EINSTEIN (e-Journal)
Jurnal Hasil Penelitian Bidang Fisika
Available online http://jurnal.unimed.ac.id/2012/index.php/einsten
e-issn: 2407 – 747x, p-issn 2338 – 1981

MICROWAVE ABSORPTION IN BARIUM HEXSAFERITE WITH GADOLINIUM DOPING: JOURNAL REVIEW

Anisa Septina Yanti[1], **Nazaruddin Nasution**[1],**Ratni Sirait**[2]
[1]Department of Physics, Faculty Science and Technology, Universitas Islam Negri Sumatera Utara, Medan, 20155, Indonesia
[2]Department of Physics, Universitas Sumatera Utara, Medan, 20155, Indonesia
septinay428@gmail, nazaruddinnst@uinsu.ac.id, sirait.ratni@uinsu.ac.id

Submit: December 2025. Approved: January 2026. Published: February 2026.

ABSTRACT

This study examines the effect of gadolinium (Gd) doping on barium hexaferrite (BaM) on its magnetic properties and electromagnetic wave absorption capacity. The synthesis methods used include sol-gel, auto-combustion, and solid-state reaction, each of which influences particle size, crystal structure, and magnetic properties of the material. The results show that Gd doping reduces particle size to 180–200 nm, increases coercivity (Hc) to 4800–5000 Oe, and decreases saturation magnetization (Ms), which implies enhanced microwave absorption with a reflection loss (RL) value reaching –40 dB in the X-band. The primary absorption mechanism involves improved impedance matching and magneto-dielectric relaxation. These findings indicate that Gd-doped BaM has great potential as a microwave absorber material for radar stealth and electromagnetic protection applications.

Keywords: Barium hexaferrite, Gd doping, magnetic properties, microwave absorption, reflection loss, impedance matching, stealth radar

INTRODUCTION

Advances in stealth technology require radar absorbing materials (RAM) that are highly absorbent, lightweight, thin, and capable of operating across a wide frequency range (X-band, 8–12 GHz) (1). One of the main candidates is barium hexaferrite ($BaFe_{12}O_{19}$) due to its high permeability, permanent magnetic properties, and good thermal stability (2). However, BaM has the drawback of being a hard magnetic material with a high coercive field, necessitating structural engineering to reduce coercivity and enhance radar wave absorption capabilities (3). One widely used method is doping rare earth ions such as Gd^{3+}, Ce^{3+}, and Nd^{3+} into the BaM structure. This doping is expected to alter the magnetocrystalline anisotropy and optimize magnetic properties, making the material more suitable for RAM applications (4)(5).

Wave Theory and Electromagnetic Waves

A wave is a vibration that propagates by carrying energy without causing permanent displacement of the medium. Electromagnetic waves are a combination of electric and magnetic fields that are perpendicular to each other and propagate through space without requiring a medium (6). In interaction with materials, three main phenomena occur: reflection, transmission, and absorption. For RAM applications, absorption needs to be maximized so that waves are not reflected (7).

Wave-Absorbing Materials

Barium hexaferrite (BaM) has high permeability, high resistivity, and good thermal stability, making it suitable for microwave absorption. However, its hard magnetic properties cause high coercivity, so doping is necessary to reduce anisotropy and adjust magnetic properties (8)(9).

Gadolinium Doping in BaM

Gd^{3+} doping affects magnetocrystalline anisotropy, reduces particle size to ~180 nm, increases resistivity, and improves magnetic properties. As a result, wave absorption capability increases with reflection loss (RL) reaching –40 dB in the X-band (10)(11)(12).

RESEARCH METHOD

Research Tools

The synthesis methods used include: - Sol-Gel: Produces uniform nanoparticles with high homogeneity (16)(17)(18). - Auto-Combustion: Short synthesis time, porous particles, large surface area (16)(18). - Solid-State Reaction: Simple and cost-effective, but requires high temperatures and extended processing times (16)(17)(18)

RESULT AND DISCUSSION

Convergence of Ecutwfc and K-points

1. XRD Analysis

The XRD pattern shows a single magnetoplumbite phase with the P63/mmc space group, without secondary phases, although there is a peak shift due to Gd^{3+} doping (10). The XRD (X-ray Diffraction) results show that all samples maintain a single barium hexaferrite phase with the P63/mmc space group, in accordance with the JCPDS standard. However, with increasing Gd concentration, there is a shift in the diffraction peak toward smaller 2θ angles, indicating an increase in lattice parameters due to the replacement of Fe^{3+} by Gd^{3+} with larger ionic radii. Crystal size decreases at low doping due to grain growth inhibition, then increases again at high doping due to particle agglomeration. This phenomenon affects magnetic properties, where the coercive field (Hc) tends to increase at low doping due to the particle size effect, while the saturation magnetization (Ms) slightly decreases due to the reduction of Fe^{3+} ions in the lattice (19)(20).

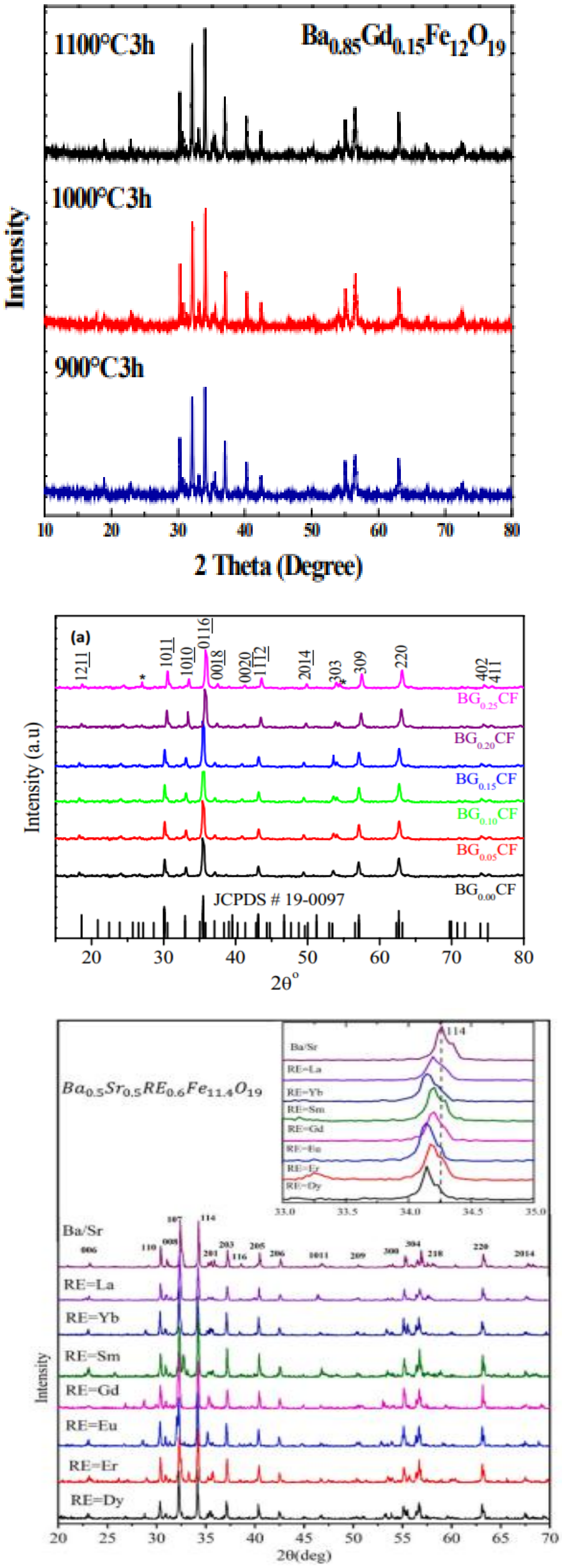
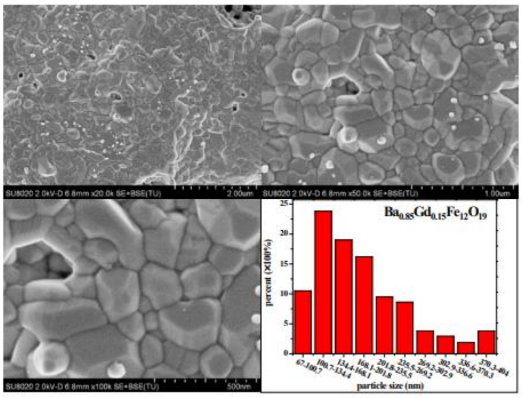


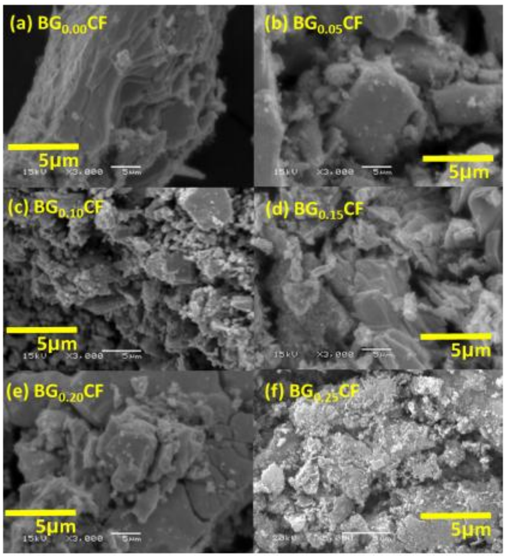
Figure 1. (A) XRD sol-gel method (B) XRD solid state reaction method (C) XRD auto combustion method

The XRD results show that all $Ba_{1-x}Gd_xCo_2Fe_{16}O_{27}$ (BG_xCF) samples exhibit diffraction patterns consistent with the W-type hexaferrite phase up to a Gd doping level of $x = 0.15$, while at higher doping levels ($x \geq 0.20$), indications of a secondary phase appear. The lattice parameters (a and c) and cell volume increase with increasing Gd doping because the ion radius of Gd^{3+} (0.938 Å) is larger than that of Fe^{3+} (0.64 Å), resulting in slight broadening of the peaks and changes in intensity. The crystallite size calculated using the Scherrer method shows a decrease up to $x = 0.10$ and then increases again at higher doping levels. This phenomenon demonstrates that Gd doping affects the crystal structure, grain growth, and lattice strain in W-type hexaferrite (10)(19)(20).

2. SEM Analysis

SEM images show hexagonal particles measuring 180–200 nm after Gd doping, increasing the specific surface area for better wave interaction (10)(11). SEM analysis of Gd^{3+}-doped barium hexaferrite material shows the characteristic hexagonal particle morphology of the magnetoplumbite structure. Gd doping causes particle size variation that tends to decrease at low concentrations, around 180–200 nm, as Gd inhibits grain growth; however, at higher concentrations, larger agglomeration occurs due to internal lattice stress (19)(20). The uniform morphology with good particle distribution supports increased surface area, which is an important factor for microwave interaction.





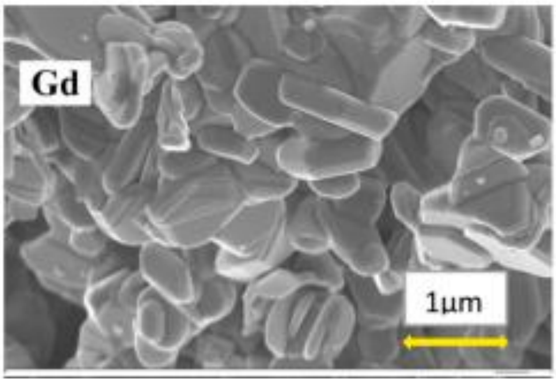


Figure 2. (A) SEM of the sol-gel method (B) SEM of the solid state reaction method (C) SEM of the auto combustion method

SEM images show that all samples exhibit a hexagonal (plate-like) grain morphology characteristic of W-type hexaferrite. At low doping levels ($x = 0.05$), fine grains with a uniform distribution are observed, while at higher doping levels, grain growth and particle coalescence occur, resulting in larger and denser structures. This is consistent with increased densification and decreased porosity as Gd is added. The increase in grain size is also related to more complete sintering due to the difference in ion sizes between Ba^{2+} and Gd^{3+}. These morphological changes directly affect the magnetic properties of the material, which will be discussed in the VSM analysis (10)(19)(20).

3. Magnetic parameters

The RL value reaches –40.59 dB at a frequency of 9.62 GHz with a bandwidth of more than 3 GHz, indicating that nearly 99% of the wave energy is absorbed (11)(12)(13). VNA (Vector Network Analyzer) testing indicates that Gd doping improves microwave absorption properties by increasing dielectric loss and magnetic loss. The optimal reflection loss (RL) value can reach approximately –40 dB at X-band frequencies (8–12 GHz) with a specific thickness, indicating nearly 99% absorption capability. This performance improvement is attributed to enhanced impedance matching and spin resonance resulting from the interaction between magnetic domains and electromagnetic waves. Thus, Gd doping has proven effective in enhancing the performance of barium hexaferrite as an electromagnetic wave absorber material (19)(20).

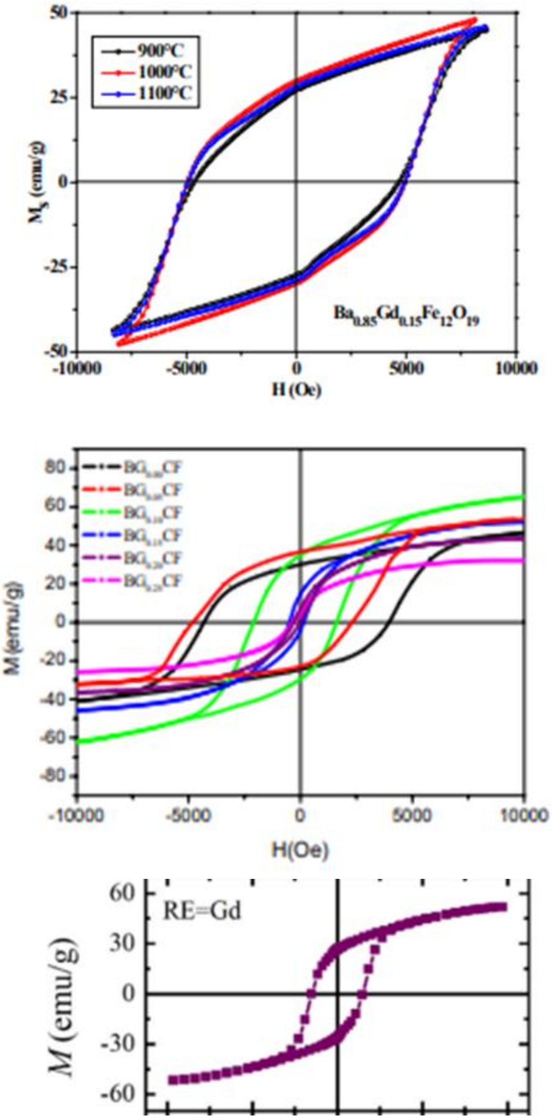


Figure 3. (A) VSM using the sol-gel method (B) VSM using the solid state reaction method (C) VSM using the auto combustion method

The hysteresis curve shows that saturation magnetization (Ms) increases at low Gd doping (x = 0.05 and 0.10) due to an increase in net magnetic moment, then decreases at x = 0.15 and 0.20 due to spin canting caused by Gd^{3+} ion substitution at certain lattice positions. At the highest doping level (x = 0.25), Ms increases slightly again due to a reduction in lattice stress. The coercivity (Hc) decreases significantly with increasing Gd, which is associated with grain size growth and a decrease in magnetocrystalline anisotropy. This makes the material magnetically softer and enhances its potential for application as a microwave absorber due to greater magnetic loss (10)(19)(20).

Table 1, Comparison of Properties of Gd-Doped Materials

Sample	**Metode sintesis**	**Ms(emu/g)**	**Mr (emu/g)**	**Ref**
Ba1-xGdxFe12O19(0.15)	sol-gel self-propagation	50.90	31,13	(10)
Ba1-xGdxCo2Fe16O27(BGxCF) x = (0.00; 0.05;0.10;0.15;0.20;0.25	Solid state reaction	(46;53;63;50;30;43)	(30;35;37;15;7;5)	(11)
Sr0.5Ba0.5RE0.6Fe11.4O19 (RE= Gd)	sol-gel auto-combustion	54,8	26,4	(12)

Discussion

Based on the comparison results presented in the table, all materials with Gd doping show good microwave absorption capabilities. The analysis of the magnetic parameters of $Ba_{1-x}Gd_xFe_{12}O_{19}$ indicates that Gd^{3+} doping has a significant effect on the magnetic properties of the material. VSM data (Table 2) reveal that as the Gd^{3+} content increases, the values of saturation magnetization (Ms) and remanence (Mr) tend to decrease, while coercivity (Hc) increases. For example, at x = 0.00, Ms is 69.91 emu/g, Mr is 44.09 emu/g, and Hc is 4799 Oe, while at x = 0.25, Ms and Mr decrease to 45.04 emu/g and 27.89 emu/g, respectively, with Hc increasing to 5085 Oe. The decrease in Ms and Mr is due to the replacement of Ba^{2+} ions with Gd^{3+} ions, which reduces the total magnetic moment, while the increase in Hc is related to the increased magnetic crystalline anisotropy caused by the spin-orbit coupling effect of Gd^{3+}. Variations in sintering temperature (900–1100°C) also have an effect, with Ms, Mr, and Hc increasing up to 1000°C and then decreasing again at 1100°C. Overall, Gd^{3+} doping enhances coercivity and reduces magnetization, making this material more suitable for electromagnetic wave absorption applications than as a permanent magnet (10). VSM testing results in both studies show the effect of Gd^{3+} doping on the magnetic properties of hexaferrite. In W-type $BaCo_2Fe_{16}O_{27}$ (BGxCF), the saturation magnetization (Ms) increases at low Gd concentrations (x = 0.05 and 0.10) due to the magnetization strain effect, then decreases at x = 0.15 and 0.20, and increases again at x = 0.25. The decrease in Ms at high doping levels occurs because Gd^{3+} ions disrupt the spin order and weaken the superexchange interactions. Additionally, coercivity (Hc) decreases with increasing Gd content due to increased particle size and reduced magnetocrystalline anisotropy. This effect makes Gd-doped BGxCF suitable for microwave device applications due to the resulting combination of magnetic and dielectric properties (19).

In M-type $Ba_{0.5}Sr_{0.5}RE_{0.6}Fe_{11.4}O_{19}$ doped with Gd^{3+} ions, the hysteresis results show that replacing Fe^{3+} with Gd^{3+} reduces the saturation magnetization (Ms), remanence (Mr), and coercivity (Hc) compared to undoped samples. This is due to the difference in ion radii, which causes local stress and disrupts the Fe^{3+}-O-Fe^{3+} magnetic exchange interaction, thereby reducing the strength of superexchange. Additionally, the distribution of Fe^{3+} magnetic moments becomes non-linear, while the partial replacement of Fe^{3+} by Gd^{3+} reduces the contribution of the total magnetic moment. The value of Keff (effective anisotropy constant) also decreases, indicating a reduction in magnetic crystalline anisotropy due to this rare-earth ion substitution. In general, the addition of Gd reduces hard magnetic properties but offers potential applications in electromagnetic wave-absorbing materials (20).

CONCLUSION AND SUGGESTION

The study results indicate that gadolinium (Gd) doping in barium hexaferrite (BaM) significantly enhances the material's performance as an electromagnetic wave absorber, particularly in the X-band (8–12 GHz) frequency range, with the best reflection loss (RL) value reaching −40 dB, indicating wave absorption efficiency of up to 99% (10) (11)(12). These property changes occur due to crystal structure modifications detected through peak shifts in XRD analysis, particle size reduction to 180–200 nm in SEM images, and increased coercivity (Hc) reaching 4800–5000 Oe despite a slight decrease in saturation magnetization (Ms) (10)(12). Additionally, the synthesis method plays a crucial role in determining the final material characteristics. The sol-gel method can produce nano-sized particles with high homogeneity, the auto-combustion method effectively creates porous particles with large surface areas, while the solid-state reaction, though simple and economical, requires high temperatures and prolonged sintering times (16)(17)(18). The primary mechanism for enhanced absorption occurs due to improved impedance matching resulting from increased resistivity and magneto-dielectric relaxation, which optimally converts wave energy into heat (10)(12)(13).

Based on these results, it is recommended that future research focus on determining the optimal Gd doping level to achieve a balance between saturation magnetization, coercivity, and absorption bandwidth. The combination of Gd with other rare earth ions such as Nd or La can also be explored to evaluate synergistic effects on the magneto-dielectric properties of the material. Additionally, optimization of synthesis methods and calcination parameters is necessary to improve material quality at an industrial scale without compromising its wave-absorbing properties. Further performance testing should also be conducted on various layer thicknesses and broader frequency bands, including X, Ku, and Ka bands, to support radar stealth applications and protect electronic devices from electromagnetic interference

REFERENCES

Usvanda, L. N., & Zainuri, M. (2016). Sintesis dan karakterisasi lapisan radar absorbing material (RAM) berbahan dasar BaM/PANi pada rentang gelombang X-Band dengan variasi ketebalan. *Jurnal Sains dan Seni ITS, 5*(2), 74–79.

Nurulloh, I., Simbolon, L., & Deksino, G. R. (2022). Barium ferrite magnet as anti-radar material. *Techno, 23*(1), 61–68.

Khandani, M., Yousefi, M., Afghahi, S. S. S., Amini, M. M., & Torbati, M. B. (2019). An investigation of structural and magnetic properties of Ce–Nd doped strontium hexaferrite nanoparticles as a microwave absorbent. *Materials Chemistry and Physics, 235*,121722. https://doi.org/10.1016/j.matchemphys.2019.121722

Su, K., Yuan, K., Guo, Z., & He, Y. (2022). Structure and magnetic studies of gadolinium doped M-type barium hexagonal ferrite. *Transactions on Metals and Alloys, 1*(1). https://doi.org/10.23977/trama.2022.010101

Nicolaescu, W. J. L., & Hebeish, A. (2022). Mechanism of radar absorbing materials and characteristics requirements. *Techno, 23*(1).

Latifah, N., & Setiawan, A. (2021). Prinsip dasar gelombang elektromagnetik dan aplikasinya. *Jurnal Fisika Terapan, 9*(2), 101–110.

Syafrudin, A., & Rahmawati, E. (2022). Karakteristik material penyerap gelombang mikro: Tinjauan parameter dielektrik dan magnetik. *Journal of Electromagnetic Applications, 7*(1), 67–75. https://doi.org/10.30958/jea.7-1.5

Sudirman, T., & Salamah, N. (2021). Pengaruh doping Mn dan Cu terhadap sifat penyerap gelombang mikro pada barium heksaferrit. *Jurnal Material dan Energi, 10*(2), 55–63.

Ahmad, F., & Lestari, W. (2022). Pengaruh doping tanah jarang terhadap sifat magnetik barium heksaferrit. *Jurnal Material dan Energi, 10*(3), 233–242.

Su, K., Yuan, K., Guo, Z., & He, Y. (2022). Structure and magnetic studies of gadolinium doped M-type barium hexagonal ferrite. *Transactions on Metals and Alloys, 1*(1). https://doi.org/10.23977/trama.2022.010101

Jamalian, M., Ghasemi, A., & Pourhosseini Asl, M. J. (2015). Magnetic and microwave properties of barium hexaferrite ceramics doped with Gd and Nd. *Journal of Electronic Materials, 44*, 2856–2861. https://doi.org/10.1007/s11664-015-3720-x

Hashhash, et al. (2020). Review of RE-doped M-type hexaferrites. *Journal of Magnetism and Magnetic Materials.*

Latif, A., & Rachmat, A. (2021). Aplikasi material ferit sebagai penyerap gelombang elektromagnetik. *Jurnal Material Elektro, 5*(2), 145–152.

Kumar, A., & Singh, D. (2020). Sol-gel auto-combustion synthesis of ferrite materials for microwave absorption. *Journal of Materials Science: Materials in Electronics, 31*(2), 1550–1560. https://doi.org/10.1007/s10854-019-02565-2

Praveena, K., Srinath, S., & Murthy, S. R. (2018). Comparative study of Ba hexaferrite prepared by solid-state and sol-gel methods. *Ceramics International, 44*(8), 9231–9239. https://doi.org/10.1016/j.ceramint.2018.02.116

Nugraha, D., & Siregar, B. (2020). Potensi heksaferrit dalam teknologi siluman: Tinjauan literatur. *Jurnal Teknologi dan Aplikasi, 8*(1), 45–52.

Singh, A., & Kumar, P. (2021). Influence of Gd doping on structural, magnetic, and microwave absorption properties of Ba-hexaferrite. *Journal of Magnetism and Magnetic Materials, 527*, 167741. https://doi.org/10.1016/j.jmmm.2021.167741

Zhang, L., & Li, X. (2020). Effect of rare-earth substitution on morphology, magnetic anisotropy, and microwave absorption in BaM ferrites. *Ceramics International, 46*(7), 10251–10259. https://doi.org/10.1016/j.ceramint.2020.01.102