

CoNi-Decorated Biomass-Derived Carbon with Synergistic Dielectric-Magnetic Loss for High-Performance Electromagnetic Wave Absorption

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Abstract

Biomass-derived carbon (BC) materials exhibit great application prospects in developing lightweight, high-efficiency, and broadband electromagnetic wave (EMW) absorbers. However, pristine BC suffers from a single electromagnetic (EM) loss mechanism and limited impedance matching tunability, resulting in insufficient attenuation capacity. In this work, CoNi/BC composites, featuring CoNi nanoparticles firmly anchored onto the biomass carbon matrix, were successfully synthesized using *Arundo donax*-derived BC as the support through a combined hydrothermal and thermal reduction approach. Benefiting from the unique microporous structure and favorable compatibility between dielectric and magnetic components, the synergistic effects of polarization relaxation, conductive loss, and magnetic resonance collectively establish a highly efficient energy attenuation mechanism, endowing the as-prepared composites with exceptional EMW absorption performance. A minimum reflection loss of -50.17 dB is achieved, and an effective absorption bandwidth of 5.01 GHz is obtained at a thickness of only 1.9 mm. This work offers a feasible strategy for constructing low-cost, high-performance biomass-derived carbon-based magneto-dielectric heterojunction EMW absorbers, showing promising potential for practical EMW absorption applications.

1. Introduction

In recent years, with the continuous advancement of electronic technologies and wireless communication systems, electromagnetic wave (EMW) have found increasingly extensive applications in fields such as telecommunications, military operations, and healthcare, rendering them an indispensable technological cornerstone of modern society^[1–4]. However, the proliferation of wireless communication devices, the dense deployment of high-power signal transmission base stations, and the widespread use of household WiFi emitters have collectively contributed to significant environmental pollution caused by electromagnetic interference (EMI). Concurrently, the ubiquity of electronic and communication equipment has resulted in heightened public exposure to various electromagnetic (EM) fields, rendering EM radiation pollution an increasingly severe concern. Accumulating evidence indicates that EMI originating from radar systems, household appliances, and other sources not only disrupts the normal operation of electronic devices but also poses potential threats to human health, potentially inducing a range of serious disorders. Consequently, the development of high-performance, broadband, and lightweight EMW absorbers has emerged as a critical and urgent research priority in the fields of materials science and information security^[5–8].

The core principle of EMW absorption technology lies in utilizing specific materials to convert incident EM energy into thermal or other forms of energy through two primary mechanisms: dielectric loss and magnetic loss. Currently, the most widely employed EMW absorbers include semiconductors, ferrites, magnetic metals, and their alloys, but these materials generally suffer from high density, weak attenuation capability, narrow absorption bandwidth, and poor environmental stability^[9–12]. In contrast, carbon materials have emerged as promising candidates for advanced EMW absorbers that meet the stringent requirements of ‘thin thickness, light weight, broad bandwidth, and strong absorption,’ owing to

their lightweight nature, structural stability, structural diversity, and tunable dielectric/conductive properties^[13–16].

As a naturally abundant carbon source, biomass resources are regarded as ideal precursors for fabricating carbon-based functional materials due to their unique microstructures, low cost, and eco-friendliness. Extensive studies have demonstrated that novel high-performance EMW absorbers can be developed through optimizing the pore architecture of biomass-derived carbon (BC) and tailoring the specific surface area^[17, 18]. For instance, Wu et al.^[19] prepared biomass-derived hierarchical porous carbon containing micropores, mesopores, and macropores from rice husks via KOH activation and one-step carbonization, achieving precise regulation of the pore structure by adjusting the heat-treatment temperature, with a minimum reflection loss ($RL_{\min}$) of -47.46 dB at a thickness of 2.8 mm. Yue et al.^[20] fabricated porous carbon with an array-like structure from waste okara through a hydrothermal route combined with thermal treatment, attaining an effective absorption bandwidth (EAB) of 4.8 GHz at 3.5 mm. Lu et al.^[21] synthesized porous BC from banana peels via hydrothermal-assisted activation carbonization, which delivered an $RL_{\min}$ of -53 dB and an EAB of 4.2 GHz at a thin thickness of 1.7 mm.

Despite the impressive absorption performance of the above-mentioned BC-based materials, their loss mechanisms remain predominantly governed by a single dielectric loss process. According to the EM complementarity theory, the impedance matching state between dielectric loss and magnetic loss critically determines the ultimate EMW absorption performance of a material. Magnetic metals (Co, Fe, Ni, and their alloys) have become the primary functional fillers in magnetic carbon-based EMW absorbers, owing to their strong magnetic loss, high saturation magnetization and permeability, as well as their favorable role in optimizing impedance matching via magnetic response^[22–24]. Consequently, numerous efforts have been devoted to integrating various BC with magnetic components, yielding remarkable results^[25]. For example, Qiu et al.^[26] composited longan shell-derived activated carbon with Co nanoparticles, realizing an $RL_{\min}$ of -40.64 dB at an thickness of only 1.8 mm. Ji et al.^[27] fabricated a 3D porous carbon framework from hemp biomass and uniformly anchored CoNi alloy nanoparticles onto it. The composite achieved an $RL_{\min}$ of -43.82 dB at 2.9 mm and an EAB of 5.12 GHz at 2.3 mm. Xiao et al.^[28] used fir-derived carbon to grow in situ N-doped carbon nanotubes loaded with Co nanoparticles via CVD. The Fir@Co@CNT composite achieved an $RL_{\min}$ of -43.03 dB and an EAB of 4.3 GHz at 1.5 mm.

Based on the above analysis, this study selects *Arundo donax*, a globally distributed invasive species, as the precursor for BC. *Arundo donax* offers advantages such as rapid growth and high biomass yield, making it not only a low-cost and stable raw material but also consistent with the principles of green and sustainable development. Using porous carbon derived from *Arundo donax* as a support, CoNi nanoparticles firmly anchored on the biomass carbon matrix were successfully fabricated. Owing to the synergistic effects of the unique microporous structure and multiple loss mechanisms, the as-prepared composites exhibit outstanding EMW absorption performance. A $RL_{\min}$ of -50.17 dB is achieved, and the EAB is broadened to 5.01 GHz at a thickness of only 1.9 mm. This work provides a feasible

fabrication strategy for low-cost, high-performance BC-based magneto-dielectric heterojunction EMW absorbers, demonstrating great potential for applications in the field of EMW absorption.

2. Experimental section

2.1 Materials

Cobalt(II) nitrate hexahydrate ($\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), nickel(II) nitrate hexahydrate ($\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), and urea ($\text{CH}_4\text{N}_2\text{O}$) were of analytical grade and used as received without further purification. Arundo donax collected from the surrounding areas of Guanxi Province.

2.2 Preparation of Arundo donax-Derived Carbon Materials

Fresh Arundo donax was thoroughly washed with deionized water and dried in an oven at 80 °C. The dried sample was then pulverized using a grinder and sieved through a 300-mesh screen to obtain fine powder. The resulting powder was placed in a graphite boat and loaded into a tubular furnace. Under a high-purity nitrogen (N_2) atmosphere, the sample was heated to 450 °C at a ramp rate of 5 °C/min and maintained at this temperature for 2 h. After the furnace was naturally cooled to ambient temperature, the black solid product was collected and ground into powder for further use, denoted as Arundo donax-derived carbon.

2.3 Preparation of CoNi/BC Composites

The CoNi/BC composites were synthesized via a two-step method combining hydrothermal treatment and subsequent thermal reduction. To optimize the mass ratio of CoNi alloy to carbon support, the $\text{Co}^{2+}/\text{Ni}^{2+}$ molar ratio was fixed at 4:4, while the amount of Arundo donax-derived carbon was varied. Three batches with Co:Ni: carbon molar ratios of 4:4:9, 4:4:18, and 4:4:27 were designed. Taking the molar ratio of 4:4:18 as a representative example, stoichiometric amounts of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, $\text{CH}_4\text{N}_2\text{O}$, and the biochar were dissolved in 60 mL of deionized water under magnetic stirring for 0.5 h to form a homogeneous solution. The resulting solution was transferred into a 100 mL Teflon-lined stainless-steel autoclave and maintained at 180 °C for 12 h. After the hydrothermal reaction, the autoclave was allowed to cool naturally to room temperature. The obtained precipitate was alternately washed with deionized water and absolute ethanol several times, collected by vacuum filtration, and dried in an oven at 60 °C for 12 h, yielding a black precursor powder.

Subsequently, the precursor was placed in a tubular furnace and subjected to thermal reduction at 700 °C for 2 h under a flowing H_2/Ar atmosphere (5% H_2) with a heating rate of 5 °C/min. After natural cooling to room temperature, the final product was obtained and designated as CNC2. For comparison, two additional batches with Co: Ni: BC molar ratios of 4:4:9 and 4:4:27 were prepared following the identical procedure and denoted as CNC1 and CNC3, respectively. Furthermore, to investigate the effect of pyrolysis temperature on the structure and properties of the composites, the CNC2 precursor was

thermally treated at 600 °C and 800 °C under otherwise identical conditions. The resulting samples were labeled as CNC2-600 and CNC2-800, respectively.

2.4 Characterization

The crystal structure and phase composition of the as-prepared specimens were determined by X-ray diffraction (XRD, Empyrean PIXcel3D, PANalytical). Raman spectroscopy (LabRAM HR Evolution) was employed to investigate the carbon configuration and the degree of graphitic ordering within the CoNi/BC composites. The surface elemental composition and chemical states were investigated by X-ray photoelectron spectroscopy (XPS, K-Alpha, Thermo Scientific). Microstructural observations and elemental mapping were conducted via field-emission scanning electron microscopy (FESEM, TESCAN MIRA LMS) and transmission electron microscopy (TEM, FEI Tecnai G2F20) coupled with an energy-dispersive X-ray spectroscopy (EDS) system. Nitrogen physisorption measurements were carried out at 77 K on a surface area and porosity analyzer (ASAP 2460, Micromeritics), with the specific surface area derived using the Brunauer-Emmett-Teller (BET) method. The frequency-dependent complex permittivity (ϵ' and ϵ'') and complex permeability (μ' and μ'') were acquired over the 2–18 GHz range using a vector network analyzer (VNA, N5230C, Agilent Technologies). For EM measurements, the as-synthesized products were compounded with paraffin wax at a loading of 50 wt% and subsequently compacted into toroidal rings with an inner diameter of 3.04 mm and an outer diameter of 7.00 mm.

3. Results and discussion

3.1 Compositional and microstructural characterization

The XRD patterns of all samples are shown in Fig. 1(a). Three distinct diffraction peaks located at approximately 44.36° , 51.68° , and 76.12° are observed for all samples, which correspond to the (111), (200), and (220) crystal planes of the CoNi alloy (PDF#04-005-8490), respectively^[29]. The XRD results confirm the successful formation of the CoNi alloy in the as-prepared composites. No characteristic diffraction peaks corresponding to carbon are detected in the patterns, which is attributed to the relatively low crystallinity of the carbonaceous component. Raman spectroscopy was further employed to characterize the carbon structure of the as-prepared samples. As shown in Fig. 1(b), all samples exhibit two distinct characteristic peaks at approximately 1338 cm^{-1} and 1590 cm^{-1} , corresponding to the D band and G band of carbonaceous materials, respectively^[30]. The D band is associated with structural defects and disordered carbon, while the G band reflects the graphitic degree of the carbon skeleton. The intensity ratio of these two bands (I_D/I_G) is commonly used to evaluate the graphitization degree, with a higher ratio indicating a lower graphitization degree. The I_D/I_G values for CNC1, CNC2, CNC3, CNC2-600, and CNC2-800 were calculated to be 3.27, 3.30, 3.32, 2.77, and 3.35, respectively. These results reveal two distinct trends. On one hand, as the pyrolysis temperature increased from 600 °C to 800 °C, the I_D/I_G value exhibits a notable increase from 2.77 to 3.35, suggesting a significant decline in the graphitization degree. This observation can be attributed to the sintering and agglomeration of CoNi alloy nanoparticles at elevated temperatures, which reduces the available

metallic surface area for catalytic graphitization of the surrounding carbon matrix. Additionally, higher-temperature pyrolysis may promote the release of volatile components and induce structural rearrangement within the carbon framework, generating more edge defects and vacancies. On the other hand, with increasing BC content, the I_D/I_G ratio shows only a marginal increase from 3.27 to 3.32, indicating a slight decrease in graphitization degree. This trend is likely ascribed to the dilution effect of the carbon support, in which the Arundo donax-derived biochar possesses an intrinsically disordered structure with abundant defects, and its higher proportion reduces the relative content of CoNi alloy per unit mass, thereby weakening the catalytic effect of alloy on graphitization. Furthermore, the high I_D/I_G ratio of the composites arises from their abundant structural defects, which serve as polarization centers to boost dielectric loss through enhanced interfacial and dipole polarization.

The chemical states of the constituent elements in the CNC2 sample were further investigated by high-resolution XPS. As shown in Fig. 1(c), the XPS survey spectrum distinctly reveals the presence of C 1s, Ni 2p, and Co 2p photoelectron peaks. The Ni 2p spectrum exhibits two main peaks at 855.58 and 873.15 eV, which are assigned to Ni 2p_{3/2} and Ni 2p_{1/2}, respectively, accompanied by their satellite peaks at 861.68 and 879.80 eV (Fig. 1(d)). In addition, a characteristic peak observed at 852.1 eV is attributed to metallic Ni⁰ [31]. The Co 2p spectrum (Fig. 1(e)) displays two major peaks at 780.88 and 797.08 eV, corresponding to Co 2p_{3/2} and Co 2p_{1/2}, along with satellite features at 785.28 and 802.84 eV. The peak at 778.0 eV is characteristic of metallic Co⁰, confirming the existence of zero-valent cobalt [32]. The C 1s spectrum (Fig. 1(f)) is deconvoluted into three components at binding energies of approximately 283.9, 284.9, and 288.4 eV, which are attributable to C-metal (C-Co/C-Ni), sp²/sp³ hybridized carbon (C-C/C = C), and oxygen-containing functional groups (C-O/C = O), respectively [33]. The emergence of the C-metal peak provides direct evidence for the strong interfacial bonding between CoNi alloy nanoparticles and the carbon support, which is expected to enhance polarization effects at the heterogeneous interfaces.

Nitrogen adsorption-desorption measurements were performed to characterize the porous structure and specific surface area of the CoNi/BC composites. As shown in Fig. 2, all samples exhibit typical type IV isotherms with distinct H3-type hysteresis loops, indicating the coexistence of mesopores and micropores within the composites [34]. With increasing biochar content, the specific surface area increases significantly from 55.32 to 99.71 m²/g, and further to 134.04 m²/g. This enhancement is attributed to the intrinsically high specific surface area and porous nature of the Arundo donax-derived biochar. In contrast, the average pore diameter shows only marginal variations, with values of 4.43, 4.49, and 4.30 nm, respectively. A larger specific surface area generally provides more abundant surface active sites, which is beneficial for enhancing interfacial polarization and multiple scattering of EMW, thereby facilitating effective dissipation of EM energy. For the samples prepared at different pyrolysis temperatures (CNC2-600, CNC2, and CNC2-800), the specific surface areas are determined to be 110.33, 99.71, and 94.87 m²/g, respectively, exhibiting a gradual decreasing trend with increasing temperature. Meanwhile, the average pore diameters show relatively minor changes, with values of 4.05, 4.49, and 3.19 nm, respectively. This trend can be ascribed to two main factors. First, the structural rearrangement of the carbon skeleton at elevated temperatures induces the collapse or closure of partial micropores,

resulting from the ordered stacking of carbon layers, and thus reduces the specific surface area. Second, high-temperature treatment promotes the migration and agglomeration of CoNi alloy nanoparticles, which may block certain pore channels and further decrease the specific surface area.

Figure 3(a-e) presents the SEM images of all samples. All samples exhibit a morphology consisting of bulky biochar matrix with nanoparticles attached on the surface. With increasing biochar content, the amount of surface-loaded nanoparticles decreases. The pyrolysis temperature exerts a pronounced influence on the morphology and size of the nanoparticles. As the temperature rises, the nanoparticle size gradually increases. Specifically, the sample prepared at 600 °C (Fig. 3(d)) shows a continuous bulk structure with extremely fine nanoparticles. When the temperature increases to 700 °C and 800 °C (Fig. 3(b, e)), the structural continuity of the carbon matrix is disrupted and pore structures emerge, which can be attributed to the release of volatile components from the carbon skeleton at elevated temperatures, accompanied by the continued growth of metallic particles. To gain further insight into the microstructure, the CNC2 sample was characterized by TEM. The elemental mapping results (Fig. 3(f)) reveal that carbon is uniformly distributed throughout the structure, while Co and Ni are homogeneously dispersed along the edges of the carbon matrix. Low-magnification TEM image (Fig. 3(g)) show numerous nanoparticles anchored on the amorphous carbon support. High-resolution TEM images (Fig. 3(h, i)) display distinct lattice fringes with a spacing of approximately 0.204 nm, corresponding to the (111) plane of the CoNi alloy ^[12].

3.2 EMW Absorption Performance and Mechanism Analysis

Reflection loss (RL) and absorption bandwidth are two core parameters for evaluating the EMW absorption performance of materials. The RL value can be calculated based on the transmission line theory, and the corresponding formula is expressed as follows^[35, 36].

$$RL \text{ (dB)} = 20 \log \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right|$$

1

$$Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[j \frac{2\pi}{c} \sqrt{\mu_r \epsilon_r} f d \right]$$

2

where Z_{in} represents the input impedance of the absorber, Z_0 is the characteristic impedance of free space, and f , c , d , and j denote the frequency, the speed of light in vacuum, the matching thickness, and the imaginary unit, respectively. The terms ϵ_r and μ_r refer to the complex permittivity ($\epsilon_r = \epsilon' - j\epsilon''$) and complex permeability ($\mu_r = \mu' - j\mu''$), respectively. When the RL value is below -10 dB, it is generally considered that 90% of the incident EMW is absorbed, and the corresponding frequency range is defined

as the EAB^[37, 38]. At a relatively low sintering temperature, the metallic phase is insufficiently reduced, resulting in poor crystallinity of the composites and consequently unsatisfactory absorption performance. The $RL_{\min}$ value of the CNC2-600 sample is only -17.68 dB, with a corresponding EAB of 2.33 GHz, as shown in Fig. 4(a). As the temperature increases, the proportion of the active components in the samples rises, and the absorption performance of CNC1, CNC2, and CNC3 improves markedly, with $RL_{\min}$ values reaching -50.09 dB, -50.17 dB, and -40.72 dB, respectively, while the maximum EAB broadens to 4.59 , 5.01 , and 4.53 GHz, respectively (Fig. 4(b–d)). It can be observed that the carbon content exerts a discernible influence on the absorption performance of the CNC samples. Specifically, the absorption performance first increases and then decreases with increasing carbon content, with CNC2 exhibiting the optimal performance. This trend is presumably attributable to the favorable synergy between the carbon matrix and the magnetic components, which not only provides sufficient dielectric loss and magnetic loss but also maintains good impedance matching, thereby allowing EMW to effectively penetrate the material interior and be attenuated through multiple synergistic mechanisms. When the pyrolysis temperature is further elevated to 800°C , the absorption performance of CNC-800 deteriorates significantly, with an $RL_{\min}$ of -14.54 dB and an EAB reduced to 3.22 GHz (Fig. 4(e)). This degradation may be due to the excessively large grain size of CoNi, enhanced crystallinity, increased electrical conductivity, and partial destruction of the carbon framework at higher temperatures, all of which are unfavorable for the incidence and attenuation of EMW. As shown in Fig. 4(f), among all samples, CNC2 exhibits superior performance in terms of both EAB and RL. Furthermore, in comparison with previously reported BC-based composite absorbers, CNC2 also demonstrates competitive performance, as summarized in Table 1.

Table 1
EMW absorption performance of BC-based composite absorbers.

EMW absorber	RL		EAB		Ref.
	RL _{min} (dB)	d(mm)	EAB(GHz)	d(mm)	
Rice husk derived BC	-47.5	2.8	3.4	2.8	[19]
Fir wood derived BC/CoFe composites	-54.4	2.2	2.6	2.4	[27]
Fir@Co@CNT composites	-43.0	1.5	4.3	1.5	[28]
Hemp biomass derived CoNi composites	-43.8	2.9	5.1	2.3	[27]
Soybean derived porous carbon	-62.8	3.0	4.2	3.0	[39]
CoNi/porous walnut shell carbon	-48.8	2.6	4.1	1.6	[40]
Lignin-based FeCo@C	-48.5	2.5	4.5	2.5	[41]
Coconut shell derived ZnFe ₂ O ₄ /C composite	-37.3	2.0	2.4	2.0	[42]
Agaric derived Fe/Fe ₃ O ₄ /BC composite	-30.4	2.1	2.4	2.1	[43]
Bamboo fungus derived Ni@CBF-800	-61.2	3.8	4.4	3.8	[44]
Rice husk derived BC	-47.4	2.8	3.4	2.8	[45]
Arundo donax derived CoNi/BC	-50.1	2.8	5.0	1.9	This work

To further elucidate the underlying EMW absorption mechanisms, the frequency-dependent behaviors of complex permittivity and complex permeability are systematically investigated in this study. The real parts (ϵ' and μ') represent the storage capability of electric and magnetic energy, respectively, while the imaginary parts (ϵ'' and μ'') denote the corresponding dissipation capability. The dielectric loss tangent ($\tan\delta\epsilon = \epsilon''/\epsilon'$) and magnetic loss tangent ($\tan\delta\mu = \mu''/\mu'$) reflect the overall dielectric and magnetic loss levels of the materials. The relevant results are presented in Fig. 5(a-c). The dielectric response is co-regulated by the carbon content and pyrolysis temperature, exhibiting a distinct non-linear behavior. As shown in Fig. 5(a), with increasing either parameter, first decreases and then increases, reaching a minimum at CNC2. This non-monotonic trend originates from the competitive interplay between polarization and conduction mechanisms. At low pyrolysis temperatures or low carbon loadings, abundant polar functional groups (e.g., -COOH, -OH) and structural defects in the matrix induce strong dipole orientation polarization, leading to relatively high ϵ' values^[13]. As the temperature rises or the carbon content increases, these polar groups undergo thermal decomposition and removal, causing a

sharp drop in dipole concentration. Meanwhile, the carbon particles have not yet formed an effective percolating conductive network, so the overall polarization intensity weakens and ϵ' falls to its minimum. Once the CNC2 threshold is exceeded, the carbon layers gradually graphitize, generating numerous sp^2 -hybridized carbon microcrystallites and conductive clusters. These components, together with residual amorphous carbon and CoNi metallic particles, create abundant heterogeneous interfaces that trigger pronounced interfacial polarization, thereby boosting ϵ' again. Regarding the ϵ'' shown in Fig. 5(b), it exhibits a rise-then-fall trend with increasing pyrolysis temperature, whereas it shows a monotonically increasing dependence on carbon content. Specifically, as the temperature rises from CNC2-600 to CNC2, the crystalline degree of the metallic phase and the graphitic order both improve, leading to a substantial increase in carrier mobility. Under such conditions, conduction loss ($\epsilon'' \propto \sigma/\omega\epsilon_0$) becomes dominant, resulting in a sharp enhancement of ϵ'' . Upon further elevating the temperature, the graphitic microcrystallites become more ordered, and structural defects and dangling bonds are largely healed. Although the conductivity may remain high, the relaxation loss contribution declines, so ϵ'' decreases. In contrast, a mere increase in carbon content does not fundamentally alter the graphitic order but rather linearly raises the number of conductive pathways and heterogeneous interface density per unit volume, thus monotonically increasing ϵ'' . Since the variation amplitude of ϵ'' far exceeds that of ϵ' , the evolution of $\tan\delta\epsilon$ is predominantly governed by ϵ'' . Consequently, $\tan\delta\epsilon$ exhibits the same trends as ϵ'' , showing an initial increase followed by a decrease with temperature and a monotonic increase with carbon content, as presented in Fig. 5(c). The aforementioned dielectric response is further corroborated by Cole–Cole plots based on Debye relaxation theory^[46, 47] (Fig. 5(d)). The Cole–Cole curve of CNC2 displays multiple semicircular arcs accompanied by a linear tail, where each semicircle corresponds to a distinct polarization relaxation process and the linear tail signifies conduction loss^[48–50]. This observation indicates the coexistence of multiple polarization relaxations and strong conduction loss within the composite. The multiple relaxation processes can be attributed to two main sources. Dipole polarization arising from the inherent defects in the BC, and interfacial polarization generated by the strong coupling between the Ni-Co alloy and the carbon matrix. Meanwhile, the uniform anchoring of CoNi nanoparticles on the carbon skeleton creates an interconnected conductive network, which favors effective conduction loss.

Magnetic loss also plays an important role in EMW attenuation. As depicted in Fig. 5(e–g), the μ' values (≈ 0.85 – 1.22) of all samples are significantly higher than the corresponding μ'' values (≈ 0 – 0.25), indicating that the materials predominantly store magnetic energy. The $\tan\delta\mu$ values fluctuate in the range of 0 – 0.45 , and the frequency-dependent profiles of μ' , μ'' , and $\tan\delta\mu$ are similar for all samples, suggesting a consistent magnetic loss mechanism. The magnetic loss mainly originates from ferromagnetic resonance and eddy current loss. In the low-frequency region (2 – 7 GHz), distinct resonance peaks in μ' and μ'' are observed, which are attributed to natural resonance, while the resonance peaks in the high-frequency range (12 – 18 GHz) correspond to exchange resonance^[51, 52]. To discriminate the eddy current contribution, the eddy current coefficient C_0 () is analyzed. If C_0 remained constant over the frequency range, eddy-current loss would be the dominant mechanism^[53, 54]. However, as shown in Fig. 5(h), the C_0 value exhibits pronounced fluctuations across the entire 2 – 18 GHz

frequency range, indicating that eddy current loss is not the dominant contributor to the magnetic loss in this system. This observation confirms that the existence of BC effectively suppresses the strong eddy current loss typically induced by the high electrical conductivity of the magnetic CoNi alloy.

The EMW absorption performance of a material is governed by both its impedance matching characteristics and attenuation capability. Impedance matching serves as the key criterion for determining whether incident EMW can effectively penetrate into the material interior, whereas attenuation capability reflects the intrinsic dissipation intensity of the material toward the incident waves. The degree of impedance matching is quantified by the normalized input impedance $|Z_{in}/Z_0|$, which is calculated according to Eq. (2). When this value approaches unity, the material achieves optimal impedance matching with free space, allowing EMW to maximally transmit into the material^[55]. Figure 6(a–e) presents the impedance matching performance of samples prepared under different pyrolysis temperatures and carbon contents. Compared with carbon content, pyrolysis temperature exerts a more pronounced influence on impedance matching. At pyrolysis temperatures of 600°C and 800°C, the $|Z_{in}/Z_0|$ values deviate considerably from the critical value of 1, indicating severely mismatched impedance. Under such conditions, a large portion of EMW is reflected at the material surface and fails to enter the interior. In contrast, the samples synthesized at 700°C exhibit $|Z_{in}/Z_0|$ values close to unity across most frequency ranges, enabling efficient wave penetration and subsequent attenuation through polarization relaxation, conduction loss, and magnetic resonance effects. Carbon content exerts a relatively minor influence on impedance matching. Nevertheless, an appropriate amount of BC with low electrical conductivity can effectively alleviate the skin effect of the magnetic CoNi alloy, thereby contributing to the maintenance of favorable impedance matching.

The attenuation capability is quantified by the attenuation constant (α), which is calculated according to Eq. (3)^[38]:

$$\alpha = \frac{\sqrt{2}\pi f}{c} \times \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon') + \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon')^2 + (\mu\varepsilon + \mu'\varepsilon')^2}}$$

3

and the results are shown in Fig. 6(f). The variation in carbon content exhibits a relatively limited influence on α , with CNC2 showing only a marginally higher value than the other two samples. In contrast, the effect of temperature is substantially more significant, as α exhibits a clear stepwise increase from CNC2-600 to CNC2-800. It is worth noting that the trend of the α does not fully coincide with the absorption performance, suggesting that in the present system, impedance matching plays a decisive role in determining the overall absorption performance. Taking CNC2-800 as an example, despite its exceptionally strong attenuation capability, the severely mismatched impedance prevents EMW from effectively entering the material, rendering its superior attenuation practically ineffective. In summary, the CNC2 composite possesses both near-perfect impedance matching and strong

attenuation capability. The synergistic interplay between these two factors is responsible for its outstanding EMW absorption performance.

Based on the above analysis, the underlying EMW absorption mechanisms of the CNC composites can be summarized into the following four aspects. First, dipole polarization arises from the intrinsic structural defects within the BC matrix. Second, interfacial polarization is induced by the strong interfacial coupling between the CoNi alloy and the carbon matrix. Third, the CoNi nanoparticles are uniformly anchored on the carbon skeleton, forming an interconnected conductive network that facilitates effective conduction loss. Fourth, the highly magnetic CoNi alloy generates magnetic resonance effects under an alternating external EM field, further enhancing the energy dissipation of the incident waves. The synergistic cooperation of these multiple loss mechanisms constitutes the physical basis for the high-efficiency EMW absorption performance of the CNC composites.

4. Conclusion

In this study, CoNi/BC composites with CoNi nanoparticles anchored on the surface of a BC matrix were successfully fabricated via a hydrothermal method followed by thermal reduction, using Arundo donax-derived carbon as the substrate for in-situ growth of CoNi nanoparticles. By tuning the biomass carbon content and pyrolysis temperature, the optimal sample CNC2 demonstrates superior impedance matching and strong attenuation, which together lead to the best absorption performance. At a matching thickness of 2.8 mm, the $RL_{\min}$ reaches -50.17 dB. At a thickness of 1.9 mm, the EAB broadens to 5.01 GHz. The significantly enhanced performance of the CNC2 composite is primarily attributed to the precise regulation of electrical conductivity by the appropriate carbon content and pyrolysis temperature, which effectively optimizes the impedance matching condition and allows EMW to efficiently enter the material interior. On this basis, the synergistic effects of polarization relaxation, conduction loss, and magnetic resonance collectively establish a highly efficient energy attenuation mechanism. This work provides a feasible strategy for constructing low-cost, high-performance biomass-derived carbon-based magneto-dielectric heterojunction EMW absorbers.

Declarations

Author Contribution

Shasha Jiang, Fangyu Gan and Qingrong Yao conceived and designed the study. Zhenpeng Li and Yuncong Zhang performed the experiments and collected the data. Lingxiao Zhang, Jiang Wang, Jianqiu Deng, Jiayi Gan and Weichao Huang analyzed the data. Zhenpeng Li and Fangyu Gan wrote the main manuscript text, Zhao Lu provided funding, and all authors reviewed the manuscript.

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References

1. M.J. Shi, Z.R. Jia, D. Lan, Z.G. Gao, S.Y. Zhang, G.L. Wu, Enhanced polarization relaxation of multidimensional bimetallic selenide nanocomposites for electromagnetic wave absorption, *Adv. Funct. Mater.* 35(49) (2025) 02261.
2. M. Zhou, Z. Yu, Q.M. Yan, X.Y. Zhang, Asymmetric structural design for absorption-dominated electromagnetic interference shielding composites, *Adv. Funct. Mater.* 35(23) (2025) 2423884.
3. S.J. Zhang, J.J. Zheng, Z.W. Zhao, S.X. Du, D. Lan, Z.G. Gao, G.L. Wu, New prospects in built-in electric fields for electromagnetic wave absorption: from fundamentals to interdisciplinary applications, *Adv. Funct. Mater.* 36(1) (2026) e13762.
4. H.L. Lv, Z.H. Yang, H.G. Pan, R.B. Wu, Electromagnetic absorption materials: Current progress and new frontiers, *Prog. Mater. Sci.* 127 (2022) 100946.
5. X.Y. Ren, D. Lan, Z.G. Gao, S.Y. Zhang, Y. Zhang, M.K. He, Z.R. Jia, G.L. Wu, Semiconductor-based electromagnetic wave absorption materials: Review and perspectives, *J. Mater. Sci. Technol.* 255 (2026) 236-258.
6. G. D.M, Y. Cui, P.F. Ju, L.C. Sun, F.H. Wang, L. Liu, Multiple heterogeneous interfaces based on electromagnetic wave path design for electromagnetic wave absorption, *Advanced Composites and Hybrid Materials* 9 (2026) 12.
7. H.Y. Peng, D. Zhang, Z.P. Xie, S.Q. Lu, Y.C. Liu, F. Liang, Recent advances in structural design of carbon/magnetic composites and their electromagnetic wave absorption applications, *Small* 21(8) (2025) 2408570.
8. J.H. Zhu, L. Cheng, S.Y. Zhang, D. Lan, G.R. Wu, Z.G. Gao, Z.R. Jia, 0D/1D hollow heterogeneous structure to induce self-assembly of CNTs for optimized self-anticorrosion and electromagnetic wave absorption performance, *Carbon* 238 (2025) 120310.
9. Y.C. Chen, L.C. Cheng, T.R. Xia, M. Wang, H.Y. Zhou, Q.R. Yao, Y.Z. Zhai, Effect of Bi doping on the structure and wave absorption properties of barium ferrite, *Ceram. Int.* 48 (2022) 3963-3973.
10. F.Y. Gan, Z.P. Li, Q.R. Yao, S.S. Jiang, X.C. Yu, J.Q. Deng, Z. Lu, L.C. Cheng, M.M. Zhao, H.Y. Zhou, Modulating polarization and conduction loss for optimized electromagnetic wave absorption performance of FeNi/ZnO/C/Ni₃ZnCo_{0.7} composites, *Chem. Eng. J.* 500 (2024) 156589.
11. F.Y. Gan, Q.R. Rao, J.Q. Deng, L.C. Cheng, Y. Zhong, Z. Lu, F. Wang, J. Wang, H.Y. Zhou, G.H. Rao, Controllable architecture of ZnO/FeNi composites derived from trimetallic ZnFeNi layered double hydroxides for high-performance electromagnetic wave absorbers, *Small* 19(27) (2023) 2300257.
12. X. Li, Z.C. Wu, W.B. You, L.T. Yang, R.C. Che, Self-assembly MXene-rGO/CoNi film with massive continuous heterointerfaces and enhanced magnetic coupling for superior microwave absorber,

Nano-Micro Lett. 14(1) (2022) 73.

13. W.H. Huang, M. Song, S. Wang, B.K. Wang, J.C. Ma, T. Liu, Y.N. Zhang, Y.F. Kang, R.C. Che, Dual-step redox engineering of 2D CoNi-alloy embedded B, N-doped carbon layers toward tunable electromagnetic wave absorption and light-weight infrared stealth heat insulation devices, *Adv. Mater.* 36(30) (2024) 2403322.
14. K.L. Zhang, Y.H. Liu, Y.N. Liu, Y. Y.F. Yan, G.S. Ma, B. Zhong, R.C. Che, X.X. Huang, Tracking regulatory mechanism of trace Fe on graphene electromagnetic wave absorption, *Nano-Micro Lett.* 16(1) (2024) 66.
15. J.T. Liu, Y.C. Zheng, X. Hou, X.R. Feng, K. Jiang, M. Wang, Structured carbon for electromagnetic shielding and microwave absorption from carbonization of waste Polymer: A review, *Chem. Eng. J.* 496 (2024) 154013.
16. H.H. Wang, H.B. Zhang, J.Y. Cheng, T.T. Liu, D.Q. Zhang, G.P. Zheng, S.R. Zhai, M.S. Cao, Building the conformal protection of VB-group VS₂ laminated heterostructure based on biomass-derived carbon for excellent broadband electromagnetic waves absorption, *J. Materiomics* 9(3) (2023) 492-501.
17. R. Peymanfar, A. Mirkhan, Biomass-derived materials: Promising, affordable, capable, simple, and lightweight microwave absorbing structures, *Chem. Eng. J.* 446 (2022).
18. H.T. Guan, Q.Y. Wang, X.F. Wu, J. Pang, Z.Y. Jiang, G. Chen, C.J. Dong, L.H. Wang, C.H. Gong, Biomass derived porous carbon (BPC) and their composites as lightweight and efficient microwave absorption materials, *Compos. Part B-Eng.* 207 (2021).
19. Z. Wu, Z. Meng, C. Yao, Y. Deng, G. Zhang, Y. Wang, Rice husk derived hierarchical porous carbon with lightweight and efficient microwave absorption, *Mater. Chem. Phys.* 275 (2022).
20. J. Yue, J.Q. Yu, S.H. Jiang, Y.M. Chen, Biomass carbon materials with porous array structures derived from soybean dregs for effective electromagnetic wave absorption, *Diam. Relat. Mater.* 126 (2022).
21. Y.M. Lu, X.N. Zhao, Q.L. Tian, Y. Lin, P. Li, Y. Tao, Z.Q. Wang, J.G. Ma, H.Y. Xu, Y.C. Liu, Hierarchical porous biomass-derived carbon with rich nitrogen doping for high-performance microwave absorption and tensile strain sensing, *Carbon* 224 (2024).
22. S. Sumanta, K. Rajesh, S.H. Sung, Low-value biomass-derived carbon composites for electromagnetic wave absorption and shielding: A review, *New Carbon Mater.* 40(2) (2025) 293-316.
23. K.Y. Feng, J. Jiang, L.G. Ren, Q.C. He, Y.C. He, Y.Q. Wang, Magnetic porous carbon composites for efficient electromagnetic wave absorption, *Adv. Eng. Mater.* 25(8) (2023) 01353.
24. W. Yang, C.A. Wang, B. Jiang, R. Li, H.X. Bai, N. Ta, S.X. Du, C. Zhang, Z.X. Li, X.B. Wang, Y.F. Li, Lightweight 3D interconnected porous carbon with robust cavity skeleton derived from petroleum pitch for effective multi-band electromagnetic wave absorption, *Carbon* 200 (2022) 390-400.
25. P.T. Hu, S. Dong, X.T. Li, J.M. Chen, P. Hu, Flower-like NiCo₂S₄ microspheres based on nanosheet self-assembly anchored on 3D biomass-derived carbon for efficient microwave absorption, *ACS Sustainable Chem. Eng.* 8(27) (2020) 10230-10241.

26. K.Y. Qiu, T.N. Man, Z.S. Nong, M.W. Zhu, K.M. Ma, S.W. Lu, Construction of Co/biomass-derived carbon composites for enhanced microwave absorption performance, *Cryst. Growth Des.* 26(13) (2026) 4864-4874.
27. Y. Ji, Z.M. Wang, B.Y. Li, L.N. Liu, X.C. Zhang, A biomass-derived porous carbon–CoNi nanocomposite for lightweight and efficient electromagnetic wave absorption, *Mater. Res. Bull.* 206 (2027) 114423.
28. J.Y. Xiao, B. Wen, X.F. Liu, Y. Chen, J.X. Niu, S.Y. Yang, W. Yuan, M. Yu, G.R. Yang, S.J. Ding, In-situ growth of carbon nanotubes for the modification of wood-derived biomass porous carbon to achieve efficient Low/Mid-Frequency electromagnetic wave absorption, *J. Colloid Interface Sci.* 676 (2024) 33-44.
29. C. Li, X.S. Qi, X. Gong, Q. Peng, Y.L. Chen, R. Xie, W. Zhong, Magnetic-dielectric synergy and interfacial engineering to design yolk–shell structured CoNi@void@C and CoNi@void@C@MoS₂ nanocomposites with tunable and strong wideband microwave absorption, *Nano Res.* 15(7) (2022) 6761-6771.
30. Y.G. Qu, Z.Y. Liu, X. Li, Y.F. Si, R.X. Xu, D. Liu, Ultrafine well-dispersed Co nanocrystals onto crumpled sphere-like rGO for superior low-frequency microwave absorption, *Carbon* 213 (2023) 118280.
31. Y.P. Zhao, Z.C. Lin, L. Huang, Z.T. Meng, H. Yu, X. Kou, Z.Y. Zou, P. Huang, Y.C. Wang, D. Xi, P.F. Yin, G.H. Su, Z.Q. Fan, Z.P. Su, D.B. Xu, L.J. Pan, L.J. Xu, Simultaneous optimization of conduction and polarization losses in CNT@NiCo compounds for superior electromagnetic wave absorption, *J. Mater. Sci. Technol.* 166 (2023) 34-46.
32. R.W. Shu, C.Q.G. X.H. Li, L.Y. W, Synthesis of FeCoNi/C decorated graphene composites derived from trimetallic metal-organic framework as ultrathin and high-performance electromagnetic wave absorbers, *J. Colloid Interface Sci.* 630 (2023) 754-762.
33. N.X. Zhai, J.H. Luo, M.W. Xiao, Y.C. Zhang, W.X. Yan, Y. Xu, In situ construction of Co@nitrogen-doped carbon/Ni nanocomposite for broadband electromagnetic wave absorption, *Carbon* 203 (2023) 416-425.
34. L.T. Li, J.R. Liu, F. Pan, J. Qiao, X. Zhang, J.P. Lin, W. Liu, Q.L. Wu, S.F. Tao, F. Wu, Z.J. Zeng, Structural engineering of rare earth metal-organic frameworks derivatives with high anisotropy for high-efficiency electromagnetic wave absorption, *Chem. Eng. J.* 481 (2024) 148383.
35. F.Y. Gan, Q.R. Yao, J.Q. Deng, F. Wang, L.C. Cheng, Y.C. Chen, H.Y. Zhou, Y. Zhong, H.B. Yang, Y.Z. Zhao, Layered double hydroxides derived 3D flower-like FeNi@C microspheres as lightweight and high-efficient electromagnetic wave absorber, *Carbon* 196 (2022) 639-648.
36. S.D. Cai, G.R. Su, Z.S. Li, F.Y. Gan, Q.R. Yao, L.C. Cheng, J. Wang, Magnetic-dielectric synergy in Y₂O₃/Fe/C microspheres for high-performance broadband electromagnetic absorption, *J. Alloys Compd.* 1040 (2025) 183473.
37. F.Y. Gan, Y.L. Jiang, Q.R. Yao, J.Q. Deng, L.C. Cheng, Y. Zhong, L. Zhao, J. Wang, Q.X. Long, g. H.Y. Zhou, G.H. Rao, Construction of core-shell ZnO@ZnO/FeNi microrods with improved impedance matching and electromagnetic wave absorption performance, *Ceram. Int.* 49 (2023) 25074–25084.

38. Z.S. Li, F.Y. Gan, J.C. Han, Q.R. Yao, L.C. Cheng, J. Wang, J.Q. Deng, Z. Lu, Q.X. Long, Y. Zhong, H.Y. Zhou, G.H. Rao, MOFs-derived 3D flower-like $\text{Y}_2\text{O}_3/\text{C}$ microspheres with efficient electromagnetic wave absorption properties, *J. Alloys Compd.* 995 (2024) 174728.
39. Y. Tian, D. Estevez, M.Y. Peng, C.F. Li, X. Lv, H.J. Wei, F.X. Qin, Trimodal pore engineering on biomass-derived carbon composites for efficient microwave absorption, *Compos. Commun.* 57 (2025) 102474.
40. Y.R. Huang, J. Huang, X.R. Wang, Z.Y. Chen, Y. Chen, Z.X. Liu, Z.Q. Xu, G.M. Yuan, Sustainably synthesized Co-Ni bimetal modified waste walnut shell biomass-derived carbon composite: High-efficiency microwave absorption performance and synergistic mechanism, *Biomass & Bioenergy* 215 (2026) 109603.
41. L. Hu, H. Pan, L.H. Xu, Y.H. Wang, X.Q. Fu, M. Wang, Y.F. Cai, A tunable structure lignin-derived carbon-based magnetic composite for efficient electromagnetic wave absorption, *Mater. Sci. Eng. B* 302 (2024) 117229.
42. M. Wang, T. Xu, H. Pan, L.H. Xu, Y. Teng, X.Q. Fu, R. Zhang, Q. Li, The coconut shell-derived porous carbon supported hollow spherical ZnFe_2O_4 as an efficient electromagnetic wave absorption material, *Carbon Lett.* 35(6) (2025) 2895-2906.
43. J.B. Su, R. Yang, P.K. Zhang, B.L. Wang, H. Zhao, W.H. Zhang, W.K. Wang, C.B. Wang, $\text{Fe}/\text{Fe}_3\text{O}_4$ /biomass carbon derived from agaric to achieve high-performance microwave absorption *Diam. Relat. Mater.* 129 (2022) 109386.
44. J.R. Zhao, H. Wang, J.M. Jiao, Y. Li, Z. Wang, C. Fang, Q., Rational construction of $\text{Ni}@\text{CBF-x}$ composites derived from bamboo fungus for enhanced microwave absorption with a 10 % filler content, *J. Alloys Compd.* 968 (2023).
45. Z.H. Wu, C. Yao, Z.Z. Meng, Y. Deng, Y. Wang, J.Y. Liu, Y.B. Wang, H.F. Zhou, Biomass-derived crocodile skin-like porous carbon for high-performance microwave absorption, *Adv. Sustain. Syst.* 6(6) (2022) 2100454.
46. Q. Han, Z.S. Li, S.D. Cai, F.Y. Gan, Q.R. Yao, L.C. Cheng, J. Wang, $\text{Y}_2\text{O}_3/\text{Ni}/\text{C}$ composites derived from MOFs for high-efficiency and tunable electromagnetic wave absorption, *J. Mater. Sci.: Mater. Electron.* 37(3) (2026) 188.
47. Y. Shen, Z.Q. Ma, F. Yan, C.L. Zhu, X.T. Zhang, Y.J. Chen, Enhanced interfacial polarization loss of $\text{FeS}/\text{MoS}_2@\text{N-doped}$ carbon sandwich-walled nanotubes enables high-performance electromagnetic wave absorption, *Adv. Funct. Mater.* 35(26) (2025) 2423947.
48. Y. L. Pan, L. Cheng, D. Lan, S. Y. Zhang, M. K. He, G. R. Wu, Z. G. Gao, Z. R. Jia, G. L. Wu, Conductor-semiconductor heterointerface polarization enhancement for superior electromagnetic wave absorption, *J. Mater. Sci. Technol.* 244 (2026) 129-141.
49. X.K. Lu, Xi. Li, K. Wei, Z.W. Yang, W.Z. Gao, H.C. Xu, C.Y. Zhang, H.L. Xu, H.J. Wu, X.Y. Wei, Vacancy-triggered active modulation on the thermal response of interfacial polarization enables highly stable broad-temperature electromagnetic wave absorption, *Adv. Funct. Mater.* 36(11) (2026) e18206.

50. Q. Wan, B. Zhang, L.C. Yu, T.L. Sun, G.B. Gao, Synergistic 0D/1D/2D engineering of $\text{Fe}_3\text{O}_4/\text{CNTCs}/\text{NiCoCu-LDH}$ heterostructures for enhanced ultrathin broadband electromagnetic wave absorption, *J. Mater. Sci. Technol.* 262 (2026) 119-129.
51. R.H. Yang, D.F. Zhang, N.P. Li, H.Y. Zhang, G.X. Zeng, D. Lan, Nitrogen-doped carbon nanotubes-locally-grown three-dimensional $\text{CeO}_2/\text{C}/\text{Co}$ foam enabling fabulous hydrophobicity, thermal insulation, and highly efficient microwave absorption, *Chem. Eng. J.* 506 (2025) 160007.
52. C.H. Wei, L.Z. Shi, M.Q. Li, M.K. He, M.J. Li, X.R. Jing, P.B. Liu, J.W. Gu, Hollow engineering of sandwich $\text{NC}@\text{Co}/\text{NC}@\text{MnO}_2$ composites toward strong wideband electromagnetic wave attenuation, *J. Mater. Sci. Technol.* 175 (2024) 194-203.
53. L. Huang, M. Wang, L.C.Cheng, S.K. Pan, Q.R. Yao, H.Y. Zhou., Fast and efficient synthesis of a new adjustable perovskite-structured ferrite $\text{La}_{1-x}\text{Ca}_x\text{FeO}_3$ microwave absorbent, *J. Alloy. Compd.* 892 (2022) 162167.
54. S. Ajia, H. Asa, Y. Toyoda, M. Sato, M. Matsuura, N. Tezuka, S. Sugimoto, Development of an alternative approach for electromagnetic wave absorbers using Fe–Cr–Co alloy powders, *J. Alloys Compd.* 903, (2022).
55. J.Y. Lu, L. Xu, C. Xie, C. Zhang, Microwave-driven dielectric-magnetic regulation of $\text{graphite}@\alpha\text{-MnO}_2$ toward enhanced electromagnetic wave absorption, *Adv. Sci.* 12(34) (2025) e04489.

Figures

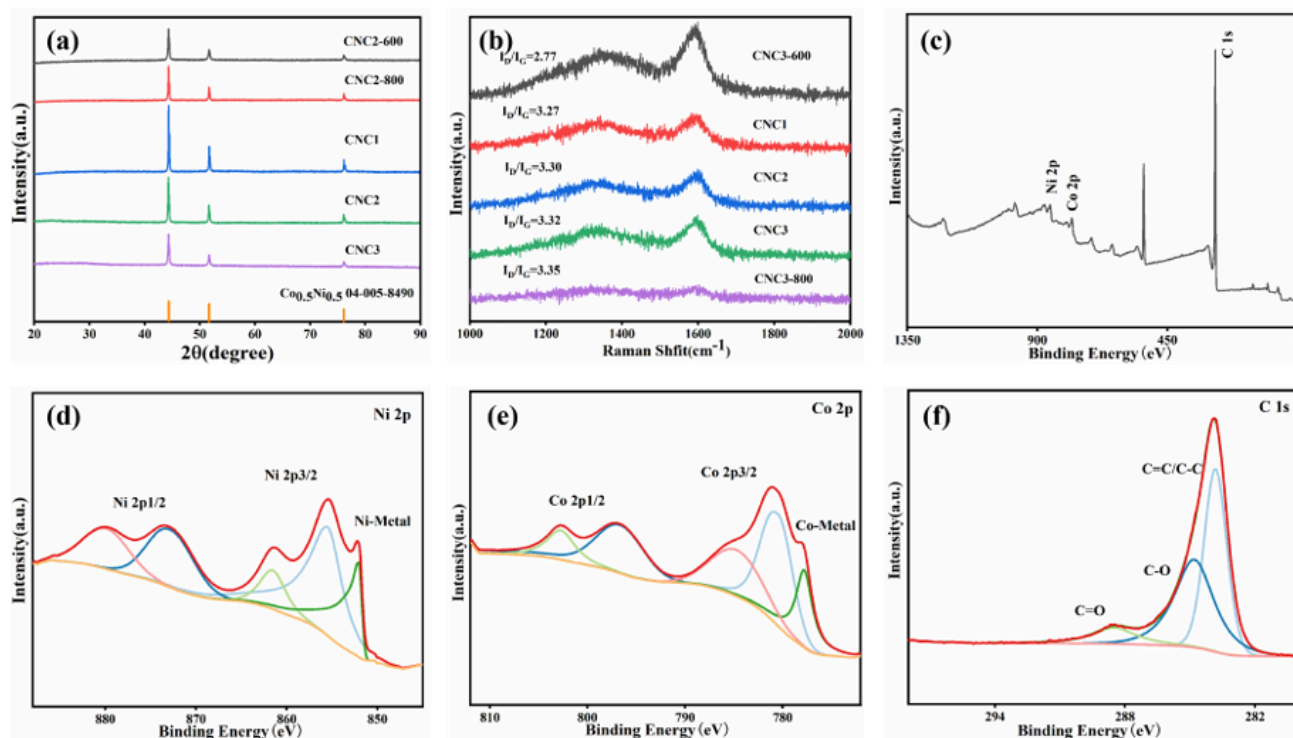


Figure 1

(a) XRD patterns and (b) Raman spectra of all samples; XPS spectra of the CNC2 sample: (c) survey spectrum, (d) Ni 2p, (e) Co 2p, and (f) C 1s.

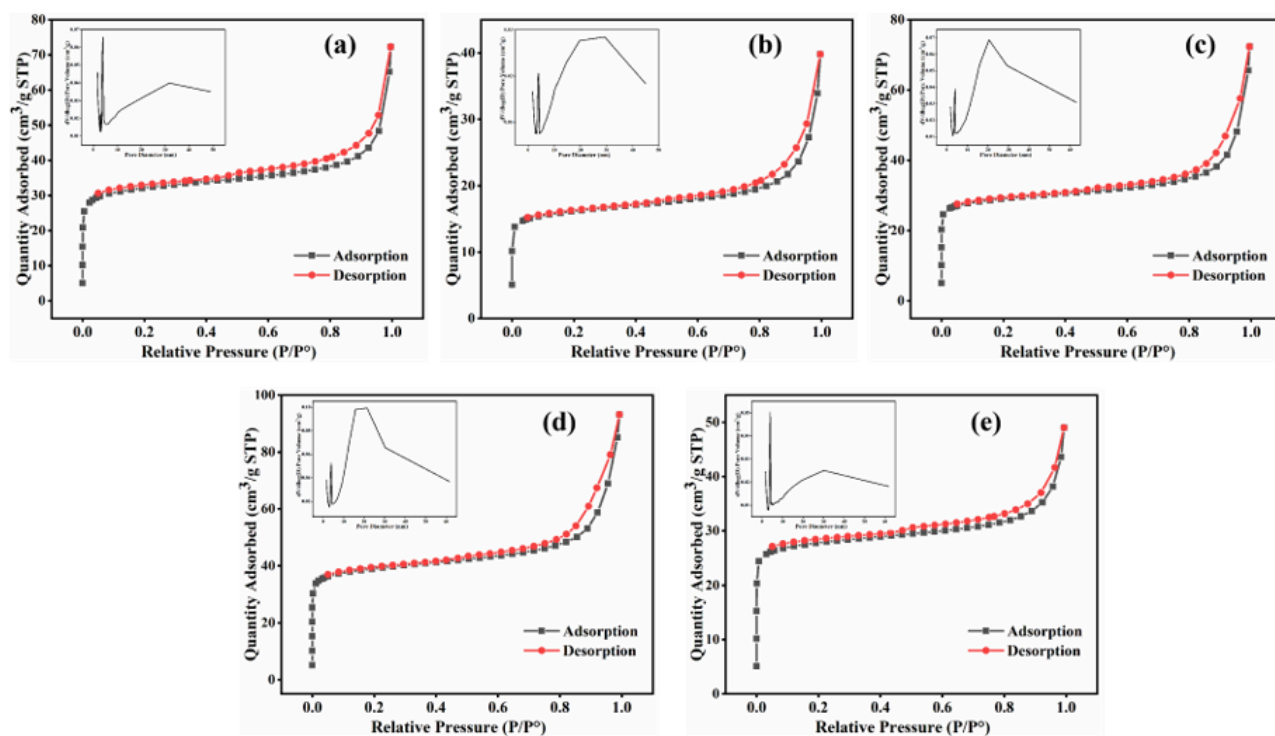


Figure 2

N_2 adsorption-desorption isotherms with inset illustrations of BJH pore size distributions for (a) CNC2-600, (b) CNC1, (c) CNC2, (d) CNC3, and (e) CNC2-800.

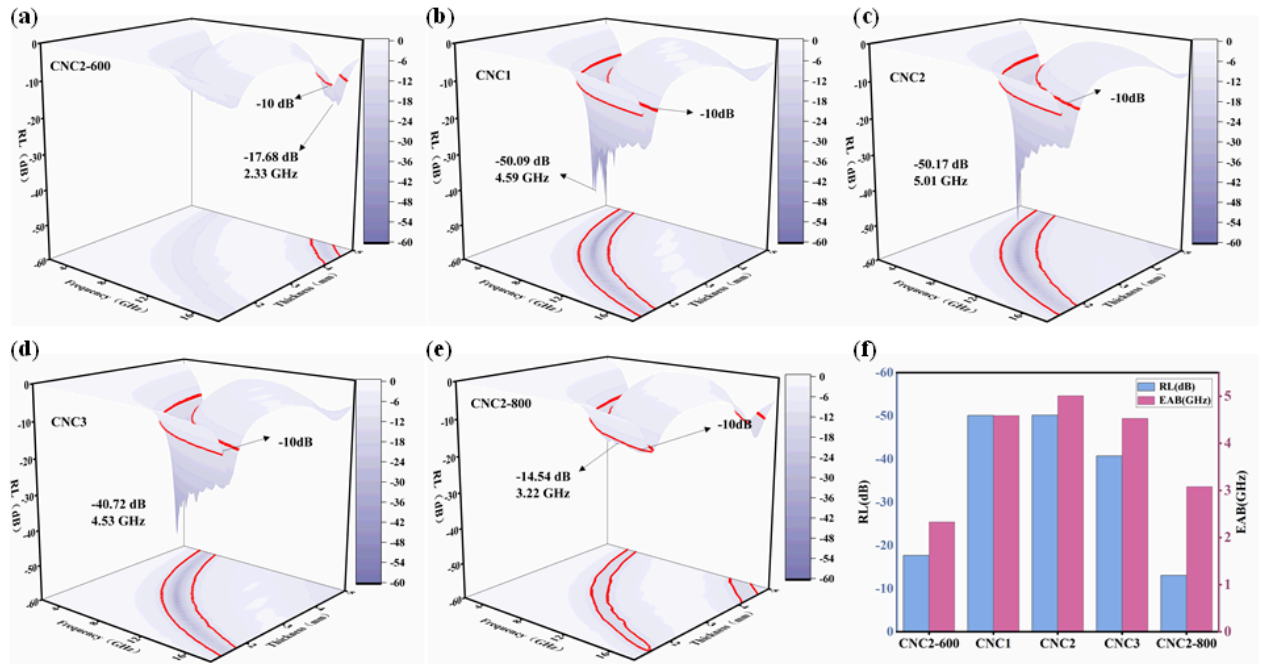


Figure 4

Three-dimensional RL maps of all samples: (a) CNC2-600, (b) CNC1, (c) CNC2, (d) CNC3, (e) CNC2-800; (f) bar chart of the EMW absorption performance of all samples.

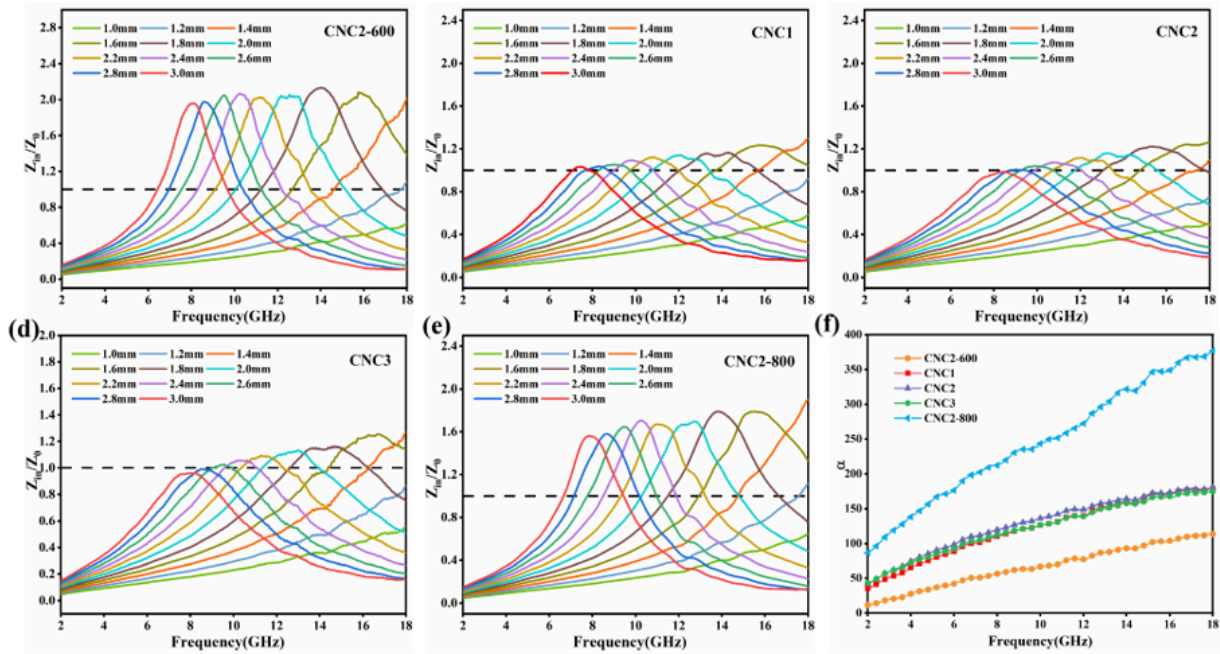


Figure 6

Impedance matching parameters of the samples: (a) CNC2-600, (b) CNC1, (c) CNC2, (d) CNC3, (e) CNC2-800; (f) n values of the samples.

