



SiBCN/FeSiAl composite torsion gradient cavity metamaterial enables microwave absorption at elevated temperature

Mengke Qiao, Xiangcheng Li , Pingan Chen, Yingli Zhu, Fu Chen, Jiang Wu, Gangtao Luo

Keywords:

High-temperature resistance, metamaterial, torsion, gradient, cavity

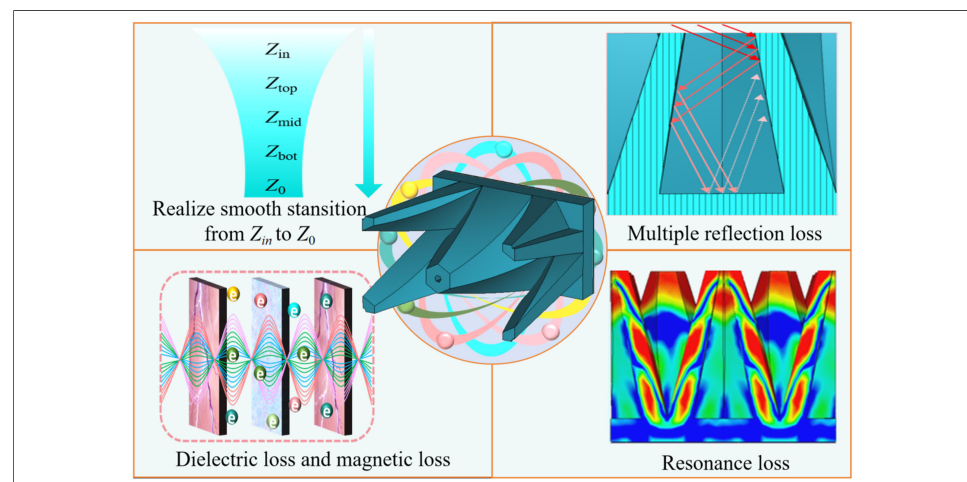
Citation: Qiao, M.; Li, X.; Chen, P.; Zhu, Y.; Chen, F.; Wu, J.; Luo, G. SiBCN/FeSiAl composite torsion gradient cavity metamaterial enables microwave absorption at elevated temperature. *Microstructures* 2026, 6, 20260113. <https://dx.doi.org/10.20517/microstructures.2026.119>

Received: 31 May 2026
First Decision: 1 Jul 2026
Revised: 9 Jul 2026
Accepted: 28 Jul 2026
Published: 28 Aug 2026

Academic Editors:
 Dae-Yong Jeong, Qinchuan He

Copy Editor:
 Ping Zhang

Production Editor:
 Ping Zhang



Abstract

In high-temperature, broadband microwave stealth applications, conventional absorbing materials fail to reconcile thermal stability with strong absorption and wide-spectrum microwave dissipation. To overcome the challenge, this study proposes and validates high-temperature-resistant torsion gradient cavity metamaterial absorbers composed of a SiBCN ceramic matrix and flake-shaped FeSiAl. The torsion gradient cavity structure induces four electromagnetic resonances within the 2-18 GHz range, enabling the real part of the effective complex permittivity (ϵ'_{eff}) to be broadly tuned from -3.2 to 88 and that of the equivalent complex permeability (μ'_{eff}) from -53.7 to 34.0. Meanwhile, the imaginary part of the permeability (μ''_{eff}) is substantially elevated from near zero in the pristine dielectric medium to a range of 1.8-92.2. These characteristics activate multiple synergistic microwave loss mechanisms, achieving simulated full-band absorption coverage across 2-18 GHz, while the measured effective absorption bandwidth is 2.4-18 GHz at room temperature and 3.0-18 GHz at 800 °C, with the minimum reflection loss (RL_{min}) values below -20 dB at all temperatures. Thereby realizing the synergistic optimization of high-temperature tolerance and broadband, high-efficiency microwave absorption. The experimental results are in good agreement with simulations, enriching the design



Key Laboratory of High Temperature Electromagnetic Materials and Structure of MOE, Wuhan University of Science and Technology, Wuhan 430081, Hubei, China.

Correspondence to: Prof. Xiangcheng Li, Key Laboratory of High Temperature Electromagnetic Materials and Structure of MOE, Wuhan University of Science and Technology, Wuhan 430081, Hubei, China. E-mail: lixiangcheng@wust.edu.cn

methodology and technological implementation pathways for microwave-absorbing materials deployed in high-temperature extreme environments.

INTRODUCTION

The rapid development of electronic devices and wireless communication technologies has not only improved human life but also exacerbated the problem of electromagnetic radiation pollution^[1]. On the one hand, electromagnetic pollution causes interference to electronic equipment, resulting in signal loss or interruption, known as electromagnetic interference (EMI). On the other hand, it poses adverse effects on human health^[2]. To address these challenges, there is an urgent need to develop microwave-absorbing materials capable of absorbing and converting electromagnetic energy^[3–5]. Conventional microwave absorbers achieve absorption under resonant thickness by tuning their dispersion characteristics. However, owing to the $\lambda/4$ resonance effect, the required matching thickness at low frequencies is excessively large, while the absorption bandwidth remains narrow, severely limiting their practical applications.

Metamaterial absorbers, enabled by artificially engineered subwavelength structures, have demonstrated remarkable potential for extending effective absorption bandwidths [EAB, Reflection Loss (RL) ≤ -10 dB]^[6–8]. Various innovative strategies have been employed to broaden their bandwidth in current research, including structural symmetry design, gradient sizing, fractal geometries, lumped elements, and multilayer stacking, positioning them as highly promising candidates for applications such as stealth technology, electromagnetic compatibility, and wireless communications^[9–13]. Among these material systems, SiBCN ceramics stand out due to their exceptional high-temperature structural stability and tunable electromagnetic loss characteristics. Furthermore, their electromagnetic parameters can be effectively tailored through compositional engineering and microstructural design, rendering SiBCN an ideal platform for constructing high-performance electromagnetic wave-absorbing metamaterials capable of operating across wide temperature and frequency ranges^[14–17].

Leveraging the inherent excellent microwave absorption potential of SiBCN, its integration with metamaterials through judicious geometric parameter design enables it to operate over a wide temperature range. Huang *et al.*^[18] employed SiC_x/SiBCN composites as the structural backbone. By optimizing the metamaterial architecture and geometric parameters, the resulting truncated pyramid array of SiC_x/SiBCN composites exhibited outstanding broadband and temperature-insensitive microwave absorption properties. Attributable to the gradient impedance matching optimization and multiple attenuation effects arising from the multiscale design, the material maintained an effective absorption bandwidth of 12.5 GHz (5.5–18 GHz) at 1,100 °C, covering 89% of the tested frequency range. Liu *et al.*^[14] fabricated ceramic metamaterials with triply periodic minimal surface (TPMS) structures using photopolymerization molding with preceramic polymers. The low-density helical architecture enhanced multiple reflection losses of microwaves within the macro-scale interpenetrating channel structure. At a thickness of 2.21 mm, this structure achieved an EAB of 3.09 GHz and an $RL_{\min}$ as low as -70.6 dB. Liu *et al.*^[15] combined additive manufacturing (AM), impregnation, pyrolysis, and polymer-derived ceramic (PDC) techniques. Using porous Al₂O₃ as the matrix and depositing a polymer-derived SiBCN coating on the surface of a nano-layered Mo₂C-PyC absorber (SiBCN-Mo₂C/PyC-Al₂O₃), they developed a novel intercalated hierarchical lattice metamaterial. Benefiting from the superior impedance matching enabled by the hierarchical structure and the strong intrinsic electromagnetic attenuation capacity of the absorber, the as-prepared metamaterial achieved an ultra-wide effective absorption bandwidth of 36 GHz covering the 4~40 GHz range at 500 °C, with a $RL_{\min}$ of -32.7 dB. Although the above SiBCN-based metamaterial structures have achieved broadband absorption to some extent, realizing full band microwave absorption, particularly in the low-frequency S and C bands (2~8 GHz), remains highly challenging due to the long wavelength and strong penetration capability of

microwaves in this regime.

One of the core bottlenecks in achieving low-frequency and broadband absorption is the excessive thickness of the absorber. The key to reducing thickness lies in increasing the refractive index of the material, defined as the real part of the geometric mean of the complex permittivity and complex permeability. Two primary strategies are typically employed: introducing magnetic absorbers to enhance permeability, or increasing the filling ratio of conductive absorbers to raise permittivity. However, a high concentration of conductive fillers tends to cause large dielectric losses, leading to impedance mismatch between the absorber and free space^[19]. FeSiAl possesses favorable permeability and conductivity, enabling effective absorption and attenuation of microwave waves. By adjusting the size and thickness of flake-shaped FeSiAl, microwave absorption at different frequencies can be achieved^[20–22]. Therefore, in this study, SiBCN and flake-shaped FeSiAl are adopted as the matrix material to investigate their microwave characteristics at varying mixing ratios. Furthermore, through metamaterial structural design, the design, fabrication, and microwave properties of SiBCN/FeSiAl based bioinspired microwave metamaterials are systematically studied.

MATERIALS AND METHODS

Preparation of SiBCN/FeSiAl composites

To prepare SiBCN/FeSiAl composites, we first fabricated SiBCN ceramics via a polymer precursor method^[23]. Subsequently, SiBCN ceramics with a flake-like graphene structure were obtained through high-energy ball milling. The prepared SiBCN was then incorporated into flake-shaped FeSiAl to tailor the microwave properties. Epoxy resin was selected as a temporary binder to take advantage of its good processability for fabricating complex-shaped green bodies. The preparation procedure is illustrated in Figure 1. Specifically, the SiBCN and flake-shaped FeSiAl were weighed according to a predetermined ratio and placed into a ball milling jar. Ball milling was conducted at a ball-to-powder ratio of 5:1 and a rotational speed of 300 r/min for one hour. The as-obtained composite powder was uniformly blended with epoxy resin. Subsequently, the slurry was poured into a pre-designed mold. After drying and solidification, the material was released from the mold to obtain the green body. After green-body forming, the debinding process was carried out under an argon atmosphere. First, heating to 50 °C at 1 °C/min, then to 300 °C at 0.2 °C/min with a 1 h hold, followed by heating to 500 °C at 0.1 °C/min with a 2 h hold, and finally to 800 °C at 0.5 °C/min with a 2 h hold to ensure complete decomposition and volatilization of the resin. The sample was then sintered at 1,500 °C for 3 h.

Electromagnetic performance of SiBCN/FeSiAl composites

The microstructures of flake-shaped FeSiAl powder and the composite powder were characterized using field-emission scanning electron microscopy (FESEM, Nova 400 NanoSEM, USA). Coaxial ring (inner diameter of 3.04 mm, outer diameter of 7.0 mm), waveguide fixture, and torsion metamaterial absorber (dimensions of 180 mm × 180 mm × 15 mm) samples were fabricated via mold casting. The complex permittivity and complex permeability of the microwave absorbing materials were measured over the frequency range of 2 to 18 GHz using a vector network analyzer (VNA, Ceyear 3672c) equipped with a coaxial test fixture. To evaluate the microwave absorption performance of the SiBCN/FeSiAl based metamaterial at elevated temperatures, a custom-designed experimental setup incorporating an antenna-based measurement system combined with a programmable heating stage was employed. This setup allowed for in situ reflectivity testing across a broad temperature interval, spanning from ambient conditions up to 800 °C, all while preserving thermal stability. The measurement procedure followed a three-step sequence. Initially, the specimen was raised to the desired temperature at a ramp rate of 10 °C/min. Subsequently, it was held isothermally for 15 min to achieve thermal equilibration. Finally, reflectivity data were acquired over the 2~18 GHz frequency band using the arch-based technique.

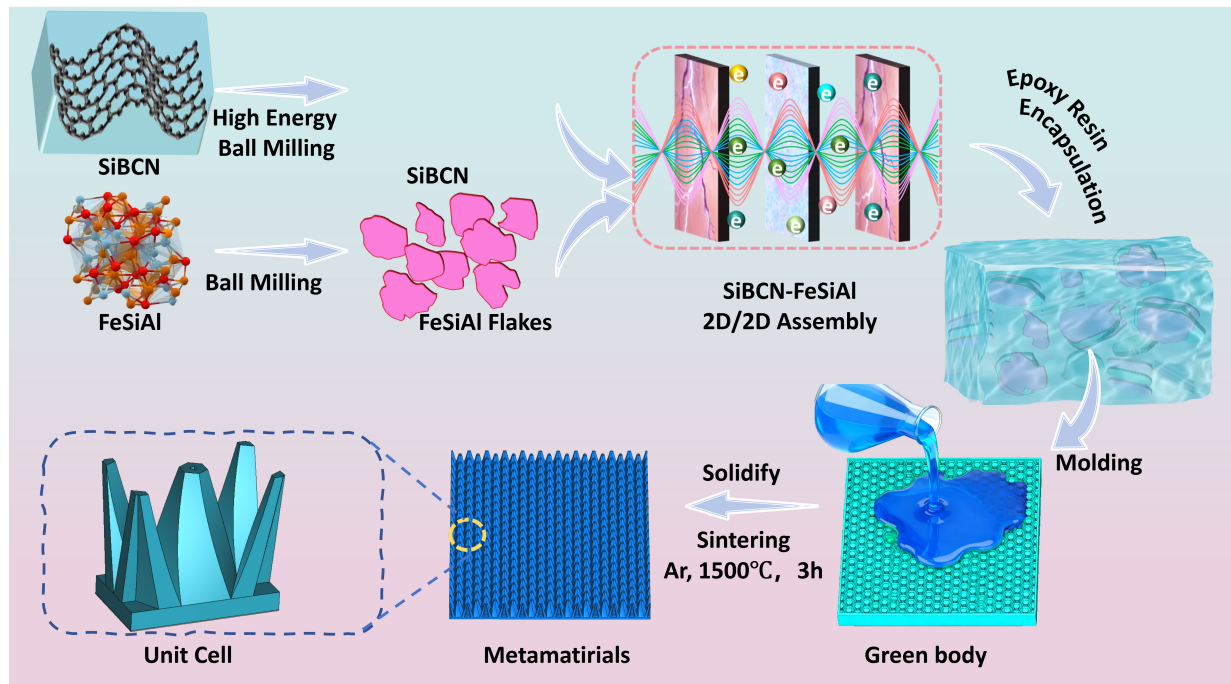


Figure 1. Schematic illustration of the preparation of SiBCN/FeSiAl metamaterial absorber.

As shown in the X-ray diffraction (XRD) pattern [Figure 2A], the final sample is a fully inorganic ceramic matrix composite, composed of BN, FeSiAl, SiC, CN, FeSi and graphene, together with the residual amorphous SiBCN matrix (corresponding to the broad diffuse hump in the pattern), where the sharp diffraction peaks superimposed on the amorphous hump indicate that the SiBCN matrix underwent partial crystallization at 1,500 °C, which is consistent with the reported high-temperature crystallization behavior of SiBCN ceramics in the literature. Figure 2B–D presents the matrix material with 20% SiBCN. As shown in Figure 2B, FeSiAl exhibits a flake-like structure. FeSiAl alloy possesses a high saturation magnetization (M_s). When applied in the GHz frequency range, this alloy achieves effective dissipation of microwave wave energy primarily through eddy current loss mechanisms and natural resonance effects. The flake-shaped FeSiAl exhibits magnetocrystalline anisotropy, which can overcome the Snoek limit and enhance the magnetic loss capability. According to previous studies, the main constituents of SiBCN ceramics are Si_3N_4 , SiC, and graphite. The high-energy collisions and local instantaneous high temperatures generated during high-energy ball milling induce exfoliation, amorphization, and even vaporization-redeposition of graphite, thereby producing flake-like graphene. The dielectric loss generated by its excellent electrical conductivity can combine with the microwave synergy effect formed after compositing with FeSiAl to efficiently absorb and attenuate microwave waves.

Figure 3A–D presents the complex permittivity ($\epsilon_r = \epsilon' - i\epsilon''$) and relative complex permeability ($\mu_r = \mu' - i\mu''$) of SiBCN/FeSiAl composites with varying SiBCN proportions after heat treatment. The measurements were conducted using the coaxial transmission line method with a VNA, over the frequency range of 2 to 18 GHz at room temperature. The hysteresis effect between dielectric polarization and the alternating microwave wave gives rise to frequency dispersion characteristics in ϵ' . As shown in Figure 3A, the ϵ' values of the composites with different SiBCN proportions vary within the ranges of 38.26~26.96, 40.19~26.41, and 32.48~23.06, respectively. Among them, the sample containing 20% SiBCN exhibits the largest ϵ' . Furthermore, this sample demonstrates the highest ϵ'' and μ'' values compared to the other samples, indicating stronger microwave attenuation capability. In addition, the $\tan\delta_c$ value of the 20% SiBCN sample is also the highest. Therefore, the 20% SiBCN sample exhibits the optimal microwave attenuation performance.

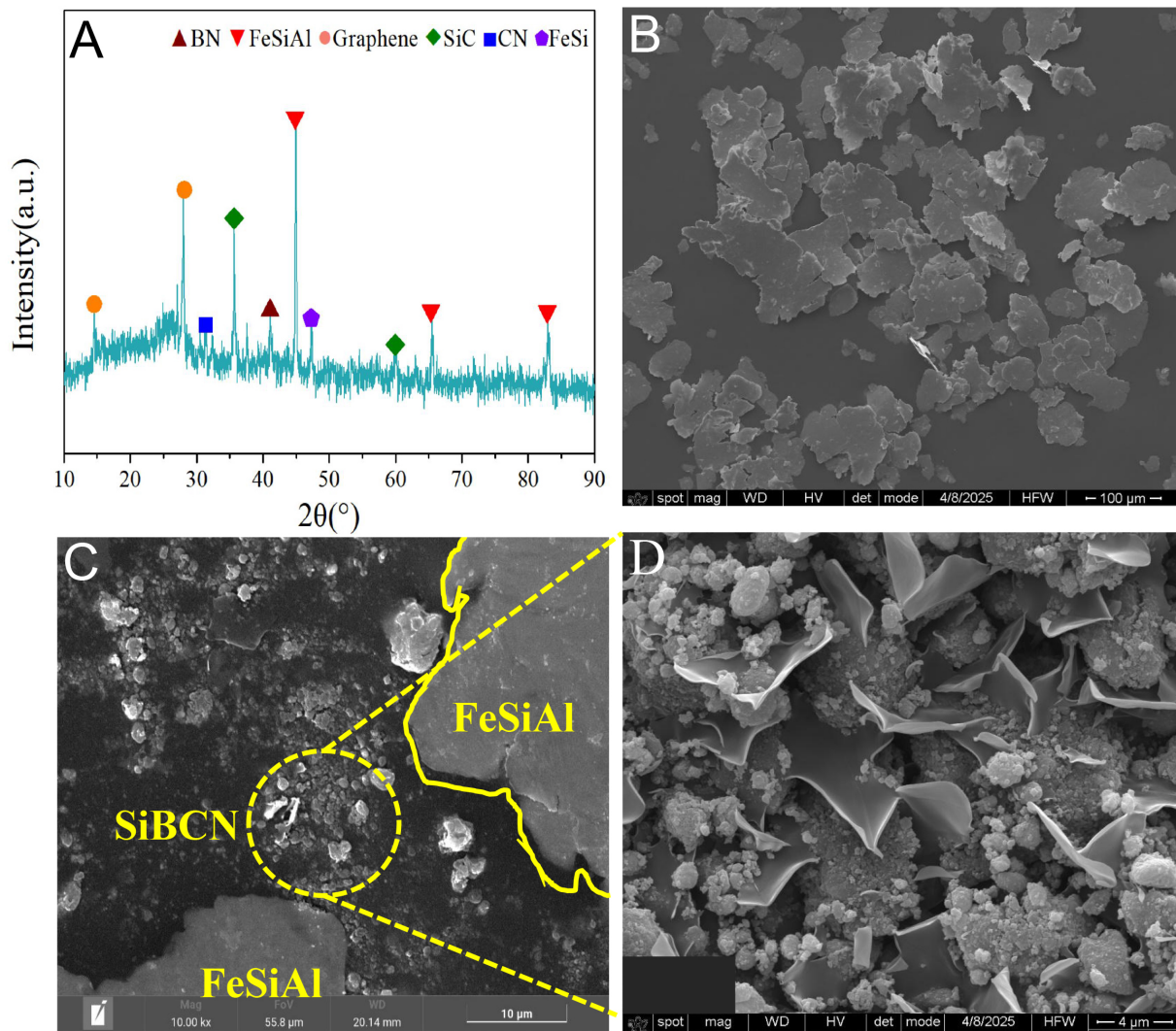


Figure 2. (A) XRD patterns of the sintered sample, (B–D) SEM images of the matrix material with 20%SiBCN. XRD: X-ray diffraction; SEM: scanning electron microscopy.

Impedance matching characteristics represent one of the key factors determining whether microwaves can enter the absorbing material in large quantities to be dissipated. [Figure 3E](#) shows the impedance matching curves of the composite ceramics with different SiBCN contents with a thickness of 5 mm. It can be observed from the figure that as the SiBCN content increases, the impedance matching value of the composite gradually improves. This indicates that the addition of SiBCN enables more microwaves to enter the ceramic and be dissipated. The dielectric loss tangent ($\tan\delta_e$) and magnetic loss tangent ($\tan\delta_m$) of the composite ceramics with different SiBCN contents are shown in [Figure 3F](#).

According to transmission line theory, for a single-layer electromagnetic medium, the microwave absorption performance can be characterized by the RL values. Therefore, the RL values of the SiBCN/FeSiAl composites with different proportions can be calculated based on the complex permittivity and complex permeability as follows^[24]:

$$Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \frac{j2\pi f d \sqrt{\mu_r \epsilon_r}}{c} \quad (1)$$

$$RL = 20 \lg \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| \quad (2)$$

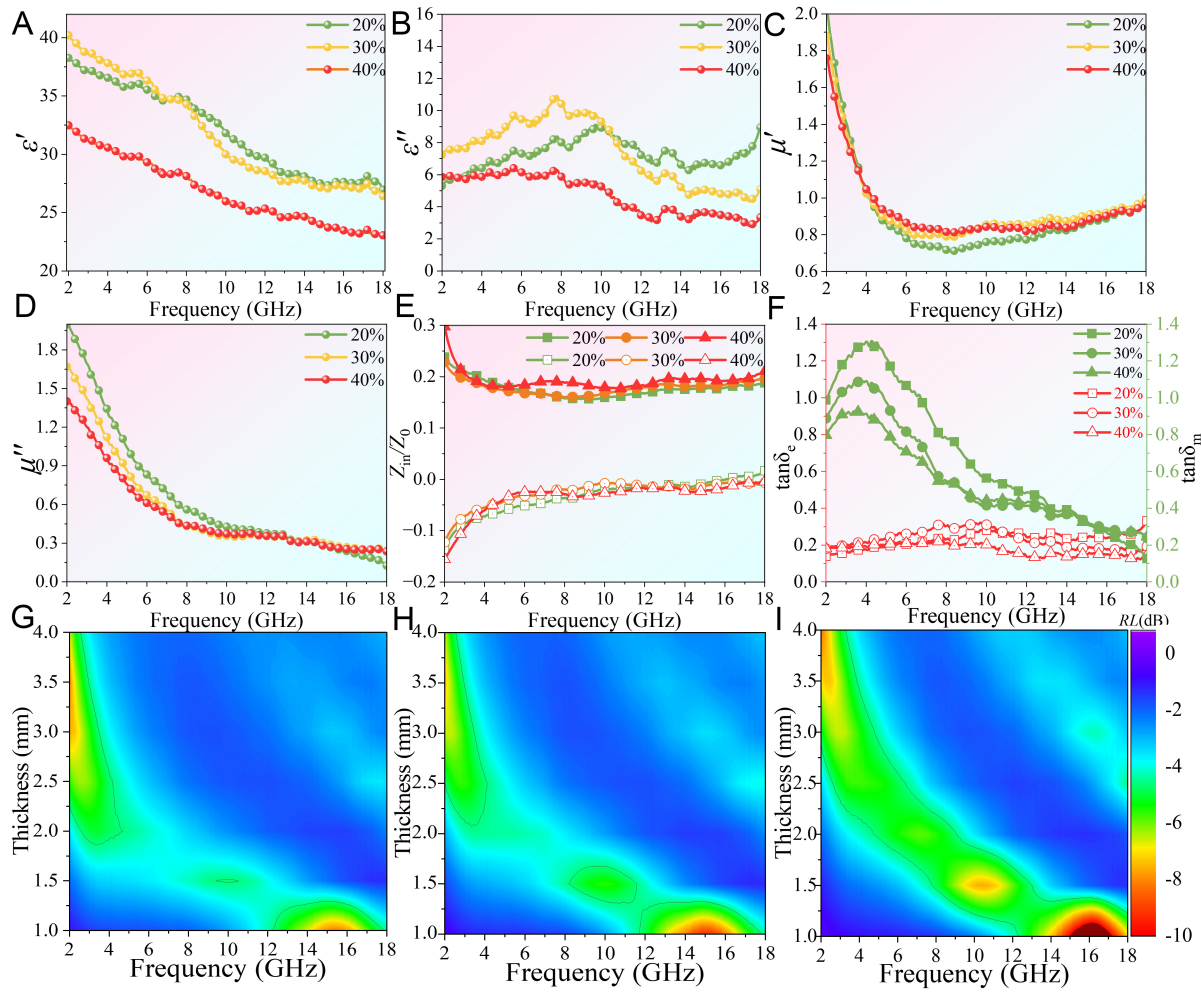


Figure 3. The refractive electromagnetic parameters (A) ϵ' , (B) ϵ'' , (C) μ' , (D) μ'' , (E) Impedance matching, (F) $\tan\delta_e$, and RL with different proportions of SiBCN in the SiBCN/FeSiAl composite material (G) 20%, (H) 30%, (I) 40%. RL: Reflection less.

where Z_{in} is the input impedance at the interface between the material and free space, Z_0 is the characteristic impedance of free space (377Ω), f is the frequency, d is the thickness, and c is the speed of light in vacuum. The RL of the composites with different proportions was calculated, and the results are shown in Figure 3G–I.

It can be observed from the figures that when the SiBCN content is 20%, the microwave attenuation capability of the composite ceramic is relatively weak. The RL_{min} is only -8.3 dB at 15.44 GHz, and the bandwidth with RL below -5 dB is 9.44 GHz. When the SiBCN content is increased to 30%, as shown in Figure 3H, the RL_{min} and the bandwidth for RL < -5 dB are -9.34 dB and 10.72 GHz, respectively. For the sample with 40% SiBCN content, as shown in Figure 3I, the RL_{min} and the bandwidth for RL < -5 dB reach -12.72 dB and 16 GHz, respectively. The reason why the RL performance of the composite gradually enhances with increasing SiBCN content can be explained by Figure 3C. Although the 20% SiBCN sample exhibits the highest ϵ'' and $\tan\delta_e$, its relatively high complex permittivity leads to poor impedance matching with free space, causing most of the incident microwaves to be reflected at the surface rather than entering the absorber. In contrast, the 40% SiBCN sample, despite showing a slightly lower dielectric loss, provides a complex permittivity-to-permeability ratio that is closer to the ideal matching condition ($Z_{in}/Z_0 \rightarrow 1$), allowing more microwaves to penetrate into the material and be effectively dissipated, which ultimately yields the lowest RL_{min} and the broadest effective absorption bandwidth.

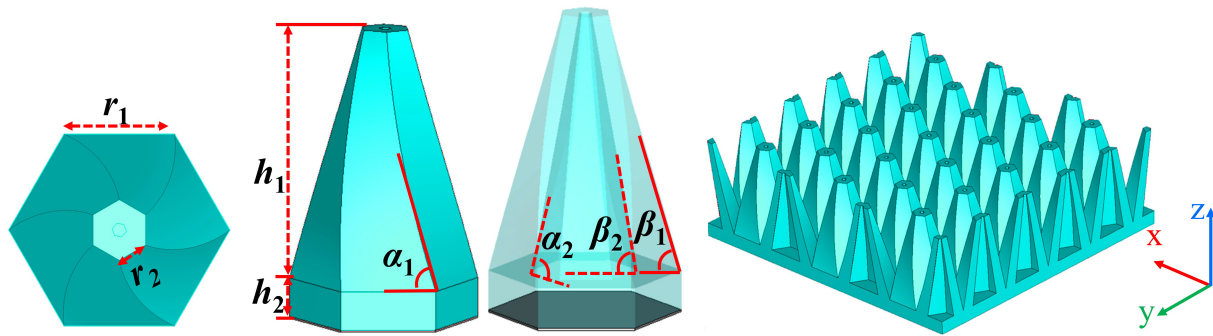


Figure 4. Schematic diagram of the SiBCN/FeSiAl torsion gradient cavity metamaterial.

Design and simulation of the torsion metamaterial

The Nautiloidea represents an elegant gradient spiral architecture. Through the impedance-gradient design of this spiral composite structure, microwaves can gradually dissipate energy when penetrating the material rather than being directly reflected. The constant angle of the spiral ensures directional wave transmission, while the gradient dimensional variation corresponds to the isometric increase of the nautilus shell chambers, which is expected to achieve smooth wave energy attenuation. Therefore, leveraging the spatial hierarchy of the spiral structure, this study designed a torsion gradient cavity metamaterial absorber using the composite ceramic with SiBCN/FeSiAl. The structure is illustrated in Figure 4. The torsion gradient cavity metamaterial absorber consists of periodically arranged unit cells. Here, h_1 represents the height of the gradient structure, h_2 represents the height of the matrix layer, α_1 and β_1 are the twist angle and tilt angle of the gradient structure, respectively, while α_2 and β_2 are the twist angle and tilt angle of the inner chamber structure. Additionally, r_1 and r_2 represent the radii of the upper and lower bases of the unit cell, respectively.

Numerical simulations of the torsion gradient cavity metamaterial's microwave absorption were performed using the frequency-domain solver of Computer Simulation Technology (CST) Microwave Studio. The analysis focused on the 2~18 GHz band, which covers key operational bands for Wireless Local Area Network (WLAN), satellite links, and military radar. The incident wave was generated via a Floquet port, defined with its electric field in the +X direction and magnetic field in the +Y direction. As in the reflectivity measurements, a perfect electric conductor boundary was introduced behind the test sample, acting as an equivalent to the metal reflector plate employed in the actual RL testing.

Figure 5 illustrates the significant variation in the RL of the torsion gradient cavity metamaterial, designed with the 20% SiBCN ceramic matrix as an example, as a function of structural parameters. The influence of parameter h_1 on the RL of the torsion gradient cavity metamaterial is presented in Figure 5A and E. As h_1 increases, the microwave transmission path is prolonged, which enhances energy dissipation and thereby improves the RL performance. Concurrently, the resonance wavelength undergoes a redshift, with the reflection band shifting toward the lower-frequency regime. A reduced RL value corresponds to superior absorption capability. Specifically, an RL below -10 dB signifies that over 90% of the incident microwave energy is absorbed. At $h_1 = 10$ mm, the EAB extends across the entire 2-18 GHz range, with a strong-absorption bandwidth (RL < -20 dB, absorptivity > 99%) of 6.2 GHz. Moreover, when h_1 is increased to 11 mm, a minimum RL of -50.1 dB is achieved at 12.73 GHz, demonstrating outstanding absorption performance under this condition. Further increments in h_1 , however, lead to a saturation trend in the absorption bandwidth. As shown in Figure 5B and F, as r_1 increases from 3.5 mm to 6.5 mm, the bandwidth of the strong microwave absorption region first decreases from 9.4 GHz to 3.5 GHz, then gradually broadens to 6.1 GHz, and subsequently decreases to 2.4 GHz. The size of r_1 directly determines the unit cell dimension of the metamaterial, thereby affecting the resonance frequency, electromagnetic localization effect, and

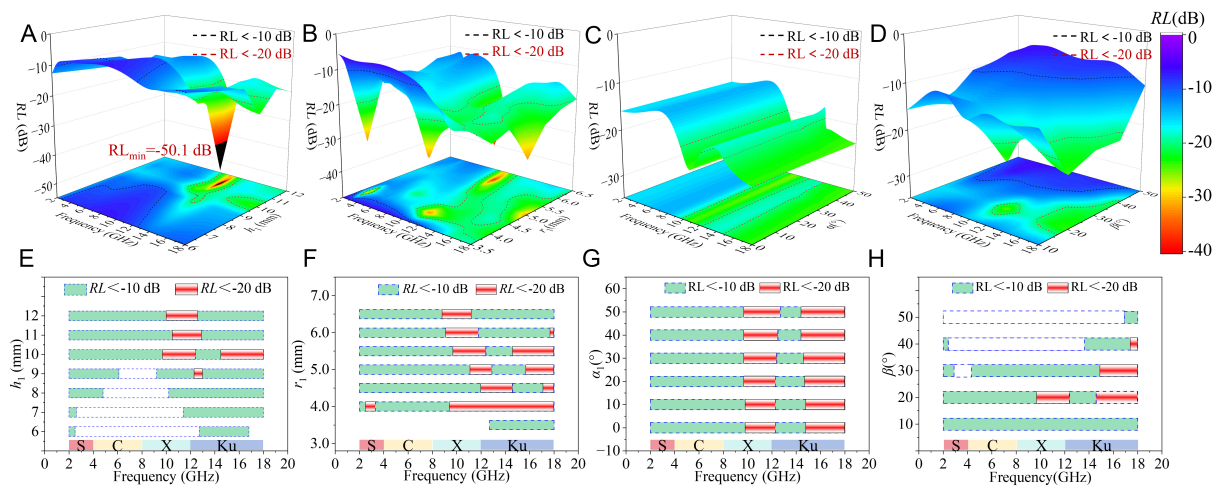


Figure 5. Simulating results of RL values and of torsion metamaterial with different structure parameters: (A and E) h_1 , (B and F) r_1 , (C and G) α_1 , (D and H) β_1 . RL: Reflection less.

impedance matching performance of the metamaterial. A smaller unit cell size leads to a higher resonance frequency, as smaller structures can support microwave resonance at higher frequencies. An appropriate unit cell size can enhance the local microwave field, thereby improving absorption efficiency. Moreover, a smaller unit cell size typically increases the surface current path, enhancing absorption.

As observed in Figure 5C and G, with fixed parameters $h_1 = 13$ mm, $h_2 = 2$ mm, $r_1 = 5.5$ mm, $r_2 = 3.0$ mm, $\alpha_2 = 10^\circ$, $\beta_1 = -10^\circ$, $\beta_2 = -15^\circ$, both the microwave loss performance and the loss bandwidth gradually increase with increasing α_1 . The EAB consistently covers 2~18 GHz. Within the strong absorption region, the bandwidth expands from 5.7 GHz to 6.6 GHz, while the reflection peak value slightly intensifies from -25.2 dB to -25.4 dB. This behavior can be attributed to variations in the helical angle α_1 , which alter the conical configuration of the helical segment and its impedance matching characteristics with free space. Additionally, the gradient structural design induces complex multiple reflections and inter-unit interactions, significantly enhancing interference losses arising from path differences. As shown in Figure 5D and H, with an increase in β_1 , the strong absorption bandwidth of the torsion gradient cavity metamaterial first broadens and then narrows. Superior microwave absorption performance is observed in the high-frequency region (X-Ku band). Based on a multi-objective synergistic optimization strategy that prioritizes maximizing the EAB as the primary goal, achieving the lowest possible $RL_{\min}$ as the secondary goal, while also taking into account structural thickness and fabrication feasibility. In terms of the optimization algorithm, we employed a Trust Region Optimization Algorithm, with the optimization objective set as $RL < -10$ dB over the full 2~18 GHz frequency range, and with predefined upper and lower bounds for each parameter. This algorithm constructs a linear model based on a “trust region” around the starting point of the primary optimization data, first performing a global coarse-grid scan to identify high-performance regions, followed by a localized refined search within these regions until convergence is achieved. The optimal design parameters are determined as follows: $h_1 = 13$ mm, $h_2 = 2$ mm, $r_1 = 5.5$ mm, $r_2 = 3.0$ mm, $\alpha_1 = 30^\circ$, $\alpha_2 = 10^\circ$, $\beta_1 = -10^\circ$, $\beta_2 = -15^\circ$.

RESULTS AND DISCUSSION

Electromagnetic wave absorption performance of torsion gradient cavity metamaterial

Based on the optimized structural parameters, the electromagnetic parameters of SiBCN/FeSiAl composite materials were simulated at different ratios. The results are shown in Figure 6A. The EAB of the metamaterial structure calculated based on different electromagnetic parameter materials all cover 2~18 GHz, proving that the absorption performance of the absorbing metamaterial is concentrated on its

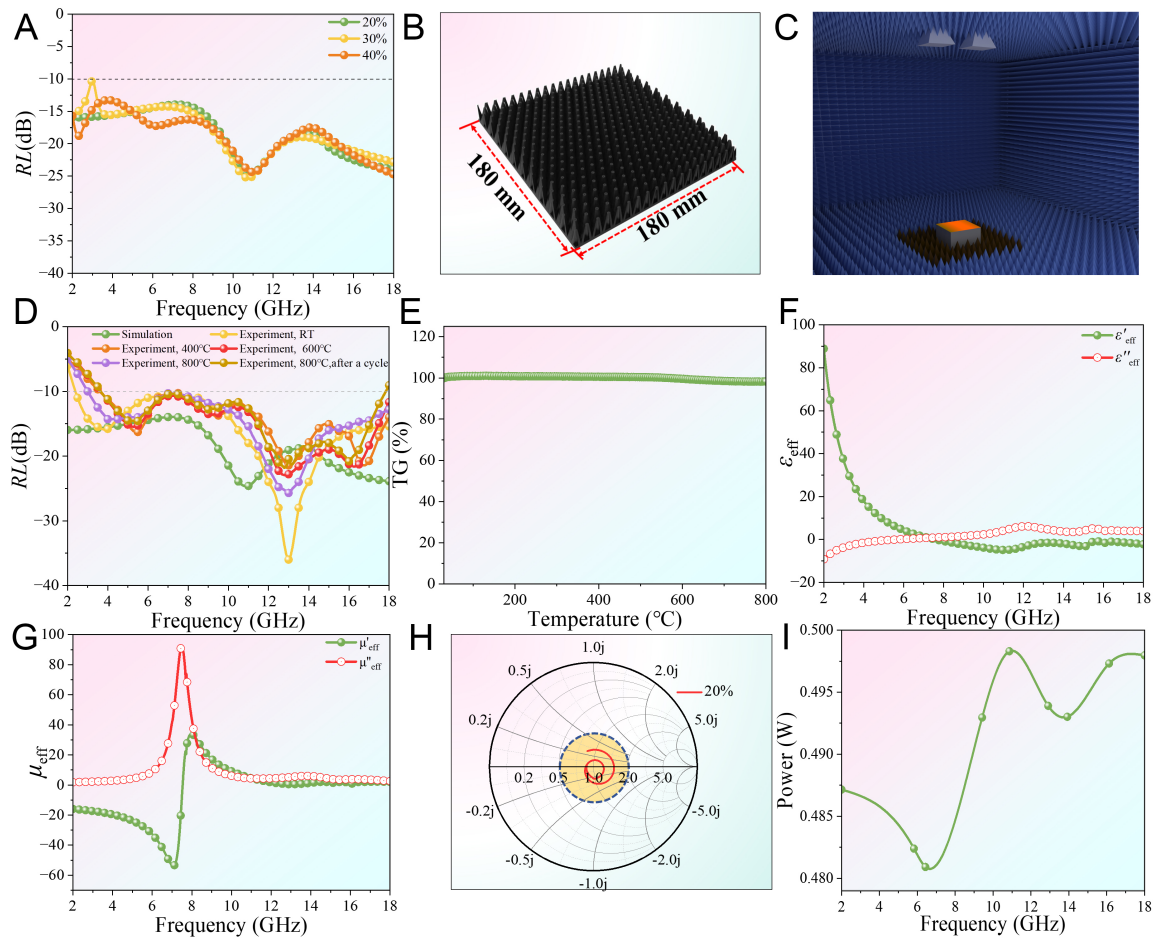


Figure 6. (A) RL with different proportions of SiBCN/FeSiAl metamaterial, (B) test sample, (C) test environment, (D) measured RL curves of the sample, (E) TG curve of the matrix material with 20% SiBCN, (F) effective dielectric constant ϵ_{eff} (G) effective magnetic permeability μ_{eff} , (H) Smith chart of the metamaterial absorbers (the orange shadowed region represents impedance near perfect matching impedance; (I) Power at different frequencies of the metamaterial absorbers. TG: Thermogravimetry; RT: room temperature; RL : reflection less.

structural geometric parameters rather than the intrinsic electromagnetic parameters of the material. To evaluate the high-temperature electromagnetic wave (EMW) absorption performance of the torsion gradient cavity metamaterial, the metamaterial array was processed into a 180 mm × 180 mm sample, and the reflection loss was tested as shown in Figure 6B–D. The test results show that the simulated EAB covers 2–18 GHz with an RL_{min} of -24.4 dB at 10.86 GHz. At room temperature, the measured EAB is 2.4–18 GHz with an RL_{min} of -36 dB at 13 GHz. At 400 °C, the EAB is 3.6–18 GHz with an RL_{min} of -21.5 dB at 13.1 GHz. At 600 °C, the EAB is 3.6–18 GHz with an RL_{min} of -23 dB at 12.8 GHz. At 800 °C, the EAB is 3.0–18 GHz with an RL_{min} of -25.7 dB at 13 GHz. The experimental results are in good overall agreement with the simulations, with all measured RL_{min} values below -20 dB and EAB values exceeding 14.4 GHz across the entire temperature range. After one thermal cycle, the EAB at 800 °C is 3.7–17.9 GHz, with a RL_{min} of -21.7 dB at 12.6 GHz. Furthermore, the RL_{min} variation remains within 16%, and the peak frequency shift is less than 0.4 GHz after thermal cycling, fully demonstrating that this composite exhibits excellent and stable microwave absorption performance across the broad temperature range of 25–800 °C. Figure 6E shows the thermogravimetry (TG) curve of the matrix material with 20% SiBCN. It can be seen from the figure that there is almost no obvious weight change for the material. The TG analysis results demonstrate the structural reliability and oxidation resistance of this composite material under high-temperature service conditions, providing strong support for its practical engineering applications.

The absorption peak frequency shifts from 10.86 GHz in simulation to 13.0 GHz in experiment, with a deviation of +2.14 GHz (approximately 19.7%). The $RL_{\min}$ changes from -24.4 dB to -36 dB, with a deviation of 11.6 dB. The EAB changes from 16 GHz (2~18 GHz) to 15.6 GHz (2.4~18 GHz), with a deviation of 0.4 GHz (approximately 2.5%). These deviations primarily originate from the following factors. First, fabrication tolerance is the main cause of the high-frequency shift of the absorption peak, as feature sizes in the metamaterial structure are subject to machining errors of approximately ± 0.1 mm, and according to the inverse relationship between resonant frequency and structural dimensions, dimensional shrinkage directly leads to a shift of the resonant frequency toward higher frequencies. Second, measurement errors in electromagnetic parameters introduce approximately $\pm 5\%$ uncertainty in the complex permittivity and permeability used as simulation inputs, which in turn affects the accuracy of RL peak depth calculations. Third, surface roughness and finite-size effects also influence the measured results, because the simulation assumes an ideally smooth surface and infinite periodic boundary conditions, whereas the measured sample has a finite size (180 mm $\times$ 180 mm), and edge diffraction effects can introduce certain frequency drifts and loss variations. Fourth, measurement uncertainties in the arch-reflector test system can introduce approximately ± 0.2 GHz frequency deviation and approximately ± 1.5 dB amplitude error. Based on the above analysis, the deviations between simulation and experiment fall within a reasonable range, and the two are in strong agreement in terms of the number of absorption peaks and overall trend, which fully verifies the reliability of the simulation model and design methodology.

The equivalent dielectric constant (ϵ_{eff}) and equivalent magnetic permeability (μ_{eff}) of the structure were calculated using the equivalent medium theory^[25,26]. As shown in Figure 6F and G, the real part of the effective complex dielectric constant of the structure is distributed between -3.2 and 88. The real part of the effective complex magnetic permeability is distributed between -53.7 and 34.0, and the imaginary part of the permeability increases from 0 of the dielectric material to 1.8~92.2, indicating that the design of the torsion gradient cavity metamaterial significantly improves the microwave loss performance of the material. As a representative technology in the field of electronics, the Smith Chart provides a fast, low-computation, and graphical method to evaluate impedance-matching performance. The Smith impedance spectrum of the torsion gradient cavity metamaterial is shown in Figure 6H. The metamaterial has four intersections with the horizontal real axis, indicating that the metamaterial structure has four resonances, and the projection of the real axis of the impedance curve is between 0.5 and 2, indicating that the impedance of the structure is nearly ideal and meets the requirement of $RL < -10$ dB. This is something that a single material cannot achieve. Figure 6I shows the power at different frequencies of the metamaterial absorber.

Broadband microwave absorption mechanism of torsion gradient cavity metamaterial

The microwave loss mechanism of the torsion gradient cavity metamaterial is visually demonstrated by analyzing the electric field distribution, magnetic field distribution, and power loss density distribution at the start frequency (2.00 GHz), the $RL_{\min}$ frequency point (10.86 GHz), and the ending frequency point (18.00 GHz), as shown in Figure 7. The figure that extensive electric field concentration appears on the sample surface. This strong electric field concentration is attributed to the improved impedance matching and the high equivalent permittivity resulting from the torsion gradient cavity metamaterial. Within the torsion gradient cavity metamaterial structure, the magnetic field distribution exhibits a clear frequency-dependent spatial shift. While it remains largely confined to the lower layer at low frequencies, it progressively migrates to the upper layer with increasing frequency. This behavior suggests that the bottom layer plays a dominant role in absorbing low-frequency microwaves. The power loss density distribution at 2.00 GHz is mainly concentrated in the lower layer, which is consistent with the magnetic field distribution. This indicates that at 2.00 GHz, magnetic loss plays a dominant role in the lower layer. As the frequency increases, significant changes occur in the electric and magnetic fields on the surface of the material, which indicates the structural effect of the metamaterial. As frequency increases, both the electric and magnetic

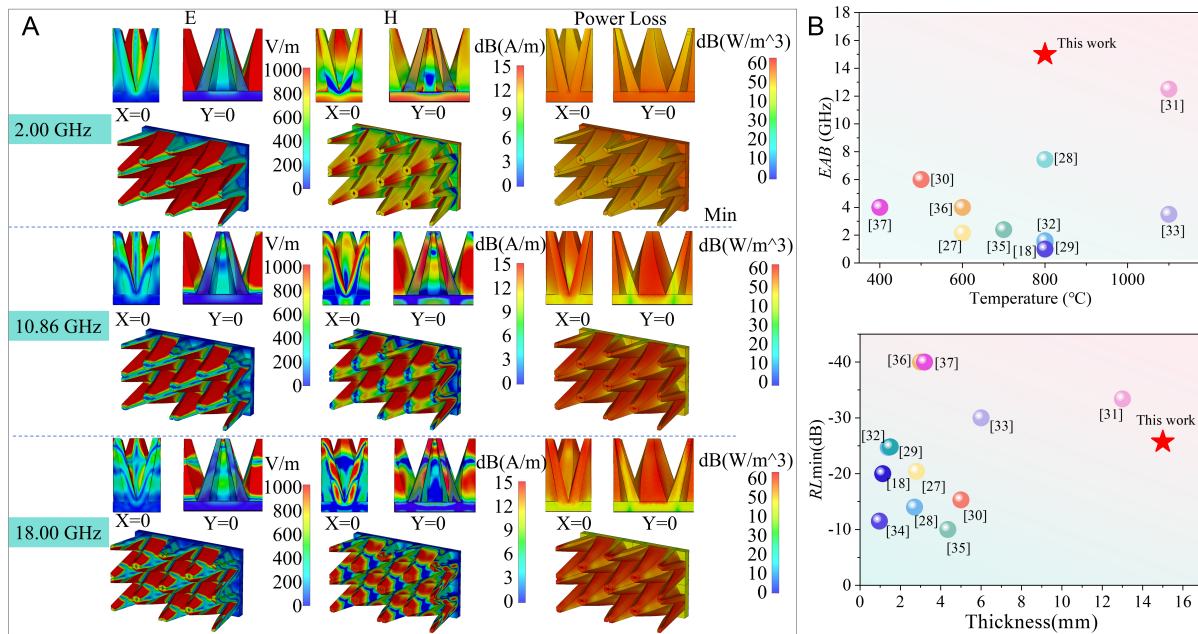


Figure 7. (A) Distributions of the electric field, magnetic field, and power loss density of the metamaterial absorber at 2 GHz, 10.86 GHz, and 18 GHz; (B) Comparisons of EMW absorption bandwidth RL_{min} and thickness (The performance data of the referenced samples are compiled from Ref. [18,27–37]). EMW: Electromagnetic wave.

fields on the material surface change significantly, reflecting the structural effect of the metamaterial. The strong electric and magnetic fields near and inside the cavity of the metamaterial indicate the presence of edge diffraction or secondary scattering in these regions. The metastructure achieves broadband absorption through a combination of material loss and structural effects. At 10.86 GHz, the combined effect of electric loss on the surface and magnetic loss inside the material results in the maximum electromagnetic loss. The microwave loss at 18.00 GHz also results from the combined action of electric loss and magnetic loss. By extracting the electric and magnetic field distributions at each frequency point using CST field monitors, we obtained the quantitative loss contributions at each frequency: the total power loss is 0.487 W at 2 GHz, 0.498 W at 10.86 GHz, and 0.498 W at 18 GHz. Combined with the effective electromagnetic parameters of the material at each frequency for loss contribution separation, where $\epsilon'' = -9.23$ and $\mu'' = 1.85$ at 2 GHz, $\epsilon'' = 3.79$ and $\mu'' = 4.49$ at 10.86 GHz, and $\epsilon'' = 3.90$ and $\mu'' = 2.63$ at 18 GHz. The quantitative results reveal that at the low-frequency band of 2 GHz, magnetic loss dominates due to the negative ϵ'' value reflecting low-frequency dispersive behavior. At the intermediate frequency of 10.86 GHz, electric and magnetic losses reach a synergistic balance, jointly contributing to the formation of the strong absorption peak. At the high frequency of 18 GHz, ϵ'' further increases to 3.90 with significantly enhanced electric loss contribution, while μ'' decreases to 2.63 with relatively weakened magnetic loss, yet the total loss level remains high. These quantitative results are in strong agreement with the qualitative trends observed in the field distribution and power loss density contour maps at different frequencies. Therefore, a rational structural design enables the absorber to exhibit not only a nearly ideal electromagnetic response but also multiple loss mechanisms simultaneously, thereby enhancing its electromagnetic wave absorption capability.

A comparison between the torsion gradient cavity metamaterial designed in this work and the high-temperature-resistant metamaterial structures previously reported in the literature is presented in Figure 7B. The figure shows that the operating temperature range of previously reported metamaterials for microwave absorption spans from 400 °C to 1,100 °C. Due to thermal attenuation of the complex permeability and complex permittivity at elevated temperatures, impedance mismatch is aggravated, while the increased

electrical conductivity enhances surface reflection. Consequently, the microwave absorption bandwidth at high temperatures is often limited, typically below 8 GHz. In contrast, the metamaterial designed in this work achieves a microwave absorption bandwidth of 15 GHz while maintaining a low $RL_{\min}$ value. Therefore, the SiBCN/FeSiAl torsion gradient cavity metamaterial not only demonstrates excellent electromagnetic wave absorption capability but also offers high-temperature resistance, a wide frequency band, strong absorption, and multi-functional integration compared to other composite materials. This work further demonstrates its distinctive strengths in high-temperature suitability and structural integrability.

CONCLUSION

This paper proposes a robust microwave absorber design based on strong magnetoelectric coupling loss between SiBCN ceramics and flake-shaped FeSiAl, with a torsion gradient cavity metastructure constructed via a bioinspired strategy. A regional optimization algorithm was employed to optimize the structural parameters of this metamaterial. Owing to synergistic microwave loss mechanisms involving resonance loss, dielectric loss, and magnetic loss, the absorption bandwidth was effectively regulated. The metamaterial exhibits near-perfect simulated absorption performance over the frequency range of 2 GHz to 18 GHz, while the measured EAB is 2.4~18 GHz at room temperature and 3.0~18 GHz at 800 °C. Experimental results demonstrate that the proposed metamaterial exhibits excellent high-temperature stable microwave absorption performance. The material-structure synergistic approach presented in this study provides an efficient and systematic technical route for the design of high-temperature broadband microwave absorbing metamaterials.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of the study and performed data analysis and interpretation: Qiao, M.; Li, X.

Performed data acquisition, as well as provided administrative, technical, and material support: Chen, P.; Zhu, Y.; Chen, F.; Wu, J.; Luo, G.

Availability of data and materials

The data generated and analyzed in this study are available from the corresponding author upon reasonable request.

AI and AI-assisted tools statement

Not applicable.

Financial support and sponsorship

This work is supported by the National Natural Science Foundation of China (U2541259, 52304410), National Key Research and Development Program of China(2024YFB3714603), and Major Project of Hubei Province (Functional Coating and Materials, 2023BAA003-1).

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Copyright

© The Author(s) 2026.

REFERENCES

1. Zhang, X.; Qiao, J.; Wu, N.; et al. Conductive bimetal-organic frameworks with volcano-type fine-tuned dielectric properties for electromagnetic wave absorption. *ACS. Nano.* **2025**, *19*, 26761-9. DOI
2. Ma, J.; Zhao, B.; Xiang, H.; et al. High-entropy spinel ferrites MFe_2O_4 ($\text{M} = \text{Mg, Mn, Fe, Co, Ni, Cu, Zn}$) with tunable electromagnetic properties and strong microwave absorption. *J. Adv. Ceram.* **2022**, *11*, 754-68. DOI
3. Peng, Y.; Liu, J.; Feng, Z.; et al. Multi-component heterogeneous interface engineering and magnetic domain evolution for broadband electromagnetic wave attenuation. *Chem. Eng. J.* **2025**, *524*, 168991. DOI
4. You, Y.; Fang, G.; Fan, M.; Guo, J.; Li, Q.; Wan, J. Leveraging novel microwave techniques for tailoring the microstructure of energy storage materials. *Microstructures* **2024**, *4*, 2024034. DOI
5. Wang, Q.; An, W.; Bai, X.; Gao, Z.; Wu, H. Ultra-wideband metamaterial absorber based on a hybrid structure of resistor-reinforced cross kite frame. *Mater. Des.* **2026**, *264*, 115833. DOI
6. Qu, N.; Sun, H.; Sun, Y.; et al. 2D/2D coupled MOF/Fe composite metamaterials enable robust ultra-broadband microwave absorption. *Nat. Commun.* **2024**, *15*, 5642. DOI
7. Tan, R.; Zhou, J.; Chen, P. Chainmail-inspired conformable and switchable microwave metamaterial absorber. *Nat. Commun.* **2026**, *17*, 11. DOI PubMed PMC
8. Li, T.; Du, J.; Sun, J.; et al. Bioinspired free-space architecture engineering for broadband electromagnetic absorption and thermal management in graphene-based fibrous textiles. *Adv. Funct. Mater.* **2026**, *36*, e30666. DOI
9. Guan, C.; Chen, J.; Sun, F.; et al. Realization and characterization of broadband absorbing FRCM via microwave curing process. *Adv. Compos. Hybrid. Mater.* **2026**, *9*, 1738. DOI
10. Zhou, Q.; Shi, T.; Xue, B.; et al. Gradient carbonyl-iron/carbon-fiber reinforced composite metamaterial for ultra-broadband electromagnetic wave absorption by multi-scale integrated design. *Int. J. Miner. Metall. Mater.* **2023**, *30*, 1198-206. DOI
11. Jin, H.; Pang, H.; Guan, R.; et al. Topological fractal multifunctional metamaterial with broadband microwave absorption and hydrophobic characteristics. *Mater. Today. Phys.* **2025**, *55*, 101757. DOI
12. Liu, Y.; Ibrahim, S.; Majid, N. A.; et al. Adaptive impedance matching in microwave and terahertz metamaterial absorbers using PIN diodes and GaN HEMTs. *J. Phys. D. Appl. Phys.* **2024**, *57*, 315101. DOI
13. An, Z.; Huang, Y.; Zhang, R. High-temperature multispectral stealth metastructure from the microwave-infrared compatible design. *Compos. Part. B. Eng.* **2023**, *259*, 110737. DOI
14. Liu, C.; Guo, X.; Tong, Y.; et al. Vat photopolymerization 3D printing SiBCN ceramic metamaterials with strong electromagnetic wave absorption. *Addit. Manuf.* **2024**, *87*, 104239. DOI
15. Liu, X.; Zhou, Q.; Ma, X.; et al. Intercalated SiBCN-Mo₂C/PyC-Al₂O₃ ceramic hierarchical lattice metastructure: a new paradigm for ultrabroad bandwidth-to-thermal electromagnetic absorption. *Adv. Funct. Mater.* **2026**, *36*, e75349. DOI
16. Zhang, Q.; You, X.; Wang, Y.; et al. Permittivity qualification, prediction, and regulation of absorption composites for high-efficiency microwave compatibility and management. *Adv. Compos. Hybrid. Mater.* **2026**, *9*, 1604. DOI
17. Liu, Z.; He, Z.; Liu, H.; et al. Hierarchical SiBCNFe composite ceramics enabling broadband electromagnetic wave absorption and corrosion resistance. *J. Adv. Ceram.* **2025**, *14*, 9221213. DOI
18. Huang, B.; Cao, Y.; Ye, F.; Liang, J.; Li, C.; Fan, X. Multiscale synergistic design of SiCf/SiBCN-based metamaterial for high-performance electromagnetic wave absorption in a wide temperature domain. *J. Mater. Sci. Technol.* **2026**, *249*, 203-13. DOI
19. Li, D.; Ma, Q.; Lin, C.; et al. Ultrahigh permittivity of surface-state-dominated Bi₂Te₃ nanosheets for low-frequency microwave absorption. *Research* **2025**, *8*, 0886. DOI
20. Zou, B.; Zhang, Y.; Wang, Y.; Cao, X. Microwave-absorbing functionalization of LaMgAl₁₁O₁₉ composite thermal barrier coatings by atmospheric plasma spraying. *J. Adv. Ceram.* **2024**, *13*, 1523-34. DOI
21. Yang, X.; Wu, L.; Hou, J.; et al. Symmetrical growth of carbon nanotube arrays on FeSiAl micro-flake for enhancement of lithium-ion battery capacity. *Carbon* **2022**, *189*, 93-103. DOI
22. Yan, X.; Zhao, H.; Liu, F.; Yu, C.; Jiang, X.; Guo, J. Dual-layer self-healing composites with temperature-responsive intelligent broadband microwave absorption. *Mater. Horiz.* **2026**, *13*, 1582-94. DOI
23. Qiao, M.; Li, X.; Chen, P.; Zhu, Y. Enhanced microwave absorption of refractory SiBCN metamaterials. *J. Am. Ceram. Soc.* **2024**, *107*, 3360-7. DOI
24. Li, T.; Qiao, M.; Chen, F.; Li, X. Electrostatic self-assembled CS/Ti₃C₂T_x/Co@CNT composites with gradient carbon structure and wideband microwave absorption. *Nano. Res.* **2025**, *18*, 94907696. DOI
25. Qiao, M.; Li, X.; Chen, P.; Zhu, Y. Bionic metamaterial microwave blackbody with temperature insensitivity for C~Ku bands. *Plasmonics* **2024**, *19*, 2537-43. DOI

26. Qiao, M.; Li, X.; Liao, Z.; Chen, P.; Zhu, Y. Multioctagonal ring metamaterial with broadband microwave absorption at elevated temperature. *Phys. Status. Solidi. Rapid. Res. Lett.* **2023**, *17*, 2200478. DOI
27. Gui, B.; Wang, J.; Zhu, Y.; et al. High temperature infrared-radar compatible stealthy metamaterial based on an ultrathin high-entropy alloy. *Opt. Express.* **2022**, *30*, 45426-35. DOI
28. Zheng, L.; Feng, R.; Qiao, Y.; et al. Broadband metamaterial absorber with temperature scalability up to 1000 °C. *IEEE. Trans. Antennas. Propag.* **2025**, *73*, 8909-21. DOI
29. Zhao, S.; Ma, H.; Sui, S.; et al. High temperature insensitive ultra-thin electromagnetic metasurface based on ytterbium monosilicate ceramic coating. *Ceram. Int.* **2021**, *47*, 31860-7. DOI
30. Zhao, S.; Ma, H.; Shao, T.; et al. High temperature metamaterial enhanced electromagnetic absorbing coating prepared with alumina ceramic. *J. Alloys. Compd.* **2021**, *874*, 159822. DOI
31. Zhou, Q.; Yin, X.; Ye, F.; et al. Multiscale designed SiC_f/Si₃N₄ composite for low and high frequency cooperative electromagnetic absorption. *J. Am. Ceram. Soc.* **2018**, *101*, 5552-63. DOI
32. Luo, W.; Wang, X.; Chen, X.; et al. Perfect absorption based on a ceramic anapole metamaterial. *Mater. Horiz.* **2023**, *10*, 1769-79. DOI
33. Li, Y.; Li, W.; Wang, Y.; Cao, J.; Guan, J. Refractory metamaterial microwave absorber with strong absorption insensitive to temperature. *Adv. Opt. Mater.* **2018**, *6*, 1800691. DOI
34. Yang, J.; Liu, X.; Gong, W.; Wang, T.; Wang, X.; Gong, R. Temperature-insensitive and enhanced microwave absorption of TiB₂/Al₂O₃/MgAl₂O₄ composites: design, fabrication, and characterization. *J. Alloys. Compd.* **2022**, *894*, 162144. DOI
35. Shao, T.; Ma, H.; Wang, J.; et al. Ultra-thin and high temperature NiCrAlY alloy metamaterial enhanced radar absorbing coating. *J. Alloys. Compd.* **2020**, *832*, 154945. DOI
36. Zhao, M.; Zhu, H.; Qin, B.; et al. High-temperature stealth across multi-infrared and microwave bands with efficient radiative thermal management. *Nano. Micro. Lett.* **2025**, *17*, 199. DOI PubMed PMC
37. Qiao, J.; Liu, Y. Broadband metamaterial absorber with thermal insensitivity up to 600 °C. *Appl. Phys. A.* **2021**, *127*, 4863. DOI

Disclaimer/Publisher's Note: All statements, opinions, and data contained in this publication are solely those of the individual author(s) and contributor(s) and do not necessarily reflect those of OAE and/or the editor(s). OAE and/or the editor(s) disclaim any responsibility for harm to persons or property resulting from the use of any ideas, methods, instructions, or products mentioned in the content.



© The Author(s) 2026. Open Access This article is licensed under a Creative Commons Attribution 4.0 International License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, sharing, adaptation, distribution and reproduction in any medium or format, for any purpose, even commercially, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.