



Original Article

Effect of Thickness on Microwave Absorption Properties of $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ Hexaferrite

Thi Anh Ho¹, Duy Cuong Le¹, Duy Xuan Nguyen¹, Chung Chien Do¹,
Tran Quang Dat², Nguyen Quy Tuan³, Huynh Ngoc Toan^{4,5}, Ngo Tran^{4,5,*}

¹VNU University of Engineering and Technology, VNU Town, Hoa Lac, Hanoi, Vietnam

²Le Quy Don Technical University, 236 Hoang Quoc Viet, Hanoi, Vietnam

³The University of Danang - University of Science and Education, 459 Ton Duc Thang, Da Nang, Vietnam

⁴Institute of Research and Development, Duy Tan University, 254 Nguyen Van Linh, Danang, Vietnam

⁵Faculty of Natural Sciences, Duy Tan University, 254 Nguyen Van Linh, Danang, Vietnam

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Abstract: This study investigates the thickness-dependent microwave absorption performance of $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ (Co_2Z) hexaferrite synthesized via a conventional solid-state reaction method. Structural analysis and Rietveld refinement confirm the dominance of the Z-type phase over the Y-type phase. SEM observations show plate-like hexagonal particles, with a crystallite size of ~ 117.5 nm and an average grain size of ~ 2.56 μm . Magnetic measurements indicate soft magnetic behavior, with a saturation magnetization of 58.80 emu/g and a low coercivity of 91.73 Oe. The as-prepared Co_2Z sample exhibits strong microwave absorption performance over a wide frequency range, which can be effectively tuned by adjusting the sample thickness from 1 to 6 mm. The optimal absorption intensity reaches -27.7 dB at 2.75 GHz for a thickness of 6 mm, corresponding to $\sim 99.9\%$ attenuation of incident electromagnetic waves. In addition, a broad effective absorption bandwidth (EAB) of 5.5 GHz is obtained at 2 mm in Ku band, while the maximum EAB of ~ 6.1 GHz is achieved at an optimal thickness of 2.5 mm, covering multiple frequency bands from C to Ku. The enhanced microwave absorption performance can be attributed to the synergistic effects of impedance matching, natural ferromagnetic resonance, and multiple dielectric relaxation processes. These results indicate that the Co_2Z hexaferrite is a promising candidate for tunable microwave absorption applications.

Keywords: solid-state reaction, Z-type hexaferrite, MAMs, microwave absorption, reflection loss, effective absorption bandwidth.

* Corresponding author.

E-mail address: tranngo@duytan.edu.vn

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1. Introduction

Microwave absorbing materials (MAMs) have attracted considerable research attention in recent decades owing to the rapid development of electronic devices and wireless communication systems operating across increasingly wide frequency ranges [1-3]. Electromagnetic interference (EMI) generated by these systems not only degrades the performance of sensitive electronic equipment but also poses potential risks to human health, thereby driving the urgent demand for high-performance microwave absorbers [4-6]. An ideal microwave-absorbing material is generally expected to exhibit strong attenuation, a broad effective absorption bandwidth (EAB), low density, and good thermal and chemical stability [7, 8]. Among the various candidates, magnetic materials, particularly ferrites, have emerged as promising systems due to the synergistic contribution of dielectric and magnetic losses [9-11]. Magnetic ferrites remain attractive for electromagnetic (EM) wave absorption due to their high electrical resistivity, which suppresses eddy-current losses at high frequencies, along with their excellent chemical stability [10, 12, 13]. However, conventional spinel ferrites are typically limited by the Snoek limit, which restricts their effective operation to frequencies below 1 GHz [14, 15].

In contrast, Z-type hexaferrites with the general formula $\text{Ba}_3\text{Me}_2\text{Fe}_{24}\text{O}_{41}$ (where *Me* denotes a divalent transition metal cation) have attracted increasing interest as broadband microwave absorbers. In particular, $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ (Co_2Z) exhibits planar magnetic anisotropy, enabling natural ferromagnetic resonance at GHz frequencies, making it suitable for microwave absorption applications [16-18]. According to the superexchange interaction model, the magnetic moments in these structures arise from the alignment of Fe^{3+} ions across ten distinct Wyckoff sites, where the substitution of Co^{2+} ions significantly modulates the magnetic spin structure and planar anisotropy. This structural complexity gives rise to strong planar magnetic anisotropy and natural ferromagnetic resonance in the GHz range, which are beneficial for microwave absorption [8, 19-21].

In addition to intrinsic properties, the EM response is also strongly influenced by geometric factors, particularly the sample thickness [5, 22]. Based on transmission line theory, reflection loss (RL) follows the quarter-wavelength ($\lambda/4$) matching condition, where destructive interference occurs at specific thickness–frequency combinations [13, 23]. Moreover, the attenuation mechanism in such systems arises from the synergistic effects of magnetic resonance and various dielectric relaxation processes, which can be analyzed using Cole–Cole plots and attenuation-related parameters [12, 24].

However, the crystal structure of Z-type hexaferrite is remarkably complex, characterized by a large unit cell with a specific stacking sequence of S, R, and T structural blocks (STSRS*T*S*R*), stacked along the *c*-axis, often treated as a combination of M-type and Y-type hexaferrites [19]. This crystallographic complexity makes the synthesis of single-phase Co_2Z via conventional solid-state reaction pathways kinetically challenging, often leading to the coexistence of intermediate Y-, M-, and W-type hexaferrites [10].

To address the challenges of synthesizing high-purity $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$, this study successfully prepared the hexaferrite via a straightforward solid-state reaction route. The phase purity, surface morphology, and magnetic behavior of the resulting material were systematically investigated using X-ray diffraction (XRD), scanning electron microscopy (SEM), and vibrating sample magnetometry (VSM). The primary focus was the evaluation of microwave absorption performance as a function of sample thickness, varied from 1 to 6 mm over the 2–18 GHz frequency range. Furthermore, the underlying attenuation mechanisms were elucidated by analyzing normalized input impedance and dielectric relaxation processes, as represented by Cole–Cole plots.

2. Experimental

2.1. Material Synthesis

$\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ hexaferrite was prepared by a standard solid-state reaction. High-purity precursors ($\geq 99.9\%$), specifically BaCO_3 , $\text{CoCO}_3 \cdot 6\text{H}_2\text{O}$, and Fe_2O_3 sourced from Sigma-Aldrich, served as the starting reagents. These powders were precisely weighed to achieve a 3:2:12 stoichiometric molar ratio and blended under dry conditions for 2 h in an agate mortar to ensure uniform distribution of the elements.

The initial thermal processing involved pre-calcination of the loose powder mixture at 1000°C for 8 h. Following this, the calcined material was milled for 30 min to reduce particle size and improve the quality of pressed pellets, and subsequently compacted into 1.2 cm-diameter pellets at 1.5 MPa. An intermediate pre-sintering step was conducted at 1150°C for 8 h. To optimize the phase homogeneity and structural quality of the final ceramic, the pre-sintered pellets were crushed, reground for 1 h, and re-pressed before the final sintering at 1260°C for 10 h. All thermal cycles were carried out in a Nabertherm RT 50/250/13 tubular furnace under ambient conditions, using a controlled heating ramp of $5^\circ\text{C}/\text{min}$ followed by natural cooling to room temperature. The synthesis diagram is shown in Fig. 1.

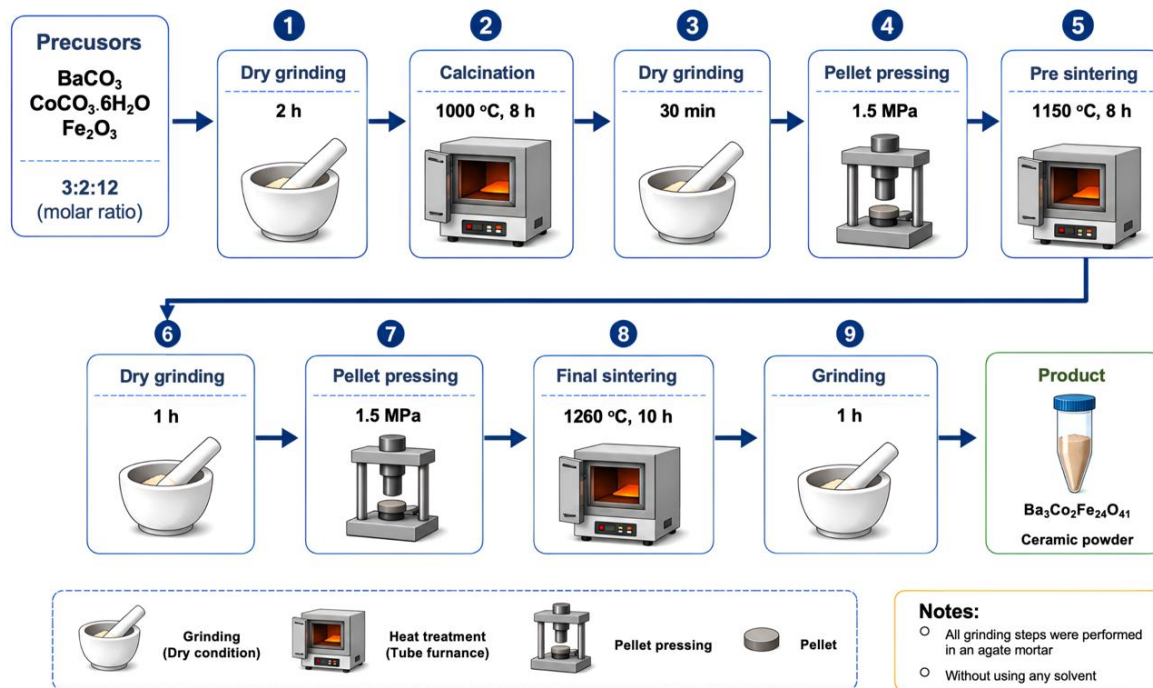


Figure 1. Synthesis diagram of $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ hexaferrite.

2.2. Characterization and EM Measurements

Phase evolution and crystallographic parameters of the synthesized samples were evaluated via X-ray diffraction (XRD; Equinox 5000, Thermo Scientific) utilizing $\text{Cu } K\alpha$ radiation ($\lambda = 1.54056 \text{ \AA}$). Structural details, including lattice constants and the relative fraction of hexaferrite phases, were extracted using Rietveld refinement via the FullProf Suite. The surface morphology and grain structure were characterized using scanning electron microscopy (SEM; JSM-IT200, JEOL).

Magnetic performance was analyzed at room temperature with a vibrating sample magnetometer (VSM; 7404, Lake Shore). To determine the electromagnetic (EM) properties, complex permittivity and permeability spectra were recorded using a vector network analyzer (VNA; Keysight N5242A PNA-X). For these measurements, the ferrite powders were dispersed in a paraffin matrix at a 40:60 volume ratio. The composite was then molded into toroidal specimens with an inner diameter of 3.04 mm and an outer diameter of 7.00 mm, and a thickness of 2.00 mm. The complex permittivity and permeability were extracted from the measured S-parameters using the Nicolson–Ross–Weir (NRW) method. Finally, the microwave absorption performance was calculated from these EM parameters using transmission-line theory.

3. Results and Discussion

3.1. X-ray Analysis

XRD patterns of the as-prepared Co_2Z sample are shown in Fig. 2(a), along with the standard ICDD card No. 00-019-0097 for Z-type hexaferrite. The main characteristic reflections observed at $2\theta = 23.38^\circ, 30.37^\circ, 32.53^\circ, 34.97^\circ, 36.72^\circ, 41.00^\circ, 53.91^\circ, 55.46^\circ,$ and 61.15° can be indexed to (0014), (110), (1016), (1110), (1112), (1116), (303), (1030), and (220) planes, respectively, indicating the formation of the hexagonal Z-type phase with space group $P6_3/mmc$, in agreement with previous reports, reference data [12, 23].

However, a small number of additional peaks marked with asterisks (*) are identified as belonging to $\text{Ba}_2\text{Co}_2\text{Fe}_{12}\text{O}_{22}$ (Co_2Y) secondary phase, indicating that the sample consists of a mixture of Z- and Y-type hexaferrite phases. Such multiphase coexistence is commonly observed in Z-type hexaferrite prepared via solid-state reaction [14], as Z-type structure forms sequentially through intermediate Y-type phase according to the reaction $\text{Co}_2\text{Y} + \text{BaM} \rightarrow \text{Co}_2\text{Z}$ (BaM denotes $\text{BaFe}_{12}\text{O}_{19}$) [25], making the complete phase transformation kinetically demanding [26,27]. In the present work, the relatively short sintering duration and the limited mixing homogeneity likely prevented the completion of this transformation, resulting in the observed residual Co_2Y phase.

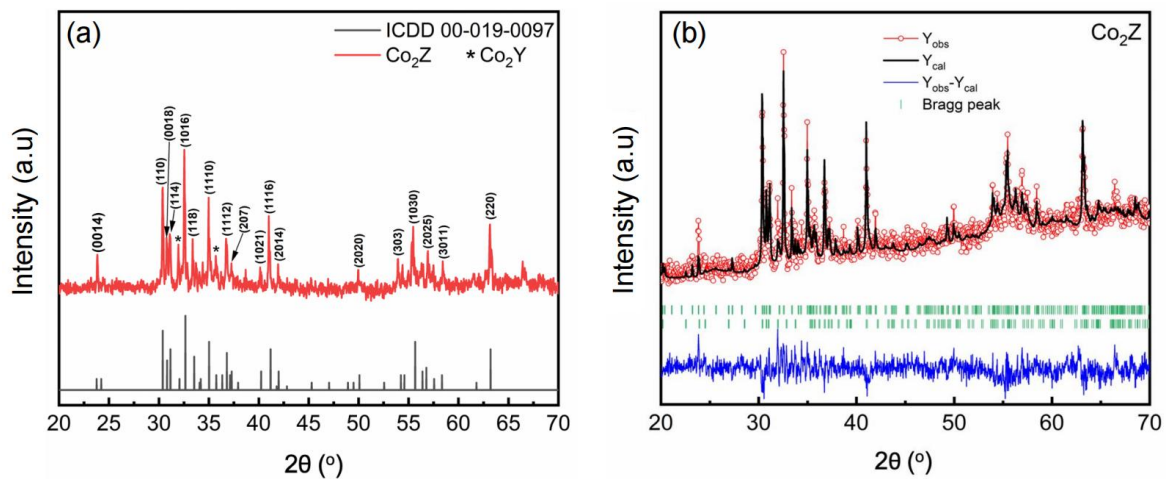


Figure 2. (a) XRD pattern and (b) Rietveld refinement for $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample

To quantify the phase composition, Rietveld refinement was performed (Fig. 2(b)). The close agreement between the observed (Y_{obs}) and calculated (Y_{cal}) patterns, evidenced by the low-intensity

difference curve ($Y_{\text{obs}} - Y_{\text{cal}}$), confirms the reliability of the refinement. The analysis yields phase ratios of 84.53% Z-type and 15.47% Y-type (as shown in Table 1), demonstrating that Z-type phase is the strongly dominant constituent and that the synthesis conditions are generally well-suited for obtaining Z-type hexaferrite. The presence of a small amount of residual Co_2Y phase suggests that the solid-state transformation was not fully completed. One possible reason is the relatively short intermediate dry-grinding step, which may have limited the homogeneity of the precursor powders before the final sintering process. Future studies will investigate the effects of prolonged grinding and wet-grinding conditions on phase evolution and phase purity. The refined lattice parameters of both phases are consistent with previously reported values for their respective hexaferrite structures [12,28], confirming the correct crystallographic assignment. The estimated crystallite size is approximately 117.5 nm, which is typical for hexaferrites synthesized by high-temperature solid-state reaction [21] and is expected to support well-developed long-range magnetic ordering, which is favorable for microwave absorption.

Table 1. Structural parameters, phase fractions, and average crystallite size of the prepared $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample

Phase	Phase ratio (%)	Lattice constant			D (nm)
		a (Å)	b (Å)	c (Å)	
Co_2Z	84.53	5.885	5.885	52.262	117.54
Co_2Y	15.47	5.884	5.884	43.557	

3.2. Morphology

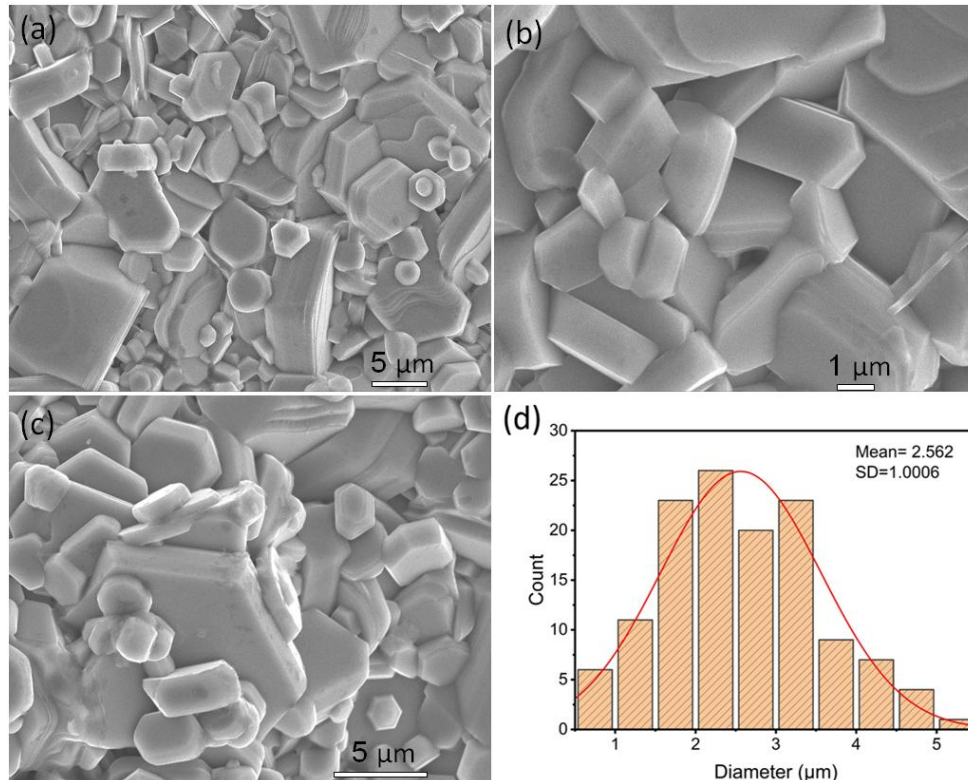


Figure 3. (a-c) SEM images with different magnifications and (d) size distribution histogram for $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample.

SEM image and corresponding particle size distribution of as-prepared Co₂Z sample are shown in Fig. 3. As seen in Fig. 3(a) and (c), the sample at lower magnification consists of well-developed particles with predominantly polygonal and platelet-like morphologies exhibiting smooth faceted surfaces, which is typical of hexaferrites prepared by high-temperature solid-state synthesis [29]. The plate-like habit of the particles reflects the anisotropic crystal growth along the ab-plane favored by the hexagonal crystal symmetry of the hexaferrite structure. Moderate inter-particle agglomeration is also evident, which is typical for ceramic powders processed at elevated sintering temperatures [30]. Fig. 3(b) presents a higher-magnification view that clearly reveals the well-defined polygonal facets and smooth surfaces of individual particles, confirming the good crystallinity of the synthesized material and consistent with the sharp diffraction peaks observed in XRD analysis. Slight variations in particle shape and aspect ratio are also observed across the images, which may be attributed to the coexistence of Co₂Z and Co₂Y hexaferrite phases identified by XRD, as the two phases share similar but not identical crystal habits and growth kinetics.

The particle size distribution, determined by statistical analysis of SEM images and shown in Fig. 3(d), follows an approximately log-normal distribution with a mean diameter of 2.562 μm and a standard deviation (SD) of 1.0006 μm , spanning approximately 0.5–5.5 μm . The relatively broad size distribution reflects the grain growth and coarsening that typically accompany high-temperature solid-state sintering. Notably, the mean grain size at the micrometer scale is significantly larger than the average crystallite size of 117.54 nm determined from Rietveld refinement, indicating that each observed particle is a polycrystalline aggregate composed of multiple coherently diffracting domains. This grain-to-crystallite size discrepancy is commonly observed in sintered solid-state hexaferrites and reflects the coalescence of primary crystallites into larger grains during sintering [31].

3.3. Magnetic Properties

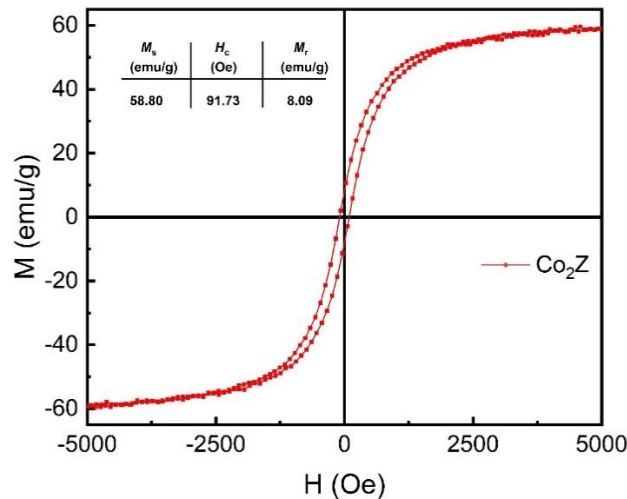


Figure 4. $M(H)$ loop of Ba₃Co₂Fe₂₄O₄₁ sample.

Magnetic hysteresis loop of as-prepared Co₂Z sample measured at room temperature is shown in Fig. 4, and the inset shows the magnetic parameters. The sample displays typical soft magnetic behavior, characterized by a narrow hysteresis loop, with a saturation magnetization (M_s) of 58.8 emu/g, a coercivity (H_c) of 91.73 Oe, and a remanent magnetization (M_r) of 8.09 emu/g. The low H_c confirms the soft magnetic nature of the material, reflecting the planar magnetocrystalline anisotropy characteristic

of Co_2Z hexaferrite, in which spin orientation is confined within the basal plane and requires only a small applied field for reversal. The low M_r and H_c values further indicate that magnetization is predominantly governed by domain-wall displacement, consistent with a multidomain magnetic structure [12, 14].

Despite the presence of the residual Co_2Y hexaferrite secondary phase revealed by XRD, the sample exhibits a relatively high M_s of 58.8 emu/g, comparable to previously reported values for Z-type hexaferrites [12, 32]. This result demonstrates that the overall magnetic response remains dominated by the magnetically active Co_2Z phase, and that strong magnetic performance can be maintained under relatively simple processing conditions without requiring complete phase purity. The high M_s is particularly advantageous for microwave absorption applications, as it provides a significant magnetic loss contribution through natural ferromagnetic resonance in the GHz frequency range, as discussed further in the following section.

3.4. Electromagnetic Properties

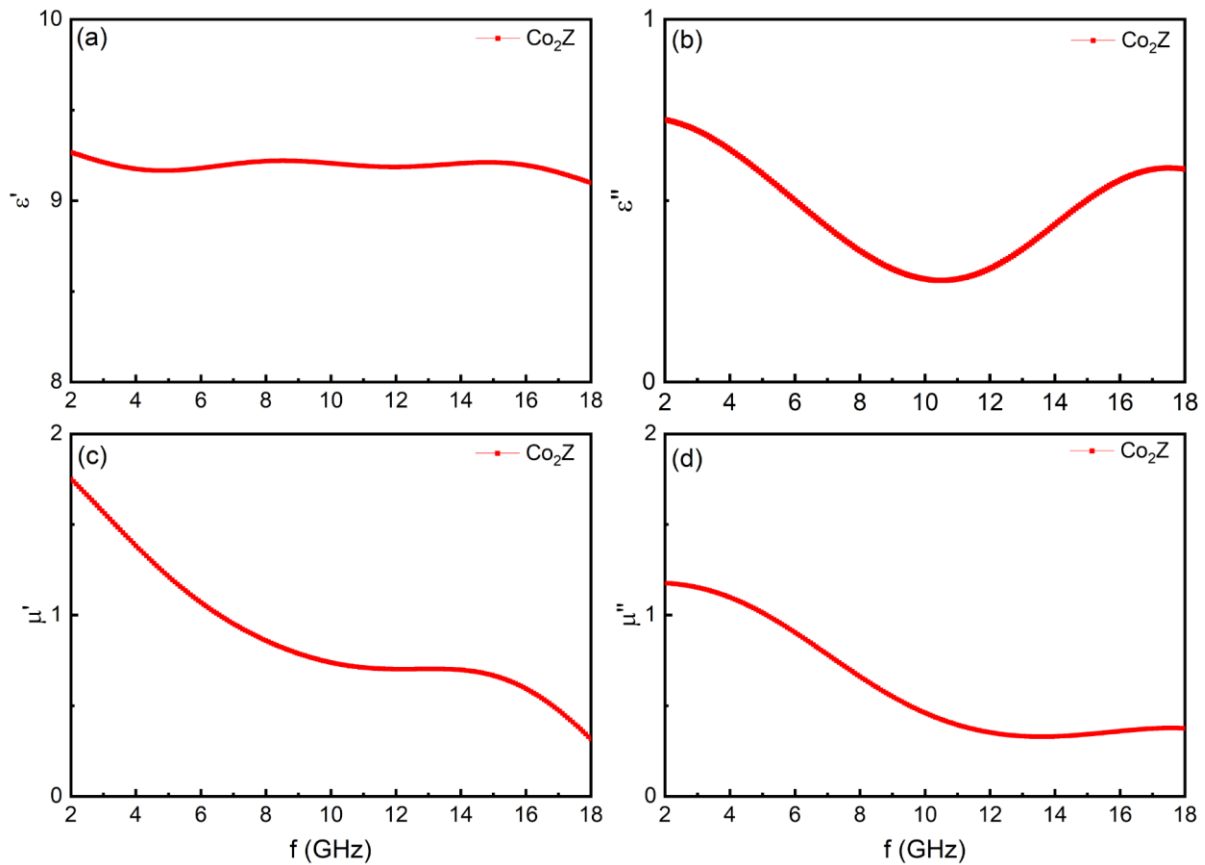


Figure 5. Frequency-responsive behavior of the complex permittivity components (a) real (ϵ') and (b) imaginary (ϵ'') alongside the complex permeability components (c) real (μ') and (d) imaginary (μ'') of $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample.

Fig. 5 illustrates the frequency-dependent behavior of the complex permittivity (ϵ' , ϵ'') and permeability (μ' , μ'') for the $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample in the frequency range of 2–18 GHz. Theoretically, the real parts (ϵ' , μ') represent the EM energy storage capability, whereas the imaginary parts (ϵ'' , μ'') correspond to the energy dissipation ability of the material [32].

As shown in Fig. 5(a), ϵ' values remain relatively stable within the range of approximately 9.1–9.3, indicating weak frequency dispersion and stable dielectric polarization. The ϵ'' values (Fig. 5(b)) are significantly smaller, varying between 0.28 and 0.72, and exhibit a non-monotonic behavior with a broad minimum around 10–11 GHz. This could be attributed to the frequency-dependent dielectric loss originating from interfacial and dipolar polarization. Regarding magnetic properties, μ' values (Fig. 5(c)) demonstrate a gradual declining tendency from 1.75 at 2 GHz to 0.32 at 18 GHz, which is a typical characteristic of natural magnetic resonance in hexaferrite materials [12]. Similarly, μ'' (Fig. 5(d)) decreases from 1.18 to 0.32 with slight fluctuations, confirming the presence of magnetic loss mechanisms such as natural resonance and eddy current effects. This behavior is consistent with Snoek's law, which describes the trade-off among permeability, resonance frequency, and saturation magnetization in magnetic materials [10].

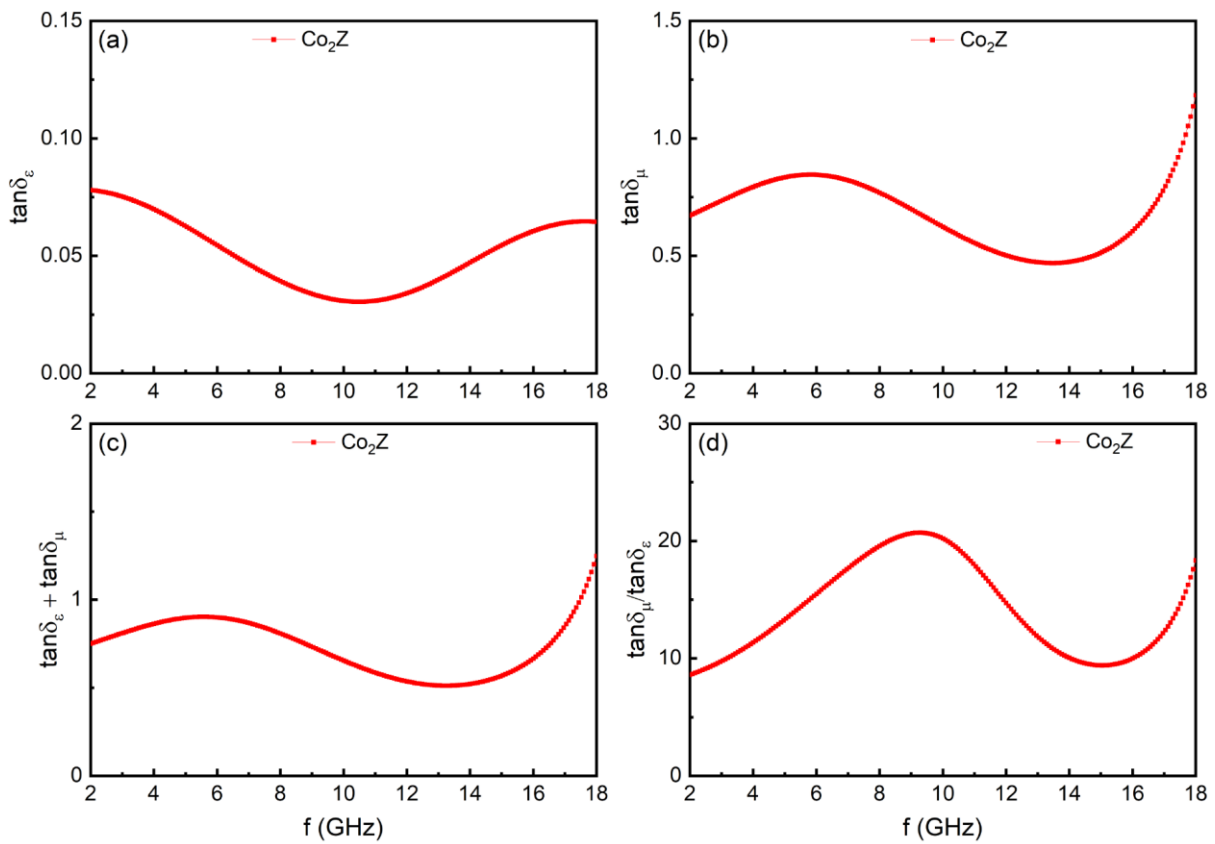


Figure 6. Frequency-responsive behavior of (a) $\tan\delta_\epsilon$, (b) $\tan\delta_\mu$, (c) $\tan\delta_\epsilon + \tan\delta_\mu$, and (d) $\tan\delta_\mu/\tan\delta_\epsilon$ of $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample.

To further evaluate EM energy dissipation characteristics, the dielectric loss tangent ($\tan\delta_\epsilon = \epsilon''/\epsilon'$) and magnetic loss tangent ($\tan\delta_\mu = \mu''/\mu'$) were calculated and are presented in Fig. 6. As observed in Fig. 6(a), $\tan\delta_\epsilon$ values vary moderately between ~0.03 and ~0.08, following a trend consistent with the behavior. In contrast, $\tan\delta_\mu$ values (Fig. 6(b)) are substantially larger, ranging from 0.46 to 1.2 at high frequencies. This clearly demonstrates that magnetic loss is the dominant attenuation mechanism in this Co_2Z hexaferrite material. The total loss tangent ($\tan\delta_\epsilon + \tan\delta_\mu$) shown in Fig. 6(c) reflects the superposition of dielectric and magnetic contributions, showing a characteristic minimum near 13 GHz

before increasing toward the high-frequency end. Particularly noteworthy is the ratio $\tan\delta_\mu/\tan\delta_\epsilon$ presented in Fig. 6(d). This ratio remains well above unity throughout the 2–18 GHz range and reaches a maximum of ~ 20 near 9–10 GHz. This observation unambiguously confirms that magnetic loss overwhelmingly dominates over dielectric loss. This magnetic-loss-dominant character is a distinctive advantage of Co₂Z hexaferrite, driven by its planar anisotropy, which enables a high resonance frequency while maintaining significant permeability. The combination of moderate, stable permittivity with high, broadband magnetic loss is expected to facilitate excellent impedance matching ($Z_{in}/Z_0 \approx 1$) and superior microwave absorption performance, as discussed in the subsequent section [1, 22].

3.5. Microwave Absorption Characteristics

Microwave attenuation capability of the synthesized hexaferrite was assessed through transmission line theory. RL, which serves as a primary indicator of absorption performance, is derived from the measured complex permittivity ($\epsilon_r = \epsilon' - i\epsilon''$) and permeability ($\mu_r = \mu' - i\mu''$) according to the following expressions [13, 34]:

$$Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[j \left(\frac{2\pi f d}{c} \right) \sqrt{\mu_r \epsilon_r} \right] \quad (1)$$

$$RL \text{ (dB)} = 20 \log_{10} \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| \quad (2)$$

where Z_{in} represents the input impedance at the interface of the absorber, Z_0 is the characteristic impedance of vacuum ($\sim 377 \Omega$), f , d , and c denote the EM wave frequency, thickness of the material layer, and the velocity of light, respectively. Optimal microwave absorption occurs when Z_{in} closely aligns with Z_0 , a condition known as impedance matching. Under these circumstances, incident EM waves penetrate the material with minimal surface reflection, leading to efficient internal energy dissipation. Based on these EM parameters, RL values of the Ba₃Co₂Fe₂₄O₄₁ sample were calculated over the frequency range of 2–18 GHz for different sample thicknesses.

Fig. 7 illustrates RL curves as a function of frequency in the 2–18 GHz range for various thicknesses (1–6 mm). It is evident that microwave absorption performance strongly depends on sample thickness. As the thickness increases, the absorption peaks shift gradually toward lower frequencies, a phenomenon that can be well explained by the quarter-wavelength ($\lambda/4$) matching mechanism. For thin samples (1–1.5 mm), RL values remain relatively shallow (ranging from -3.3 to -8.6 dB), indicating limited attenuation capability in the high-frequency region. The material begins to exhibit effective absorption ($RL \leq -10$ dB, corresponding to over 90% energy attenuation) once the thickness reaches 1.75 mm.

Notably, at a thickness of 2 mm, a prominent absorption peak of -19.3 dB is achieved at 13.7 GHz, accompanied by a broad EAB of ~ 5.5 GHz. This excellent performance in the Ku band is primarily due to optimized impedance matching, which allows most incident EM waves to enter the material rather than being reflected at the surface. With a further increase in thickness to 6 mm, a minimum RL of -27.7 dB is recorded at 2.75 GHz (L band), signifying an absorption efficiency of nearly 99.99%. However, a clear trade-off between absorption intensity and bandwidth is observed, as the EAB narrows to 1.7 GHz at this thickness. Overall, the results suggest that thinner samples are ideally suited for Ku band applications, while intermediate thicknesses (~ 2.5 – 3.5 mm) provide superior broadband coverage in X band. Thicker samples ($t > 5$ mm) are more effective for low-frequency attenuation (S and C bands), albeit with a reduced absorption bandwidth.

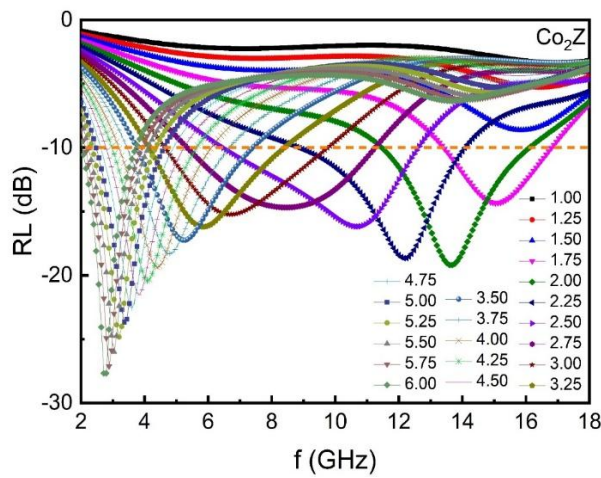


Figure 7. RL as a function of f and t for $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample.

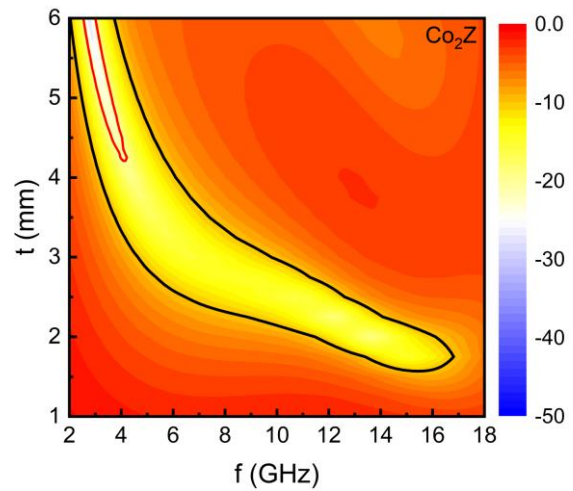


Figure 8. Contour RL maps as a function of f and t for $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample.

Fig. 8 presents the 2D contour map of RL as a function of frequency and sample thickness for the sample. As previously analyzed, the absorption peaks shift gradually toward lower frequencies as the thickness increases, forming a continuous effective absorption region that closely follows the quarter-wavelength matching condition. From the contour map, the effective absorption region ($\text{RL} \leq -10$ dB), corresponding to over 90% EM wave attenuation, is clearly discernible as a continuous band across the measured frequency range. For thicker samples (5–6 mm), microwave attenuation is primarily in the low-frequency range (~2.5–5 GHz). In contrast, for thinner samples (1.75–2.5 mm), the absorption performance shifts significantly toward higher frequencies (~12–17 GHz). Notably, a strong localized absorption minimum is observed at 6 mm and ~3 GHz, which is highly consistent with the RL results discussed in Fig. 7.

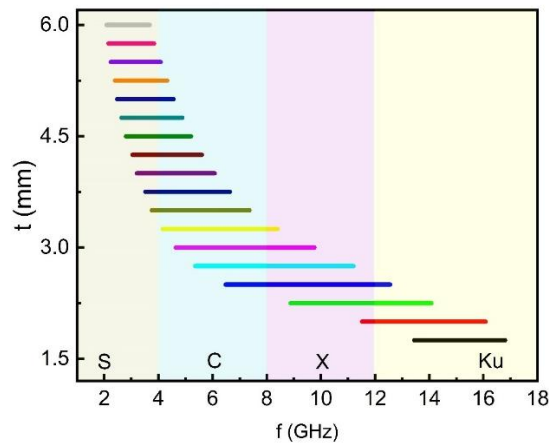


Figure 9. Effective absorption bandwidth values of $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample over the thickness range of 1.75–6.0 mm.

Fig. 9 further summarizes EAB for various thicknesses to evaluate the material's practical applicability. For thicker samples ($t \geq 4.75$ mm), EAB is relatively narrow and confined to the S band

region. However, as the thickness decreases, EAB expands significantly and extends into higher-frequency regimes. Specifically, at a thickness of $t \approx 2.5$ mm, the sample achieves its broadest EAB (~ 6.1 GHz), effectively covering multiple frequency bands from C to Ku. This result indicates an optimal balance between absorption intensity and bandwidth, likely due to the achievement of ideal impedance-matching conditions in this region. Overall, these results demonstrate that the microwave absorption performance of the material can be effectively tuned by adjusting the sample thickness, enabling flexibility for different frequency applications.

To further elucidate the microwave absorption mechanism, the impedance matching condition and dielectric relaxation behavior were analyzed based on the normalized input impedance (Z_{in}/Z_0), eddy current loss and Cole–Cole plots versus frequency. Cole–Cole plot (Fig. 10(a)) exhibits multiple distorted semicircles rather than a single perfect arc, indicating the coexistence of multiple Debye relaxation processes in the material [1]. These relaxation processes are generally associated with dipolar, interfacial, and defect-induced polarization within the heterogeneous structure. In addition, the presence of an extended tail in the low-frequency region suggests the contribution of conductive loss, further enhancing dielectric dissipation.

The magnetic loss mechanism was examined using the parameter $C_0 = \mu''(\mu')^{-2}f^1$ (Fig. 10(b)), which is commonly used to evaluate eddy-current loss [10,12]. If eddy current loss were dominant, this parameter would remain constant with frequency. However, C_0 curve shows a clear frequency dependence, decreasing from ~ 0.2 at 2 GHz to a minimum of ~ 0.05 around 14 GHz, followed by a noticeable increase at higher frequencies. This behavior indicates that eddy-current losses do not dominate the magnetic dissipation in this sample. Instead, natural ferromagnetic resonance (NFMR) is the primary mechanism governing magnetic loss, arising from the planar magnetocrystalline anisotropy of the Co_2Z hexaferrite phase and dominating spin dynamics at GHz frequencies [12,22]. The increase observed at higher frequencies (above ~ 16 GHz) may be related to the onset of additional resonance processes, such as exchange resonance.

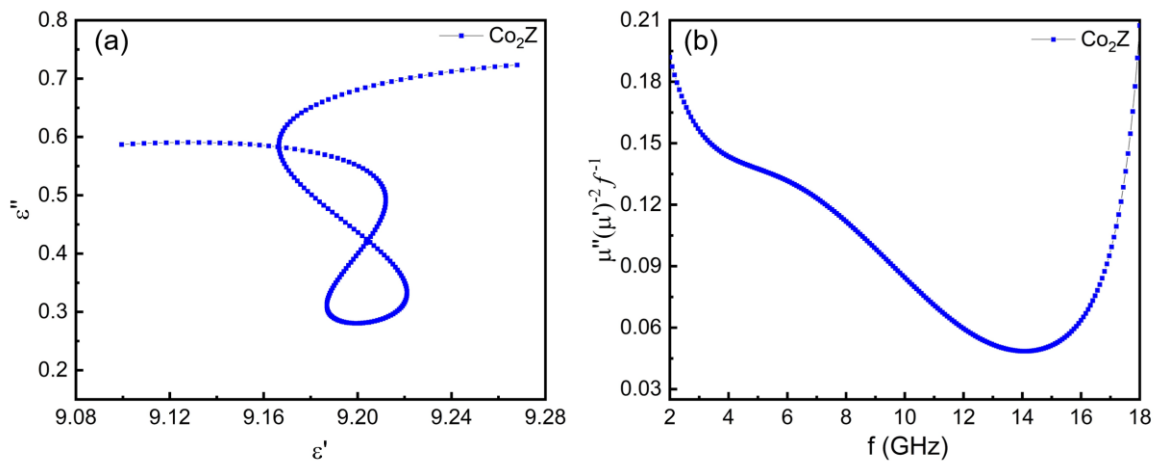


Figure 10. (a) Cole-Cole plots and (b) eddy current loss versus frequency of $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample.

As seen in Fig. 11, the variation of Z_{in}/Z_0 with frequency depends strongly on the sample thickness. It is noted that the frequencies at which Z_{in}/Z_0 approaches unity and shifts toward lower frequencies with increasing thickness, consistent with the quarter-wavelength matching condition discussed earlier. For the sample with $t = 2$ mm, Z_{in}/Z_0 remains around ~ 0.8 over a relatively broad frequency range, indicating moderate impedance matching but with a wider matching bandwidth. In contrast, for thicker

samples ($t = 6$ mm), the maximum Z_{in}/Z_0 value increases to ~ 0.9 – 0.95 , approaching the ideal matching condition ($Z_{in}/Z_0 \approx 1$), but the matching region becomes narrower. This behavior explains the previously observed trade-off between absorption bandwidth and intensity.

It is important to clearly distinguish between the two complementary mechanisms that govern the microwave absorption performance of the present Co_2Z hexaferrite. Impedance matching, expressed by the condition ($Z_{in}/Z_0 \approx 1$), is an intrinsic material property that determines how efficiently an incident electromagnetic wave can enter the absorber rather than being reflected at the air–material interface. It is governed by the complex permittivity and permeability of the composite through the transmission-line expression for (Z_{in}). When this ratio approaches unity, surface reflection is minimized, and the majority of the wave energy is available for subsequent dissipation inside the material. In contrast, the quarter-wavelength ($\lambda/4$) cancellation mechanism is a geometric interference effect. When the absorber thickness satisfies $t_m = \frac{nc}{4f_m\sqrt{|\mu_r\epsilon_r|}}$ ($n = 1, 3, 5, \dots$), the waves reflected from the front and back surfaces of the absorber interfere destructively, producing a deep reflection-loss minimum.

These two mechanisms are closely correlated but physically distinct. Good impedance matching ($Z_{in}/Z_0 \approx 1$) is a prerequisite that allows the electromagnetic wave to penetrate the absorber; the $\lambda/4$ condition then provides an additional geometric cancellation that further deepens the RL at specific thickness–frequency combinations. In the present Co_2Z system, the progressive shift of the absorption peaks toward lower frequencies with increasing thickness (Figs. 7 and 8) follows the $\lambda/4$ relation, while the corresponding improvement of Z_{in}/Z_0 toward unity at those same frequencies (Fig. 11) confirms that impedance matching is simultaneously optimized. For thinner samples ($t \approx 2$ – 2.5 mm) the matching bandwidth is broader, but the peak Z_{in}/Z_0 value remains moderate, resulting in a wide EAB. For thicker samples ($t = 6$ mm) Z_{in}/Z_0 approaches the ideal value more closely, producing a deeper $\text{RL}_{\min}$, albeit over a narrower frequency range. Thus, the observed thickness-dependent absorption performance arises from the synergistic interplay between intrinsic impedance matching and geometric $\lambda/4$ cancellation, both of which are enabled by the favorable magnetic-loss-dominated electromagnetic parameters of the $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ hexaferrite.

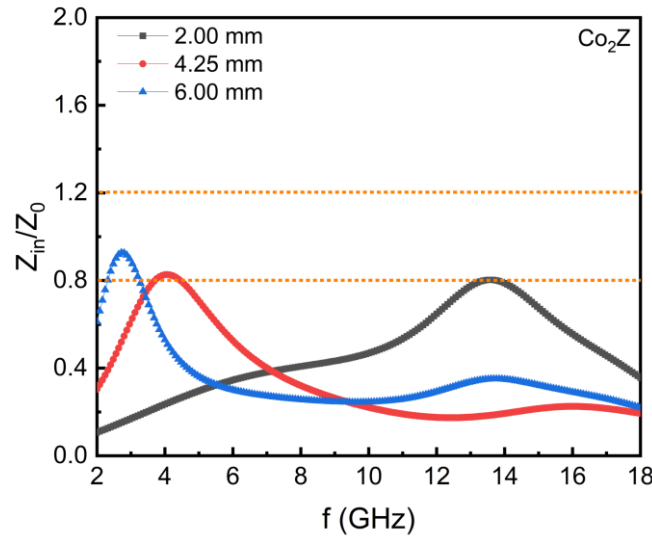


Figure 2. Impedance matching ratio of $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ sample for some specific thicknesses.

4. Conclusion

In summary, $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ hexaferrite was successfully synthesized via a conventional solid-state reaction route. Rietveld refinement confirmed a dominant Z-type phase fraction of 84.53% alongside a residual Co_2Y secondary phase of 15.47%, with refined lattice parameters consistent with previously reported data and an average crystallite size of 117.54 nm. SEM observation revealed well-developed, platelet-like particles with a mean diameter of 2.562 μm , indicating that each particle is a polycrystalline aggregate of multiple primary crystallites, as is typical of hexaferrites synthesized by high-temperature solid-state sintering. Magnetic measurements indicate the material's soft magnetic nature, characterized by a high saturation magnetization (M_s) of 58.8 emu/g and low coercivity (H_c) of 91.73 Oe. These results suggest that the secondary phase does not significantly compromise the strong magnetic performance. Electromagnetic analysis showed that magnetic loss dominates over dielectric loss, while Cole-Cole and eddy-current analyses confirmed that microwave absorption arises from the combined effects of natural ferromagnetic resonance and multiple dielectric relaxation processes. The microwave absorption behavior shows a strong dependence on sample thickness. A minimum reflection loss of -27.7 dB was achieved at 2.75 GHz for a thickness of 6 mm, while a broad effective absorption bandwidth of 5.5 GHz was obtained at 2 mm. The optimal thickness of 2.5 mm yielded the widest bandwidth (~ 6.1 GHz), covering multiple bands from C to Ku. These results demonstrate that effective EM wave attenuation can be achieved in a multiphase system via a simple synthesis route, highlighting the potential of Co_2Z hexaferrite as a tunable, cost-effective absorber.

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