

Hollow Bowl-Like MXene/FeNi₃ Heterostructures for Electromagnetic Wave Absorption and Photo-Thermo-Electric Conversion

Na Chen

na_chen@syuct.edu.cn

Shenyang University of Chemical Technology

Fang-Yuan Yi

Shenyang University of Chemical Technology

Zhen-Jie Guan

Harbin Institute of Technology

Kang-Jun Wang

Shenyang University of Chemical Technology

Jian-Tang Jiang

Harbin Institute of Technology

Research Article

Keywords: Ti₃C₂T_x MXene/FeNi₃, interfacial transport properties, heterointerface resonance, electromagnetic wave absorption, photothermal conversion

Posted Date: September 2nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10280051/v1>

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

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Driven by rapid advancement of modern electronic and wireless technologies, multifunctional electromagnetic wave absorption (EMA) materials are urgently demanded in radar camouflage, 5G/6G communications and energy utilization. However, traditional EMA absorbers face a critical challenge in reconciling the inherent trade-off between high-efficiency absorption and multifunctional integration. Inspired by bioinspired architecture, we construct a hollow bowl-like MXene/FeNi₃ heterostructure that enables precise modulation of interfacial charge distribution and band alignment, while simultaneously triggering synergistic effects among interfacial charge transport, oxygen vacancy defects and magnetic interactions. Benefiting from these merits, the optimized MXene/FeNi₃ achieves extraordinarily EMA performance with a minimum reflection loss (RL_{min}) of -77.90 dB, an effective absorption bandwidth (EAB) of 6.31 GHz, and a Radar Cross section value of -45.36 dB m². Furthermore, MXene/FeNi₃ exhibits outstanding photo-thermo-electric conversion performance, maintaining a stable surface temperature of 56.7°C for over 6 hours, along with a superior open-circuit voltage of 225.8 mV and short-circuit current of 38.9 mA under 1 sun illumination. More importantly, this architecture design strategy is readily extendable to other magnetic systems such as Co, CoFe, CoNi, and FeCoNi, establishing a versatile platform for the development of next-generation multifunctional integrated EMA materials.

1 Introduction

Driven by the rapid advances in electronic and wireless technologies, electromagnetic wave absorption (EMA) materials have become increasingly critical across diverse fields, including stealth technology, electromagnetic shielding, radar camouflage, 5G/6G communications and energy conversion [1–4]. To meet the stringent requirements of these diverse fields, high-performance EMA materials must simultaneously exhibit strong attenuation, broad effective bandwidth, minimal thickness and multifunctional capability [5–7]. In recent years, various strategies, such as structural engineering, component regulation and mixed dimension, have been proposed and implemented to enhance the EMA performance [8–10]. While these approaches have significantly improved key performance metrics including reflection loss, absorption bandwidth, and thickness reduction, most existing EMA materials still struggle to perform reliably under complex and dynamic real-world environmental conditions, primarily due to their limited functional integration [11, 12]. This functional gap becomes particularly critical in light of pressing global energy challenges and China's dual-carbon strategy, which are driving urgent demand for efficient solar energy harvesting technologies, such as photothermal and photoelectric conversion [13]. Therefore, there is a growing and compelling need to develop multifunctional EMA materials that not only exhibit outstanding electromagnetic attenuation but also actively contribute to sustainable energy conversion processes.

As an emerging family of two-dimensional transition metal carbides/nitrides, MXene has attracted significant attention in the field of multifunctional integrated materials due to its outstanding dielectric properties, high specific surface area, and abundant surface functional groups [14, 15]. These

characteristics synergistically contribute to pronounced polarization loss, conductive loss, and multiple internal reflections [16], thereby significantly enhancing overall EMA performance. Beyond these intrinsic electromagnetic attenuation capabilities, certain MXene, particularly $\text{Ti}_3\text{C}_2\text{T}_x$, exhibit a strong localized surface plasmon resonance (LSPR) effect, arising from the collective oscillation of free electrons within its highly conductive layered structure under optical excitation [17, 18]. This pronounced LSPR effect endows $\text{Ti}_3\text{C}_2\text{T}_x$ with outstanding photothermal conversion efficiency, rendering it highly suitable for solar energy harvesting [19]. However, the practical performance of $\text{Ti}_3\text{C}_2\text{T}_x$ is constrained by its intrinsic limitations. First, the lack of magnetic loss hinders impedance matching, leading to a narrow effective absorption bandwidth [20, 21]. Second, $\text{Ti}_3\text{C}_2\text{T}_x$ MXene is prone to aggregation or restacking due to strong van der Waals interactions, which reduce the interlayer spacing and accessible surface area, thereby weakening electromagnetic attenuation [22]. Furthermore, such aggregation or restacking diminishes the number of active sites and enhances plasmonic coupling [23], collectively degrading LSPR effect and consequently lowering the photothermal conversion efficiency. To address these issues, integrating magnetic components introduces complementary magnetic loss and balance impedance matching, thereby enhancing EMA performance [24]. Meanwhile, the incorporation of magnetic nanoparticles can also prevent MXene restacking, further broadening the effective absorption bandwidth [25]. Notably, the intimate interfacial contact between MXene and magnetic particles creates numerous heterogeneous junctions. Under alternating electromagnetic fields, significant charge accumulation occurs at these interfaces, generating pronounced interfacial polarization that substantially augments electromagnetic energy dissipation [26, 27]. Furthermore, this strong interfacial coupling facilitates the delocalization of charge density and the generation of additional electronic states near the Fermi level [28]. Such electronic structure modifications favor the rapid relaxation of photoexcited hot carriers, which can amplify the LSPR effect and elevate the overall photothermal conversion efficiency. Therefore, constructing MXene-based magnetic-dielectric composites and integrating hierarchical design is crucial for achieving multifunctional EMA applications.

Nature's hierarchical architecture provides valuable inspiration for the design of advanced multifunctional EMA materials. Biomimetic strategies, particularly those leveraging microstructural contributions, offer innovative approaches to enhance EMA. For instance, the bowl-like cavity structures prevalent in biological spores and viral envelopes incorporate air media, which generates abundant heterogeneous interfaces and facilitate favorable impedance matching [29, 30]. Meanwhile, this hollow configuration enables low density and establishes continuous conductive networks conducive to efficient electron transport [31, 32]. More importantly, hollow bowl-shaped configuration possess open porous structures and reduced symmetry compared to symmetrical spherical analogues, which not only promotes deeper penetration of incident electromagnetic wave but also enables diverse stacking arrangements during assembly [33]. These adaptable packing states generate a greater number of internal cavities and transmission channels, thereby further improving electromagnetic wave dissipation.

Drawing inspiration from the above biological architectures, herein we rationally design and fabricate a hollow bowl-like MXene/ FeNi_3 heterostructure (B-MXene/ FeNi_3) with tunable interface transport

properties via a facile template-assisted and in-situ growth strategy. The unique architecture incorporates magnetic FeNi_3 particles to provide pronounced magnetic loss and introduces heterointerface resonance, along with enhanced multiple internal reflections, synergistically optimizing impedance matching and overall attenuation capability. As a result, B-MXene/ FeNi_3 with an appropriate FeNi_3 loadings exhibits exceptional broadband EMA performance, achieving a minimum a RL of -61.44 dB and an EAB of 6.31 GHz. Density functional theory (DFT) calculations were performed to elucidate the underlying enhancement mechanism. The results reveal a clear directional electron transfer from FeNi_3 to MXene, establishing a robust built-in electric field (BIEF), which not only promotes interfacial polarization but also strengthens conductive loss. Furthermore, this charge-engineered BIEF also imparts efficient photo-thermal-electric conversion capability, delivering excellent photothermal stability for over 6 hours under 2 suns irradiation, along with a rapid output of 225.8 mV and 38.9 mA under 1 sun irradiation. This architecture engineering can be readily extended to other magnetic systems including Co, CoFe, CoNi, and FeCoNi alloys, providing a versatile platform for the rational design of multifunctional electromagnetic wave absorption materials toward high-performance electromagnetic protection and integrated solar energy utilization.

2 Results and Discussion

2.1 Constructing Hollow Bowl-Like $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/ FeNi_3 Architecture

Figure 1a illustrates the synthesis process of B-MXene/ FeNi_3 composites. Initially, MXene with ultrathin, flexible, and wrinkled 2D sheet-like morphology (Fig. 1b) are prepared via a chemical removal of aluminum from Ti_3AlC_2 MAX phase and subsequent ultrasonication-assisted exfoliation. The corresponding XRD pattern confirms the Ti_3AlC_2 precursors are completely eliminated, and the appearance of the (002) diffraction peak attests to the successful delamination into few-layered MXene (Fig. S1) [34]. These few-layer MXene sheets are then assembled into three-dimensional bowl-like architectures using PMMA microspheres as sacrificial templates, with subsequent calcination resulting in hollow bowl-structured MXene frameworks. SEM image in Fig. 1c obviously reveals a hollow bowl-like morphology of MXene skeleton. Driven by electrostatic interactions between the negatively charged surface functional groups (e.g., $-\text{O}$, $-\text{OH}$, $-\text{F}$) of MXene and $\text{Fe}^{2+}/\text{Ni}^{2+}$ ions, the adsorption of the metal ions onto the MXene with varying concentrations is achieved [35]. Then an in-situ reduction process is employed to convert the adsorbed ions into FeNi_3 particles, yielding a well-defined MXene/ FeNi_3 heterostructure with tunable interfacial properties. The resulting samples, corresponding to different FeNi_3 loadings, are denoted as B-MXene/ FeNi_3 -1, B-MXene/ FeNi_3 -2, and B-MXene/ FeNi_3 -3, respectively. As shown in Fig. 1d and Fig. S2, the spherical FeNi_3 particles with a size of $100 - 200$ nm are uniformly anchored on both the inner and outer walls of the bowl-like MXene, establishing tight interfacial contact with the MXene matrix. Under an alternating electromagnetic field, the formation of

heterojunction interface can facilitate charge transfer, which not only gives rise to significant interfacial polarization but also strengthens conduction loss [36].

TEM analysis corroborates the structural and morphological integrity of the B-MXene/FeNi₃ composites. As shown in Fig. 2a, the bowl-like architecture of the MXene framework is clearly observed, with spherical FeNi₃ particles (evident as high-contrast spots) uniformly dispersed across both the inner and outer surfaces. The pronounced contrast between bright matrix and dark FeNi₃ particles indicates the intrinsic transparency of the MXene sheets. High-resolution TEM further elucidates the intimate interfacial contact. As illustrated in Fig. 2b, an enlarged view of FeNi₃ particles reveals the lattice spacings of 0.20 nm, consistent with its (110) plane. Adjacent MXene region exhibits well-defined lattice fringes with a spacing of 0.213 nm, matching the (105) plane of MXene (Fig. 2c). Notably, discontinuous lattice fringes and localized point defects are observed throughout both FeNi₃ particles and MXene network. Such a defect-rich architecture provides ample active sites to significantly enhance dipole polarization. SAED pattern further confirms the coexistence of FeNi₃ and MXene, where distinct diffraction spots are indexed to the (110) and (200) planes of FeNi₃ and the (103) and (112) planes of MXene (Fig. 2d). Complementary HAADF-STEM image and EDS elemental mapping demonstrate a homogeneous spatial distribution of C, Ti, O, and F throughout the framework, while the signals of Fe and Ni are colocalized and precisely confined to the particle regions (Fig. 1e). Collectively, these results confirm the successful fabrication of an intimately coupled B-MXene/FeNi₃ heterostructure with well-defined interfacial integration and defect-rich characteristics. The coexistence of C, Ti, O, F, Fe, and Ni elements within B-MXene/FeNi₃ composites is further confirmed by XPS spectra (Fig. 2f). The C 1s spectrum typically shows characteristic contributions from O – C = O (289.5 eV), C – O (285.8 eV), C – C (284.8 eV), and C – F (281.9 eV) species, consistent with surface terminations and possible oxidation of MXene (Fig. S2) [37]. In the O 1s and Ti 2p spectra, signatures of Ti – C bonds from the MXene lattice and Ti – O contributions from surface groups is evident [38], along with indications of partial oxidation to TiO₂ (Fig. S3, 4). Notably, binding energies of 707.7 (Fe⁰ 2p_{3/2}) and 719.9 eV (Fe⁰ 2p_{1/2}) are observed in the Fe 2p spectra, confirming the presence of metallic Fe (Fig. 2g) [39]. Similarly, Ni 2p spectra display binding energies at 852.3 and 869.6 eV, attributed to Ni⁰ 2p_{3/2} and Ni⁰ 2p_{1/2} of metallic Ni (Fig. 2h) [40]. Accompanying satellite features are also observed in both spectra. These results verify the co-existence of metallic Fe and Ni, corroborating the successful formation of FeNi₃ within the composite.

The XRD analysis confirms the successful formation of B-MXene/FeNi₃ composites and reveals critical structural evolution. As shown in Fig. 2i, the diffraction patterns show characteristic peaks of crystalline FeNi₃ at 44.3°, 51.5° and 75.9°, corresponding to the (111), (200) and (220) planes of FeNi₃ (PDF#38–0419), alongside the (002) and (110) peaks of Ti₃C₂T_x MXene. A notable structural change is observed at the (002) peak of MXene. For pristine bowl-like MXene, this peak is located at 6.71°, corresponding to an interlayer spacing of 13.18 Å. Upon construction of B-MXene/FeNi₃ composites, the (002) peak progressively shifts to lower angles of 6.47°, 5.71°, and 5.59° for B-MXene/FeNi₃-1, B-MXene/FeNi₃-2, and B-MXene/FeNi₃-3, respectively. This systematic shift indicates a continuous expansion of the

interlayer distance, with calculated d -spacings increasing to 13.70 Å, 15.51 Å, and 15.82 Å, corresponding to interlayer expansions of 0.52 Å, 2.33 Å, and 2.64 Å relative to pristine MXene, respectively. These results strongly suggest the intercalation of Fe and Ni species into the MXene interlayers during the adsorption-reduction process [25, 34]. Raman spectra reveal the structural integrity and defect evolution of the synthesized B-MXene/FeNi₃ composites. The spectra exhibit distinct A_{1g} and E_g vibrational modes at 152.8, 411.2, and 607.2, which involve the in-plane displacements of Ti, C, and surface functional groups (Fig. 2j) [41, 42]. The characteristic structure of B-MXene also confirmed by the two typical carbon-related bands. The D band at 1344 cm⁻¹, indicative of disordered carbon, and the G band at 1581 cm⁻¹, attributed to graphitized carbon. Compared to the pristine bowl-like MXene, a notable increase in the relative intensity between the D and the G bands (I_D/I_G) is observed for the B-MXene/FeNi₃ composites, indicating a higher density of structural defects within the carbon matrix following the integration of FeNi₃. EPR spectroscopy is employed to probe the defect states and unpaired electron environment within the B-MXene/FeNi₃ heterostructure. As shown in Fig. 2k, the pristine bowl-like MXene exhibits a symmetric Lorentzian EPR signal centered at a g-factor of approximately 2.003, characteristic of unpaired electrons localized associated with structural defects in the MXene carbon matrix. Upon formation of the B-MXene/FeNi₃ composite, the EPR spectrum exhibits a pronounced increase in signal intensity, clearly indicating that the introduction of FeNi₃ nanoparticles induces a higher concentration of paramagnetic centers at the heterointerface. These defects can act as polarization centers to enhance polarization relaxation and boost electron transportation to improve electrical conductivity, thereby ensuring competent dielectric loss for electromagnetic wave attenuation. The surface functionality, primarily comprising = O, -F, and -OH, is further confirmed by the presence of characteristic vibrational modes in the FT-IR spectrum (Fig. 2l). N₂ adsorption-desorption analysis reveals that B-MXene and B-MXene/FeNi₃ exhibit a type IV curve with an H4-type hysteresis loop, characteristic of micro-mesoporous structures. The measured BET surface areas decrease progressively from 246.5 m² g⁻¹ for pristine MXene to 30.4 m² g⁻¹ for the composite with the highest FeNi₃ loading (B-MXene/FeNi₃-3). This trend clearly indicates that the introduction of FeNi₃ particles partially occupies the MXene surface, leading to a moderate reduction in specific surface area while retaining the essential porous framework. The micro-mesopores, together with larger BET surface area can optimize impedance matching and extend propagation pathways for electromagnetic wave, thereby enhancing overall absorption efficiency.

2.2 Electromagnetic Properties of B-MXene/FeNi₃ Architecture

To investigate the EMA performances, the complex permittivity (ϵ' and ϵ'') and complex permeability (μ' and μ'') of B-MXene and B-MXene/FeNi₃ were systematically measured using a vector network analyzer (VNA) within the frequency range of 2 – 18 GHz. As depicted in Fig. S5, ϵ' value of pristine few-layered MXene decreases from 7.48 to 5.48, while ϵ'' value increases from 0.89 to 2.55. Upon reconstruction of

few-layered MXene into 3D hollow bowl-like microspheres, both ϵ' and ϵ'' values are obviously enhanced, with ϵ' ranges from 11.57 to 9.46 and ϵ'' from 2.42 to 1.91 (Fig. 3a). This reveals an increased capability for electric field storage and dielectric loss. The significant increase in ϵ' for B-MXene is attributed to the suppression of layer stacking, the construction of a continuous conductive network, and the formation of hierarchical polarization interfaces, which synergistically amplify the polarization effect [43]. Given the direct correlation between ϵ'' and conductivity [44], the observed rise in ϵ'' stems primarily from increased intrinsic defects and improved conductive network. Further analysis reveals that two peaks observed at approximately 11.85 and 14.19 GHz in the permittivity spectra demonstrate the presence of multiple relaxation processes in the bowl-like MXene. Subsequent interfacial engineering via the decoration of B-MXene with FeNi₃ spheres substantially increases the available interfacial area and promotes local polarization. As a result, the ϵ' of B-MXene/FeNi₃ exhibits a continuous upward trend, as illustrated in Fig. 3b-d. Specifically, the ϵ' reaches approximately 12.64 for B-MXene/FeNi₃-1, around 14.29 for B-MXene/FeNi₃-2, and up to roughly 18.25 for B-MXene/FeNi₃-3. Correspondingly, the ϵ'' of B-MXene/FeNi₃ also increases monotonically with increasing FeNi₃ content, rising from approximately 1.23 to 2.12, and further to 2.97. The gradually enhanced resonance peaks observed in the spectra also validate the strengthened polarization relaxation processes. The B-MXene exhibits moderate dielectric loss tangent ($\tan \delta_\epsilon = \epsilon''/\epsilon'$), while the introduction of FeNi₃ nanoparticles leads to pronounced enhancements in $\tan \delta_\epsilon$ due to the synergistic contributions of interface, dipole, and conduction. Cole-Cole curves are further plotted to gain in-depth insight into the dielectric loss mechanisms [45]. As shown in Fig. 3i, the B-MXene presents only a single semicircle, corresponding to a single polarization relaxation process. Whereas the B-MXene/FeNi₃ display multiple distorted semicircles, indicative of multiple polarization relaxation behaviors, mainly including interface and dipole polarizations. The natural nonmagnetic properties of B-MXene makes it cannot provide magnetic loss mechanisms, with its μ' and μ'' approaching 1 and 0, respectively. After incorporating FeNi₃ nanospheres, both μ' and μ'' exhibit a gradual increase with rising FeNi₃ loading, reaching values of 1.14, 1.17, and 1.34 for B-MXene/FeNi₃ - 1, - 2 and - 3, respectively. These results clearly verify the successful integration of magnetic functionality, which originates from the intrinsic magnetic properties of FeNi₃ component. This is further supported by the magnetic hysteresis loops presented in Fig. 3f. With the FeNi₃ content increases, the Ms and coercivity gradually improve to 27.43 emu/g and 39.59 Oe for B-MXene/FeNi₃ - 1, 38.37 emu/g and 40.22 Oe for B-MXene/FeNi₃ - 2, and 42.36 emu/g and 40.61 Oe for B-MXene/FeNi₃ - 3. Furthermore, the dispersed FeNi₃ nanospheres on the B-MXene surface induce strong magnetic coupling effects. Such a unique component configuration, combined with enhanced magnetic coupling, is responsible for the improved permeability [46, 47]. Accordingly, the magnetic loss tangent ($\tan \delta_\mu$) is significantly enhanced (Fig. 3g), unambiguously demonstrating that the rational design of a dielectric matrix integrated with intimately anchored magnetic constituents can significantly boost magnetic loss. The C₀ curves in Fig. 3h illustrate that this enhanced magnetic loss is ascribed to the natural resonance, exchange resonance, and eddy current effects [48, 49]. Analysis of electromagnetic parameters reveals that FeNi₃ incorporation significantly elevates both permittivity and permeability. To evaluate the overall

electromagnetic wave attenuation capability, the attenuation constant (α) was calculated and displayed in Fig. 3j. The sequence of the α follows the order of $B\text{-MXene/FeNi}_3 - 2 > B\text{-MXene/FeNi}_3 - 1 > B\text{-MXene/FeNi}_3 - 3 > B\text{-MXene}$. Notably, the $B\text{-MXene/FeNi}_3 - 2$ exhibits the highest α value among all samples, signifying its best electromagnetic wave attenuation performance.

To elucidate the electronic configurations and underlying polarization-dominated dielectric loss mechanism of MXene/FeNi₃ composite, density functional theory (DFT) calculations were performed. The optimized structure of pristine B-MXene, FeNi₃ and B-MXene/FeNi₃ are displayed in Fig. 4a-c. The density of states (DOS) of B-MXene/FeNi₃ exhibits a pronounced non-zero value at the Fermi level, confirming its metallic conductive nature. Moreover, the DOS near the Fermi level is markedly enhanced in B-MXene/FeNi₃ composite compared to isolated components (Fig. 4e). Orbital-projected DOS analysis (Fig. 4e₁-e₃) further reveals pronounced overlapping peaks between the Fe/Ni 3d orbitals and the Ti 3d orbitals, as well as the O-terminal 2p orbitals of the MXene surface, providing a theoretical basis for the experimentally observed enhancement in conduction loss. To clarify the driving force for heterojunction formation, the work functions (Φ) were evaluated (Fig. 4f, g). The lower work-function of FeNi₃ indicates that its Fermi level resides higher than that of MXene. This thermodynamic imbalance drives spontaneous electron transfer from FeNi₃ to MXene, leading to the accumulation of positive charges on FeNi₃ and negative charges on MXene. Consequently, a robust built-in electric field is established at the heterointerface [50, 51], which induces interfacial polarization and thereby enhancing dielectric loss. Furthermore, associated charge redistribution leads to characteristic band bending, with the MXene side shifting downward and the FeNi₃ side shifting upward (Fig. 4h). Charge density difference analysis clearly visualizes this interfacial charge dynamics, showing an electron depletion region around MXene and a corresponding electron accumulation around the adjacent FeNi₃ (Fig. 4d). Quantitative Bader charge analysis further confirms an interfacial charge transfer of 2.53 e.

2.3 Microwave Absorption Performance of B-MXene/FeNi₃ Architecture

The EMA performances of B-MXene/FeNi₃ heterostructures were evaluated based on reflection loss ($RL_{\min}$) and effective absorption bandwidth (EAB). Few-layer MXene shows relatively poor EMA performances, with a minimum RL ($RL_{\min}$) of - 21.10 dB under 5.00 mm and a maximum EAB of 2.81 GHz at 2.11 mm (Fig. S7). Upon construction of a hollow bowl-like architecture, both $RL_{\min}$ and EAB are significantly optimized with a reduced thickness. As shown in Fig. 5a, B-MXene presents a stronger $RL_{\min}$ of - 60.61 dB at 4.47 mm and a broadened EAB of 3.41 GHz at 1.95 mm. The subsequent introduction of FeNi₃ nanospheres further enhanced the EMA performances, with B-MXene/FeNi₃-1 achieving an $RL_{\min}$ of - 56.28 dB at 1.67 mm (Fig. 5b₁) and B-MXene/FeNi₃-2 showing an $RL_{\min}$ of - 61.44 dB under 2.33 mm (Fig. 5c₁). Strikingly, B-MXene/FeNi₃-3 exhibits the most pronounced absorption improvement, achieving a $RL_{\min}$ of - 77.90 dB (Fig. 5d₁). The FeNi₃ contents have a more

pronounced effect on EAB (Fig. 5a₂–d₂). This influence is clearly reflected in the 2D RL mappings (Fig. 3b₂, c₂), where B–MXene/FeNi₃–1 and B–MXene/FeNi₃–2 achieve broad EAB values of 5.87 GHz at 1.49 and 6.31 GHz at 1.91 mm, respectively. Additionally, Fig. 5e–h demonstrates that under thickness of 1.5, 2.0, and 2.5 mm, B–MXene/FeNi₃–2 consistently delivers the broadest EAB among all samples. Although B–MXene/FeNi₃–3 shows the strongest $RL_{\min}$, B–MXene/FeNi₃–2 offers superior frequency bandwidth. A comprehensive comparison of $RL_{\min}$ and EAB reveal B–MXene/FeNi₃–2 exhibits the most balanced and optimal EMA performances, positioning it as a promising candidate for lightweight, broadband, and high-efficiency microwave absorption applications. Impedance matching plays a key role in EMA performance, and this characteristic can be assessed using Z_{in}/Z_0 . Typically, a Z_{in}/Z_0 value falls in 0.8 – 1.2 signifies favorable electromagnetic wave penetration into absorbers. As illustrated in Fig. 5i – l, B–MXene/FeNi₃–2 displays superior impedance matching compared to the other samples, which directly contributes to its broadest EAB.

2.4 RCS Simulation, Photo-Thermal-Electric Conversion and EMA Mechanism of B–MXene/FeNi₃

A fundamental requirement for electromagnetic wave absorbers to counter radar detection is their ability to maintain stealth. Under realistic far-field conditions, radar cross section (RCS) acts as a key indicator to quantify the stealth capability [52]. To demonstrate this, 3D radars plane wave scattering signatures of B–MXene and B–MXene/FeNi₃ are presented in Fig. 6a. Compared to B–MXene, B–MXene/FeNi₃ exhibit substantially suppressed reflection signals, with B–MXene/FeNi₃–2 showing the lowest intensity. This suggests B–MXene/FeNi₃–2 dissipates the highest amount of electromagnetic energy, corroborating its superior EMA performances. To further evaluate this capability, Fig. 6b presents 2D RCS plots (– 60 – 60°). The RCS of PEC plate is 11.78 dB m² at normal incidence (Fig. S6). In contrast, B–MXene/FeNi₃–2 maintains RCS signal below – 15.15 dB m² across all detection angles, with a minimum RCS value of – 45.36 dB m². These results demonstrate that heterostructure not only enables tunable EMA performances but also holds promise for designing stealth coating.

The photothermal conversion properties of B–MXene and B–MXene/FeNi₃ composites were evaluated under simulated solar illumination. All samples exhibited rapid temperature increases within 1 min of irradiation. At a power density of 100 mW m^{–2}, MXene/FeNi₃ samples reached temperatures of 52.6°C, 56.7°C and 53.2°C, respectively, significantly exceeding the 49.1°C attained by pristine B–MXene (Fig. 6c). Upon cessation of irradiation, the temperature rapidly decreased to ambient temperature. When the power density was increased to 125, 150, 175 and 200 mW m^{–2}, the corresponding equilibrium temperatures increased progressively to 67.2°C, 77.4°C and 96.9°C, respectively, demonstrating a distinct power-dependent photothermal response (Fig. 6d). The temporal temperature profile of B–MXene/FeNi₃–2 under a constant 200 mW m^{–2} illumination is shown in Fig. 6e. This heterostructure maintained a stable temperature of approximately 96°C for more than 6 hours, demonstrating

exceptional photothermal durability. Corresponding infrared thermal images visually corroborate the uniform and steady heat distribution across the surface, further validating its outstanding cycling stability. The strong broadband absorption capability of MXene/FeNi₃ renders it highly effective for solar-driven thermoelectric conversion. To evaluate this functionality, the open-circuit voltage (VOC) and short-circuit current (ISC) were systematically measured (Fig. 6f-g). Both electrical outputs rose rapidly within 1 min, stabilizing at their maximum value within about 2 min. Under 1 sun radiation, B-MXene/FeNi₃-2 achieves a notably high VOC of 225.8 mV and a ISC of 38.9 mA, substantially outperforming the pure B-MXene sample (174.2 mV and 30.7 mA). When the light intensity was elevated to 2 suns, the electrical performance further improved to 322.6 mV and 56.9 mA, respectively. Such outstanding performance is attributed to the balanced composition, optimized interfacial coupling, and 3D thermal transport network of B-MXene/FeNi - 2, which collectively facilitate efficient photo-thermo-electric synergistic conversion. These results not only confirm the critical role of electronic structure modulation, including charge transfer and orbital hybridization as revealed by DFT calculations, in determining energy conversion performance, both also provides a new direction for developing integrated solar-thermal-electrical energy recovery systems based on MXene composites.

The proposed architectural design strategy is broadly applicable to other magnetic systems, including Co, CoFe, CoNi, and FeCoNi alloys (Fig. S8-10). We demonstrate that by systematically tailoring the metallic composition, particle size distribution, and interfacial contact architecture, the absorption bandwidth, photothermal conversion efficiency, and photoresponsivity can be independently and precisely modulated. Beyond providing a versatile structural engineering route, this work deepens the fundamental understanding of dielectric-magnetic-optical coupling in MXene-based hybrids. It thus establishes a robust materials-by-design framework for lightweight multifunctional composites, with direct implications for aerospace stealth, infrared camouflage, solar-thermal harvesting, and wearable optoelectronics.

3 Conclusion

A novel hollow bowl-like heterostructure, featuring magnetic FeNi₃ particles growing on both interior and exterior surfaces, was constructed through template-driven assembly followed by in-situ reduction process. By precisely tuning FeNi₃ particle concentration, the interfacial charge distribution and band alignment were regulated, enabling modulation of interfacial coupling strength. This resulted in superior interfacial transport properties, effectively boosting polarization and conduction loss characteristics. Combined with strong magnetic coupling behavior of FeNi₃, a synergistic enhancement of multiple loss mechanisms is created in B-MXene/FeNi₃, leading to superior EMA performances. Specifically, the optimized B-MXene/FeNi₃-2 sample achieves a RL_{min} of - 61.44 dB at 8.48 GHz under 2.33 mm, along with a wide EAB of 6.31 GHz at 1.91 mm. Additionally, an RCS value reaches - 45.36 dB m², demonstrating significant potential for stealth-related fields. Furthermore, the electronic structure modulation in B-MXene/FeNi₃ directly strengthens the LSPR effect, and the hollow bowl-like architectonics and continuous conductive network boost light absorption and thermal transport,

collectively enabling efficient solar-to-heat conversion. This work demonstrates the effective regulation of interfacial transport and magnetic properties by coupled structural and component engineering, offering a valuable reference for the advancement of multifunctional EMA materials.

Declarations

Author Contribution

Na Chen: Writing original draft, Funding acquisition. Fang-Yuan Yi: Experiment, Investigation, Data curation. Zhen-Jie Guan: Investigation, Validation, Formal analysis. Kang-Jun Wang: Methodology, Supervision. Jian-Tang Jiang: Resources, Formal analysis. All authors reviewed the manuscript.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (52403356), the Natural Science Foundation of Liaoning Province (2024-MS-128), the Shenyang Young and Middle-aged Scientific and Technological Talent Program (RC240019), Key Project in Science & Technology of SYUCT (2025DB001), and the "Outstanding youth" plan Funds of Shenyang University of Chemical and Technology (2022YQ002).

Data Availability

All raw and processed experimental data generated in this study, including electromagnetic wave absorption, photothermal conversion, photoelectric response, microscopic and spectroscopic characterization data, are available from the corresponding author upon reasonable request.

Supplementary material:

Experimental section. XRD pattern, XPS spectrum, electromagnetic parameters, and EMA performance of few-layer MXene. RCS simulation result.

References

1. Zhu P, Liu G, Teng J, Meng J, Xiao H, Bourouis H, Yan M, Wu C (2026) Robust Multisource Built-In Electric Fields in High-Entropy MXene-Derived Nitrides for Efficient Electromagnetic Wave Absorptions. *ACS Nano* 20(24):17396–17412. <https://doi.org/10.1021/acsnano.6c02913>
2. Rao L, Zhao X, Wang X, Li B, Zhang C, Chen G, Liang C, You W, Wu Z, Wang L, Che R (2026) Oriented diffusion tailors interfacial strain-polarization coupling for broadband electromagnetic absorption. *Nat Commun* 17:4585. <https://doi.org/10.1038/s41467-026-71015-9>

3. Liu X, Qian Y, Yu L, Si Z, Wu L, Wan G, Xu X, Wang G Regulating Local Coordination Environment of Single-Atom Co Absorbers for Dielectric-Magnetic Dual Loss Modulation. *Adv Mater* 38(25):e72966. <https://doi.org/10.1002/adma.72966>
4. Peng H, Cai B, Zhang Y, Gao L, Zhao P-Y, Zhou L, Zhang S, Liang W, Xuan Q-F, Koo MC, Liang C-M, Li W-P, Hou Z-L, Zhou T, Wang G-S (2025) Radar-Terahertz-Infrared Compatible Stealth Coaxial Silver Nanowire@Carbon Nano-Cable Aerogel. *Angew Chem Int Ed* 64(10):e202421090. <https://doi.org/10.1002/anie.202421090>
5. Liu P, He Z, Li X, Ding L, Liu S, Kong J (2025) Multifunctional Hollow Carbon Microspheres Enable Superior Electromagnetic Wave Response and Corrosion Barrier. *Adv Mater* 37(35):2500646. <https://doi.org/10.1002/adma.202500646>
6. Chen N, Pan X-F, Wang R-Y, Han B-B, Li J-X, Guan Z-J, Wang K-J, Jiang J-T (2025) Hetero-Interfaces Strategy Based on Fe_3O_4 Microspheres to Construct Multi-Band Tunable and Anticorrosive Absorbers. *J Mater Sci Technol* 227:1–10. <https://doi.org/10.1016/j.jmst.2024.11.062>
7. Luo J, Lv Z, Zhang Z, Zhang L, Xu H, Mao Z (2026) Biaxially Oriented High-Thermal-Conductivity Electromagnetic Wave Absorber Based on Interlayer Phonon Bridge Construction. *ACS Nano* 20(16):12738–12752. <https://doi.org/10.1021/acsnano.6c03623>
8. Shi M, Jia Z, Lan D, Gao Z, Zhang S, Wu G (2025) Enhanced Polarization Relaxation of Multidimensional Bimetallic Selenide Nanocomposites for Electromagnetic Wave Absorption. *Adv Funct Mater* 35(49):e02261. <https://doi.org/10.1002/adfm.202502261>
9. Chen N, Wang R-Y, Pan X-F, Han B-B, Li J-X, Guan Z-J, Jiang J-T, Wang K-J, San X-G, Liu P (2025) Hollow Engineering of Core–Shell Fe_3O_4 @ MoS_2 Microspheres with Controllable Interior Toward Optimized Electromagnetic Attenuation. *Adv Compos Hybrid Mater* 8(4):302. <https://doi.org/10.1007/s42114-025-01393-z>
10. Wen J, Liu Y, Hui S, Deng L, Zhang L, Fan X, Chen Q, Liu X, Li X, Yan N, Wu H (2025) Lattice Compressive Strain-Controlled Electromagnetic Wave Absorption in TMDs by Plasma-Assisted Rapid Annealing. *Matter* 8(9):102151. <https://doi.org/10.1016/j.matt.2025.102151>
11. Qi J, Liang C, Ruan K, Li M, Guo H, He M, Qiu H, Guo Y, Gu J (2025) Cactus-Like Architecture for Synergistic Microwave Absorption and Thermal Management. *Nat Sci Rev* 12(11). <https://doi.org/10.1093/nsr/nwaf394>
12. Chang L, Zhang X, Liu T, Li B, Ji Y, Sun G, Wang Z, Zhang X, Cao M, Li L (2026) Multifunctional Three-Dimensional Porous MXene-Based Film with Superior Electromagnetic Wave Absorption and Flexible Electronics Performance. *Nano-Micro Lett* 18(1):184. <https://doi.org/10.1007/s40820-025-02034-2>
13. Li X, Han Y, Wang C, Cui S, Shi M, Ma J, Liu T, Wang F, Zhang J, Huang W (2026) Atomic-Level Heterometallic Engineering in Single-Crystalline Polyoxometalate-Based MOF for Efficient Solar Photo-Thermo-Electric Conversion. *J Am Chem Soc* 148(7):7460–7471. <https://doi.org/10.1021/jacs.5c20698>

14. Zhang S, Wu J, Hou Z-L, Hu P, Cai B, Liang C, Zhou L, Liang W, Xue Y, Koo MC, Zhao P-Y, Liu L-M, Liu M, Wang G-S (2026) Regular-Wrinkling Tunable MXene Lattice for Electromagnetic Interference Shielding. *Nat Commun* 17(1):1275. <https://doi.org/10.1038/s41467-025-68035-2>
15. Han B, Wang X, Li M, Wang Y, Wang X, Wang Z, Zhang X, Zhang M, Zhao J (2026) MXene-Enabled Induced-Current Regulation to Amplify Eddy-Current Loss in Liquid Metal Composites for Efficient Microwave Absorption. <https://doi.org/10.1007/s42114-026-01926-0>. *Adv Compos Hybrid Mater*
16. Zhu L, Li N, Zhang H, Yu J, Hu Z, Wang Y (2026) Architecting Hierarchical Porous MXene/CoNi@CNT Hybrids for High-Performance Microwave Absorption via Synergistic Dielectric–Magnetic Regulation. *ACS Appl Mater Interfaces* 18(1):2455–2467. <https://doi.org/10.1021/acsami.5c20152>
17. Zhou Y, Zhang Y, Pang Y, Guo H, Guo Y, Li M, Shi X, Gu J (2025) Thermally Conductive $\text{Ti}_3\text{C}_2\text{T}_x$ Fibers with Superior Electrical Conductivity. *Nano-Micro Lett* 17(1):235. <https://doi.org/10.1007/s40820-025-01752-x>
18. Ben Ayed A, Namvari M (2025) Design strategies in developing MXene-Based Anti-Icing/Deicing Coatings: Toward Energy-Efficient and Durable Solutions. *Adv Compos Hybrid Mater* 8(6):410. <https://doi.org/10.1007/s42114-025-01469-w>
19. Qiao J, Song Q, Xuan L, Liu J, Zhang X, Zheng S, Lin J, Cai W, Zhang Q, Zeng Z, Wu N (2024) Dual Cross-Linked Magnetic MXene Aerogel with High Strength and Durability Enables Multifunctionality. *Adv Funct Mater* 34(33):2401687. <https://doi.org/10.1002/adfm.202401687>
20. Zhang S, Liang C-M, Zhou L, Wu J, Koo MC, Wu Z, Chen Y-T, Wang G-S (2026) Heterolayered Carbonized MXene/Polyimide Aerogel for Low-Reflection Electromagnetic Interference Shielding and Multi-Spectrum Compatible Protection. *Nano-Micro Lett* 18(1):204. <https://doi.org/10.1007/s40820-025-02027-1>
21. Zeng X, Zhao C, Jiang X, Yu R, Che R (2023) Functional Tailoring of Multi-Dimensional Pure MXene Nanostructures for Significantly Accelerated Electromagnetic Wave Absorption. *Small* 19(41):2303393. <https://doi.org/10.1002/smll.202303393>
22. Zhang Y, Ruan K, Zhou K, Gu J (2023) Controlled Distributed $\text{Ti}_3\text{C}_2\text{T}_x$ Hollow Microspheres on Thermally Conductive Polyimide Composite Films for Excellent Electromagnetic Interference Shielding. *Adv Mater* 35(16):2211642. <https://doi.org/10.1002/adma.202211642>
23. Fang M, Li Q, Yang D, Zhou B, Feng Y, Liu C (2023) Synergistic Light-to-Heat Conversion Effect of MXene-Based Transparent Film with Insulating PDMS/ Fe_3O_4 Coating. *Compos Part A* 174:107745. <https://doi.org/10.1016/j.compositesa.2023.107745>
24. Lin S, Lin J, Xiong Z, He X, Li X, Liu C, Wang C, Zeng X, Nie X, Che R (2024) Micro-Helical Ni_3Fe Chain Encapsulated in Ultralight MXene/C Aerogel to Realize Multi-Functionality: Radar Stealth, Thermal Insulation, Fire Resistance, and Mechanical Properties. *Chem Eng J* 492:152248. <https://doi.org/10.1016/j.cej.2024.152248>
25. Wang X, Dong G, Pan F, Lin C, Yuan B, Yang Y, Lu W (2025) Metal–Support Interaction Induced Electron Localization in Rationally Designed Metal Sites Anchored MXene Enables Boosted

- Electromagnetic Wave Attenuation. *Nano-Micro Lett* 17(1):309. <https://doi.org/10.1007/s40820-025-01819-9>
26. Liang J, Sun J, Li Y, Zhou D, Zhu S, Liu P, He Z, Liu H, Kong J (2026) Accelerated Carrier Kinetics in Hollow Cubic Mott–Schottky CoFe@carbon Composites for High-Efficiency Broadband Electromagnetic Wave Absorption. *Small* 22(9):e12791. <https://doi.org/10.1002/sml.202512791>
 27. Chen N, Han B-B, Li J, Hu J, Guan Z-J, Jiang J-T, Wang K-J, Pan Y-T (2026) Yolk–Shell Engineering on Single-Component Fe₃O₄ to Realize Magnetic–Dielectric Synergy for Enhanced Microwave Absorption: Experimental and Simulation Insights. *ACS Appl Mater Interfaces* 18(11):17143–17155. <https://doi.org/10.1021/acsami.6c00749>
 28. Xu T, Tan S, Li S, Chen T, Wu Y, Hao Y, Liu C, Ji G (2024) Synergistic Densification in Hybrid Organic-Inorganic MXenes for Optimized Photothermal Conversion. *Adv Funct Mater* 34(29):2400424. <https://doi.org/10.1002/adfm.202400424>
 29. Ma M, Lan D, Zhang L, Wang Y, Jia Z, Gao Z, Qiu H, Wu G (2026) Hollow Hierarchical Structures Enabled Synergistic Loss Mechanisms for Ultra-Broadband Microwave Absorption. *J Mater Sci Technol* 273:69–77. <https://doi.org/10.1016/j.jmst.2026.03.014>
 30. Li X, Wang X, Li M, Zhu W, Luo H, Lu X, Xu H, Xue J, Ye F, Wu H, Fan X (2025) Built-In Electric Field Enhancement Strategy Induced by Cross-Dimensional Nano-Heterointerface Design for Electromagnetic Wave Absorption. *Adv Funct Mater* 35(18):2407217. <https://doi.org/10.1002/adfm.202407217>
 31. Liu W, Jia K, Yao T, Shen L, Wang D (2024) Graphene-Wrapped Magnetic Multichamber Ti₃C₂T_x Spheres for Stable Broadband Microwave Absorption. *ACS Appl Mater Interfaces* 16(38):51118–51128. <https://doi.org/10.1021/acsami.4c10905>
 32. Wu Z, Tan X, Wang J, Xing Y, Huang P, Li B, Liu L (2024) MXene Hollow Spheres Supported by a C–Co Exoskeleton Grow MWCNTs for Efficient Microwave Absorption. *Nano-Micro Lett* 16(1):107. <https://doi.org/10.1007/s40820-024-01326-3>
 33. Du Q, Men Q, Li R, Cheng Y, Zhao B, Che R (2022) Electrostatic Adsorption Enables Layer Stacking Thickness-Dependent Hollow Ti₃C₂T_x MXene Bowls for Superior Electromagnetic Wave Absorption. *Small* 18(47):2203609. <https://doi.org/10.1002/sml.202203609>
 34. Wang J, Zhang L, Yan J, Yun J, Zhao W, Dai K, Wang H, Sun Y (2024) MXene-Based Ultrathin Electromagnetic Wave Absorber with Hydrophobicity, Anticorrosion, and Quantitatively Classified Electrical Losses by Intercalation Growth Nucleation Engineering. *Adv Funct Mater* 34(37):2402419. <https://doi.org/10.1002/adfm.202402419>
 35. Liu A, Qiu H, Lu X, Guo H, Hu J, Liang C, He M, Yu Z, Zhang Y, Kong J, Gu J (2025) Asymmetric Structural MXene/PBO Aerogels for High-Performance Electromagnetic Interference Shielding with Ultra-Low Reflection. *Adv Mater* 37(5):2414085. <https://doi.org/10.1002/adma.202414085>
 36. Jiang X, Wang Q, Song L, Lu H, Xu H, Shao G, Wang H, Zhang R, Wang C, Fan B (2024) Enhancing Electromagnetic Wave Absorption with Core-Shell Structured SiO₂@MXene@MoS₂ Nanospheres. *Carbon Energy* 6(8):e502. <https://doi.org/10.1002/cey2.502>

37. Tan Y-N, Zeng X, Wu Z, Lv H, Xie Y, Lou Z, Gao Y (2026) Light/Heavy Rare Earth-Doped Mo-MXene: Excellent Electromagnetic Wave Absorption Based on Dual-Domain Synergistic Attenuation. *Adv Funct Mater* 36(26):e25167. <https://doi.org/10.1002/adfm.202525167>
38. Mai T, Chen L, Wang P-L, Liu Q, Ma M-G (2024) Hollow Metal–Organic Framework/MXene/Nanocellulose Composite Films for Giga/Terahertz Electromagnetic Shielding and Photothermal Conversion. *Nano-Micro Lett* 16(1):169. <https://doi.org/10.1007/s40820-024-01386-5>
39. Zeng X, Deng X, Yu Z, Zhang X, Lu J, Gao Y (2026) Evolution of Fe Single Atom in SiOC Ceramic Fibers and Their High-Temperature and Ultrathin Electromagnetic Wave Absorption. *Adv Mater* 38(14):e21533. <https://doi.org/10.1002/adma.202521533>
40. Liang X, Ren S, Xiao W, Wang Y, Man Z (2026) Design of Ferromagnetic-Dielectric Nanoheterostructures with Tunable Magnetoelectric Properties for Microwave Absorption. *ACS Appl Nano Mater* 9(11):5144–5155. <https://doi.org/10.1021/acsnm.5c05843>
41. Yang C, Chen C, Dong X, Pi E, Guo J, Yan K, Wang W, Wang D (2025) Ultra-Flexible Heterogeneous-Structured Hollow-Fe₃O₄@MXene/Silver Nanowire/Bacterial Cellulose Composite Film for Wide-Band Electromagnetic Interference Shielding Applications. *Small* 21(44):e08856. <https://doi.org/10.1002/sml.202508856>
42. Wang R, Ren S, Jin Y, Dong W, Chen P (2025) Interfacial Engineered MXene Heterostructures for Broadband Electromagnetic Wave Absorption and Thermal Insulation. *Small* 21(49):e05577. <https://doi.org/10.1002/sml.202505577>
43. Thakur A, Kim J, Wyatt BC, Gogotsi Y, Anasori B (2026) Composition–Structure–Property Relationships in MXenes. *Nat Rev Mater* 11:516–531. <https://doi.org/10.1038/s41578-026-00911-9>
44. Cai B, Zhou L, Zhao P-Y, Peng H-L, Hou Z-L, Hu P, Liu L-M, Wang G-S (2024) Interface-Induced Dual-Pinning Mechanism Enhances Low-Frequency Electromagnetic Wave Loss. *Nat Commun* 15(1):3299. <https://doi.org/10.1038/s41467-024-47537-5>
45. Zhang X, Qiao J, Wu N, Xin G, Yue S, Ma X, Pan F, Zeng Z, Liu J (2025) Conductive Bimetal–Organic Frameworks with Volcano-Type Fine-Tuned Dielectric Properties for Electromagnetic Wave Absorption. *ACS Nano* 19(29):26761–26769. <https://doi.org/10.1021/acsnano.5c06832>
46. Zhou L, Hu P, Bai M, Leng N, Cai B, Peng H-L, Zhao P-Y, Guo Y, He M, Wang G-S, Gu J (2025) Harnessing the Electronic Spin States of Single Atoms for Precise Electromagnetic Modulation. *Adv Mater* 37(7):2418321. <https://doi.org/10.1002/adma.202418321>
47. Yang X, Wu Z, Pei K, Qian Y, Lv X, Liu M, Zhang R, Yang K, Ying M, Lai Y, Che R (2025) Confining Magnetic Response by the Surface Reorganization of Buckling Permalloy Microspheres for Boosting Microwave Absorption. *ACS Nano* 19(9):9144–9155. <https://doi.org/10.1021/acsnano.4c18320>
48. Wu Q, Ma Z, Wang C, Tao Y, Wang S, Jin Z, Gao T, Li C, Liu P (2025) Carbon Nanofibers with Small-Sized Co Nanoparticles and Structural Defects via a Confined-Coordination Growth Strategy Toward Electromagnetic Wave Absorption. *J Adv Ceram* 14(12):9221210. <https://doi.org/10.26599/JAC.2025.9221210>

49. Chen J, Wang C, Wu Q, Liu S, Zhang R, Liu Z, Liu C, Liu P (2026) Electrospinning of Carbon Fibers with Hollow Spherical Cavities and Embedded Ni@C Nanospheres Toward Wideband Electromagnetic Wave Absorption. Carbon 246:120919. <https://doi.org/10.1016/j.carbon.2025.120919>
50. Zhang Y, Hu P, Zhao P-Y, Cai B, Peng H, Yang S-H, Koo MC, Liang C, Wang G-S (2025) Phosphorus Vacancy-Induced Built-In Electric Field for Electromagnetic Properties Modulation. Adv Sci 12(30):e02857. <https://doi.org/10.1002/advs.202502857>
51. Zhang S, Zheng J, Zhao Z, Du S, Lan D, Gao Z, Wu G (2026) New Prospects in Built-In Electric Fields for Electromagnetic Wave Absorption: from Fundamentals to Interdisciplinary Applications. Adv Funct Mater 36(1):e13762. <https://doi.org/10.1002/adfm.202513762>
52. Li J, Xie H, Wang Q, Wang T (2026) Sulfidation-induced phase engineering of NiCo₂S₄/MXene-nitrogen-doped carbon aerogels for boosting electromagnetic wave absorption. Adv Compos Hybrid Mater. <https://doi.org/10.1007/s42114-026-01908-2>

Figures

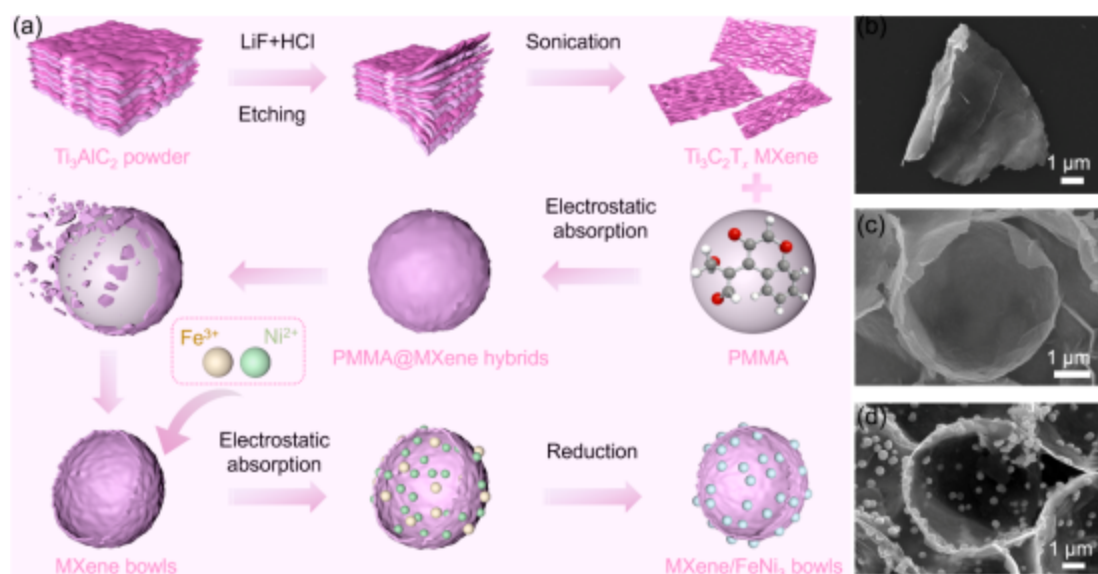


Figure 1

Schematic illustration of the preparation process of (a) 3D bowl-like MXene/FeNi₃ heterostructure. (b) SEM image of few-layer MXene, (c) 3D bowl-like MXene, and (d) B-MXene/FeNi₃ heterostructure.

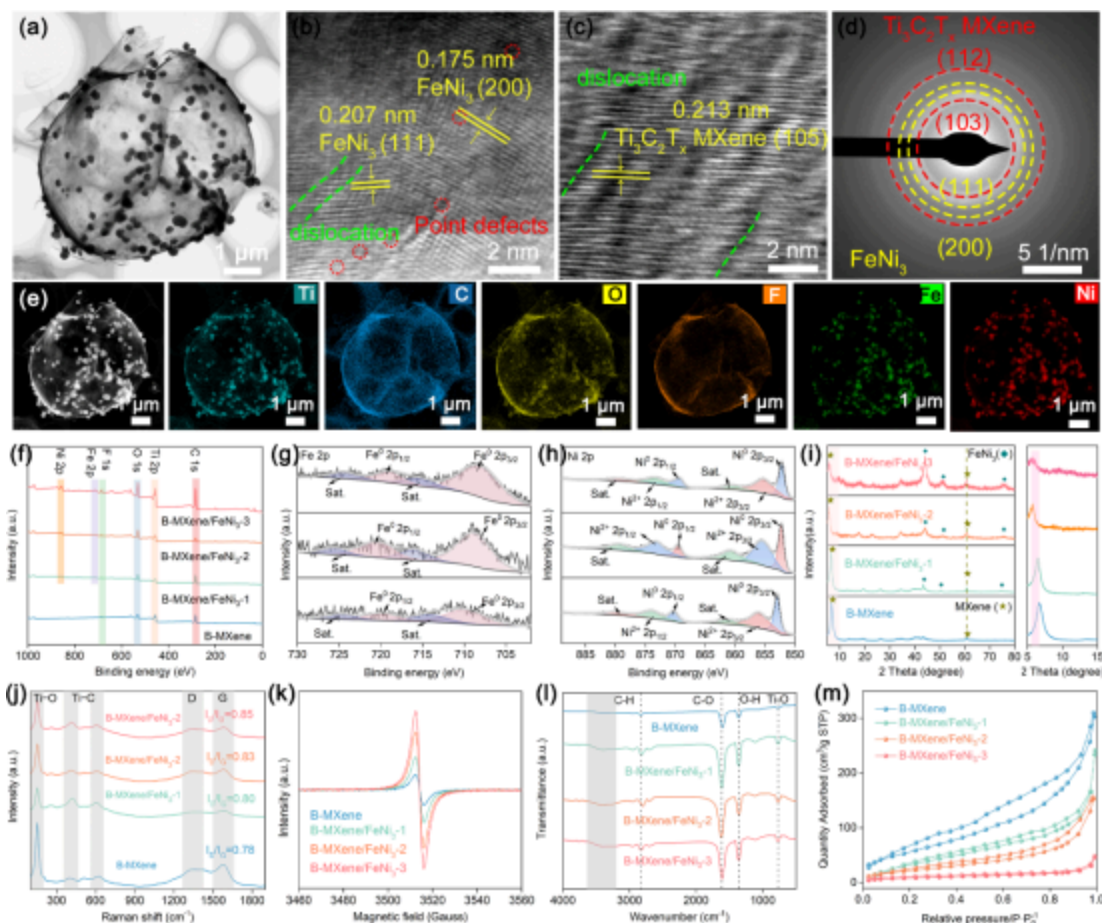


Figure 2

3D bowl-like MXene@FeNi₃ heterostructure analysis. (a, b) TEM image. (b) HR-TEM of FeNi₃ particles. (c) HR-TEM of MXene. (d) SEAD pattern. (e) HAADF-STEM image and corresponding elements mapping. (f) XPS spectra and corresponding high-resolution spectra of (g) Fe 2p and Ni 2p. (i) XRD patterns and local enlargement of B-MXene/FeNi₃-1 to B-MXene/FeNi₃-3. (j) Raman spectra. (k) EPR spectra. (l) FT-IR spectra. (m) Room-temperature magnetic hysteresis loops.

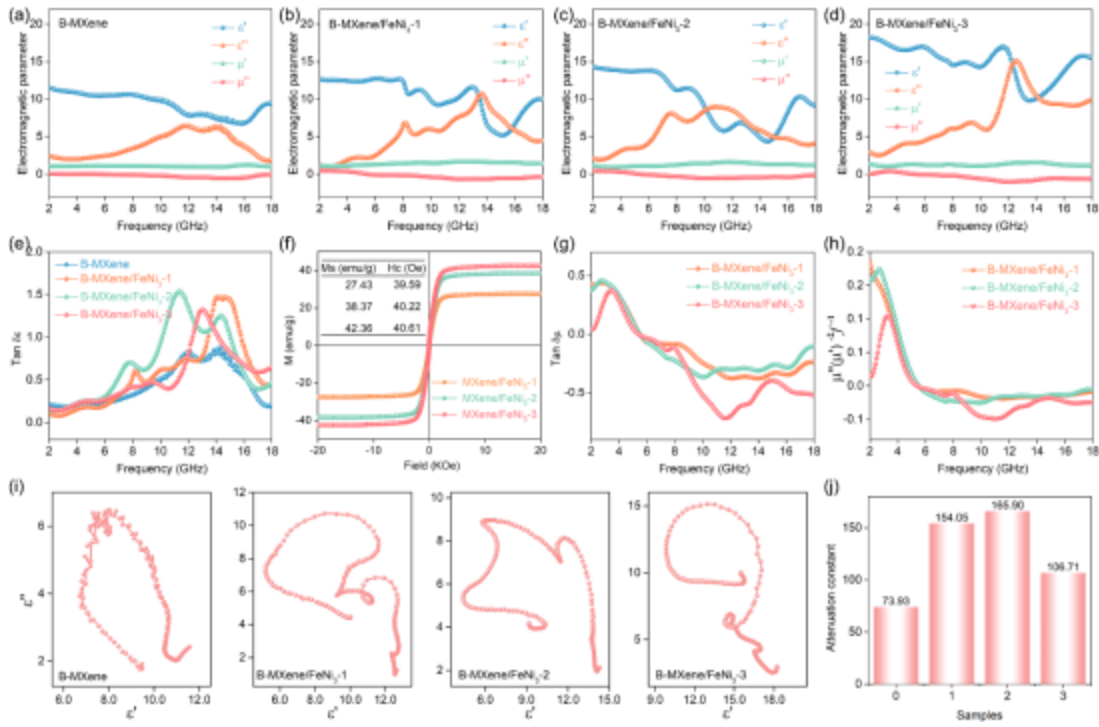


Figure 3

Electromagnetic properties analysis of B-MXene and B-MXene@FeNi₃ hybrids. Complex permittivity and permittivity of (a) B-MXene, (b) B-MXene@FeNi₃-1, (c) B-MXene@FeNi₃-2, and (d) B-MXene@FeNi₃-3. (e) Dielectric loss tangent. (f) Magnetic hysteresis loops. (g) Magnetic loss tangent. (h) C_0 curves. (i) Cole-Cole curves. (k) Attenuation coefficient.

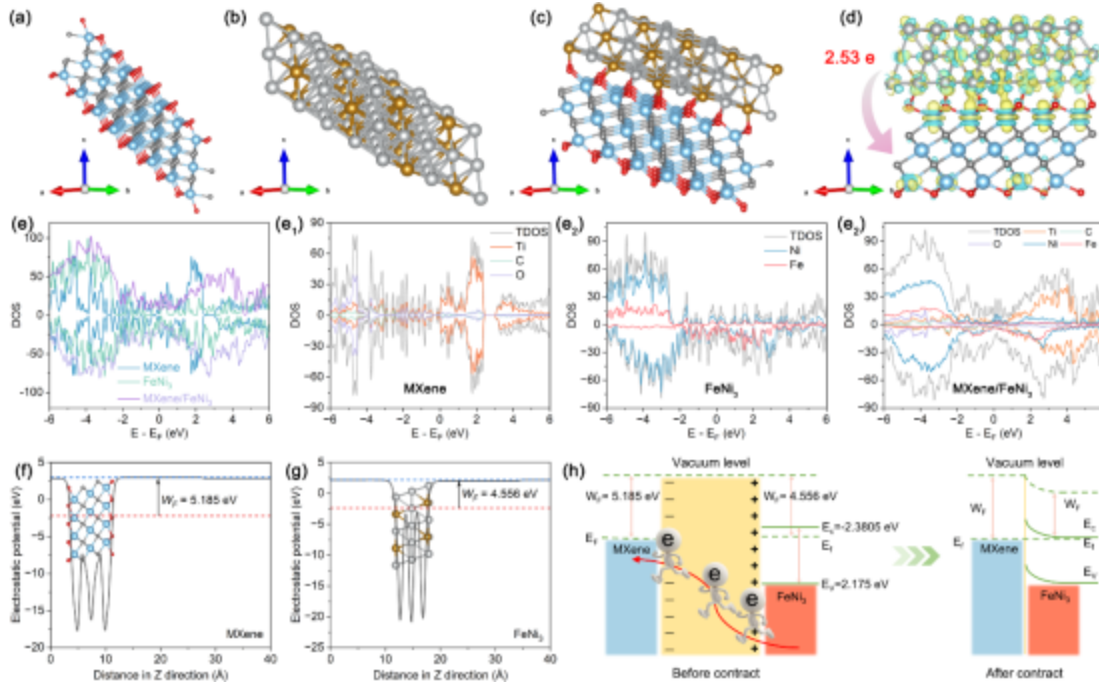


Figure 4

Density Functional Theory (DFT) calculations of B-MXene/FeNi₃ heterostructure. Optimized atomic structure of (a) FeNi₃, (b) B-MXene, and (c) B-MXene/FeNi₃. (d) Differential charge density distribution and Bader charge analysis of B-MXene/FeNi₃ interface. (e) Calculated density of states and projected density of states for (e₁) FeNi₃, (e₂) B-MXene, and (e₃) B-MXene/FeNi₃. Work function of (f₁) FeNi₃, (f₂) B-MXene, and (f₃) B-MXene/FeNi₃. (g) Schematic illustration of energy band alignment before and after contact in B-MXene/FeNi₃.

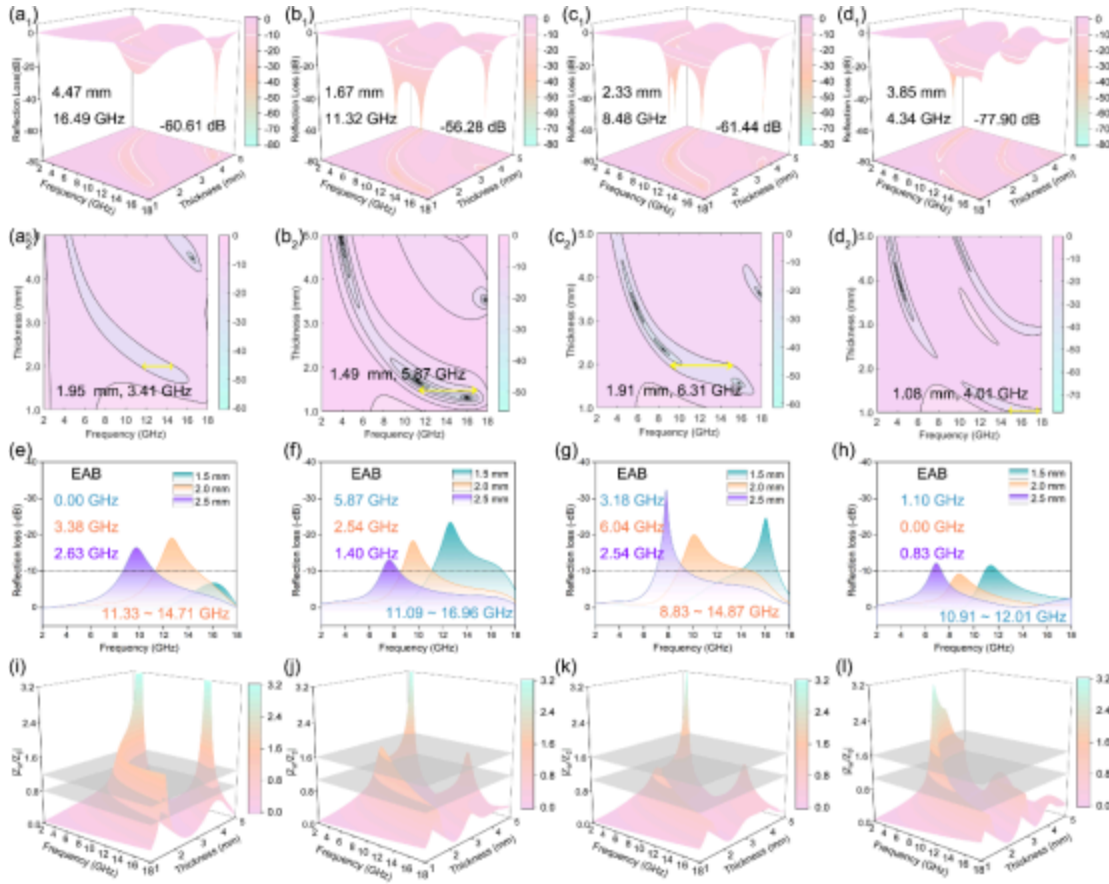


Figure 5

EMA performance analysis of B-MXene and B-MXene/FeNi₃ hybrids. (a-d) 3D and 2D RL diagrams. (e-h) EAB at 1.5, 2.0 and 2.5 mm. (i-l) 3D Z values plots. (a, e, i) B-MXene, (b, f, j) B-MXene/FeNi₃-1, (c, g, k) B-MXene/FeNi₃-2 and (d, h, l) B-MXene/FeNi₃-3.

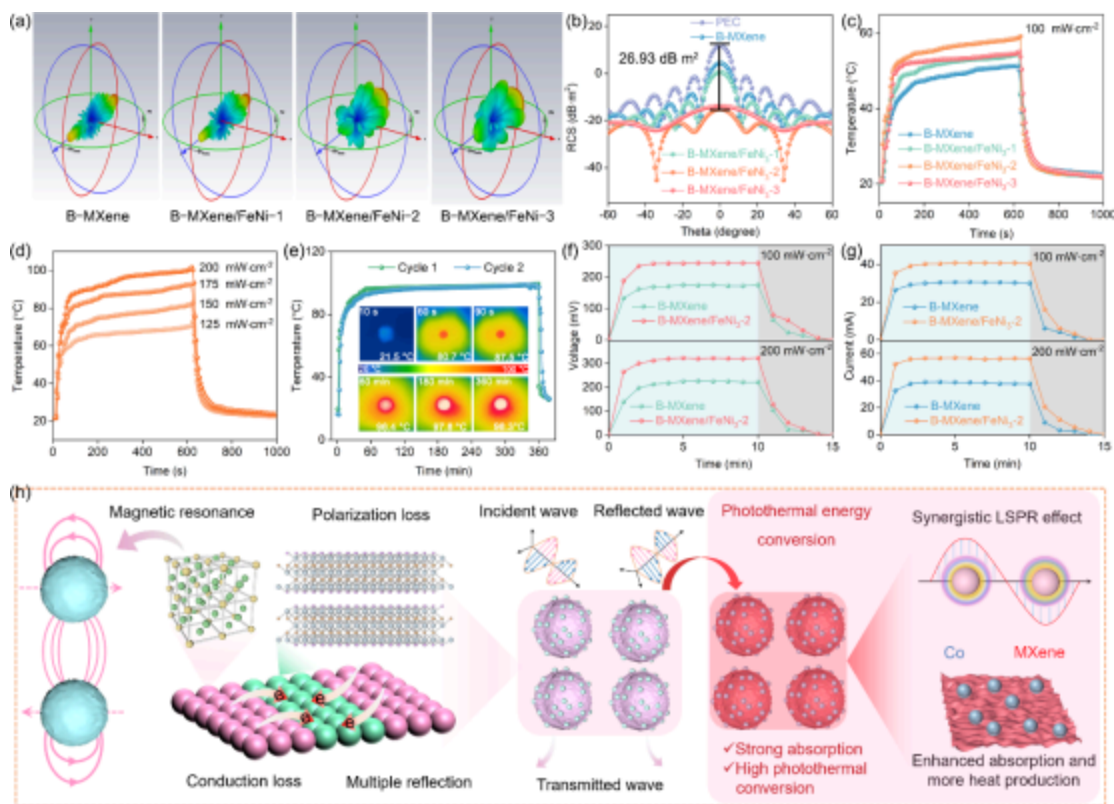


Figure 6

(a) 3D RCS simulation results. (b) RCS curves from -60° to 60° . (c) Surface temperature curves of B-MXene and B-MXene/FeNi₃ under 100 mW m^{-2} . (d) Photothermal temperature curves of B-MXene/FeNi₃-2 at various light power densities. (e) Long-time photothermal stability and infrared thermal images of B-MXene/FeNi₃-2 under 2 suns irradiation. (f) open-circuit voltage. (g) short-circuit currents. (h) Schematic illustration of the EMA mechanisms in B-MXene/FeNi₃ hybrids.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryInformation.docx](#)