, while the imaginary part reflects the capacity to dissipate electromagnetic energy[73]. According to the metal back-panel theory, reflection loss (RL) represents microwave absorption performance, which was simulated using measured electromagnetic parameters through

$$RL = 20\log|(Z_{in} - Z_0)/(Z_{in} + Z_0)| \text{ and } Z_{in} = Z_0(\sqrt{\mu_r/\varepsilon_r})\tanh[j(2\pi fd/c)\sqrt{\varepsilon_r\mu_r}]$$

where Z_{in} and Z_0 = 377 Ω denote the material impedance and vacuum impedance; d, c, and f represent the absorber thickness, velocity of light, and measured frequency, respectively[74]. μ_r is the permeability, with a value of 1 in dielectric materials. When the RL is below -10 dB, 90% microwave attenuation was expected. Here, the frequency range with RL below -10 dB was considered as the effective absorbing bandwidth (EAB). The characterization of electromagnetic parameters can be performed through two primary methodologies: rectangular waveguide techniques and coaxial transmission-reflection measurements. The coaxial approach demonstrates distinct advantages in the 2-18 GHz frequency range, offering both measurement efficiency and standardization benefits. This method accommodates test specimens with uniform dimensions (ϕ_{out} = 7 mm, ϕ_{in} = 3.04 mm, thickness d = 2 mm), significantly simplifying sample preparation procedures. Conversely, waveguide characterization presents inherent technical constraints. The method's effectiveness is limited by three key factors: (1) cutoff frequency requirements; (2) mode matching complexities; and (3) resonant oscillation interference. These limitations necessitate the use of frequency-specific sample geometries (X-band: 22.8 × 10.16 mm; Ku-band: 15.90 × 8.03 mm) to ensure accurate absorption property evaluation across different operational bands.

As given in the Debye equation $\varepsilon_r'' = \varepsilon_p'' + \varepsilon_c'' = (\varepsilon_s - \varepsilon_\infty)\omega\tau/(1 + \omega^2\tau(T)^2) + \sigma(T)/(\varepsilon_0\omega)$, here, ε_0, ε_s, ε_∞, ω, τ, σ represent the permittivity of free space, the static permittivity, the relative permittivity at the high-frequency limit, the relaxation time, the angular frequency, and the conductivity, respectively[75]. ε_c'' indicates conductivity loss, which is closely associated with the conductivity of the material. Qin *et al.* divided conductive losses into two models[76]. The first type is the electron transfer model. Free charges can rapidly migrate within the material under the influence of an external electric field. The latter is the electronic hopping model. The presence of various interfaces and defects in dielectric materials makes it difficult for free charges to migrate quickly. Nonetheless, the establishment of macroscopic conductive networks reduces the energy barrier for electron hopping, enhancing charge transfer in microwave-absorbing materials[77]. With the rise of temperature, the intensification of electron thermal motion promotes the increase of conductivity. However, excessively high conductivity undoubtedly leads to impedance mismatches.

Conductive loss serves a pivotal role in MSMCs, particularly for units incorporating conductive components such as carbon-based materials and conductive polymers. Under the action of the electromagnetic wave electric field, charge carriers (electrons or holes) inside the functional unit undergo directed migration, forming a conductive current. In the process of migration, the carriers collide with the lattice and impurities, converting electromagnetic energy into thermal energy to achieve efficient microwave attenuation[76]. For instance, in graphene-based MSMCs, the localized conductive networks provided optimal transport pathways for charge carriers. When electromagnetic waves are incident, a large number of charge carriers migrated within the conductive network, resulting in significant conductive loss[78]. As temperature increases, the discrete distribution of functional units in the matrix restricts charge carriers to migrating and hopping only within the internal conductive networks, precluding inter-unit transport[79]. Therefore, the decoupling of electrical conductivity and impedance matching can be achieved in MSMCs, ensuring stable electromagnetic wave absorption across a wide temperature range.

ε_p'' represents polarization loss, which is mainly divided into interface polarization and dipole polarization under the microwave frequency band[80]. The interface polarization effect is also known as the Maxwell-Wagner-Sillar effect. Heterogeneous interfaces constructed from materials with significant differences in Fermi levels can significantly enhance the interfacial polarization ability of composite materials[81]. The design of porous and hollow structures can also enhance interfacial polarization. Dipole polarization refers to the motion of dipoles in polarized or non-polar molecules under an alternating electromagnetic field. The dipole polarization of non-polar molecules in an electromagnetic field is called displacement polarization, while the dipole polarization of polar molecules in an electromagnetic field is called orientation polarization. Defect-induced polarization is also an important supplement to polarization relaxation. Defect sites in absorbers can trap charge carriers and break the balance of charge distribution, thus leading to the polarization process and corresponding EM energy loss.

The polarization loss holds significant importance in MSMCs. Due to the presence of numerous heterogeneous interfaces and defect centers within the functional units, bound charges within the dielectric undergo minute displacements under an electric field, leading to the separation of positive and negative charge centers and the generation of electric dipoles[82,83]. These dipoles subsequently align and orient themselves under the influence of the electric field. As the electric field frequency increases, the electric dipoles exhibit relaxation phenomena, leading to polarization loss caused by the repeated reorientation of electric dipoles during the relaxation process, which results in the dissipation of electromagnetic wave energy[84-86]. The phase and interfacial structures are crucial for modulating the electromagnetic parameters and dictating the electromagnetic wave absorption performance[87,88]. Furthermore, sub-wavelength functional units can be composed of materials with high Fermi level differences to enhance interface polarization[89]. In general, the efficiency of polarization loss can be effectively improved by rationally designing the structure and optimizing material components.

Multiple reflection and scattering represent a distinctive feature of MSMCs, setting them apart from traditional wave absorbing materials. Owing to the structural complexity within the material, electromagnetic waves incident on the surface experience repeated reflection and scattering at the interfaces. The propagation trajectory of electromagnetic waves is altered by each reflection and scattering, extending the transmission path length within the material and enhancing energy dissipation through prolonged wave-matter interactions[90]. Conventional MAMs permit the penetration of electromagnetic waves into the composites solely under the condition of satisfied impedance matching, subsequent to which reflection and scattering phenomena may occur[91]. Nevertheless, when impedance matching deteriorates marginally, most of the electromagnetic waves are reflected into free space, resulting in a significant reduction in the microwave absorption performance of the absorbing material. MSMCs have broken through the strict impedance matching requirements of traditional MAMs. Owing to the discrete distribution of sub-wavelength functional units within the matrix, metamaterials demonstrate exceptional anti-reflection properties. When electromagnetic waves penetrate the interior of metacomposites and interact with the surfaces of functional units, a portion of the waves propagates into the functional units and undergoes energy dissipation, while another portion is reflected toward the surfaces of adjacent functional units, leading to subsequent reflection and dissipation events. Even if the conductivity of the functional units increases, leading to a slight deterioration in the impedance matching of the metacomposites, electromagnetic waves can still reflect among the functional units instead of being reflected into free space. Therefore, MSMCs have a strong ability to dissipate electromagnetic waves, benefiting from the contributions of reflection and scattering.

More importantly, the design of the dimensions and spatial configuration of sub-wavelength functional units can manipulate the reflection behavior of electromagnetic waves among functional units. The extended propagation paths of electromagnetic waves significantly promote energy dissipation by intensifying their interaction with lossy media. Although optimized multiple-reflection dynamics facilitate the effective attenuation of electromagnetic energy through longer paths inside functional units, excessive reflections can also prevent electromagnetic waves from entering the material. Therefore, it is of vital importance to design structures and functional units that can effectively balance multiple reflections and scattering. MSMCs demonstrate superiority in matching the size of functional units with the wavelength of electromagnetic waves; the electromagnetic waves can be controlled to reflect and scatter between functional units by adjusting the electrical conductivity of functional units, thereby promoting the absorption of electromagnetic waves.

The exceptional electromagnetic absorption performance of MSMCs stems from the synergistic effects of multiple loss mechanisms, primarily including conductive loss, polarization loss, and enhanced attenuation resulting from multiple reflection-scattering effects [Figure 2]. Taken together, MSMCs achieve significant improvements in microwave absorption performance by integrating multiple absorption mechanisms through ingenious structural design and multi-component synergy. However, further research is needed to elucidate the synergistic interplay among the absorption mechanisms, as well as the quantitative relationships between structure and performance. With the continuous advancement of research, it is anticipated that the intrinsic mechanisms of wave absorption in MSMCs will be further unraveled, thereby providing a robust theoretical foundation for the development of higher-performance microwave absorption materials.

MICROWAVE ABSORPTION PERFORMANCE ENHANCEMENT STRATEGIES

Controllable dispersion of fillers

Conventional MAMs are typically prepared by simple mixing of fillers and matrix. However, this approach suffers from significant drawbacks due to the ineffective control of filler dispersion, leading to serious agglomeration in the matrix. The agglomeration of fillers not only leads to inhomogeneous internal structures but also generates larger particle clusters, hindering the sufficient interaction between electromagnetic waves and fillers during propagation, thereby greatly reducing absorption efficiency. Additionally, the agglomeration phenomenon may also alter the electrical and magnetic properties of the material, disrupt its inherent impedance matching, and consequently lead to a marked decline in overall absorption performance.

To address this issue, engineering fillers into mesoscopic functional units has emerged as a transformative strategy. Mesoscopic functional units, characterized by well-defined geometric morphologies and dimensions spanning the nanometer to micrometer range, enable precise control over structural architecture and chemical composition through advanced fabrication techniques. For instance, integrating electrospinning, size tailoring, microfluidics, and spray drying technologies enables the fabrication of functional units with well-defined morphologies (e.g., spheroidal or lamellar) and hierarchical internal

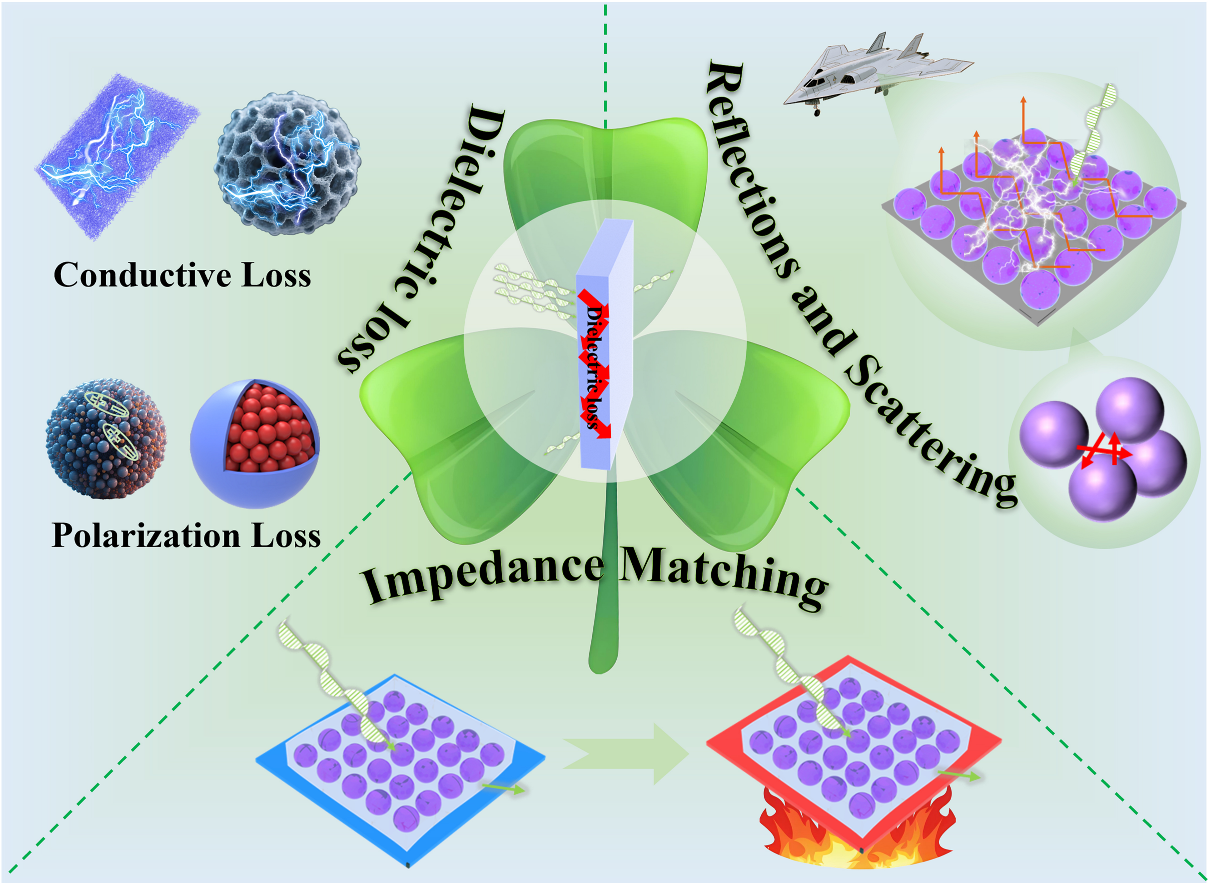

Figure 2. Schematic diagram of the microwave absorption mechanism for the mesoscopic metacomposites.

structures (e.g., core-shell or porous architectures)[92-94]. These mesoscopic functional units exhibit distinct advantages over traditional fillers in terms of their dispersed distribution within the matrix. On one hand, the structural stability of functional units allows them to retain their morphology within the matrix, effectively preventing agglomeration. On the other hand, microspherical functional units exhibit superior fluidity, thereby enabling more uniform dispersion in the matrix. In addition, mesoscopic functional units can be directionally assembled within the matrix to attain homogeneous dispersion. Meng *et al.* fabricated graphene/Fe_3O_4 microspheres using an electrospinning-freeze drying process[95]. The Cole-Cole plots of powder filler exhibit polarization behavior induced by interfaces and defects, while those of microsphere filler displayed more pronounced conductive loss characteristics. The Cole-Cole plot results of the two composites indicated that agglomeration of powder fillers in the matrix hinders the construction of a complete conductive network, whereas the local conductive networks within the microspheres facilitate the optimization of microwave absorption performance[95]. As depicted in Figure 3A, graphene microspheres can achieve good dispersion and distribution in polymer matrices, and microspheres can act as independent loss units to suppress the establishment of macroscopic conductive networks[92].

Recently, Jiang *et al.* further demonstrated the design advantages of MSMCs. They fabricated reduced graphene oxide@carbon spheres (RGO@carbon), yielding RGO@carbon MSMCs that exhibited outstanding microwave absorption performance (absorption bandwidth can cover the entire X-band only with 3.0 wt.% filler)[79]. When the microsphere structure was mechanically ground into powders via mechanical milling, the RGO@carbon powders failed to efficiently dissipate electromagnetic waves[79]. As shown in Figure 3B,

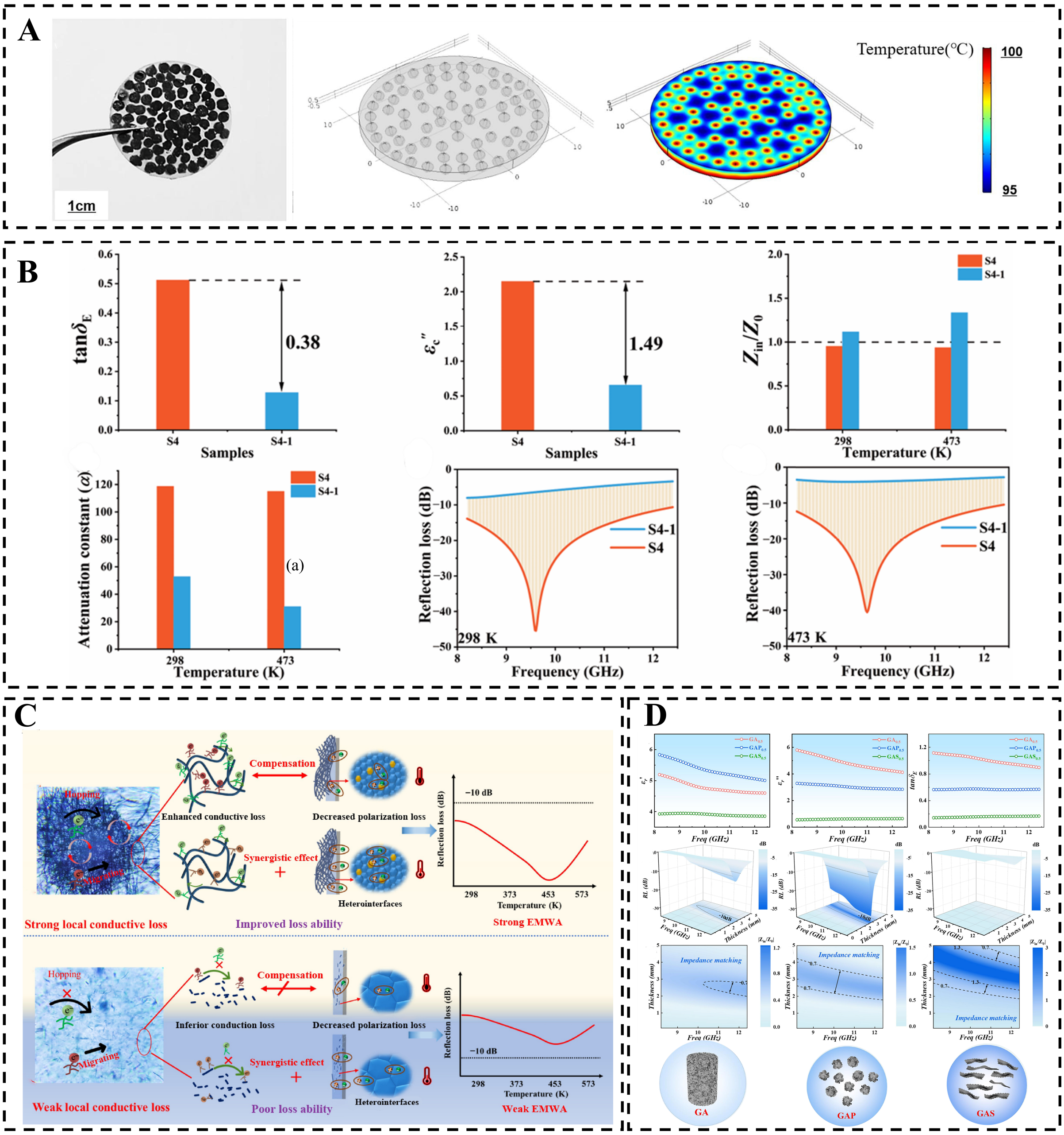

Figure 3. (A) Dispersion image and temperature distribution simulation of graphene microspheres in polymer matrix[92]. Copyright 2019, Elsevier; (B) A comparison of dielectric loss capability between RGO@carbon mesoscopic metacomposites and RGO@carbon powder composites[79]. Copyright 2022, Springer Nature; (C) Microwave absorption performance of composites with TiN/ZrO_2 nanofibrous membranes and TiN/ZrO_2 powders[71]. Copyright 2023, Springer Nature; (D) Permittivity, impedance matching, and microwave absorption capacity of graphene aerogel monoliths, graphene aerogel microspheres, and graphene powders[96]. Copyright 2025, Elsevier. RGO@carbon: Reduced graphene oxide@carbon spheres; TiN/ZrO_2: titanium nitride/zirconium dioxide.

the dielectric loss performance of RGO@carbon powders declined more sharply than that of RGO@carbon spheres. Beyond microsphere architectures, flexible layered thin films can also serve as mesoscale microwave absorption units. Significantly, the mesoscale film units can be directionally aligned within the matrix to enhance the electromagnetic wave attenuation ability of the absorber. Titanium nitride/zirconium dioxide (TiN/ZrO_2) stands out as a premier flexible dielectric loss film material, enabling substantial electromagnetic wave attenuation when micrometer-scale TiN/ZrO_2 films are homogeneously dispersed in a polydimethylsiloxane (PDMS) matrix[71]. As demonstrated in Figure 3C, the MSMCs exhibited significant electromagnetic wave dissipation attributed to the synergistic interplay of conductive and polarization losses within functional units. In stark contrast, TiN/ZrO_2 powders with identical filler loadings displayed negligible microwave absorption, underscoring the pivotal role of mesoscopic architecture in enabling efficient loss mechanisms. Zhang *et al.* systematically compared the microwave absorption properties of bulk graphene aerogels, graphene aerogel microspheres, and graphene powders under the same filler content[96]. As shown in Figure 3D, the macroscopic conductive network of graphene aerogel bulk materials endowed them with strong loss capacity but severely deteriorated the impedance-matching characteristics. Graphene powders, conversely, exhibit optimal impedance matching but suffer from insufficient loss capacity, primarily due to agglomeration-induced discontinuous conductive paths. In contrast, MSMCs constructed from graphene aerogel microspheres strike a balance between impedance matching and loss capability, enabling the composites to achieve broadband electromagnetic wave dissipation across the entire X-band.

The interaction among functional units and the substrate plays a pivotal role in determining absorption performance. Generally, the stable structure of the functional unit ensures that its wave absorption performance can be fully utilized. For example, functional units with special internal structures, such as porous structures, could increase the number of reflections and scatterings of electromagnetic waves within the unit, thereby enhancing energy dissipation. Concurrently, the interface between the functional unit and the matrix is also a critical region in the absorption process. Charge accumulation and polarization phenomena at the interface induce additional Maxwell-Wagner relaxation losses, further boosting absorption efficiency. Studies have demonstrated that the microwave absorption performance of MSMCs can be substantially enhanced through rational design of functional unit architecture and surface chemistry, coupled with optimization of matrix-unit interfacial bonding strength. This improvement is often attributed to synergistic enhancements in impedance matching and dielectric loss mechanisms, underscoring the critical role of mesoscale structural engineering in advanced microwave absorption materials.

Excellent impedance matching and strong dielectric loss capability

In practical applications, microwave absorbers must maintain stable performance across varying temperature conditions, making wide-temperature operability a critical requirement. Conventional macroscale continuous conductive networks experience a significant increase in electron migration rates and a decrease in electron hopping energy barriers as temperature rises, leading to degraded impedance matching characteristics and absorption efficiency[97]. To address this issue, traditional strategies focus on enhancing high-temperature microwave absorption capability through microscale component and structural design, specifically by reducing the content of absorbent and enhancing the polarization ability[98]. However, traditional strategies often achieve impedance matching at elevated temperatures by sacrificing loss performance. This trade-off underscores the need for innovative designs that simultaneously satisfy both impedance matching and strong loss characteristics over a broad temperature range.

The design strategy of MSMCs transforms the macroscopic continuous conductive network into discrete functional units. Although the increase in temperature enhances the thermal mobility of electrons, charges can only move within the unit and cannot jump between functional units. The conductivity of metacomposites does not significantly increase at high temperatures, ensuring satisfactory impedance matching over a wide temperature range. Furthermore, the abundant conductive network (e.g., CNTs and graphene) within the sub-wavelength functional units endows it with strong loss capability. Discrete mesoscopic functional units exhibit temperature-stable microwave absorption characteristics. Upon electromagnetic wave irradiation, confined electron migration and hopping within the network generate substantial Joule heating, effectively dissipating incident energy. Crucially, the spatial isolation of these units mitigates macroscopic conductivity-induced reflection, allowing enhanced wave penetration and multi-path absorption. This architecture-temperature synergy results in stable performance across broad temperature ranges, outperforming conventional continuous networks prone to thermal conductivity fluctuations. For instance, Shao *et al.* employed a wet-spinning technique to fabricate nanofiber microspheres, which feature a hierarchical local conductive network[99]. When integrated with paraffin wax, the resulting absorbing composite achieved a remarkable minimum RL of -72.34 dB at an ultralow filler loading of just 1.2 wt.%, accompanied by a broad absorption bandwidth of 8.12 GHz [Figure 4A]. Meanwhile, Jiang *et al.* pioneered the discovery that MSMCs exhibit unique advantages in high-temperature microwave absorption[79]. By constructing localized conductive networks within RGO@carbon microspheres [Figure 4B], the metacomposites with only 3.0 wt.% filler loading demonstrated an effective absorption bandwidth (RL < -10 dB) covering the entire X-band across temperatures from 298 to 473 K, with a minimum RL of -57 dB at 433 K. Due to the decoupling of conductivity and impedance matching achieved by the functional unit, it exhibited temperature insensitive electromagnetic performance at high temperatures.

Graphene nanosheets (GNs) exhibit a large specific surface area and exceptional electrical conductivity; however, their pronounced impedance mismatch arising from excessive conductivity limits microwave absorption applications. The advent of MSMCs has enabled GNs to achieve unique advantages in this field. Fang *et al.* fabricated GNs/PES composites via a simple solution-blending strategy combined with solvent evaporation[100]. During the synthesis process, the GNs spontaneously self-assembled into mesoscale microcluster architectures that served as functional units. As illustrated in Figure 4C, the design of functional unit significantly optimized impedance matching and loss characteristics of the GNs/PES electromagnetic composites, which demonstrated stable absorption bandwidth and strong absorption peaks (RL < -25 dB) across 293-453 K. More recently, Zhang *et al.* developed MSMCs using RGO microspheres as functional units[96]. Figure 4D revealed negligible fluctuations in the real/imaginary parts of the dielectric constant over broad temperatures, with RGO metacomposites maintaining stable microwave absorption performance (RL < -10 dB) from 293 to 453 K.

Apart from the conductive loss, the polarization loss represents a critical component of dielectric loss. Thermally induced polarization loss decreases with increasing temperature, enabling synergistic compensation for the concurrent rise in conductive loss. Thus, enhancing polarization loss within mesoscopic functional units plays a pivotal role in optimizing microwave absorption performance. Predominant polarization mechanisms in such units encompass dipole polarization (e.g., from functional groups) and interfacial polarization (e.g., Maxwell-Wagner relaxation at filler-matrix interfaces). Li *et al.* fabricated MXene@graphene oxide hybrid aerogel microspheres via rapid freezing-assisted electrospinning[101]. As can be seen in Figure 5A, the microspheres exhibited a rich conductive network internally, and the formation of numerous heterojunctions between MXene and GO significantly enhanced the interfacial polarization of the composite material. The stacking defects and surface functional groups present in both dielectric materials further enhance the dipole polarization. The presence of multiple semicircles in the Cole-Cole curve indicated that MXene@graphene oxide hybrid aerogel microspheres exhibited multiple dielectric relaxations. Constructing core-shell architecture has emerged as a pivotal design strategy for boosting interfacial polarization. Zhi *et al.* employed coaxial electrospinning to fabricate aerogel microspheres with core-shell double-layer structures[102]. Figure 5B clearly revealed the core-shell morphology of carbon/graphene microspheres, and Cole-Cole plot analysis confirmed that polarization losses constitute a significant fraction of total dielectric losses, alongside conductive dissipation. Simulation results demonstrate that compared to single-layer graphene microspheres, the core-shell carbon/graphene microspheres exhibited a higher volume loss density, underscoring their superior attenuation capability.

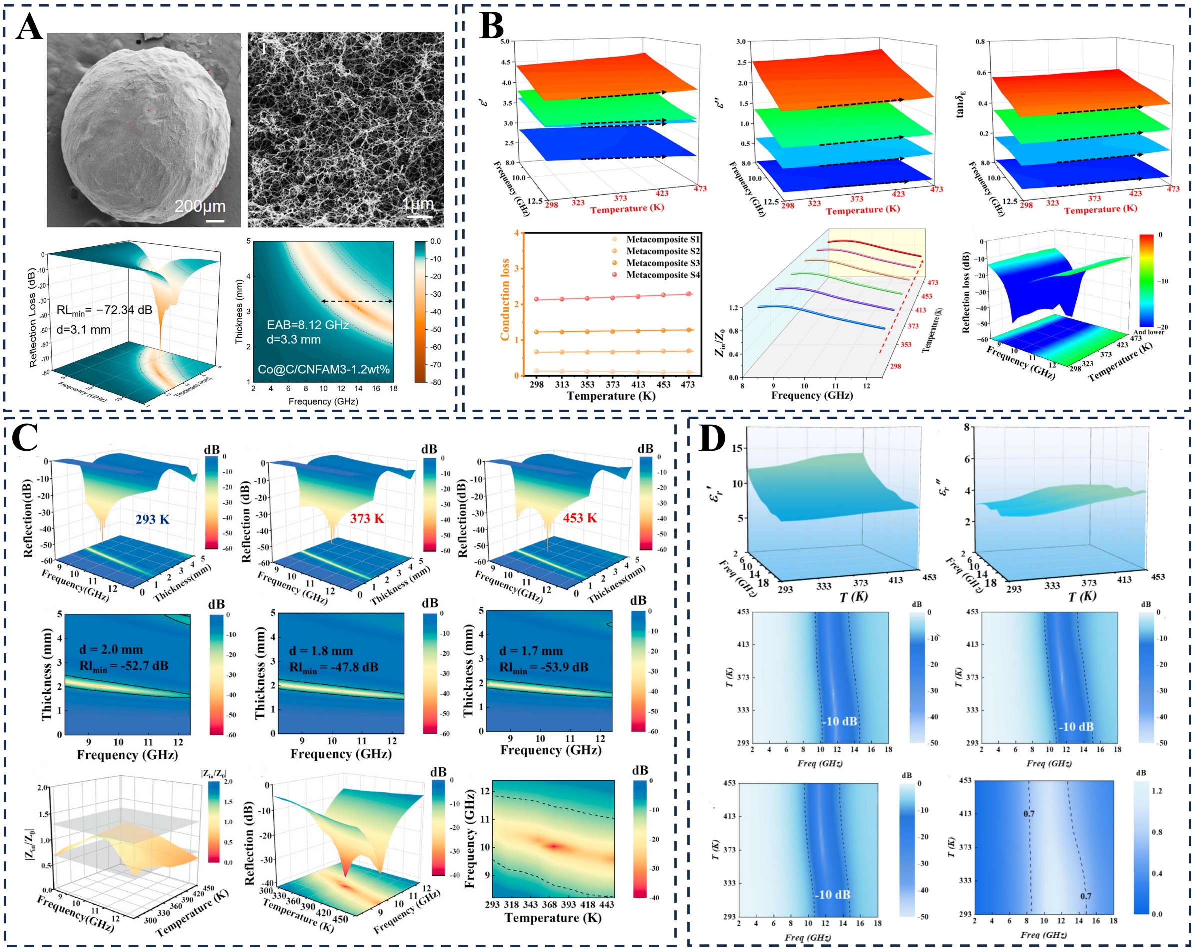

Figure 4. (A) SEM image of nanofibrous microspheres and microwave absorption performance of their paraffin wax composite[99]. Copyright 2024, Elsevier; (B) Permittivity, impedance matching characteristics, and reflection loss of RGO@carbon mesoscale metacomposites across a broad temperature range[79]. Copyright 2022, Springer Nature; (C) Electromagnetic wave absorption performance of GNs/PES composites over a broad temperature range[100]. Copyright 2024, Elsevier; (D) Variation in dielectric properties and absorption bandwidth of RGO microsphere-based mesoscopic metacomposites[96]. Copyright 2025, Elsevier. SEM: Scanning electron microscopy; RGO@carbon: reduced graphene oxide@carbon spheres.

Beyond carbon-based systems, ceramic-based materials exhibit unique advantages in high-temperature applications. From the previous summary, it is evident that the maximum operational temperature of carbon-based materials is constrained to approximately 573 K. Exceeding this threshold in high-temperature aerobic environments leads to oxidation, which significantly compromises the microwave absorption performance of the composite material[103]. In contrast, ceramic-based materials are predominantly utilized in ultra-high-temperature applications[104]. Jing *et al.* designed ATO/SiO_2 microspheres, where the abundant heterointerfaces between ATO and SiO_2 confer enhanced polarization relaxation loss to the composite material[105]. As illustrated in Figure 5C, polarization relaxation loss within the microspheres could be tuned by optimizing ATO/SiO_2 ratios. Owing to the discrete design of MSMC functional units and synergistic conductive-polarization losses in ATO/SiO_2 microspheres, the metacomposite achieved strong electromagnetic wave dissipation across a wide temperature range. Similarly, Wang *et al.* fabricated Ti_3SiC_2/Al_2O_3-13%TiO_2 microspheres using granulation technology, and scanning electron microscopy (SEM) images reveal abundant heterogeneous interfaces within the microspheres [Figure 5D][106]. Leveraging intrinsic unit polarization loss and the construction of a local

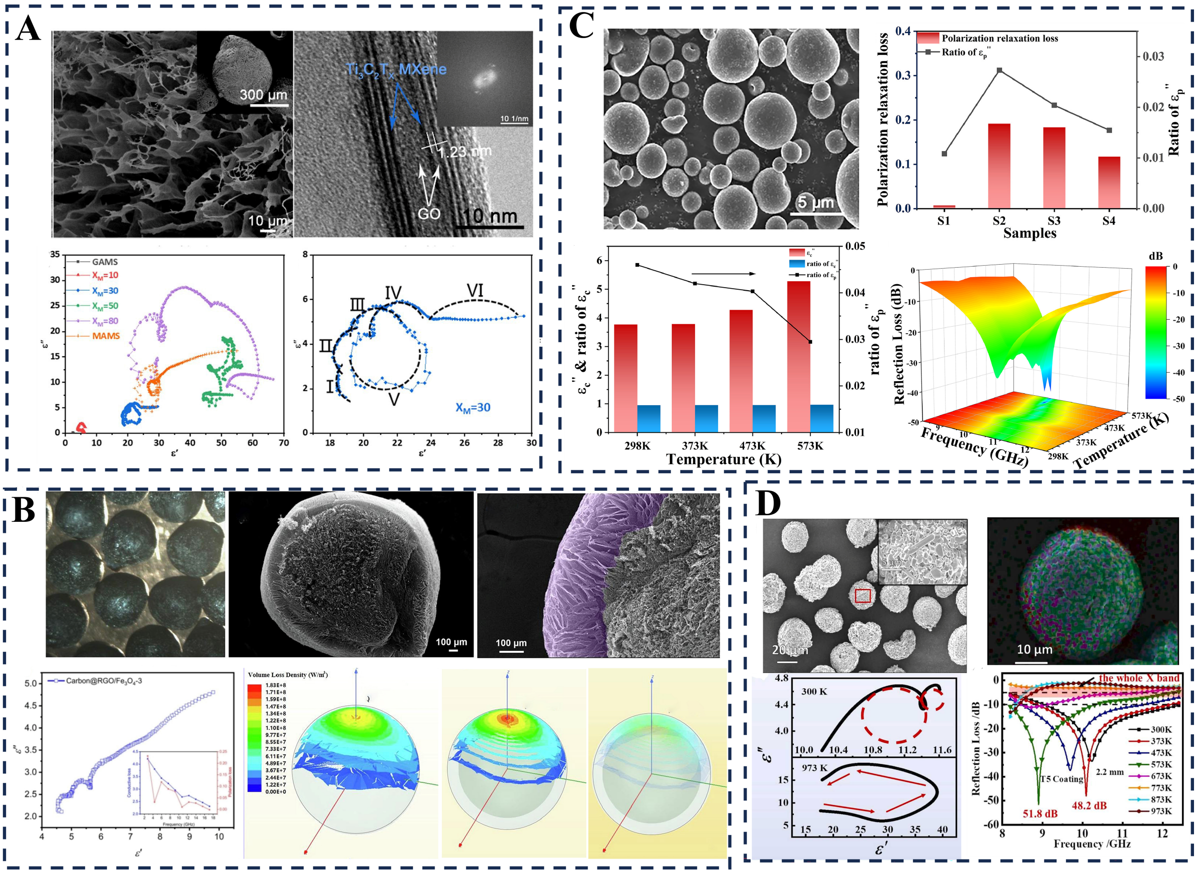

Figure 5. (A) Electron microscopy image and Cole-Cole plot of MXene@graphene oxide hybrid aerogel microspheres[101]. Copyright 2020, Elsevier; (B) Core-shell structure, Cole-Cole plot, and simulated volumetric loss density of carbon/graphene microspheres[102]. Copyright 2022, Elsevier; (C) The functional unit architecture of ATO/SiO_2 mesoscopic metacomposite, contribution of polarization loss, and reflection loss values across a broad temperature range[105]. Copyright 2024, Elsevier; (D) Ti_3SiC_2/Al_2O_3-13%TiO_2 microsphere structure, polarization capacity and electromagnetic wave absorption performance of the composite material[106]. Copyright 2024, Elsevier.

conductive network, the material maintains a notable effective absorption bandwidth of 2.2 GHz at 873 K[106].

Although the existing research preliminarily shows that the optimization of the loss and impedance matching performance of the composite material can be considered by means of the design of the sub-wavelength scale absorbing unit. Research indicates that these functional units can optimize both loss capability and impedance matching performance [Table 1]. However, the research on mesoscopic absorbers is still in its infancy, the structure design of functional unit is relatively simple, and the combination of mesoscopic functional unit with micro-component and structure design is not yet sufficiently developed. Therefore, it is imperative to engineer hierarchical design strategies that bridge mesoscale architectures with micro/nanoscale functionalities to unlock the full potential of metacomposites in broadband microwave absorption.

Multiple reflection-scattering mechanism for enhanced microwave absorption performance

Based on the physical mechanisms of electromagnetic wave-matter interaction, multiple reflection-scattering effects can effectively enhance absorption performance by extending the propagation path of electromagnetic waves within materials and increasing coupling with absorptive media. From the

Table 1. Microwave absorption performance of mesoscopic metacomposites

Absorbers	Minimum RL value		Loading content (wt.%)	EAB		Refs.
	(d) mm	RL_{min} (dB)		(d) mm	F (GHz)	
CSA-RGO AMs	3.6	– 63	4	3.6	7.04	[63]
PI-NC-GAMs	3.43	-63.6	1	2.57	7.45	[65]
RGO@carbon spheres	4	-57	3	4	4.2	[79]
TiN/ZrO_2 nanofibrous membranes	1.9	54.6	16.67	1.9	1.64	[71]
IL/GO spheres	2.46	-65	2	2.2	3.5	[96]
Graphene nanosheets	2	-52.7	9	2	4.2	[100]
MXene@graphene oxide microspheres	1.2	-49.1	10	1.2	2.9	[101]
ATO/SiO_2	1.8	-47.8	60	1.8	2.4	[105]
Hollow graphene aerogels	3.4	-52.7	5	3.4	3.9	[107]
$TiN/ZrO_2/C$ ternary nanofiber membranes	2.3	-51.7	10	2.3	3.2	[108]
$H@ZnO/C/Fe_3O_4$ GAM	4.2	-61.5	5	4.2	6.63	[109]

EAB: Effective absorbing bandwidth; RL: reflection loss; GAM: graphene-based aerogel microspheres; RGO@carbon: reduced graphene oxide@carbon spheres; $TiN/ZrO_2/C$: titanium nitride/zirconium oxide/carbon.

perspective of the structure-property relationship of MSMCs, the conductivity of functional units, unit scale, and arrangement pattern are the core parameters for regulating multiple reflection scattering effects, which collectively establish multi-dimensional loss channels through synergistic interactions. Among these, conductivity determines the reflection efficiency of electromagnetic waves on the unit surface and the intensity of internal conduction loss, unit scale influences scattering patterns and frequency response characteristics, while arrangement patterns regulate the propagation trajectory and scattering probability of electromagnetic waves through spatial periodicity or disorder. In-depth exploration of the influence mechanism on the multiple reflection and scattering effect not only helps to reveal the internal relationship between the mesoscopic scale structure and the absorption performance but also provides a theoretical basis and technical path for the precise control of the absorption performance based on the structural design.

The conductivity of functional units represents a pivotal factor governing absorption performance, intimately linked to multiple reflection-scattering mechanisms. For units with favorable conductivity, induced currents form on their surfaces as electromagnetic waves impinge. Owing to electromagnetic induction, incident waves generate surface charges that flow through the conductive network of the functional unit, creating induced currents that attenuate the electromagnetic wave through Ohmic loss[110,111]. In traditional micro-designed absorption materials, when the conductivity of the absorptive agent increases, the interaction between the composite material and electromagnetic waves results in reflection due to impedance mismatch[112]. At this point, electromagnetic waves are reflected into free space, thereby reducing the microwave absorption ability. In stark contrast, moderate conductivity enhancement in MSMCs promotes inter-unit reflection-scattering. The reflection and scattering effects on the functional unit surfaces make the propagation path of electromagnetic waves within the material more complex, increasing the opportunities for interaction between electromagnetic waves and functional units as well as the matrix[113]. This interaction not only includes reflection and scattering but may also cause multiple reflections and refractions of electromagnetic waves among the functional units, further increasing energy loss. For instance, Li *et al.* employed triaxial coaxial spinning to fabricate two types of hollow microsphere architectures[107]. Among these, hollow RGO spheres exhibited superior impedance matching, whereas ball-in-ball graphene aerogel spheres featured stronger conductive loss but poorer impedance matching. Notably, BGAS2 microspheres demonstrated superior microwave absorption performance, highlighting that tuning functional unit conductivity can enhance wave absorption via promoted reflection-scattering mechanisms[107]. As shown in Figure 6A, the composite material exhibited remarkably robust electromagnetic wave absorption performance, even as its impedance matching worsens with rising temperature[108].

The spatial arrangement of functional units within the matrix represents a critical parameter for tailoring multiple reflection-scattering mechanisms. Different arrangement patterns can drastically alter electromagnetic wave propagation paths and interaction mechanisms within the material. When functional units are arranged in an ordered manner, such as in a regular array, electromagnetic waves encounter periodically arranged functional units during propagation. This periodic structure induces special scattering and interference effects on the electromagnetic waves. Under certain specific incident angles and frequencies, ordered functional units can form Bragg scattering, causing electromagnetic waves of specific frequencies to be strongly reflected or scattered, thereby achieving absorption of electromagnetic waves in specific frequency bands. Zhang *et al.* fabricated titanium nitride/zirconium oxide/carbon ($TiN/ZrO_2/C$) ternary nanofiber membranes and incorporated them as mesoscale functional units into a PDMS matrix[108]. As revealed by Computer Simulation Technology (CST) simulation results [Figure 6B], the three distinct distribution patterns exhibited markedly different electromagnetic wave reflection behaviors in the metacomposite. The 3 × 3 ordered arrangement yields the highest intra-composite wave reflection, enabling the metacomposite to achieve a minimum RL of -51.7 dB at 453 K with an effective absorption bandwidth of 2.3 GHz.

Similarly, Chen *et al.* synthesized three microsphere types with different dielectric properties and constructed absorbers featuring distinct stacking architectures[109]. Upon entering the composite absorber, electromagnetic waves undergo interlayer multiple reflection-scattering, extending their propagation path and time. Partial waves reflect at dielectric layer interfaces, while the remaining penetrate to subsequent layers, creating interference between reflected waves that promotes energy dissipation. As shown in Figure 6C, the C-HC-C (C and HC represent microspheres with different dielectric properties) stacked model displayed the highest absorption amplitude, attributed to optimized structure and prolonged wave-matter interaction[109]. Li *et al.* constructed graphene-based aerogel microspheres (GAM) with hollow and core-shell structures[114]. Simulations of various layered structures of GAM arranged in single/double-layer arrays were conducted to investigate the group coupling effects on microwave absorption performance through synergistic absorption, interference, and resonant attenuation mechanisms[114]. As shown in the electric field distribution intensity maps [Figure 6D], double-layer GAM arrays significantly broaden the electromagnetic response range compared to single layers, attributed to the synergistic reaction of the second array that enhances scattered wave multiplicity and intra-array oscillations. Additionally, with the introduction of the double-layer structure, the volume loss density of double-layered heterogeneous GAMs (DTGAM) and hollow GAMs (HGAM) significantly increases. Multi-layer structures can cause gradient impedance mismatches, leading to reflections and scattering between different layers, thereby producing cancellation effects.

In addition to ordered array arrangements, disordered arrangements of functional units also have unique advantages. Disordered arrangements can disrupt the regularity of electromagnetic wave propagation, causing electromagnetic waves to undergo more random reflections and scatterings within the material[115-117]. This random reflection and scattering process can broaden the absorption frequency band, enabling it to absorb electromagnetic waves across a wider frequency range. Recently, researchers have investigated the differences in electromagnetic wave reflection between structures exhibiting disordered distributions and those with ordered periodic arrangements. The findings reveal that the reflection phase of super-uniform and disordered structures demonstrates a more non-uniform distribution. The operational

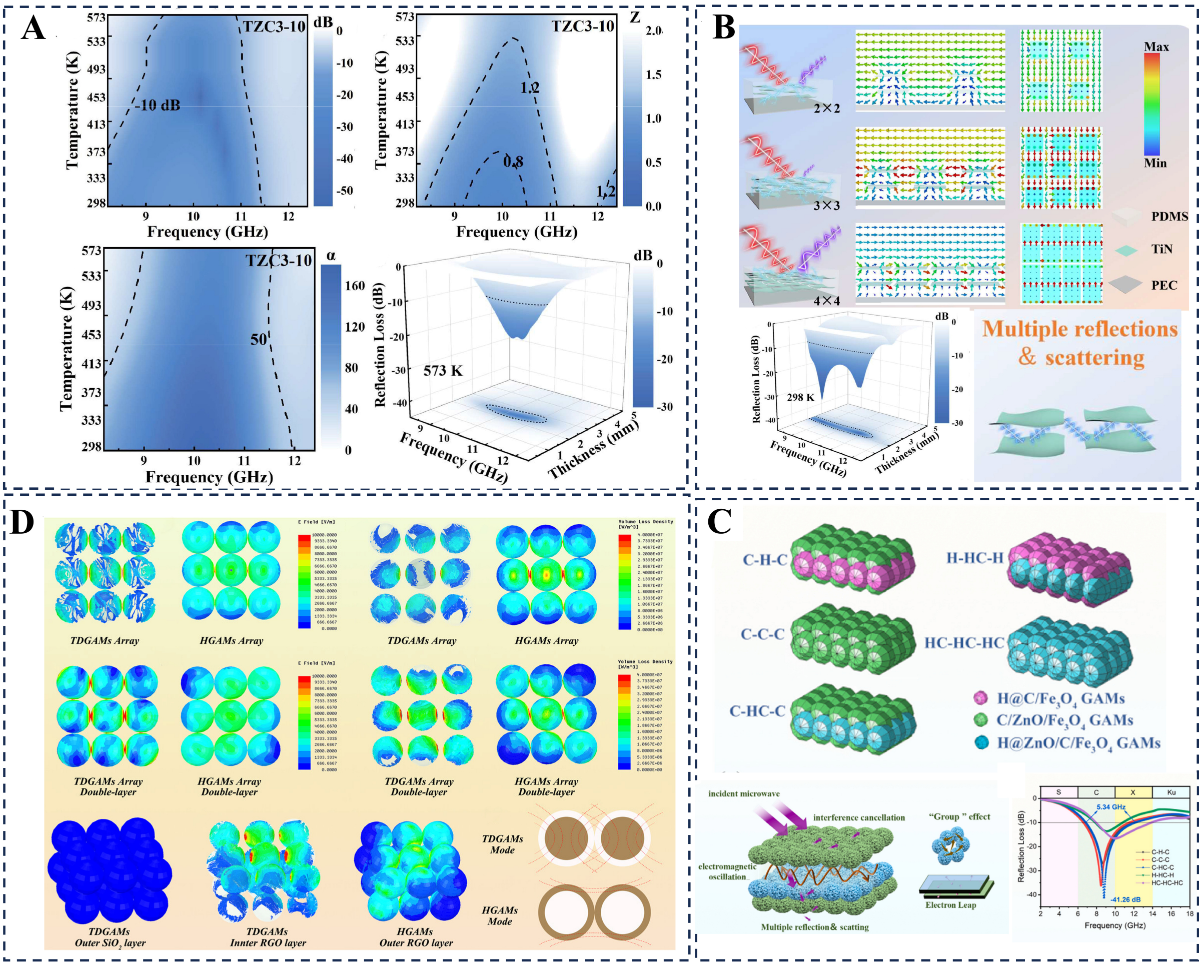

Figure 6. (A) Microwave absorption properties of TZC3-10 mesoscopic metacomposites[108]. Copyright 2025, Elsevier; (B) Electric field distribution and electromagnetic wave absorption performance of TiN/ZrO_2/C film-based mesoscopic metacomposites[108]. Copyright 2025, Elsevier; (C) RL values of composites under different stacking arrangements[109]. Copyright 2025, Elsevier; (D) Electric field distribution and volumetric loss density profiles of monolayer and bilayer graphene aerogel microsphere-based mesoscopic metacomposites[114]. Copyright 2025, Wiley-VCH GmbH. TiN/ZrO_2/C: Titanium nitride/zirconium oxide/carbon; RL: reflection loss.

bandwidth of ultra-uniform and disordered materials has exceeded 1 GHz, whereas the corresponding bandwidth for periodic metasurfaces is 86%[118]. Such disorder-engineered MSMCs represent a pivotal frontier for future research, aiming to integrate randomness-induced broadband absorption with ordered structure-tailored frequency selectivity.

The size of mesoscopic functional units exerts a profound influence on multiple reflection-scattering mechanisms. Based on electromagnetic wave propagation theory, when unit dimensions are comparable to or on the order of the incident wavelength, strong scattering effects occur, drastically altering wave propagation directions and forming complex scattering trajectories within the material[119-121]. As the scale of functional units decreases, the number of scattering events increases due to the higher areal density of smaller units, thereby increasing the probability of electromagnetic waves encountering functional units. However, when unit dimensions fall below the electromagnetic skin depth, waves penetrate the units rather than scatter, diminishing RL[122]. For instance, Shao *et al.* fabricated aramid-derived hard carbon nanofiber aerogel microspheres of varying sizes using wet spinning technology[123]. These aerogel microspheres exhibit distinct electromagnetic response characteristics depending on their size. The presence of macroscopic gaps between adjacent microspheres and microscopic pores within individual microspheres improves impedance matching and facilitates multiple internal reflections and wave scattering. Consequently, the aerogel microspheres with the smallest size demonstrate the strongest absorption capacity, achieving a maximum absorption amplitude of -70 dB, which is attributed to the enhanced reflection and scattering effects[123]. Larger units, despite higher individual scattering intensity, exhibit reduced overall scattering efficiency due to their lower packing density. The size of functional units can influence the dielectric properties of materials. In the case of MXene with varying lateral dimensions (105 and 171 μm), larger microsheets exhibit wider interlayer spacing, which facilitates electron transfer and interfacial polarization, thereby enhancing both conduction loss and interfacial polarization loss. Consequently, the dielectric performance of larger-sized MXene is significantly improved[124]. Therefore, the multiple reflection scattering performance can be optimized by precisely controlling the scale of functional units, ultimately achieving remarkable adsorption performance. Altogether, the electrical conductivity, unit size, and arrangement of functional units synergistically modulate the multiple reflection and scattering processes via their unique action mechanisms, which provides a theoretical basis and design direction for the improvement of microwave absorption performance of MSMCs. In practical applications, these factors need to be considered comprehensively to optimize the absorption properties of the materials.

Benefiting from the controllable dispersion and distribution of functional units within the matrix, MSMCs have outstanding practical application prospects. Furthermore, metacomposites have stable electromagnetic wave dissipation ability over a wide temperature range, which further enhances their practical application potential. However, there are still some challenges that need to be overcome before the final practical application of metacomposites. Foremost among these is the cost-effectiveness dilemma; mesoscopic architecture often relies on intricate fabrication techniques (e.g., high-precision lithography or multi-step self-assembly) and rare functional fillers (e.g., noble-metal nanoparticles or tailored nanocarbons), whose expenses escalate exponentially with production volume. Additionally, it is essential to improve the mechanical properties of metacomposites while ensuring they meet the performance criteria for microwave absorption.

CONCLUSION AND OUTLOOK

In summary, the construction of mesoscale functional units preserves their inherent structure in composites and prevents micro-nano scale filler agglomeration. The discrete distribution of these units modifies the transmission paths of free charges within the macroscopic conductive network, enabling decoupling of conductivity and impedance matching. Consequently, subwavelength-scale functional units demonstrate strong electromagnetic wave loss ability across a wide temperature range while maintaining effective impedance matching. From an electromagnetic-matter interaction perspective, MSMCs create a novel microwave absorption paradigm by manipulating reflection and scattering behaviors among functional units to amplify electromagnetic wave dissipation within the composite matrix. Despite significant advancements in MSMCs, several critical challenges remain to be addressed for breakthroughs in their overall performance:

(1) The structural design of subwavelength functional units is currently monotonous. Advancements in 3D printing technology offer new opportunities for the structural engineering of mesoscopic functional units. Future efforts should focus on creating hierarchically structured units to better understand their roles in electromagnetic wave reflection and scattering.

(2) While MSMCs have unique advantages for microwave absorption, the connection between microscopic and mesoscopic designs is insufficient. Emphasizing multi-scale design is crucial for optimizing microwave

absorption.

(3) A coupling model that integrates temperature, electromagnetic parameters, and microcarrier dynamics needs to be established to explore charge transport pathways under extreme temperatures using *in-situ* characterization techniques. Additionally, machine learning algorithms should be integrated to predict multi-scale dielectric responses validated by electromagnetic simulations.

DECLARATIONS

Authors' contributions

Writing - original draft preparation: Hao, B.
Writing - review & editing: Hao, B.; Zhang, Y. B.
Investigation: Chai, Z. H.; Li, M.; Duan, J. J.; Zhang, Y.
Supervision: Zhang, Y. B.; Gong, C. H.
Resources: Li, C. P.
Conceptualization: Gong, C. H.
Project administration: Gong, C. H.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of Interest

The authors declare no conflict of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

REFERENCES

1. Li, C.; Liang, L.; Zhang, B.; Yang, Y.; Ji, G. Magneto-dielectric synergy and multiscale hierarchical structure design enable flexible multipurpose microwave absorption and infrared stealth compatibility. *Nanomicro. Lett.* **2024**, *17*, 40. DOI PubMed PMC
2. Cao, X.; Lan, D.; Zhang, Y.; Jia, Z.; Wu, G.; Yin, P. Construction of three-dimensional conductive network and heterogeneous interfaces via different ratio for tunable microwave absorption. *Adv. Compos. Hybrid. Mater.* **2023**, *6*, 763. DOI
3. Sharma, S.; Parne, S. R.; Panda, S. S. S.; Gandi, S. Progress in microwave absorbing materials: a critical review. *Adv. Colloid. Interface. Sci.* **2024**, *327*, 103143. DOI PubMed
4. Zhao, Z.; Qing, Y.; Kong, L.; et al. Advancements in microwave absorption motivated by interdisciplinary research. *Adv. Mater.* **2024**, *36*, e2304182. DOI
5. Zhang, Z.; Cai, Z.; Wang, Z.; et al. A review on metal-organic framework-derived porous carbon-based novel microwave absorption materials. *Nanomicro. Lett.* **2021**, *13*, 56. DOI PubMed PMC
6. Wang, M.; Cao, M. Perspectives on metal-organic framework-derived microwave absorption materials. *J. Mater. Sci. Technol.* **2025**, *214*, 37-52. DOI

7. Li, N.; Zong, Z.; Zhang, F.; et al. Barium ferrite with high anisotropy for ultra-broadband microwave absorption. *Adv. Funct. Mater.* **2025**, *35*, 2414694. DOI
8. Li, Z.; Duan, Y.; Liu, X.; et al. Strategy-induced strong exchange interaction for enhancing high-temperature magnetic loss in high-entropy alloy powders. *Adv. Funct. Mater.* **2025**, 2507152. DOI
9. Xiang, X.; Yang, Z.; Fang, G.; et al. Tailoring tactics for optimizing microwave absorbing behaviors in ferrite materials. *Mater. Today. Phys.* **2023**, *36*, 101184. DOI
10. Li, W.; Xu, X.; Fan, L.; et al. Porous pure magnetic foam with engineered heterointerfaces for enhanced microwave absorption. *J. Mater. Sci. Technol.* **2025**, *234*, 113-21. DOI
11. liu, Z.; Wang, L.; Zhao, Y.; et al. Environmental adaptability and efficient electromagnetic wave protection of C/Co aerogels by anchoring Co to biomass carbon via the high-temperature induced morphological transformation of ZIF-67. *Nano. Research.* **2025**, *18*, 94907581. DOI
12. Wu, Z.; Huang, J.; Zeng, X. Dual magnetic particles modified carbon nanosheets in CoFe/Co@NC heterostructure for efficient electromagnetic synergy. *Soft. Sci.* **2024**, *4*, 42. DOI
13. Zhou, L.; Hu, P.; Bai, M.; et al. Harnessing the electronic spin states of single atoms for precise electromagnetic modulation. *Adv. Mater.* **2025**, *37*, e2418321. DOI
14. Song, X. J.; Zhang, T.; Gu, Z. X.; et al. Record enhancement of Curie temperature in host-guest inclusion ferroelectrics. *J. Am. Chem. Soc.* **2021**, *143*, 5091-8. DOI
15. Mishra, S.; Park, I. K.; Javaid, S.; Shin, S. H.; Lee, G. Enhancement of interlayer exchange coupling via intercalation in 2D magnetic bilayers: towards high Curie temperature. *Mater. Horiz.* **2024**, *11*, 4482-92. DOI PubMed
16. Mohapatra, P. P.; Singh, H. K.; Dobbidi, P. Advancements in electromagnetic microwave absorbers: Ferrites and carbonaceous materials. *Adv. Colloid. Interface. Sci.* **2025**, *337*, 103381. DOI PubMed
17. Zhang, K.; Zhang, J.; Hou, Z.; Bi, S.; Zhao, Q. Multifunctional broadband microwave absorption of flexible graphene composites. *Carbon* **2019**, *141*, 608-17. DOI
18. An, Q.; Li, D.; Liao, W.; et al. A novel ultra-wideband electromagnetic-wave-absorbing metastructure inspired by bionic gyroid structures. *Adv. Mater.* **2023**, *35*, e2300659. DOI
19. Li, J.; Chen, S.; Fan, R.; et al. Structural engineering on carbon materials for microwave absorption: From micro to macro to meta. *Carbon* **2024**, *224*, 119058. DOI
20. Liu, X.; Duan, Y.; Wu, N.; et al. Modulating electromagnetic genes through Bi-phase high-entropy engineering toward temperature-stable ultra-broadband megahertz electromagnetic wave absorption. *Nanomicro. Lett.* **2025**, *17*, 164. DOI PubMed PMC
21. Chen, H.; Cao, Y.; Wang, C.; et al. Superhydrophobic surfaces for the sustainable maintenance of building materials and stone-built heritage: the challenges, opportunities and perspectives. *Adv. Colloid. Interface. Sci.* **2025**, *335*, 103343. DOI
22. Zhai, M.; Zhao, S.; Guo, H.; et al. Bionic-structured electromagnetic interference shielding composites. *Sci. Bull. (Beijing).* **2025**, *70*, 2347-64. DOI
23. Zhang, B.; Han, Q.; Zhang, J.; Han, Z.; Niu, S.; Ren, L. Advanced bio-inspired structural materials: Local properties determine overall performance. *Materials. Today.* **2020**, *41*, 177-99. DOI
24. Wegst, U. G.; Bai, H.; Saiz, E.; Tomsia, A. P.; Ritchie, R. O. Bioinspired structural materials. *Nat. Mater.* **2015**, *14*, 23-36. DOI PubMed
25. Goodling, A. E.; Nagelberg, S.; Kaehr, B.; et al. Colouration by total internal reflection and interference at microscale concave interfaces. *Nature* **2019**, *566*, 523-7. DOI
26. Huang, L.; Duan, Y.; Dai, X.; et al. Bioinspired metamaterials: multibands electromagnetic wave adaptability and hydrophobic characteristics. *Small* **2019**, *15*, e1902730. DOI
27. Kwon, Y. W.; Park, J.; Kim, T.; et al. Flexible near-field nanopatterning with ultrathin, conformal phase masks on nonplanar substrates for biomimetic hierarchical photonic structures. *ACS. Nano.* **2016**, *10*, 4609-17. DOI
28. Duan, Y.; Xia, C.; Chen, W.; Jia, H.; Wang, M.; Shi, Y. A bio-inspired broadband absorption metamaterial: Driven by dual-structure synergistically induced current vortices. *J. Mater. Sci. Technol.* **2025**, *206*, 193-201. DOI
29. Anguita, J. V.; Ahmad, M.; Haq, S.; Allam, J.; Silva, S. R. P. Ultra-broadband light trapping using nanotextured decoupled graphene multilayers. *Sci. Adv.* **2016**, *2*, e1501238. DOI PubMed PMC
30. Lai, H.; Li, Q.; Wang, X.; Xu, S. A comprehensive morphology study on the carbon nanotube agglomerations in cementitious composite. *Carbon* **2024**, *223*, 119014. DOI
31. Zhang, W.; Ding, E.; Zhang, W.; Li, J.; Luo, C.; Zhang, L. Microstructure controllable polyimide/MXene composite aerogels for high-temperature thermal insulation and microwave absorption. *J. Mater. Chem. C.* **2023**, *11*, 9438-48. DOI
32. Hou, Z.; Xue, J.; Liu, Y.; et al. Bidirectional periodic pore structure Si-C-N multiphase ceramic with high thermostability and excellent microwave absorption properties over a wide temperature range. *J. Eur. Ceram. Soc.* **2024**, *44*, 850-7. DOI
33. Peng, Y.; Meng, X.; Wei, H.; et al. Controllable construction of hollow Ni/NiO@PPy particles for broadband and highly efficient microwave absorption. *Adv. Funct. Mater.* **2025**, *35*, 2423405. DOI
34. Liu, S.; Zhou, Y.; Zhang, F.; et al. A novel full-band microwave absorber based on scattering enhanced prism-honeycomb nested structure. *Adv. Funct. Mater.* **2025**, *35*, 2422666. DOI
35. Du, Y.; Yan, Z.; You, W.; et al. Balancing MXene surface termination and interlayer spacing enables superior microwave absorption. *Adv. Funct. Mater.* **2023**, *33*, 2301449. DOI

36. Lan, D.; Gao, Z.; Zhao, Z.; Wu, G.; Kou, K.; Wu, H. Double-shell hollow glass microspheres@Co_2SiO_4 for lightweight and efficient electromagnetic wave absorption. *Chem. Eng. J.* **2021**, *408*, 127313. DOI
37. Wang, B.; Xu, C.; Duan, G.; Xu, W.; Pi, F. Review of broadband metamaterial absorbers: from principles, design strategies, and tunable properties to functional applications. *Adv. Funct. Mater.* **2023**, *33*, 2213818. DOI
38. Wang, J.; Wu, Z.; Xing, Y.; Li, B.; Huang, P.; Liu, L. Multi-scale design of ultra-broadband microwave metamaterial absorber based on hollow carbon/MXene/Mo_2C microtube. *Small* **2023**, *19*, e2207051. DOI
39. Hao, B.; Zhang, Y.; Si, H.; et al. Multiscale design of dielectric composites for enhanced microwave absorption performance at elevated temperatures. *Adv. Funct. Mater.* **2025**, *35*, 2423897. DOI
40. Lv, H.; Yao, Y.; Yuan, M.; et al. Functional nanoporous graphene superlattice. *Nat. Commun.* **2024**, *15*, 1295. DOI PubMed PMC
41. Xiong, X.; Zhang, H.; Lv, H.; et al. Recent progress in carbon-based materials and loss mechanisms for electromagnetic wave absorption. *Carbon* **2024**, *219*, 118834. DOI
42. Zhang, F.; Li, N.; Shi, J.; et al. Recent progress on carbon-based microwave absorption materials for multifunctional applications: a review. *Composites. Part. B:. Engineering.* **2024**, *283*, 111646. DOI
43. Liao, S. Y.; Wang, X. Y.; Shi, Y. Y.; et al. Reversible switching between microwave absorption and emi shielding of VO_2 composite foam. *Small* **2024**, *20*, e2402841. DOI
44. Wang, Y.; Wang, Y.; Han, H.; et al. Multi-level structural design guided by the innovative cup filled theory for enhanced electromagnetic wave absorption. *Carbon* **2025**, *243*, 120452. DOI
45. Lv, H.; Zhou, X.; Wu, G.; Kara, U. I.; Wang, X. Engineering defects in 2D g-C_3N_4 for wideband, efficient electromagnetic absorption at elevated temperature. *J. Mater. Chem. A.* **2021**, *9*, 19710-8. DOI
46. Cao, S.; Yu, J. g-C_3N_4-based photocatalysts for hydrogen generation. *J. Phys. Chem. Lett.* **2014**, *5*, 2101-7. DOI PubMed
47. He, Y.; Su, Q.; Liu, D.; et al. Surface engineering strategy for MXene to tailor electromagnetic wave absorption performance. *Chem. Eng. J.* **2024**, *491*, 152041. DOI
48. Wang, X.; Zhao, C.; Li, C.; et al. Progress in MXene-based materials for microwave absorption. *J. Mater. Sci. Technol.* **2024**, *180*, 207-25. DOI
49. Cui, C.; Guo, R.; Ren, E.; et al. MXene-based rGO/Nb_2CT_x/Fe_3O_4 composite for high absorption of electromagnetic wave. *Chem. Eng. J.* **2021**, *405*, 126626. DOI
50. Lin, Y.; Zhou, X.; Wang, Y.; et al. Progress of MOFs composites in the field of microwave absorption. *Carbon* **2025**, *238*, 120241. DOI
51. Zhang, X.; Tian, X. L.; Qin, Y.; et al. Conductive metal-organic frameworks with tunable dielectric properties for boosting electromagnetic wave absorption. *ACS. Nano.* **2023**, *17*, 12510-8. DOI
52. Long, L.; Cai, S.; Deng, M. MoS_2-based nanocomposites toward electromagnetic wave absorption. *Mater. Res. Bull.* **2024**, *174*, 112732. DOI
53. Miao, B.; Cao, Y.; Zhu, Q.; et al. Scalable synthesis of 2D Ti_2CT_x MXene and molybdenum disulfide composites with excellent microwave absorbing performance. *Adv. Compos. Hybrid. Mater.* **2023**, *6*, 643. DOI
54. Dai, J.; Yang, H.; Wen, B.; Zhou, H.; Wang, L.; Lin, Y. Flower-like MoS_2@$Bi_2Fe_4O_9$ microspheres with hierarchical structure as electromagnetic wave absorber. *Appl. Surf. Sci.* **2019**, *479*, 1226-35. DOI
55. Oses, C.; Toher, C.; Curtarolo, S. High-entropy ceramics. *Nat. Rev. Mater.* **2020**, *5*, 295-309. DOI
56. Ma, J.; Duan, Y.; Zhu, N.; Jia, H.; Wu, N.; Pang, H. High-entropy perovskite $(Y_{0.2}La_{0.2}Sm_{0.2}Nd_{0.2}Gd_{0.2})CoO_3$ with dielectric-conductive synergy achieving wide-temperature-range EMI shielding and electromagnetic wave absorption compatibility. *Chem. Eng. J.* **2025**, *520*, 165716. DOI
57. Wu, H.; Lu, Q.; Li, Y.; et al. Rapid joule-heating synthesis for manufacturing high-entropy oxides as efficient electrocatalysts. *Nano. Lett.* **2022**, *22*, 6492-500. DOI
58. Chen, X.; Wu, Y.; Gu, W.; et al. Research progress on nanostructure design and composition regulation of carbon spheres for the microwave absorption. *Carbon* **2022**, *189*, 617-33. DOI
59. Wang, L.; Li, X.; Shi, X.; et al. Recent progress of microwave absorption microspheres by magnetic-dielectric synergy. *Nanoscale* **2021**, *13*, 2136-56. DOI
60. Zhao, X.; Yao, W.; Gao, W.; Chen, H.; Gao, C. Wet-spun superelastic graphene aerogel millispheres with group effect. *Adv. Mater.* **2017**, *29*, 1701482. DOI
61. Zhang, Y.; Liu, X.; Guo, Z.; et al. MXene@Co hollow spheres structure boosts interfacial polarization for broadband electromagnetic wave absorption. *J. Mater. Sci. Technol.* **2024**, *176*, 167-75. DOI
62. Xu, Z.; Du, J.; Wang, J.; et al. A comparative study on the microwave absorption properties of core-single-shell, core-double-shell and yolk-shell CIP/ceramic composite microparticles. *J. Magn. Magn. Mater.* **2022**, *547*, 168959. DOI
63. Tian, Y.; Zhi, D.; Li, T.; et al. Graphene-based aerogel microspheres with annual ring-like structures for broadband electromagnetic attenuation. *Chem. Eng. J.* **2023**, *464*, 142644. DOI
64. Wang, G.; Li, C.; Estevez, D.; et al. Boosting interfacial polarization through heterointerface engineering in MXene/graphene intercalated-based microspheres for electromagnetic wave absorption. *Nanomicro. Lett.* **2023**, *15*, 152. DOI PubMed PMC
65. Cai, Y.; Wang, Z.; Fei, G.; Lavorgna, M.; Xia, H. Polyimide derived carbon/graphene hybrid aerogel microspheres for strong and wide bandwidth microwave absorption. *Adv. Funct. Mater.* **2025**, *35*, 2419252. DOI
66. Fu, Z.; Pang, A.; Luo, H.; Zhou, K.; Yang, H. Research progress of ceramic matrix composites for high temperature stealth

technology based on multi-scale collaborative design. *J. Mater. Res. Technol.* **2022**, *18*, 2770-83. DOI
67. Yang, Z.; Luo, F.; Hu, Y.; Zhu, D.; Zhou, W. Dielectric and microwave absorption properties of TiAlCo ceramic fabricated by atmospheric plasma spraying. *Ceram. Int.* **2016**, *42*, 8525-30. DOI
68. Yu, Y.; Li, Z.; Wei, Z.; et al. Enhancing battery module safety with insulation material: Hollow glass microspheres incorporating aerogel of varying particle sizes. *Chem. Eng. J.* **2023**, *478*, 147400. DOI
69. Shen, G.; Wei, H.; Cai, X.; Xu, Y. Dielectric and microwave absorption performances of hollow C/TiO_2 composite microspheres. *MRS. Commun.* **2021**, *11*, 890-5. DOI
70. Wang, N.; Samani, M. K.; Li, H.; et al. Tailoring the thermal and mechanical properties of graphene film by structural engineering. *Small* **2018**, e1801346. DOI
71. Li, C.; Zhang, L.; Zhang, S.; et al. Flexible regulation engineering of titanium nitride nanofibrous membranes for efficient electromagnetic microwave absorption in wide temperature spectrum. *Nano. Res.* **2024**, *17*, 1666-75. DOI
72. Zhao, B.; Du, Y.; Yan, Z.; et al. Structural defects in phase-regulated high-entropy oxides toward superior microwave absorption properties. *Adv. Funct. Mater.* **2023**, *33*, 2209924. DOI
73. Kumar, R.; Sahoo, S.; Joanni, E. Composites based on layered materials for absorption of microwaves and electromagnetic shielding. *Carbon* **2023**, *211*, 118072. DOI
74. Yin, P.; Lan, D.; Lu, C.; et al. Research progress of structural regulation and composition optimization to strengthen absorbing mechanism in emerging composites for efficient electromagnetic protection. *J. Mater. Sci. Technol.* **2025**, *204*, 204-23. DOI
75. Jian, S.; Wu, X.; Yu, H.; Wang, L. Enhancing strategies of MOFs-derived materials for microwave absorption: review and perspective. *Adv. Colloid. Interface. Sci.* **2025**, *338*, 103412. DOI
76. Qin, M.; Zhang, L.; Wu, H. Dielectric loss mechanism in electromagnetic wave absorbing materials. *Adv. Sci. (Weinh).* **2022**, *9*, e2105553. DOI PubMed PMC
77. Shi, M.; Jia, Z.; Lan, D.; Gao, Z.; Zhang, S.; Wu, G. Enhanced polarization relaxation of multidimensional bimetallic selenide nanocomposites for electromagnetic wave absorption. *Adv. Funct. Mater.* **2025**, e02261. DOI
78. Luo, N.; Ma, Y.; Ni, Z.; Chen, F.; Fu, Q. Preparation of reduced graphene oxide aerogel microspheres with excellent electromagnetic microwave absorption performance. *Carbon* **2025**, *243*, 120466. DOI
79. Jiang, Z.; Si, H.; Li, Y.; et al. Reduced graphene oxide@carbon sphere based metacomposites for temperature-insensitive and efficient microwave absorption. *Nano. Res.* **2022**, *15*, 8546-54. DOI
80. Pan, Y.; Cheng, L.; Lan, D.; et al. Conductor-semiconductor heterointerface polarization enhancement for superior electromagnetic wave absorption. *J. Mater. Sci. Technol.* **2026**, *244*, 129-41. DOI
81. Liu, T.; Wang, C.; Zhang, X.; et al. Phase engineering in a twin-phase β/γ-MoC_x lightweight nanoflower with matched fermi level for enhancing electron transport across the polarized interfaces in electromagnetic wave attenuation. *Adv. Funct. Mater.* **2024**, *34*, 2410194. DOI
82. Zeng, X.; Nie, T.; Zhao, C.; Gao, Y.; Liu, X. *In situ* exsolution-prepared solid-solution-type sulfides with intracrystal polarization for efficient and selective absorption of low-frequency electromagnetic wave. *Adv. Sci. (Weinh).* **2024**, *11*, e2403723. DOI PubMed PMC
83. Sun, R.; Lv, H.; Lian, G.; et al. Dielectric shell regulation in synergy FeCoNi@$ZnIn_2S_4$ microspheres with broadband electromagnetic wave absorption. *Soft. Sci.* **2025**, *5*, 35. DOI
84. Quan, B.; Liang, X.; Ji, G.; et al. Dielectric polarization in electromagnetic wave absorption: review and perspective. *J. Alloys. Compd.* **2017**, *728*, 1065-75. DOI
85. Kuriakose, M.; Longuemart, S.; Depriester, M.; Delenclos, S.; Sahraoui, A. H. Maxwell-Wagner-Sillars effects on the thermal-transport properties of polymer-dispersed liquid crystals. *Phys. Rev. E. Stat. Nonlin. Soft. Matter. Phys.* **2014**, *89*, 022511. DOI PubMed
86. He, M.; Zhong, X.; Lu, X.; et al. Excellent low-frequency microwave absorption and high thermal conductivity in polydimethylsiloxane composites endowed by hydrangea-like CoNi@BN heterostructure fillers. *Adv. Mater.* **2024**, *36*, e2410186. DOI
87. Li, N.; Wen, B.; Li, X.; Yang, S.; Yang, G.; Ding, S. Phase structure-induced amplification of interfacial polarization loss for excellent electromagnetic wave absorption. *Chem. Eng. J.* **2024**, *488*, 150420. DOI
88. Zhao, Y.; Wang, L.; Liu, Z.; et al. Simple synthesis of hollow CoFe carbon fiber composites with enhanced heterogeneous interfaces and impedance matching for broadband microwave absorption. *J. Mater. Sci. Technol.* **2025**, *238*, 178-90. DOI
89. Su, X.; Wang, J.; Liu, T.; et al. Controllable atomic migration in microstructures and defects for electromagnetic wave absorption enhancement. *Adv. Funct. Mater.* **2024**, *34*, 2403397. DOI
90. Fang, X.; Li, W.; Chen, X.; Wu, Z.; Zhang, Z.; Zou, Y. Controlling the microstructure of biomass-derived porous carbon to assemble structural absorber for broadening bandwidth. *Carbon* **2022**, *198*, 70-9. DOI
91. Cao, W.; Wang, X.; Yuan, J.; Wang, W.; Cao, M. Temperature dependent microwave absorption of ultrathin graphene composites. *J. Mater. Chem. C.* **2015**, *3*, 10017-22. DOI
92. Li, C.; Zeng, X.; Tan, L.; et al. Three-dimensional interconnected graphene microsphere as fillers for enhancing thermal conductivity of polymer. *Chem. Eng. J.* **2019**, *368*, 79-87. DOI
93. Guo, Q.; Amendola, E.; Lavorgna, M.; et al. Robust and recyclable graphene/chitosan composite aerogel microspheres for adsorption of oil pollutants from water. *Carbohydr. Polym.* **2022**, *290*, 119416. DOI

94. Lefrançois, P. L.; Colò, F.; Meligrana, G.; et al. Spray-dried mesoporous mixed Cu-Ni oxide@graphene nanocomposite microspheres for high power and durable Li-ion battery anodes. *Adv. Energy. Mater.* **2018**, *8*, 1802438. DOI
95. Meng, F.; Wang, H.; Wei; et al. Generation of graphene-based aerogel microspheres for broadband and tunable high-performance microwave absorption by electrospinning-freeze drying process. *Nano. Res.* **2018**, *11*, 2847-61. DOI
96. Zhang, Y.; Si, H.; Dai, Z.; et al. Subwavelength-scale graphene aerogel powders for efficient microwave absorption composites with improved mechanical strength. *Chem. Eng. J.* **2025**, *505*, 159118. DOI
97. Wang, Z.; Yang, T.; Zhou, L.; Hou, X.; Fang, Z.; Hou, Y. Current progress and challenges of electromagnetic wave absorbing materials at high temperature. *Adv. Sci. (Weinh).* **2025**, e04286. DOI
98. Wang, C.; Ding, Y.; Yuan, Y.; et al. Graphene aerogel composites derived from recycled cigarette filters for electromagnetic wave absorption. *J. Mater. Chem. C.* **2015**, *3*, 11893-901. DOI
99. Shao, G.; Guo, L.; Xu, R.; Wu, Y.; Huang, X. Carbon nanofiber aerogel microspheres with heterogeneous skin-core structure for broadband electromagnetic wave absorption. *Carbon* **2024**, *228*, 119416. DOI
100. Fang, X.; Zhang, Y.; Pang, K.; et al. *In situ* construction of efficient electromagnetic function Graphene/PES composites based on liquid phase exfoliation strategy. *Mater. Today. Phys.* **2024**, *43*, 101408. DOI
101. Li, Y.; Meng, F.; Mei, Y.; et al. Electrospun generation of $Ti_3C_2T_x$ MXene@graphene oxide hybrid aerogel microspheres for tunable high-performance microwave absorption. *Chem. Eng. J.* **2020**, *391*, 123512. DOI
102. Zhi, D.; Li, T.; Qi, Z.; et al. Core-shell heterogeneous graphene-based aerogel microspheres for high-performance broadband microwave absorption via resonance loss and sequential attenuation. *Chem. Eng. J.* **2022**, *433*, 134496. DOI
103. Jing, W.; Hui, Z. Cost-effective preparation and high performance of high-temperature electromagnetic wave absorbing materials based on graphene nanosheets. *Ceram. Int.* **2024**, *50*, 31080-7. DOI
104. Wang, W.; Li, Z.; Gao, X.; Huang, Y.; He, R. Material extrusion 3D printing of large-scale SiC honeycomb metastructure for ultra-broadband and high temperature electromagnetic wave absorption. *Additive. Manufacturing.* **2024**, *85*, 104158. DOI
105. Jiang, Z.; Gao, Y.; Pan, Z.; et al. Pomegranate-like ATO/SiO_2 microspheres for efficient microwave absorption in wide temperature spectrum. *J. Mater. Sci. Technol.* **2024**, *174*, 195-203. DOI
106. Wang, W.; Wang, L.; Liu, G.; et al. Temperature-dependent dielectric properties and high-temperature microwave absorption performance of Ti_3SiC_2/Al_2O_3-13%TiO_2 coatings. *J. Eur. Ceram. Soc.* **2024**, *44*, 254-60. DOI
107. Li, T.; Zhi, D.; Chen, Y.; Li, B.; Zhou, Z.; Meng, F. Multiaxial electrospun generation of hollow graphene aerogel spheres for broadband high-performance microwave absorption. *Nano. Res.* **2020**, *13*, 477-84. DOI
108. Zhang, Y.; Zhang, L.; Si, H.; et al. TiN nanofiber metacomposites for efficient electromagnetic wave absorption: Insights on multiple reflections and scattering effects. *J. Mater. Sci. Technol.* **2025**, *233*, 69-79. DOI
109. Chen, D.; Li, T.; Deng, W.; et al. Dual-resonant cavities-induced hierarchical heterogeneous enhancement effect of multi-interfacial microspheres for broadband microwave absorption. *Carbon* **2025**, *238*, 120316. DOI
110. Chen, C.; Xi, J.; Zhou, E.; Peng, L.; Chen, Z.; Gao, C. Porous graphene microflowers for high-performance microwave absorption. *Nanomicro. Lett.* **2018**, *10*, 26. DOI PubMed PMC
111. Tian, Y.; Estevez, D.; Wang, G.; Peng, M.; Qin, F. Macro-ordered porous carbon nanocomposites for efficient microwave absorption. *Carbon* **2024**, *218*, 118614. DOI
112. Duan, S.; Liu, C.; Peng, K.; Xu, G.; Xu, C. A simple and reliable route to prepare high-temperature microwave high-performing absorbers. *J. Mater. Sci:. Mater. Electron.* **2021**, *32*, 25996-6006. DOI
113. Hang, T.; Zhou, L.; Li, Z.; et al. Constructing gradient reflection and scattering porous framework in composite aerogels for enhanced microwave absorption. *Carbohydr. Polym.* **2024**, *329*, 121777. DOI
114. Li, T.; Li, J.; Zhi, D.; et al. Top-level electromagnetic design of multishell resonant cavity for microspherical microwave structural absorbers. *Small. Structures.* **2025**, *6*, 2400666. DOI
115. Gao, J.; Li, Z.; Jin, Z.; Che, X. Ultra-broadband microwave absorber based on disordered metamaterials. *Opt. Express.* **2024**, *32*, 25740-54. DOI
116. Sheinfux H, Kaminer I, Genack AZ, Segev M. Interplay between evanescence and disorder in deep subwavelength photonic structures. *Nat. Commun.* **2016**, *7*, 12927. DOI PubMed PMC
117. Pichler, K.; Kühmayer, M.; Böhm, J.; et al. Random anti-lasing through coherent perfect absorption in a disordered medium. *Nature* **2019**, *567*, 351-5. DOI
118. Zhang, H.; Cheng, Q.; Chu, H.; Christogeorgos, O.; Wu, W.; Hao, Y. Hyperuniform disordered distribution metasurface for scattering reduction. *Appl. Phys. Lett.* **2021**, *118*, 101601. DOI
119. Qin, Y.; Ni, C.; Xie, X.; et al. Multiple reflection and scattering effects of the lotus seedpod-based activated carbon decorated with Co_3O_4 microwave absorbent. *J. Colloid. Interface. Sci.* **2021**, *602*, 344-54. DOI
120. Zhang, Y.; Han, M.; Hu, R.; Zhang, P.; Pan, L.; Sun, Z. Sandwiched MXene/polyimide composite foams for multiscale microwave absorption. *Sci. China. Mater.* **2024**, *67*, 272-8. DOI
121. Li, S.; Mo, W.; Sun, H.; Liu, Y.; Wang, Q. Constructing honeycomb-like hierarchical foam via electromagnetic cooperation strategy for broadband microwave absorption. *Carbon* **2023**, *215*, 118425. DOI
122. Benhamou, S. M.; Houbad, M. Optimizing the management, control, and computation of skin depth in laminated structures considering reflection effects. *Wave. Motion.* **2024**, *127*, 103292. DOI
123. Shao, G.; Xu, R.; Chen, Y.; et al. Miniaturized hard carbon nanofiber aerogels: from multiscale electromagnetic response

manipulation to integrated multifunctional absorbers. *Adv. Funct. Mater*. **2024**, *34*, 2408252. DOI

124. Wang, X.; Han, N.; Zhang, Y.; Shi, G.; Zhang, Y.; Li, D. Large-size $Ti_3C_2T_x$ microsheets for lightweight and wide-frequency microwave absorption. *J. Mater. Sci:. Mater. Electron.* **2022**, *33*, 21091-100. DOI