

Enhanced Microwave Absorbing Characteristics of Cerium Barium Ferrite Composite: Effect of Sintering Temperature Variation

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ABSTRACT. Cerium barium ferrite composites (CeBFCs) with improved microwave absorbance in the X-band spectral region are advantageous for varied advanced applications. Thus, the influence of various sintering temperatures on the microwave-absorbing traits of CeBFCs was evaluated. The main objective was to enhance the selective microwave absorption of BFC by modifying its magnetic properties through the substitution of Fe^{3+} with Ce^{3+} in the lattice structures. Four composites of CeBF were synthesized via mechanical alloying and sintered at 600, 800, 1000, and 1100°C. The produced samples were analyzed using XRD, VSM, and VNA to determine their microstructures, magnetic properties, and microwave reflection loss at X-band frequencies. XRD results revealed a significant promotion in forming a more pure crystalline barium hexaferrite phase at sintering temperatures higher than 800°C. This structural enhancement could directly influence the magnetic properties of the specimens with a progressive increase in the saturation magnetization with rising sintering temperature. In addition, the sintering temperature variation effectively modulated the electromagnetic properties (complex relative permeability and permittivity) that are vital for impedance matching and optimal wave absorption. The composite sintered at 1000°C displayed an optimal microwave absorption, indicating the lowest reflection loss within the X-band. The obtained products were shown to attenuate and dissipate surplus electromagnetic energy within the 8-12 GHz frequency range. The observed superior performance of the composites was ascribed to a balanced interplay between the magnetic and dielectric losses, leading to efficient impedance matching. It was affirmed that careful tuning of the sintering temperature can improve the crystalline phases, magnetic, electromagnetic, and microwave absorption properties of the proposed CeBFCs.

Keywords: Cerium barium ferrite, Microwave absorption, Reflection loss, Sintering temperature, X-band

INTRODUCTION

In recent years, wireless communications employing microwave (MW) frequencies within the X-band spectral region (8-12 GHz) have garnered substantial research and applied interests. Significant efforts have been dedicated to developing transmitters and radar systems capable of operating at these frequencies. The materials requisite for these applications must be able to utilize magnetic and dielectric loss mechanisms for the attenuation and dissipation of excess electromagnetic energy as thermal radiation (Kim & Koh, 2008). Consequently, research has consistently focused on various novel

magnetic materials, primarily ferrites that can absorb electromagnetic radiation (EMR) (Bibi et al., 2017; Dong et al., 2014; G. Liu et al., 2017; Luo et al., 2018; Qiao et al., 2017; Salman et al., 2016; Sun et al., 2012; Taurino et al., 2017; Yuan & Tuo, 2013).

In particular, barium hexaferrite (BHF) and its derivatives have attracted widespread attention due to their excellent magnetic anisotropy, high saturation magnetization, and strong natural resonance in the microwave region, making them highly promising as microwave absorbing (Liu et al., 2012; Bierlich et al., 2017; Salman et al., 2016). Several studies have reported that multilayered and magnetically tuned

BHF structures can significantly enhance absorption efficiency by optimizing impedance matching and magnetic loss (Handoko et al., 2020; Liu et al., 2021). For instance, multilayer barium hexaferrite nanostructures exhibited superior microwave absorption performance owing to interfacial polarization and magnetic coupling effects (Handoko et al., 2020). Similarly, magnetized barium hexaferrite samples demonstrated a pronounced enhancement of absorption within the X-band, primarily due to improved magnetic ordering and reduced eddy current loss (Handoko et al., 2024). Furthermore, systematic investigations into magnetic materials for X-band frequencies confirmed that both dielectric relaxation and magnetic resonance mechanisms are essential to achieve efficient absorption (Handoko et al., 2017).

However, optimizing the microwave absorption characteristics of these ferrites remains challenging. Some studies over the years have demonstrated that by modifying the crystalline structures (through the addition of divalent or trivalent ions in the unit cell) of such ferrites, one can alter their inherent resonance frequencies, saturation magnetization, permeability, permittivity, and magnetic field anisotropy (Bhongale et al., 2017; Rajesh Kanna et al., 2017; Widanarto et al., 2017). Accordingly, these ferrites display increased resistance to the effects of electromagnetic interference. Some researchers have exploited the extraordinary relaxation properties of the rare earth ions (REIs) utilized as dopants within the BHF to modify their magnetic and microwave absorption characteristics (Ahmed et al., 2008; Atkare et al., 2025; Chen et al., 2024; Deng et al., 2011; Jing et al., 2007; Shen et al., 2006; Sun et al., 2012; Widanarto et al., 2017). Various REIs-doped BHF composites demonstrated a low saturation magnetization (M_s) and weak coercive field (H_c), which could potentially facilitate an enhancement in the microwave (MW) absorption capacity (Qiao et al., 2017; Seyyed Afghahi et al., 2017; Widanarto et al., 2017, 2018). In this perception, an effort was made for the first time to improve the selective absorption of microwave frequencies of some barium ferrite composites (BFCs) by reducing their H_c and M_s values.

Considering the fundamental and applied interests of REIs-doped BHF, four cerium-doped barium ferrite composites (CeBFCs) were made at various sintering temperatures (600, 800, 1000, and 1100 °C) to improve their magnetic and microwave absorption properties in the X-band spectral region. Trivalent cerium ions (Ce^{3+}) replaced Fe^{3+} in the pure BHF lattice structure via controlled sintering temperature variation. Furthermore, the chosen doping agent (Ce^{3+}) as a substituent was compatible with the hexagonal lattice structure of pure BHF with excellent relaxational attributes. The obtained products were characterized using a series of analytical tools to assess the sintering temperature-induced impact of

Ce^{3+} on their crystalline phases, magnetic traits, and MW reflection loss at X-band frequencies.

EXPERIMENTAL SECTION

Materials Selection

A systematic initial study was conducted to identify the appropriate chemical reagents for developing the proposed composites. The chosen raw materials were granular cerium oxide (CeO_2 , Sigma Aldrich, purity 99%), barium carbonate powder (BaCO_3 , Merck, purity 99%), and natural gamma iron oxide ($\gamma\text{-Fe}_2\text{O}_3$). These substances were selected based on their potential to form composites exhibiting the desired properties. The granular CeO_2 was ground for an hour using a mortar.

Cerium Barium Ferrite Composites Preparation

Four CeBFCs were made using the mechanical alloying and sintered at 600, 800, 1000, and 1100 °C. The chemical composition of the composites (in mol%) was maintained at (20) CeO_2 :(20) BaO :(60) Fe_2O_3 . The precursor powders were placed in a stainless-steel vial with stainless-steel balls and subjected to milling using a Shaker Mill PPF-UG system. The mechanical alloying was performed for three hours under on-off cycles with a ball-to-powder weight ratio of 5:1 to achieve a homogeneous composite powder mixture.

Next, the resultant mixture was compacted to produce the 4 pellets, each with a thickness of 1.5 mm and a diameter of 10 mm. Thereafter, the obtained pellets were sintered for five hours at 600, 800, 1000, and 1100 °C with a heating rate of 10 °C per minute. These pellets were naturally cooled down to ambient temperature after the sintering process. Based on the sintering temperature, the pellets were coded as CeBF600, CeBF800, CeBF1000, and CeBF1100. For further analysis, some selected pellets were pulverized and bonded using resin to form a rectangular shape conforming to the WR90 sample holder dimensions of 2.3 cm × 1.0 cm × 0.5 cm.

Characterizations of The As-synthesized CeBFCs

These materials' crystalline phases and structure were determined using a SmartLab (3 kW) X-ray diffractometer with a Cu-K α line of $\lambda \cong 0.1541874$ nm. An Oxford (1.2H) vibrating sample magnetometer (VSM) was employed to assess the magnetic properties of the prepared CeBFCs. A Keysight (PNA-L N5232A) vector network analyzer (VNA) was utilized to measure the scattering parameters (S) of the arranged CeBFCs. The microwave (MW) absorption calculation was conducted to determine the S components (S_{11} , S_{12} , S_{21} , and S_{22}). It was established that the values of S_{11} and S_{21} represented the coefficients of reflection and transmission (T), respectively. Consequently, the measured values of S_{22} and S_{12} were not considered due to their similarity to S_{11} and S_{21} . The Nicholson-Ross-Weir (NRW) method was subsequently employed to derive the values of complex relative permeability

(μ_r) and permittivity (ϵ_r). Concurrently, the transmission/reflection line principle was applied to evaluate the microwave (MW) absorption characteristics of the CeBFCs by calculating the reflection loss (R_L) values with various thicknesses of samples (Rosdi et al., 2019; Widanarto et al., 2022).

RESULTS AND DISCUSSION

Figure 1 illustrates the XRD patterns of the CeBFCs sintered at 600, 800, 1000, and 1100°C. XRD results revealed various crystalline phases and provided qualitative insights into the crystallinity and grain size of the products. Variation in the sintering temperature was found to significantly affect the formation and evolution of crystalline phases in the composites. The XRD pattern of the composite sintered at 600°C exhibited relatively broader peaks with lower intensity, suggesting a low degree of crystallinity and the presence of significant amorphous phases or precursor particles. It showed the peaks related to intermediate compounds such as BaFe_2O_4 , $\text{BaFeO}_{2.9}$, CeO_2 , and other complex phases. The observed weak peak of $\text{BaFe}_{12}\text{O}_{19}$ indicated its minimal formation at the lowest temperature.

However, the XRD profile was significantly altered as the sintering temperature was increased to 800 °C, wherein the peak intensities were more pronounced, indicating an improved crystallinity and grain growth. Herein, the peaks associated with the desired $\text{BaFe}_{12}\text{O}_{19}$ phase emerged more distinctly and became increasingly prominent. Nonetheless, the minor XRD peaks related to the secondary phases, such as CeO_2 and BaCeO_3 , indicated an incomplete formation of the hexaferrite phase. The sintering effect appeared robust at 1000 and 1100 °C, in which the peaks corresponding to $\text{BaFe}_{12}\text{O}_{19}$ became notably dominant, sharp, and narrow. Clearly, it substantiated the achievement of strong crystallinity and appreciable grain growth. Peaks associated with the minor phases or precursors were scarcely detectable, implying a predominant formation of the hexaferrite phase. These findings are in good agreement with previous reports where the enhancement of crystallinity and phase purity at higher sintering temperatures led to the formation of well-ordered hexaferrite structures with improved functional properties (El Shater et al., 2018; Rosdi et al., 2019).

The microstructural evolution associated with sintering temperature plays a crucial role in determining the functional properties of the material. Higher sintering temperatures facilitate grain coalescence and densification, reducing porosity and improving grain connectivity. This leads to a denser microstructure, enhancing domain wall motion and magnetic coupling. In contrast, at lower temperatures, the presence of amorphous regions and incomplete grain growth increases grain boundary density, thereby impeding domain alignment. This microstructural refinement directly affects the magnetic

and dielectric behavior of the material and, consequently, its microwave absorption performance (Derakhshani et al., 2021; Islam et al., 2019). Similar correlations between microstructure and functional properties have been demonstrated in rare-earth doped ferrites, such as Zr–Sm co-doped (Chen et al., 2024) and Dy–Ce substituted $\text{BaFe}_{12}\text{O}_{19}$ (Atkare et al., 2025), where enhanced crystallinity and reduced defect density significantly improved magnetic ordering and absorption efficiency.

The evolution of crystalline phase purity observed here also agrees with the work of (Salman et al., 2016) and (Sun et al., 2012), which confirmed that the substitution of Ce^{3+} into the $\text{BaFe}_{12}\text{O}_{19}$ lattice can stabilize the hexagonal structure and modify the unit cell parameters by replacing Fe^{3+} ions. This substitution not only affects the magnetic anisotropy but also influences the dielectric response, thereby optimizing the electromagnetic impedance matching critical for efficient microwave absorption. Therefore, the XRD findings confirm that sintering temperature is a determining factor in tailoring the microstructure, phase purity, and crystallinity of CeBFCs, which in turn govern their magnetic and microwave absorption characteristics (Islam et al., 2019; Meng et al., 2024; Qamar et al., 2020).

Figure 2 illustrates the room-temperature magnetic hysteresis (M–H) curves of the synthesized CeBFCs. These curves demonstrate the magnetization response of the composites to the applied magnetic field, revealing key parameters such as the saturation magnetization (M_s) and coercivity (H_c). The observed hysteresis loops confirm the ferromagnetic nature of the samples, consistent with the formation of the M-type barium hexaferrite phase identified in the XRD results (**Figure 1**). A clear enhancement in the M_s value was observed with increasing sintering temperature, accompanied by a progressive widening of the hysteresis loops. The CeBF600 sample displayed the lowest M_s and the narrowest loop, while CeBF1100 exhibited the highest M_s and the broadest loop. This evolution correlates strongly with the microstructural refinement induced by higher sintering temperatures, as improved crystallinity and grain growth facilitate stronger magnetic domain alignment and exchange interaction between adjacent grains. Similar temperature-dependent improvements in M_s have been reported for Dy–Ce and La–Nd substituted $\text{BaFe}_{12}\text{O}_{19}$ ferrites, where enhanced phase purity and grain coalescence contributed to higher magnetic saturation (Atkare et al., 2025; Widanarto et al., 2017).

Interestingly, although M_s increases with temperature, the coercivity (H_c) did not show a proportional increase. In fact, Ce^{3+} substitution tends to reduce H_c due to the partial replacement of Fe^{3+} ions at the octahedral sites, which decreases magnetocrystalline anisotropy and eases domain wall motion. This effect was also observed by Salman et al.

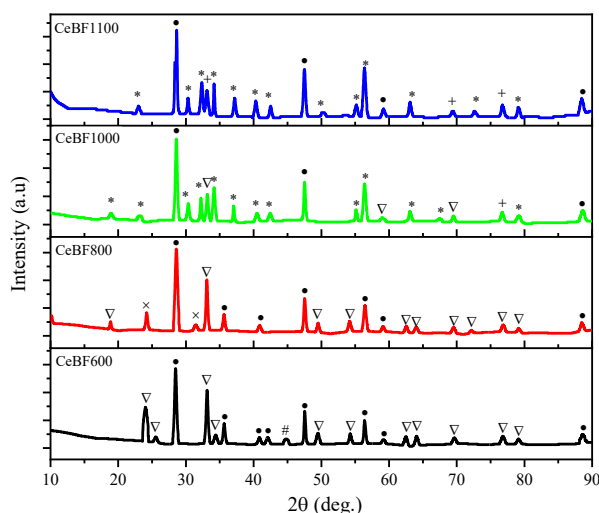


Figure 1. XRD patterns of the studied CeBFCs (* $\text{BaFe}_{12}\text{O}_{19}$; + CeO_2 ; • BaCeO_3 ; ∇ BaFe_2O_4 ; # $\text{Ba}_3\text{Fe}_2\text{O}_6$; × $\text{BaFeO}_{2.9}$)

(2016) and Sun et al. (2012), who demonstrated that rare-earth doping can soften the magnetic behavior of hexaferrites, thereby improving their microwave absorption performance. Therefore, the combined influence of Ce^{3+} substitution and sintering-induced grain growth results in a balanced magnetic behavior characterized by higher M_s and moderately low H_c values — a condition favorable for efficient electromagnetic absorption.

The relationship between microstructure and magnetic performance suggests that higher sintering temperatures promote magnetic homogeneity, reduce lattice strain, and minimize defects that could act as pinning centers for domain walls. However, excessive sintering (as in CeBF1100) may cause abnormal grain growth and a reduction in intergranular resistance, which could lead to eddy current losses. Such phenomena have also been reported by El Shater et al. (2018) and Rosdi et al. (2019), who observed similar trade-offs in high-temperature sintered ferrite composites. Thus, an optimal sintering temperature (around 1000 °C) yields a microstructure with well-developed grains and minimal defects, providing the ideal combination of magnetic softness and structural integrity required for enhanced microwave absorption.

Figure 3 shows the variation of the real and imaginary components of the relative permeability ($\mu_r = \mu' - i\mu''$) and relative permittivity ($\epsilon_r = \epsilon' - i\epsilon''$) of CeBFCs as a function of frequency. These spectra provided valuable information on the materials' interaction potential with microwaves, displaying the composites' microwave absorption capacity. The real (μ' and ϵ') and imaginary (μ'' and ϵ'') parts of the relative permeability and permittivity characterize the material's capacity to store and dissipate (loss) the incident magnetic and electric energy, respectively. A peak in the μ'' curve indicates the magnetic resonance, the primary mechanism for the magnetic energy loss at high frequencies. The

variation in the magnitude of the resonance peaks of μ'' at different frequencies for the studied composites clearly indicated a significant impact of the sintering temperature changes. This disclosure can be attributed to the sintering temperature-induced changes in the composites' magnetic anisotropy and grain size. Higher sintering temperatures promoted significant crystalline grain growth (**Figure 1**), influencing the natural resonance frequency or inducing domain wall or grain resonance, thus contributing to the magnetic loss. The reduction of μ' with the increased frequency demonstrated the effect of magnetic dispersion. Increased sintering temperature enhanced the material's crystallinity and magnetization (**Figure 1** and **2**), increasing the low-frequency value of μ' . The variation of ϵ'' was related to the dielectric losses that originated from the electrical conductivity and dielectric relaxation mechanism, wherein dielectric relaxation often dominates at microwave frequencies. The observed changes in ϵ'' values with the change of the material's sintering temperature were mainly due to the alteration of their morphology and grain boundaries. Consequently, it influenced the composites' conductivity, dielectric relaxation, and dielectric loss. The ϵ' curve exhibited relatively lower dispersion with frequency, indicating the material's ability to store electrical energy, influenced by the atomic and ionic polarization. It was inferred that the sintering temperature changes not only modified the composites' crystal structure and magnetic properties but also directly modified their electromagnetic characteristics. It is known that the achievement of effective microwave absorption depends largely on the balance between magnetic and dielectric losses, which is known as the impedance matching condition. In the current study, a careful tuning of the sintering temperatures resulted in some effective combinations of μ_r and ϵ_r , thus appreciably affecting the impedance matching and absorption efficiency.

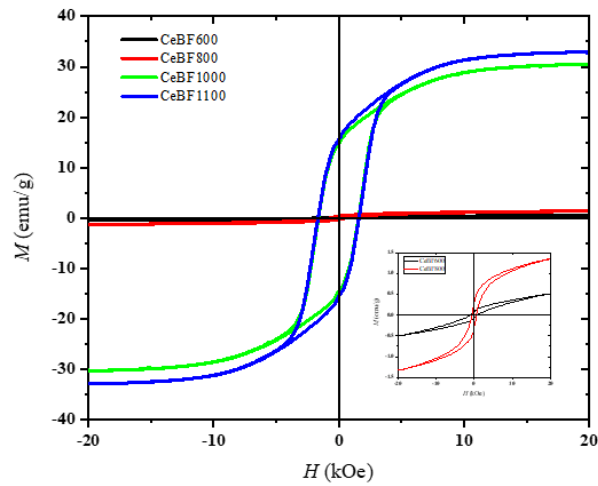


Figure 2. Room temperature M-H curves of CeBFCs

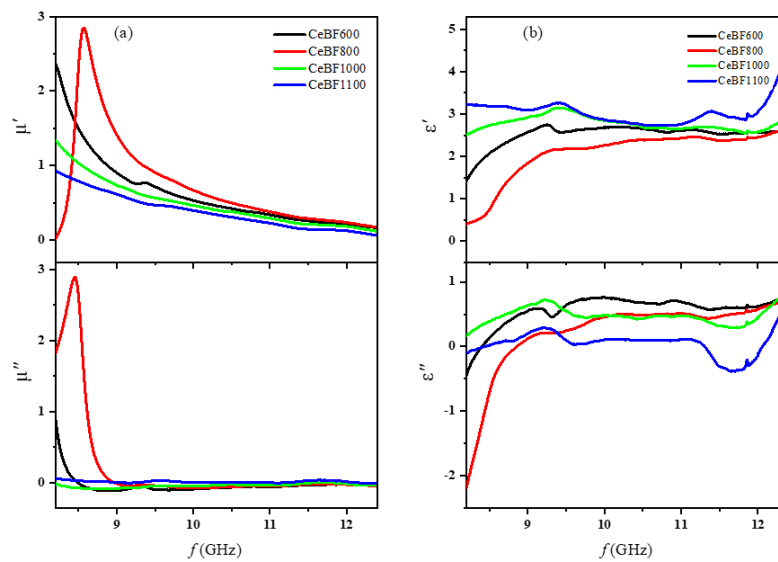


Figure 3. Variation of relative (a) permeability and (b) permittivity of CeBFCs as a function of microwave frequency

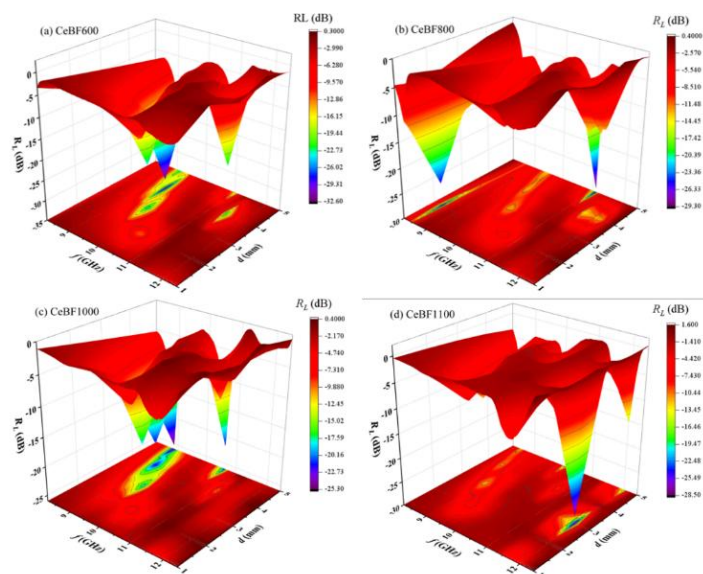


Figure 4. Three-dimensional reflection loss maps of CeBFCs as a function of frequency and thickness

Figure 4 displays three-dimensional reflection loss (R_L) maps as a function of frequency and thickness of CeBFC pellets. The values of R_L served as the primary quantitative parameter for assessing the microwave absorption performance of the proposed materials. A more negative R_L value denoted a higher degree of energy absorption. The three-dimensional R_L map's lowest point, or peak, indicated the optimal absorption condition. As expected, the R_L maps of the composite sintered at 600°C displayed comparatively lower R_L values (less negative) than other samples. This was mainly due to poor crystallinity and suboptimal magnetic phase formation, leading to decreased magnetic and dielectric losses. Conversely, as expected, the prepared samples demonstrated superior microwave absorption with enhanced hexaferrite phase formation (**Figure 1**) and improved magnetic properties (**Figure 2**) at higher temperatures. The R_L map of samples sintered at higher temperatures exhibited deeper and narrower peaks than those sintered at 600°C. The composite sintered at 1000°C yielded excellent performance. The R_L map of CeBF1000 showed markedly negative R_{Lmin} values (e.g., < -10 dB or better) at specific frequencies and thicknesses, most likely within the X-band (8-12 GHz). The optimal absorption at this temperature can be attributed to a favorable balance between the magnetic and dielectric losses, coupled with optimal impedance matching (Rosdi et al., 2019). Although the crystallinity and saturation magnetization (**Figures 1 and 2**) could reach their peak at 1000°C, the microwave absorption efficiency did not attain its optimal value. This may be due to excessive grain growth, leading to increased eddy current losses, thereby hindering an ideal impedance matching condition. In addition, the R_L map displayed some shallower peaks with a shift of the optimal frequency outside the X-band. A correlation between the sample thickness and optimal absorption frequency was ascertained from this map based on the quarter-wavelength ($\lambda/4$) interference principle (El Shater et al., 2018). Essentially, the maximum absorption occurred when the wave reflected from the front surface of the sample destructively interfered with the wave reflected from the back surface, resulting in the minimum R_L at a specific combination of frequency and thickness. However, at higher sintering temperatures (1100°C), the microwave absorption efficiency was adversely affected despite the induction of excessive grain growth and stronger crystallinity.

CONCLUSIONS

The effect of sintering temperature-induced improvement of the structural, magnetic, and microwave-absorbing properties of CeBFCs was determined for the first time. Four composites were prepared via mechanical alloying and sintered at 600, 800, 1000, and 1100°C and thoroughly

characterized. The nucleation of the desired $\text{BaFe}_{12}\text{O}_{19}$ phase became pronounced together with an improvement in the crystallinity and saturation magnetization of the composites with the increase of sintering temperature from 600°C to 1000°C. The reflection loss analysis revealed a significant improvement in the microwave absorption performance of the proposed composites with the increase of sintering temperature. The CeBF1000 sample showed the best absorption performance with the most profound minimum reflection loss within the X-band at the optimal frequency and thickness, which was ascribed to an effective balance between magnetic and dielectric losses that could facilitate an efficient impedance matching. The selective microwave absorption and magnetic characteristics of BFC were shown to be customized by substituting Fe^{3+} with Ce^{3+} in the crystalline unit cells. It is established that by controlling the sintering temperature of the proposed CeBFCs, one can tailor their crystallinity, magnetic, electromagnetic, and microwave absorption properties.

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REFERENCES

- Ahmed, M. A., Okasha, N., & Kershi, R. M. (2008). Influence of rare-earth ions on the structure and magnetic properties of barium W-type hexaferrite. *Journal of Magnetism and Magnetic Materials*, 320(6), 1146–1150. <https://doi.org/10.1016/j.jmmm.2007.11.014>
- Atkare, S. S., Alone, S. T., Fulari, A. V., Dhage, V. N., Kadam, R. H., Shirsath, S. E., & Mane, M. L. (2025). Design of multifunctional rare earth Dy–Ce substituted $\text{BaFe}_{12}\text{O}_{19}$ nanoparticles for X-band microwave absorption and EMI shielding. *Inorganic Chemistry Communications*, 179. <https://doi.org/10.1016/j.inoche.2025.114805>
- Bhongale, S. R., Ingawale, H. R., Shinde, T. J., & Vasambekar, P. N. (2017). Effect of Nd^{3+} Substitution on Structural and Magnetic Properties of Mg-Cd Ferrites Synthesized by Microwave Sintering Technique. *Journal of Rare Earths*, 2018. <https://doi.org/10.1016/j.jre.2017.11.003>
- Bibi, M., Abbas, S. M., Ahmad, N., Muhammad, B., Iqbal, Z., Rana, U. A., & Khan, S. U. D. (2017). Microwaves absorbing characteristics of metal ferrite/multiwall carbon nanotubes nanocomposites in X-band. *Composites Part B: Engineering*, 114, 139–148. <https://doi.org/10.1016/j.compositesb.2017.01.034>

- Bierlich, S., Gellersen, F., Jacob, A., & Töpfer, J. (2017). Low-temperature sintering and magnetic properties of Sc- and In-substituted M-type hexagonal barium ferrites for microwave applications. *Materials Research Bulletin*, 86, 19–23. <https://doi.org/10.1016/j.materresbull.2016.09.025>
- Chen, H., Hao, M., Su, T., Wei, Z., Wang, X., Ma, C., Miao, Y., & Gao, F. (2024). Modulation effect of Zr-Sm co-doped on microwave absorption performance of barium ferrite. *Journal of Alloys and Compounds*, 976. <https://doi.org/10.1016/j.jallcom.2023.173246>
- Deng, L., Ding, L., Zhou, K., Huang, S., Hu, Z., & Yang, B. (2011). Electromagnetic properties and microwave absorption of W-type hexagonal ferrites doped with La^{3+} . *Journal of Magnetism and Magnetic Materials*, 323(14), 1895–1898. <https://doi.org/10.1016/j.jmmm.2011.02.034>
- Derakhshani, M., Taheri-Nassaj, E., Jazirehpour, M., & Masoudpanah, S. M. (2021). Structural, magnetic, and gigahertz-range electromagnetic wave absorption properties of bulk Ni–Zn ferrite. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-88930-0>
- Dong, C., Wang, X., Zhou, P., Liu, T., Xie, J., & Deng, L. (2014). Microwave magnetic and absorption properties of M-type ferrite $\text{BaCo}_x\text{Ti}_x\text{Fe}_{12-2x}\text{O}_{19}$ in the Ka band. *Journal of Magnetism and Magnetic Materials*, 354, 340–344. <https://doi.org/10.1016/j.jmmm.2013.11.008>
- El Shater, R. E., El-Ghazzawy, E. H., & El-Nimr, M. K. (2018). Study of the sintering temperature and the sintering time period effects on the structural and magnetic properties of M-type hexaferrite $\text{BaFe}_{12}\text{O}_{19}$. *Journal of Alloys and Compounds*, 739, 327–334. <https://doi.org/10.1016/j.jallcom.2017.12.228>
- Handoko, E., Budi, S., Sugihartono, I., Marpaung, M. A., Jalil, Z., Taufiq, A., & Alaydrus, M. (2020). Microwave absorption performance of barium hexaferrite multi-nanolayers. *Materials Express*, 10(8), 1328–1336. <https://doi.org/10.1166/mex.2020.1811>
- Handoko, E., Marpaung, M. A., Jalil, Z., Rahwanto, A., Aulia, T. B., Iriani, Y., Mutiara, A. M., Utami, G. A., Fernando, J., Tarihoran, L. A., Tua Munthe, S. M., Umaisaroh, U., & Alaydrus, M. (2024). Microwave absorption studies in X-band of magnetized barium hexaferrite. *Journal of Physics: Conference Series*, 2866(1). <https://doi.org/10.1088/1742-6596/2866/1/012025>
- Handoko, E., Sugihartono, I., Marpaung, M. A., Jalil, Z., Randa, M., Kurniawan, C., & Alaydrus, M. (2017). Microwave absorbing studies of magnetic materials for X-band frequencies. *2017 International Conference on Broadband Communication, Wireless Sensors and Powering (BCWSP)*, 1–4. <https://doi.org/10.1109/BCWSP.2017.8272575>
- Islam, M. A., Rahaman, M. Z., Hasan, M., Akther Hossain, A. K. M., Rahaman, M. Z., Rahaman, M. Z. M., Hasan, A. K. M., & Akther, H. (2019). Analysis of grain growth, structural and magnetic properties of Li–Ni–Zn ferrite under the influence of sintering temperature. *Heliyon*, 5, 1199. <https://doi.org/10.1016/j.heliyon.2019>
- Jing, W., Hong, Z., Shuxin, B., Ke, C., & Changrui, Z. (2007). Microwave absorbing properties of rare-earth elements substituted W-type barium ferrite. *Journal of Magnetism and Magnetic Materials*, 312(2), 310–313. <https://doi.org/10.1016/j.jmmm.2006.10.612>
- Kim, M. S., & Koh, J. G. (2008). Microwave-absorbing characteristics of NiCoZn ferrite prepared by using a co-precipitation method. *Journal of the Korean Physical Society*, 53(2), 737–741.
- Liu, G., Wang, L., Yang, Z., & Wu, R. (2017). Synthesis of iron-based hexagonal microflakes for strong microwave attenuation. *Journal of Alloys and Compounds*, 718, 46–52. <https://doi.org/10.1016/j.jallcom.2017.05.100>
- Liu, M., Liu, Y., Guo, H., Zhang, B., Ren, L., Bashir, A., Bai, S.-L., & Ge, Y. (2021). A facile way to enhance microwave absorption properties of rGO and Fe_3O_4 based composites by multi-layered structure. *Composites Part A: Applied Science and Manufacturing*, 146, 106411. <https://doi.org/10.1016/j.compositesa.2021.106411>
- Liu, Y., Wang, T. J., Liu, Y., Li, X. J., & Liu, Y. (2012). Mechanism for synthesizing barium hexagonal ferrite by sol-gel method. *Advanced Materials Research*, 549, 105–108. <https://doi.org/10.4028/www.scientific.net/AMR.549.105>
- Luo, J., Pan, S., Cheng, L., Lin, P., He, Y., & Chang, J. (2018). Electromagnetic and microwave absorption properties of Er–Ho–Fe alloys. *Journal of Rare Earths*, 36(7), 715–720.
- Meng, X., Xu, W., Ren, X., & Zhu, M. (2024). Progress and Challenges of Ferrite Matrix Microwave Absorption Materials. In *Materials*, 17(10). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/ma17102315>
- Qamar, S., Yasin, S., Ramzan, N., Umer, A., & Akhtar, M. N. (2020). Structural, morphological and magnetic characterization of synthesized Co–Ce doped Ni ferrite /Graphene /BNO12 nanocomposites for practical applications. *Chinese Journal of Physics*, 65, 82–92. <https://doi.org/10.1016/j.cjph.2020.02.023>
- Qiao, Z., Pan, S., Xiong, J., Cheng, L., Yao, Q., & Lin, P. (2017). Magnetic and microwave absorption properties of La–Nd–Fe alloys. *Journal of*

- Magnetism and Magnetic Materials*, 423(July 2016), 197–202. <https://doi.org/10.1016/j.jmmm.2016.08.093>
- Rajesh Kanna, R., Lenin, N., Sakthipandi, K., & Sivabharathy, M. (2017). Impact of lanthanum on structural, optical, dielectric and magnetic properties of $\text{Mn}_{1-x}\text{Cu}_x\text{Fe}_{1.85}\text{La}_{0.15}\text{O}_4$ spinel nanoferrites. *Ceramics International*, 43(17), 15868–15879. <https://doi.org/10.1016/j.ceramint.2017.08.160>
- Rosdi, N., Azis, R. S., Ismail, I., Mustaffa, M. S., & Mokhtar, N. (2019). Effect of sintering temperatures on structural, magnetic and microwave properties of barium ferrites/epoxy composites. *International Journal of Innovative Technology and Exploring Engineering*, 9(1), 5445–5449. <https://doi.org/10.35940/ijitee.A8102.119119>
- Salman, S., Afghahi, S. S. S., Jafarian, M., & Atassi, Y. (2016). Microstructural and magnetic studies on $\text{BaMg}_x\text{Zn}_x\text{X}_{2-x}\text{Fe}_{12-4x}\text{O}_{19}$ ($\text{X}=\text{Zr}, \text{Ce}, \text{Sn}$) prepared via mechanical activation method to act as a microwave absorber in X-band. *Journal of Magnetism and Magnetic Materials*, 406, 184–191. <https://doi.org/10.1016/j.jmmm.2016.01.020>
- Seyyed Afghahi, S. S., Jafarian, M., Salehi, M., & Atassi, Y. (2017). Improvement of the performance of microwave X band absorbers based on pure and doped Ba-hexaferrite. *Journal of Magnetism and Magnetic Materials*, 421, 340–348. <https://doi.org/10.1016/j.jmmm.2016.08.042>
- Shen, G., Xu, Z., & Li, Y. (2006). Absorbing properties and structural design of microwave absorbers based on W-type La-doped ferrite and carbon fiber composites. *Journal of Magnetism and Magnetic Materials*, 301(2), 325–330. <https://doi.org/10.1016/j.jmmm.2005.07.007>
- Sun, C., Sun, K., & Chui, P. (2012). Microwave absorption properties of Ce-substituted M-type barium ferrite. *Journal of Magnetism and Magnetic Materials*, 324(5), 802–805. <https://doi.org/10.1016/j.jmmm.2011.09.023>
- Taurino, R., Karamanov, A., Rosa, R., Karamanova, E., Barbieri, L., Atanasova-Vladimirova, S., Avdeev, G., & Leonelli, C. (2017). New ceramic materials from MSWI bottom ash obtained by an innovative microwave-assisted sintering process. *Journal of the European Ceramic Society*, 37(1), 323–331. <https://doi.org/10.1016/j.jeurceramsoc.2016.08.011>
- Widanarto, W., Amirudin, F., Ghoshal, S. K., Effendi, M., & Cahyanto, W. T. (2017). Structural and magnetic properties of La^{3+} substituted barium–natural nanoferrites as microwave absorber in X-band. *Journal of Magnetism and Magnetic Materials*, 426, 483–486. <https://doi.org/10.1016/j.jmmm.2016.11.124>
- Widanarto, W., Ardent, E., Ghoshal, S. K., Kurniawan, C., Effendi, M., & Cahyanto, W. T. (2018). Significant reduction of saturation magnetization and microwave-reflection loss in barium-natural ferrite via Nd^{3+} substitution. *Journal of Magnetism and Magnetic Materials*, 456, 288–291. <https://doi.org/10.1016/j.jmmm.2018.02.050>
- Widanarto, W., Budianti, S. I., Ghoshal, S. K., Kurniawan, C., Handoko, E., & Alaydrus, M. (2022). Improved microwave absorption traits of coconut shells-derived activated carbon. *Diamond & Related Materials*, 126(November 2021), 109059. <https://doi.org/10.1016/j.diamond.2022.109059>
- Yuan, C. L., & Tuo, Y. S. (2013). Microwave adsorption of $\text{Sr}(\text{MnTi})_x\text{Fe}_{12-2x}\text{O}_{19}$ particles. *Journal of Magnetism and Magnetic Materials*, 342, 47–53. <https://doi.org/10.1016/j.jmmm.2013.04.038>