

ENHANCED AND MODULATED KU-BAND ABSORPTION OF A HYBRID $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ METAMATERIAL STRUCTURE

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ARTICLE INFO		ABSTRACT
Received:	16/12/2025	In this study, we designed a hybrid magnetic - metamaterials absorber (HM-MA) based on a ferrite material operating in the Ku-band. The ferrite material was fabricated using the ball milling method from NiO, ZnO, and Fe_2O_3 . The HM-MA structure consists of four layers: $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$, metallic structure (two punched-in rings with four L-shaped patterns on the edges), dielectric (FR-4), and continuous metallic layer. The structure utilizing the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ material exhibits an absorption spectrum with a peak absorption of 75%. However, under the influence of an external magnetic field of up to 2000 Oe, the structure's absorption intensity is enhanced by an additional 22%. The absorption mechanism at 0 Oe has also been analyzed in detail through the surface current density and power loss density distributions. These results contribute to expanding the practical applications of metamaterials, including radar stealth technology.
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TĂNG CƯỜNG VÀ ĐIỀU BIẾN HẤP THỤ SÓNG ĐIỆN TỪ Ở DẢI Ku CỦA CẤU TRÚC VẬT LIỆU BIẾN HÓA KẾT HỢP $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$

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THÔNG TIN BÀI BÁO		TÓM TẮT
Ngày nhận bài:	16/12/2025	Trong nghiên cứu này, chúng tôi đã thiết kế một cấu trúc vật liệu biến hóa hấp thụ sóng điện từ lai (HM-MA) dựa trên vật liệu ferrite hoạt động trong dải tần Ku. Vật liệu ferrite được chế tạo bằng phương pháp nghiền bi từ vật liệu NiO, ZnO và Fe_2O_3 . Cấu trúc HM-MA gồm bốn lớp: lớp $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$, cấu trúc kim loại (gồm hai vòng tròn đục lỗ và bốn hình chữ L ở các góc), lớp điện môi (FR-4), và lớp kim loại liên tục. Cấu trúc sử dụng vật liệu $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ cho phổ hấp thụ cực đại là 75%. Tuy nhiên, dưới tác động của từ trường ngoài lên tới 2000 Oe, cường độ hấp thụ của cấu trúc được tăng thêm 22%. Cơ chế hấp thụ ở 0 Oe cũng đã được phân tích chi tiết thông qua mật độ dòng điện bề mặt và phân bố mật độ tổn hao năng lượng. Những kết quả này góp phần mở rộng các ứng dụng thực tế của vật liệu biến hóa, bao gồm cả công nghệ tàng hình radar.
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Ngày đăng:	20/4/2026	
TỪ KHÓA		
Vật liệu biến hóa		
Hấp thụ		
Ferrite		
Từ trường ngoài		
Tăng cường		

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1. Introduction

The rapid proliferation of wireless communications and microwave electronic devices has intensified electromagnetic pollution, creating an urgent demand for lightweight, efficient microwave absorbing and shielding materials for both civilian and defense applications [1] – [4]. In general, effective absorbers should simultaneously provide strong dielectric and magnetic losses to dissipate incident microwave energy while maintaining good impedance matching to free space to suppress reflection [5].

Ferrite-based absorbers, ranging from ceramics and nanocrystals to composites and thin films, have therefore been widely investigated, because their microwave response can be tailored through composition, processing conditions, microstructure, and absorber thickness to target specific frequency bands [6] – [9]. However, conventional magnetic absorbers often require relatively large thicknesses and may exhibit weakened magnetic response at high frequencies. To address these limitations, metamaterial absorbers (MAs) with subwavelength resonant unit cells, first demonstrated by Landy et al. in 2008, have emerged as a powerful strategy to engineer effective impedance and realize near-perfect absorption in compact configurations [10]. Despite this advantage, most metallic-resonator MAs remain intrinsically narrowband and lack dynamic tunability because their absorption is dominated by fixed resonant modes [11] – [13].

A practical route toward tunable MAs is to integrate field-responsive media, including varactors, liquid crystals, graphene, phase-change materials, and ferrites. Among them, ferrites are especially attractive because their effective permeability can be continuously adjusted by an external bias magnetic field, enabling magnetic control of the MA resonance. Nickel-zinc ferrite ($\text{NiZnFe}_2\text{O}_4$) is particularly suitable for GHz applications due to its relatively high complex permeability and magnetic loss (associated with natural/exchange resonances) and its high resistivity, which suppresses eddy-current effects at microwave frequencies [2], [14], [15]. Moreover, $\text{NiZnFe}_2\text{O}_4$ offers a favorable balance between permeability and permittivity, improving impedance matching, while its ferromagnetic resonance (FMR) frequency can be shifted by composition (Ni/Zn ratio), microstructure, and synthesis route, typically falling in the GHz range [2], [14] – [21]. Although various ferrite-based MA configurations have been reported (ferrite substrates/cover layers, ferrite particles, or ferrite-metal hybrids), many still face trade-offs among bandwidth, absorption strength, tuning range, and the requirement for thin thickness [22] – [27].

Motivated by these challenges, this study proposes a small thickness hybrid magnetic - metamaterial absorber (HM-MA) that combines $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ (NZFO) with an MA architecture to enhance absorption bandwidth and magnetic-field modulation in the Ku-band. NZFO exhibits a cubic spinel structure (Fd3m), in which the cations are distributed between tetrahedral (A) and octahedral [B] sites. Upon doping, Zn^{2+} ions preferentially occupy the (A) sites, whereas Ni^{2+} ions favor the [B] sublattice. Introducing Zn^{2+} into the lattice drives Fe^{3+} ions to migrate from the A sites to the B sites, thereby strengthening the exchange interactions in the material; consequently, the saturation magnetization and magnetic permeability are significantly enhanced. As a result, tuning the electromagnetic-wave absorption performance of the material becomes easier. In addition, the presence of Zn^{2+} ions in the lattice contributes to improving the dielectric constant, enhancing electric polarization under an external electric field and increasing dielectric loss. This, in turn, helps strengthen absorption and broaden the electromagnetic-wave absorption bandwidth of the material. Recent studies indicate that, to simultaneously enhance both the magnetic permeability and the dielectric constant, a composition with a Zn fraction of 0.5 is considered the most balanced, which is particularly beneficial for broadband and magnetically tunable microwave absorption [28] – [30]. Simulations were performed to analyze the surface current distribution and power loss density in the proposed MA, in order to elucidate the underlying mechanism leading to the absorption enhancement.

2. Materials and Methods

First, the ferrite material NZFO was fabricated using a high-energy mechanical milling method combined with thermal annealing from NiO, ZnO, and Fe₂O₃ according to their mass fractions. The mixture was milled using a high-energy ball mill for 30 minutes in air. After mixing, the powder mixture was pressed into pellets at a pressure of 7000 kg/cm². These pellets were sintered in air at 1000 °C with a heating rate of 5 °C/min. Subsequently, the samples were allowed to cool naturally in the furnace to room temperature. After sintering, the sample was subjected to high-energy ball milling in air for 2 hours, yielding a fine powder as the final product. The frequency-dependent curves of the real and imaginary parts of the complex permeability and permittivity of NZFO were measured using a Keysight PNA-X N5242A vector network analyzer. In the experiment, a homogeneous mixture was prepared by mixing the NZFO material and paraffin wax, with the NZFO accounting for 40% of the total weight. The final composite, with a thickness of 2.5 mm, was pressed into a toroidal shape with an inner diameter of 3.04 mm and an outer diameter of 7.0 mm. The toroidal sample was placed in a coaxial waveguide compatible with the analyzer. Using the waveguide method, the analyzer measured the S-parameters S₁₁ (reflection coefficient) and S₁₂ (transmission coefficient) over the entire desired frequency range. The Nicholson-Ross-Weir (NRW) method was used to calculate the complex permittivity (ϵ) and permeability (μ) from the scattering data, extracting their real and imaginary components. These complex values of the NZFO permeability and permittivity were used in the CST simulation. The microstructure and the elemental composition of the sample was characterized by the scanning electron microscope (SEM; Hitachi S4800, Japan). The structure of the sample was analyzed using the X-ray diffraction (XRD) patterns obtained with a Bruker D8 Advance diffractometer, employing Cu K α radiation with a wavelength of $\lambda = 1.54056 \text{ \AA}$. The sample characteristic NZFO properties were assessed using M(H) hysteresis curve. The measurement was conducted at room temperature with a vibrating sample magnetometer VersaLab (Quantum design).

The HM-MA structure used in our simulation has a basic unit cell size of 20 x 20 mm² and consists of four layers; the first layer is a NZFO plate with a thickness of t_f , the second layer of HM-MA is copper composed of two punched-in rings with four open edges, the third layer is FR-4 substrate and the fourth layer is continuous copper plate with a thickness of t_m and a conductivity of $5.8 \times 10^7 \text{ S/m}$. The FR-4 dielectric substrate has a thickness t_d , relative permittivity of FR-4 of 4.3 and loss tangent of 0.025. The optimized structure parameters are as follows: $a = 20 \text{ mm}$, $h = 6 \text{ mm}$, $w = 1 \text{ mm}$, $t_f = 1.5 \text{ mm}$, $t_d = 0.3 \text{ mm}$, $t_m = 0.036 \text{ mm}$, $r_1 = 3 \text{ mm}$, $r_2 = 5 \text{ mm}$, and $r_3 = 7 \text{ mm}$.

For the simulation from 2 to 18 GHz, the periodic boundary conditions along the x and y axes are set. The absorption of the MA is determined via the formula:

$$A(\omega) = 1 - R(\omega) - T(\omega), \quad (1)$$

where $R(\omega) = |S_{11}(\omega)|^2$ and $T(\omega) = |S_{21}(\omega)|^2$ represent the reflection and transmission coefficients, respectively. In our structure design, since the bottom layer is a continuous copper plate, the transmission coefficient can be considered as 0. Therefore, the absorption can be simplified as $A(\omega) = 1 - |S_{11}(\omega)|^2$.

The relative impedance Z_r for our HM-MA can be calculated by:

$$Z_r = \frac{Z(\omega)}{Z_0} = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}. \quad (2)$$

It can be seen that, for the perfect absorption purpose, the relative impedance needs to be optimized around 1.0 for the real part and the imaginary part is close to be 0.

The Full Width at Half Maximum (FWHM) is used to evaluate the width of the absorption spectrum as follows:

$$\text{FWHM} = f_{\text{high}} - f_{\text{low}}, \quad (3)$$

where f_{high} and f_{low} are the frequencies at which the absorption reaches half of its peak amplitude. This amplitude is defined as the difference between the maximum peak intensity and the baseline.

3. Results and Discussion

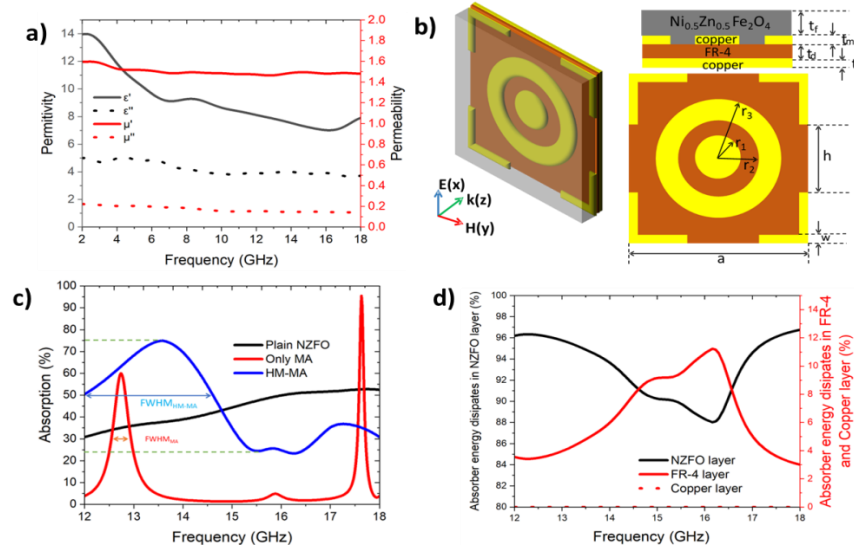


Figure 1. a) The real and imaginary part of complex permittivity and complex permeability of the NZFO, b) Schematic of HM-MA based NZFO unit cell, c) Comparison of absorption spectra for NZFO materials, metamaterials and HM-MA based NZFO and d) Captured energy dissipated in the NZFO, FR-4 and copper layers of the HM-MA structure

As shown in Figure 1(a), the complex permittivity (ϵ) and permeability (μ) of NZFO indicate that both dielectric and magnetic losses contribute to the loss characteristics. Although the significantly higher imaginary parts of permittivity values suggest that dielectric loss plays a primary role, the magnetic properties of NZFO remain crucial for absorption optimization. These magnetic properties can be actively tuned by an external magnetic field, where increased magnetization enhances the permeability [31]. This mechanism provides a vital means to adjust the overall impedance matching of the HM-MA, thereby significantly improving total absorption performance. In addition, the absorption behavior of the MA structure is primarily governed by LC resonance; consequently, the absorption spectrum is typically narrow. The incorporation of NZFO introduces additional loss to the overall structure, thereby broadening the absorption bandwidth. Figure 1(c) illustrates the absorption spectra when comparing the NZFO-based HM-MA, the conventional NZFO material, and only the metamaterial absorber in the GHz frequency range. The results indicate that the integration of the NZFO material into the metamaterial structure effectively broadens the absorption frequency range compared to the conventional material. For the conventional NZFO material of the same thickness as the HM-MA, the electromagnetic wave absorption ranges from approximately 30% to 51% within the investigated frequency range. For the MA without the NZFO material, there is only one absorption peak at 17.8 GHz with an absorption of about 96% and another peak at 12.9 GHz with an absorption lower than 60% with FWHM approximately 0.5 GHz. In contrast, the proposed HM-MA exhibits broader absorption bandwidth, with an absorption peak approximately 75% and the FWHM is enhanced to be approximately 4.6 GHz. In order to clarify the roles of different layers in the HM-MA structure, the energy dissipation fractions in the NZFO layer, FR-4 layer and copper metal layer are shown in Figure 1(d). It can be seen that, more than 87% of the energy loss occurs in the NZFO layer, while the energy loss in the FR-4 is limited to 13%. The copper layer does not

contribute to the loss since copper is a nearly perfect conductor in the GHz region. Therefore, it can be pointed out that the energy dissipation results demonstrate that the NZFO layer in the MPA is the main factor contributing to broadband absorption.

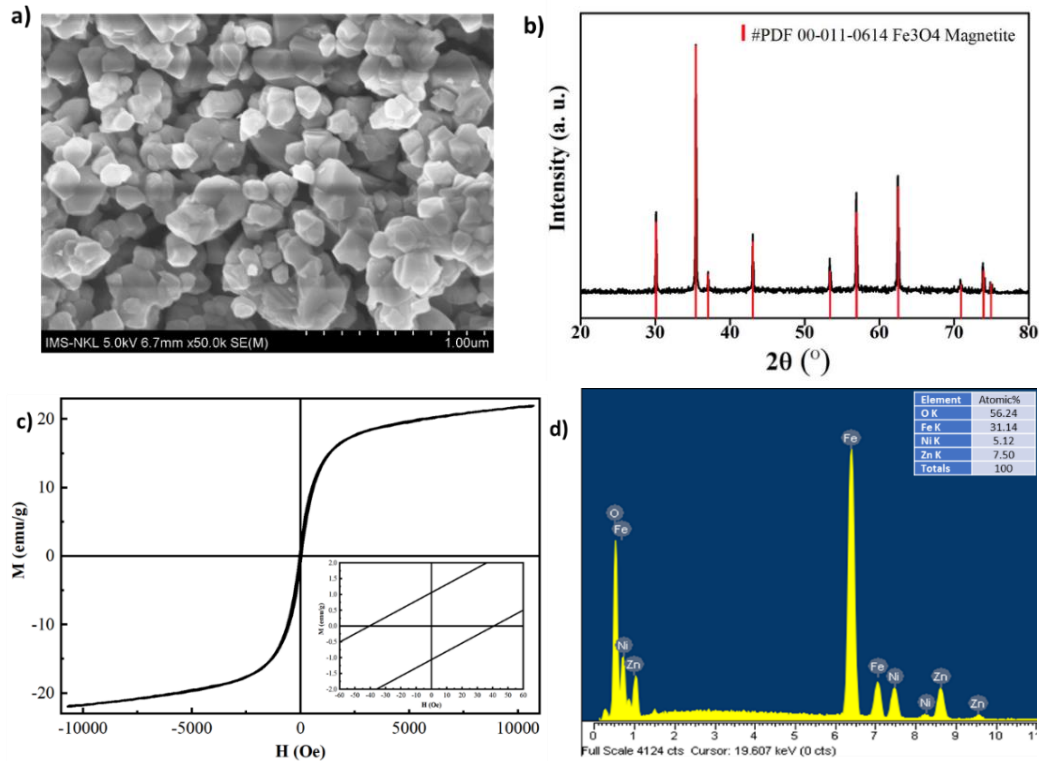


Figure 2. a) Morphology; b) XRD pattern; c) $M(H)$ loops measured at room temperature and d) EDX spectra mapping image of NZFO

Figure 2(a) presents the SEM images of NZFO sample. The particles in the sample are heterogeneous with size about 100 nanometers. Smaller particles are observed to adhere to larger particles. The crystal orientation appears random, possibly due to various interactions. The XRD pattern of NZFO at room temperature is presented in Figure 2(b). The XRD analysis indicates that the synthesized NZFO is crystalline, single-phase and have a cubic spinel structure. Figure 2(c) shows the $M(H)$ hysteresis curve of the NZFO sample at room temperature, it can be seen that the sample exhibits ferrimagnetic properties with very low magnetism, the coercivity (H_c) and saturation magnetization (M_s) as shown in Table 1. With low coercivity value, the material is easily magnetized and demagnetized, suitable for our research purpose of using external magnetic field to enhance the absorption of the structure. To verify the presence and distribution of elements in the NZFO sample, specifically Ni, Zn, Fe and O in the composite samples, we conducted elemental analysis, as shown in Figure 2(d). The result showed that the percentage ratios of elements are quite close to those of the nominal values of the samples, no presence of any foreign elements. The results are consistent with the results reported in [32], [33].

Table 1. Measured values of coercivity and saturation magnetization of NZFO material

Parameter	The coercivity H_c (Oe)	Saturation magnetization M_s (emu/g)
Value	40	22

The calculated real and imaginary parts of the relative impedance Z_r shown in Figures 3(a) and 3(b) are in good agreement with the impedance matching theory and the absorption spectrum of HM-MA. At 13.6 GHz, the HM-MA exhibits favorable impedance matching to free space, with the

real part of the relative impedance, $\text{Re}(Z_r)$, being 2.347 and the imaginary part, $\text{Im}(Z_r)$, being 1.178. This indicates that a large portion of reflection is suppressed and most of the incoming wave penetrates into the structure. In contrast, the plain NZFO shows a $\text{Re}(Z_r)$ of approximately 0.125 and an $\text{Im}(Z_r)$ of 0.25 at the same frequency implying a severe mismatch with the impedance of air. Therefore, the MA integration effectively tailors the effective impedance toward that of free space, which is consistent with the enhanced absorption peak at 13.6 GHz.

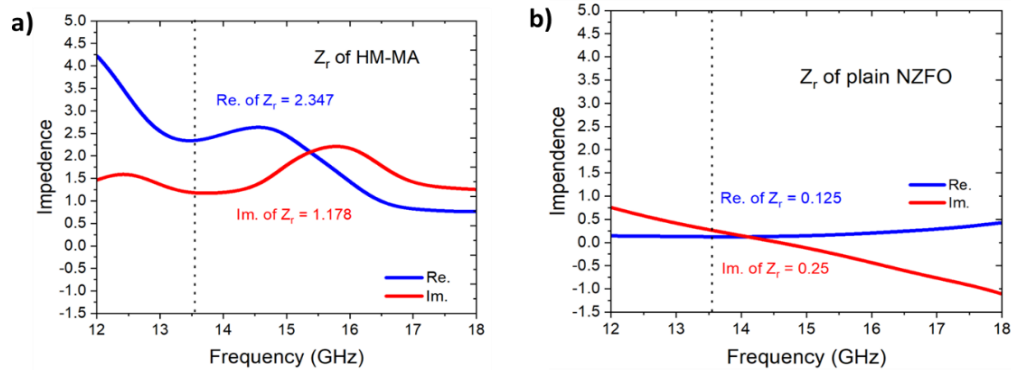


Figure 3. a) Real and imaginary parts of Z_r HM-MA based NZFO and b) real and imaginary parts of Z_r of plain NZFO

As illustrated in Figure 1(c), the most prominent absorption peaks of HM-MA are observed at 13.6 GHz. Therefore, we have selected this peak for the TE polarization mode and observation of surface current and power loss density distributions in order to clarify the absorption mechanism, as shown in Figure 4.

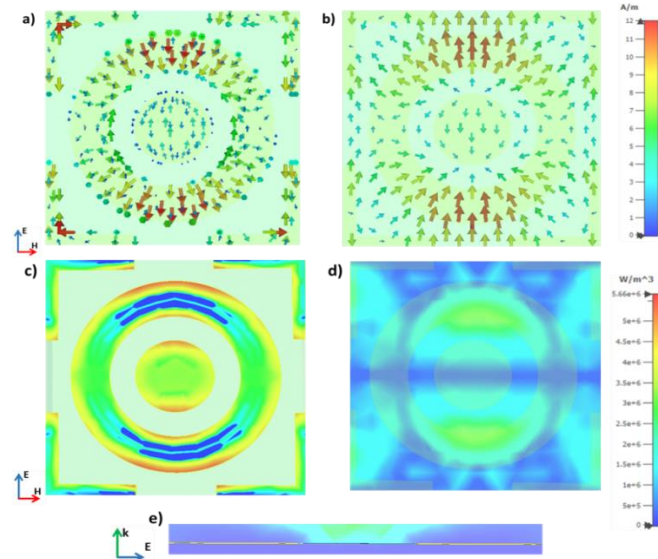


Figure 4. The surface current on the (a) the top metal patten, (b) bottom metal backplane, the power-loss density in the cross section of the (c-d) (E, H) plane at position corresponding to the metal plates and (e) the (k, E) plane at position corresponding to $y=0$ at 13.6 GHz of HM-MA based NZFO

Figure 4(a and b) show that at 13.6 GHz, the surface current is concentrated at the outer circle, partly at the central circle and the L-shaped edges at the corners of the structure. Here, the surface current at the metal layer is parallel and opposite to the current at the bottom layer, forming a magnetic dipole resonance. This resonance leads to the absorption of incident electromagnetic wave energy, creating a high absorption peak at 13.6 GHz. As observed in Figure 4 (c and d), the higher energy loss is concentrated at the outer circle, partly at the central circle and L-shaped edges at the corners of the structure. This is also observed in Figure 4(e), where the energy loss is

also shown to be concentrated at the outer circle location, the center circle, L-shaped location. The loss in the magnetic material is dominant compared to that in the bare metamaterial. It can be said that the combination of NZFO and MA structure is the main reason for the energy loss of the structure. The simulation results are consistent with the results reported in [34], [35].

Finally, the samples were fabricated and measured for validation, as shown in Figure 5. The magnetic material sheet was incorporated into the MA using a mica mold with a paraffin binder, with a mass ratio of 60% compared to NZFO. The experimental setup was used to measure the transmission and reflection coefficients, respectively. In this method, a ZNB20 Vector Network Analyzer connected to two linearly polarized (12-18 GHz) standard gain horn antennas was used to irradiate the sample with a microwave beam and measure the transmitted and reflected signals (with a small incident angle of 10°) from the sample.

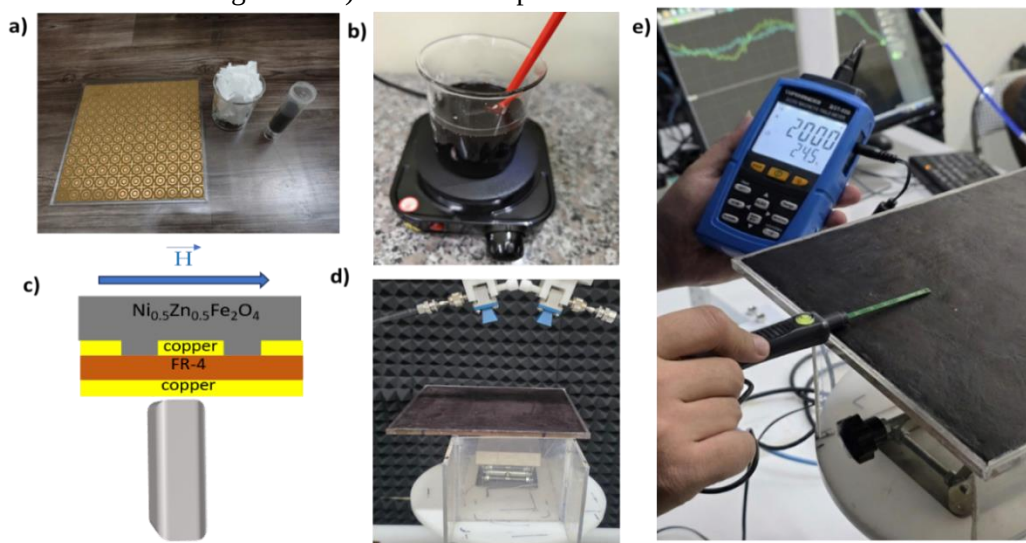


Figure 5. Process of manufacturing and measuring experimental samples: a) preparation of MA sample; b) mixing NZFO material with paraffin and pouring onto MA surface; c-e) experimental measurement

As observed in Figure 6(a), it can be seen that the results between the experimental and simulation results are quite similar. The difference between the simulation and experimental results may be due to several reasons: the surface of the fabricated sample is not flat after curing, leading to different thicknesses of the sample at the measuring points.

With the aim of enhancing and controlling the absorption of the structure, we have arranged the experiment to integrate the external magnetic field parallel to the sample surface with the intensity increasing from 0 to 2000 Oe by using a rare earth magnet NdFeB with dimensions of $100 \times 100 \times 25 \text{ mm}^3$ placed below the sample. The experimental setup is shown in Figure 5(d) and 5(e). We changed the magnetic field intensity acting on the sample by changing the distance from the magnet to the sample (using a lifting stand) and the magnetic field intensity on the surface of the sample was determined using Hall-probe measurements at the center and along the edges of the sample. The results indicate that the variation in magnetic field intensity across the investigated HM-MA area is approximately 5% relative to the average value. For the purpose of modulating the absorption characteristics of the HM-MA under an external magnetic field, this level of spatial nonuniformity of magnetic-field intensity is not significant and does not alter the fundamental nature of the observed phenomenon.

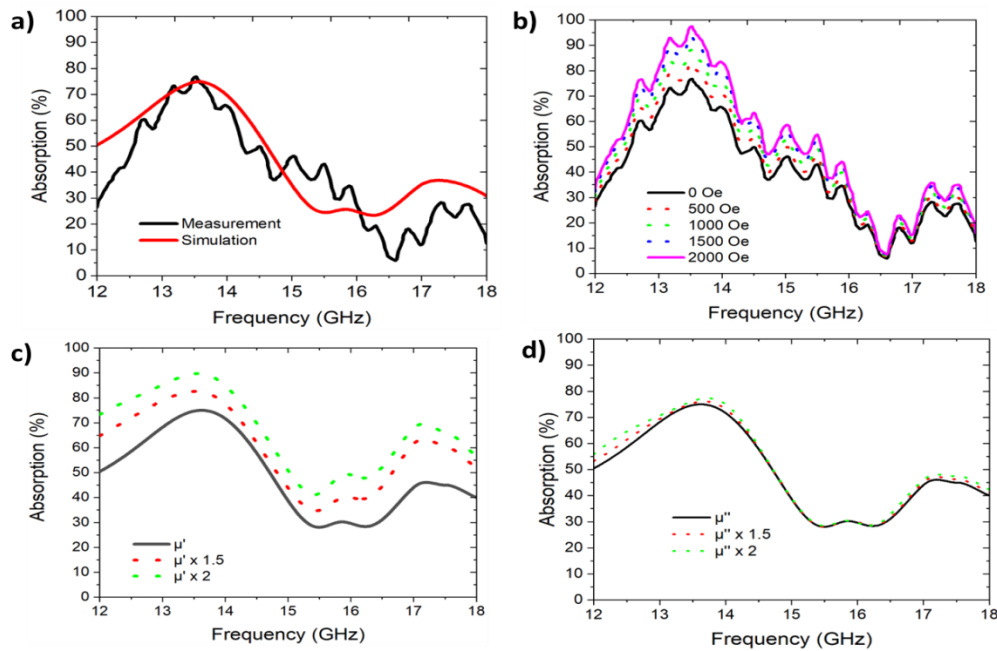


Figure 6. a) Comparison of absorption (for simulated and measurement) spectra for HM-MA based NZFO; b) Absorption spectrum of HM-MA structure when the intensity is varied from 0 to 2000 Oe; (c-d) Simulated absorption spectrums of HM-MA structure when increasing the real part and the imaginary part of the magnetic permeability by factors of 1.5 and 2.

The experimental results are shown in Figure 6(b), it can be seen that as the magnetic field strength increases, the absorption of the structure increases accordingly. When the external magnetic field value reaches 2000 Oe, the structure has an absorption of above 90% in the frequency range from 13.1 to 13.7 GHz. The enhanced absorption is attributed to the field-dependent permeability of the NZFO material. As the external magnetic field intensity increases, both the real and imaginary parts of the permeability rise, simultaneously improving the magnetic energy loss of the NZFO and optimizing the impedance matching of the HM-MA. Consequently, the absorption magnitude of HM-MA is enhanced by increasing the applied magnetic field intensity. To support this interpretation, the influences of the real and imaginary parts of permeability on the absorption spectrum of the HM-MA structure are simulated as shown in Figure 6(c) and 6(d), respectively. The results indicate that the real part of permeability plays the dominant role in contribution to the enhancement of the absorption magnitude. This behavior is distinct from most previous reports, which typically focus on shifting the absorption frequency rather than enhancing the absorption magnitude [36], [37]. We also performed a similar experiment when changing the direction of the magnetic field, perpendicular to and passing through the sample, however, the absorption spectrum of the structure did not change as the magnetic field value increased (not shown here). This shows that the direction of the magnetic field affects the absorption of the material structure.

4. Conclusions

We have proposed a HM-MA structure by incorporating ferrite material $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ to the MA structure. The HM-MA structure has an absorption of 75% at 13.6 GHz under normal conditions. Detailed analysis of the surface current distribution and power loss density revealed the absorption mechanism, demonstrating the important role of integrating magnetic materials in enhancing the bandwidth and absorption intensity. Observing the surface current distribution, it is clear that the surface current on the metal pattern is aligned parallel to the metal substrate, forming a magnetic dipole resonance. We have enhanced the absorption capacity of the structure

to 97% at 13.6 GHz and above 90% in the frequency range from 13.1 to 13.7 GHz by applying an external magnetic field, with the direction of the magnetic field parallel to the structure surface when the magnetic field value reaches 2000 Oe. The proposed structure has potential applications in stealth technology, minimizing the radar reflection cross section. Future work may further explore the possibility of optimizing the absorber design to extend the absorption bandwidth, control the absorption frequency region, and integrate it into advanced electromagnetic systems.

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Author contributions

Tang Xuan Duong: Conceptualization (equal); Visualization (lead); Formal Analysis (equal); Writing – original draft (lead); Writing – review & editing (equal). Do Khanh Tung: Formal Analysis (equal); Writing – review & editing (equal). Bui Son Tung: Validation (equal), Writing – original draft (equal); Nguyen Hai Anh: Formal Analysis (equal); Dao Son Lam: Validation (equal), Writing – original draft (equal); Bui Xuan Khuyen: Supervision (equal); Project administration (equal); Writing – review & editing (equal) Vu Dinh Lam: Conceptualization (equal); Project administration (lead); Writing – original draft (equal); Writing - review & editing (equal).

Conflict of interest statement:

The authors have no conflicts to disclose.

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