

Article

Comparative Study of FeBO₃ Crystalline Powders Prepared by Solution Technique and Their Magnetic Properties

Jacob Pfund ¹, Shuai Jiang ², Volkan Ortalan ², Nishamini Ruwanthika Jayasekara ³ , Steven L. Suib ³, Michael Newburger ⁴ and Menka Jain ^{1,5,*} 

¹ Department of Physics, University of Connecticut, Storrs, CT 06269, USA

² Department of Materials Science and Engineering, University of Connecticut, Storrs, CT 06269, USA

³ Department of Chemistry, University of Connecticut, Storrs, CT 06269, USA

⁴ Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH 45433, USA

⁵ Institute of Materials Science, University of Connecticut, Storrs, CT 06269, USA

* Correspondence: menka.jain@uconn.edu

Abstract

Iron borate (FeBO₃) has emerged as a promising candidate for magneto-optical applications owing to its unique combination of weak ferromagnetism (canted antiferromagnetic ordering) near room temperature and optical transparency in the visible range. While the growth of high-quality single crystals is well-established, the scalable synthesis of bulk polycrystalline FeBO₃ remains challenging, often hindered by the presence of impurity phases and inconsistent reproducibility. This work offers a comprehensive investigation into the synthesis of bulk FeBO₃ powder using combustion, solid-state, and flux growth approaches. The structural and magnetic properties of the resulting materials are compared, enabling a direct comparison of synthesis routes. Practical guidelines are provided for optimizing processing protocols to achieve phase-pure, highly reproducible FeBO₃, thereby advancing its integration into functional magneto-optical devices.

Keywords: magnetism; polycrystalline; flux growth; solid state; magneto-optic

1. Introduction

Single-crystal iron borate (FeBO₃) has attracted sustained research interest since it was first grown by Bernal et al. [1], owing to its unique combination of room-temperature ferromagnetism, strong Faraday rotation, and optical transparency in the visible spectrum [2–7]. It serves as an important model system for investigating magnetic anisotropy and the Dzyaloshinskii–Moriya interaction [8–10]. Among iron-based oxides, FeBO₃ exhibits one of the strongest Faraday rotations [11,12], significant magnetic anisotropy [11], and a bandgap of ~2.9 eV [13], along with comparatively higher transparency in the visible region than other ferromagnets [14]. Combined with its antiferromagnetic Néel temperature close to room temperature ($T_N \sim 347$ K) and pronounced magneto-optical response, these properties make FeBO₃ an attractive candidate for applications in magneto-optical and spintronic devices, wide-band modulators, deflectors, optical isolators, and magnetic memory elements [2,11,15–18].

Despite these advantages, the growth of FeBO₃ single crystals remains severely constrained. Crystals typically form as thin platelets and, even after decades of development, are limited to lateral dimensions of ~10 mm and thicknesses of ~200 μm [19,20]. This size limitation is particularly restrictive for Faraday rotator applications, as the total rotation



Academic Editor: Marius Andruh

Received: 5 August 2026

Revised: 21 August 2026

Accepted: 27 August 2026

Published: 3 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

depends on material thickness (optical path length). Consequently, there is strong motivation to develop polycrystalline FeBO_3 as a scalable alternative. Polycrystalline materials can achieve optical characteristics nearly identical to those of single crystals when high densification is attained through proper sintering [21–23]. Densities approaching 90% of the single-crystal value have been reported for FeBO_3 [24] suggesting that bulk polycrystalline forms could be viable for device applications. However, the synthesis of phase-pure ‘green’ FeBO_3 powder remains challenging and comparatively underdeveloped [24–34]. Persistent issues associated with its synthesis include secondary phase formation (e.g., Fe_2O_3 , B_2O_3 , Fe_3BO_6) and poor reproducibility [25,27,28,35,36].

FeBO_3 is unstable above 900 °C, decomposing into Fe_2O_3 and B_2O_3 , so several synthesis approaches at temperatures below 900 °C have been explored, though with mixed results [26]. For example, Joubert et al. [26] and Schober et al. [24] heated mixtures of $\alpha\text{-Fe}_2\text{O}_3$ and H_3BO_3 powders to temperatures of 780–860 °C. These resulted in a yellow-brown product, though without any obvious impurity X-ray diffraction (XRD) peaks. However, subsequent studies have revealed inconsistencies. Muller et al. [27] observed persistent $\alpha\text{-Fe}_2\text{O}_3$ contamination (brown powders) using comparable methods, and wet-chemical synthesis routes have resulted in mesoporous FeBO_3 , which were also brown in color, indicating Fe_3BO_6 or Fe_2O_3 impurity [28]. More recently, Biryukov et al. [31] reported 7 wt% Fe_2O_3 impurity using a solid-state growth method followed by annealing at 670 °C.

Although phase diagrams for the $\text{Fe}_2\text{O}_3\text{--B}_2\text{O}_3$ system predict FeBO_3 formation below 670 °C, or at higher temperatures under B_2O_3 -rich conditions, these conditions do not guarantee phase purity [37]. Flux-based growth methods have been developed for green FeBO_3 powders [38], though they require several weeks of firing at 810 °C in a platinum crucible.

Given these limitations and challenges, there remains a clear need for a reliable, scalable, and reproducible synthesis method for phase-pure FeBO_3 powders. Addressing this challenge would enable the development of dense polycrystalline materials suitable for practical applications, particularly for sensors, magneto-optical devices, and batteries [18,25,32,39,40]. In this work, we systematically compare three synthesis approaches for producing bulk polycrystalline FeBO_3 : citrate gel-combustion, solid-state reaction, and flux growth. We utilize structural characterizations to evaluate phase purity, crystallinity, and microstructure of the products. We then examine the magnetic properties of each material, providing a comparative analysis to identify the presence of impurities via bulk magnetic susceptibility, as well as evaluate whether polycrystalline FeBO_3 retains the magnetic properties of single crystal FeBO_3 desirable for magneto-optic applications.

2. Results and Discussion

Photos of polycrystalline FeBO_3 synthesized via three different routes—citrate gel-combustion, solid-state, and flux growth—are presented in Figure 1a–c, respectively. Only the samples grown via flux growth were of the green color associated with phase-pure single-crystal FeBO_3 [16,27]. Our investigations indicated that the choice of annealing temperature plays a less important role than the choice of synthesis technique. For example, the properly executed solid-state and flux growth techniques always formed at least some FeBO_3 in the 670–800 °C range. The solid-state method benefited from long annealing times of 100 h or greater and relatively low temperatures around 670 °C. Higher temperatures resulted in more Fe_3BO_6 production, generally yielding <50% FeBO_3 composition. The flux growth method performed much better than the solid-state route, producing >50% FeBO_3 in the entire 670–800 °C range, with a slight improvement at higher temperatures. The largest improvement to the flux growth method, however, came from increasing the batch size to as large as possible, as shown in Figure 1d. Both the solid-state and flux growth methods benefited massively from thorough homogenization of precursors. For example,

shortening the grinding time by half in either method, or removing the acetone suspension step in the flux growth method, reduced the final FeBO_3 content by as much as 40%.

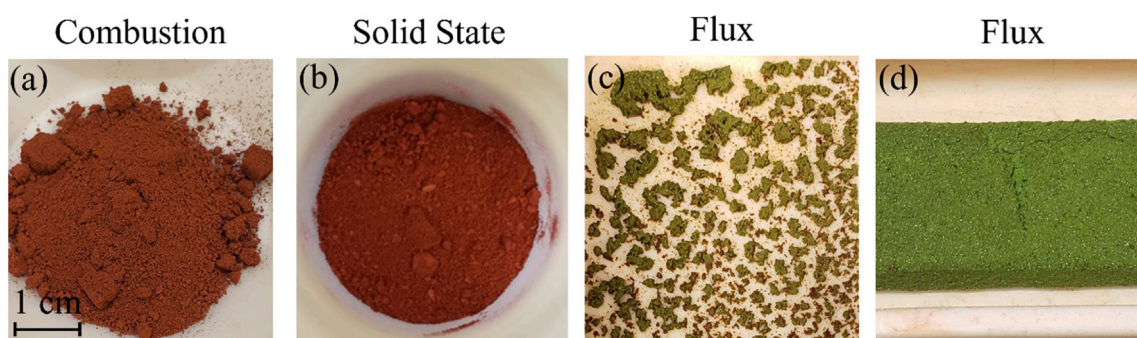


Figure 1. Final products from each synthesis method: (a) combustion, (b) solid-state, (c) flux growth with <1 g of precursor material, and (d) flux growth with >10 g of precursor material. Green color was only achieved from the flux growth route.

These observations support the hypothesis that boron access is the likely driver of the $\text{Fe}_3\text{BO}_6 \leftrightarrow \text{FeBO}_3$ conversion, and is necessary in excess for phase-pure FeBO_3 formation. In solution combustion synthesis, the formation of a gel network after solvent evaporation ensures a homogeneous distribution of Fe_2O_3 and B_2O_3 , which react to form small particles of Fe_3BO_6 during the combustion step. FeBO_3 does not form from this reaction, as there is no crystallite/ B_2O_3 glass interface present for Fe^{3+} and O^{2-} ions to diffuse out towards, as described by Jach [38]. In the solid-state reaction, even with 100% excess B_2O_3 , crystallites do not receive full exposure to liquid B_2O_3 during annealing, but there is partial coverage. Therefore, the complete conversion of all Fe_3BO_6 into FeBO_3 is not completed and we observe a mixture of the two phases. The flux growth method resolves the above issues by ensuring complete contact of crystallites with B_2O_3 , thus enabling complete conversion into FeBO_3 and preventing decomposition into Fe_3BO_6 . While the formation process of FeBO_3 is well understood, the decomposition process is not. Based on previous studies [17,26,37,38,41] and our investigations, the decomposition process and products (either Fe_3BO_6 or $\alpha\text{-Fe}_2\text{O}_3$) depend on temperature, boron availability, atmosphere, and sample morphology (powder or single crystal). We do note, however, that decomposition often becomes an issue above 810 °C regardless of other factors.

XRD spectra of the three FeBO_3 powder samples are shown in Figure 2. The combustion sample shows all major peaks of Fe_3BO_6 (PDF 2-2001) and the solid-state sample displays all major peaks of FeBO_3 (PDF 21-0423), as well as a mixture of Fe_3BO_6 and $\alpha\text{-Fe}_2\text{O}_3$ (PDF 33-0664) phases, as shown in Figure 2a. The flux-grown sample shows all major FeBO_3 peaks, which all exhibit peak splitting and/or broadening, as exemplified in Figure 2b. Table 1 lists the observed peak locations and corresponding planes for each sample. All major peaks are observed for each phase, with the expected intensity ratios based on PDF database files. It should be noted that B_2O_3 is typically amorphous and therefore does not present any distinct peaks in XRD data [42], so no statement can be made about whether excess B_2O_3 is present in any sample, which can affect magnetic properties by straining the crystallites [35].

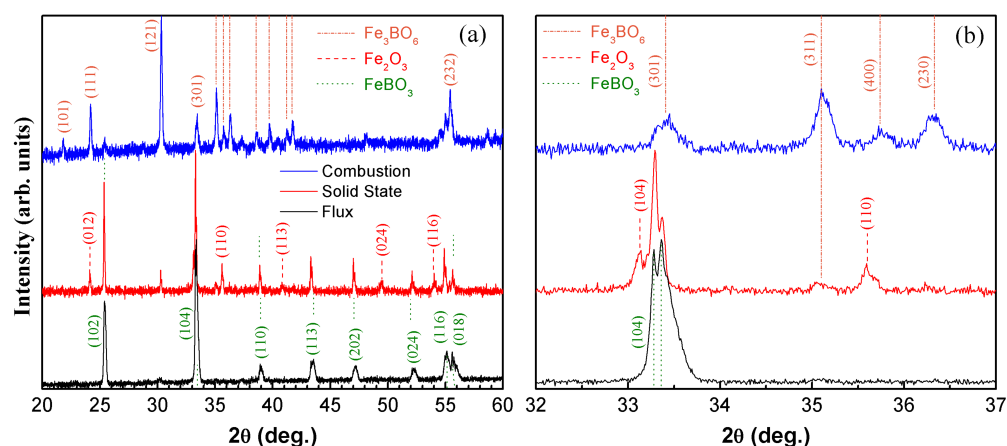


Figure 2. (a) X-ray diffraction spectra of FeBO_3 samples synthesized via combustion, solid-state, and flux growth methods. Vertical dashed lines are used to clarify which peaks belong to each phase. (b) Magnified view of the largest FeBO_3 peak to highlight peak location overlap between the three possible phases. Vertical dashed lines are used to clarify the peaks belong to each phase.

Table 1. List of XRD peaks as well as their associated phases and planes for FeBO_3 powders synthesized via combustion, solid-state, and flux growth methods.

Sample	Phase	2θ (deg.)	Plane
Combustion	Fe_3BO_6	21.79	(101)
		24.18	(111)
		30.32	(121)
		33.46	(301)
		35.10	(311)
		35.74	(400)
		36.33	(230)
		38.58	(131)
		39.73	(321)
		41.22	(401)
		41.70	(231) and (420)
		54.48	(521)
		54.98	(402) and (341)
		55.40	(232)
Solid-State	Fe_3BO_6	30.26	(121)
		24.10	(111)
		33.37	(301)
		35.06	(311)
		55.35	(232)
	$\alpha\text{-Fe}_2\text{O}_3$	24.10	(012)
		33.13	(104)
		35.59	(110)
		40.79	(113)
		49.42	(024)
		54.03	(116)
	FeBO_3	25.35	(012)
		33.28	(104)
		38.87	(110)
		43.31	(113)
		46.99	(202)
		52.10	(024)
		54.89	(116)
		55.63	(108)
		55.76	(018)

Table 1. Cont.

Sample	Phase	2 θ (deg.)	Plane
Flux Growth	FeBO ₃	25.39	(102)
		33.28	(104)
		33.36	(104)
		38.90	(110)
		43.29	(113)
		47.21	(202)
		52.22	(024)
		54.95	(116)
		55.12	(116)
		55.58	(108)
		55.72	(018)

Lattice parameters and particle sizes determined via Rietveld refinement for each phase are displayed in Table 2. The measured lattice parameters for FeBO₃ are close to single-crystal values [17,43,44] and are in good agreement with other bulk synthesis studies [11,26,27]. Fe₃BO₆ [45–47] and α -Fe₂O₃ [48,49] peaks are also in good agreement with the literature. Additionally, Table 2 lists the strain for each phase and the strain for the flux-grown powder after washing to remove excess B₂O₃. We observe a significant reduction in strain after removing B₂O₃ from the FeBO₃ crystallites.

Table 2. XRD Rietveld refinement results.

Sample	Phase	Composition (%)	<i>a</i> [Å]	<i>b</i> [Å]	<i>c</i> [Å]	<i>V</i> [Å ³]	Particle Size [nm]	Strain Pre-Wash (%)	Strain Post-Wash (%)
Combustion	Fe ₃ BO ₆	100	10.043	8.5314	4.4638	382.5	176	0.02	-
Solid-State	Fe ₃ BO ₆	12.7	10.046	8.5268	4.4661	382.6	466	0.08	-
	α -Fe ₂ O ₃	18.1	5.0388	5.0388	13.756	302.4	1079	0.10	-
	FeBO ₃	69.2	4.6272	4.6272	14.491	268.7	1163	0.06	-
Flux Growth	FeBO ₃	100	4.6276	4.6276	14.502	268.9	152	0.07	0.015

Figure 3 shows representative Raman spectra of the products from each synthesis route. The combustion sample exhibits 11 of the 60 active phonon peaks predicted at room temperature for the *Pnma* space group of Fe₃BO₆. A_g modes are represented by peaks at 208 cm⁻¹, 319 cm⁻¹, 503 cm⁻¹, 612 cm⁻¹, 717 cm⁻¹, 820 cm⁻¹, and 986 cm⁻¹, the B_{1g} at 385 cm⁻¹, and the B_{2g} peaks are observed at 446 cm⁻¹ and 889 cm⁻¹ [50,51]. Additionally, there is one peak observed at 1205 cm⁻¹, which belongs to the FeBO₃ system. FeBO₃ has five Raman-active modes predicted from the *R3c* space group, A_{1g} + 4E_g. The solid-state sample exhibits all five of the Raman-active modes for FeBO₃. These modes are observed at 277 cm⁻¹, 393 cm⁻¹, 640 cm⁻¹, 1211 cm⁻¹, and 927 cm⁻¹, which correspond to the two lattice modes, the in-plane and asymmetric breathing modes of the BO₃³⁻ ion, and the A_{1g} symmetric breathing mode, respectively [52–54]. In addition to the FeBO₃ peaks, the solid-state sample also exhibits six additional peaks characteristic of the hematite structure of α -Fe₂O₃, which also belongs to the *R3c* space group. These peaks belong to the A_{1g} modes at 230 cm⁻¹ and 502 cm⁻¹, as well as the E_g modes at 251 cm⁻¹, 296 cm⁻¹, 413 cm⁻¹, and 612 cm⁻¹ [55–57]. The flux-grown sample exhibits only the five Raman modes for FeBO₃, which supports the phase purity results indicated by the XRD data in Figure 2.

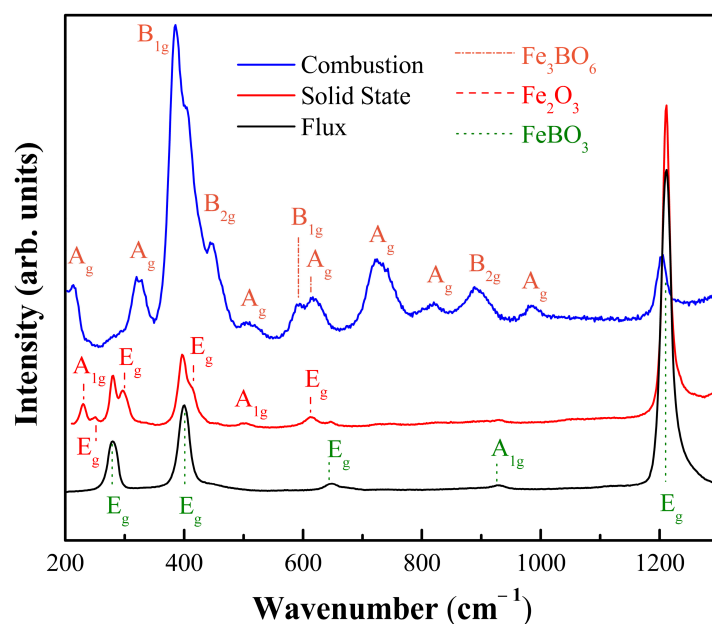


Figure 3. Raman spectra of FeBO_3 samples grown via combustion, solid-state, and flux growth methods.

As the XRD and Raman data indicate that the flux growth method produces phase-pure FeBO_3 , the sample was further investigated for its structural and microstructural properties, as shown in Figures 4 and 5. Figure 4a shows the surface of the flux-grown FeBO_3 sample after annealing but before washing. Hexagonal plate-like FeBO_3 crystals can be seen in Figure 4a embedded in a solid B_2O_3 flux. The plate-like crystals range in size from 10 to 50 μm in width and 1 to 5 μm thick, though a few plates up to 10 μm thick were observed. The inset of the Figure 4a shows an EDS map of iron (Fe) in the same area, which reveals the FeBO_3 crystals more completely due to the increased penetration depth of EDS compared to SEM. We do not report quantitative elemental analysis from EDS, as boron is present in both FeBO_3 and B_2O_3 , and the low-energy X-rays emitted by light elements such as boron suffer from sample/detector absorption, leading to inaccurate compositions. After washing away the excess flux, a mixture of crystal patterns is observed: plate-like, hexagonal prismatic, rhombohedral, and octagonal, as revealed in Figure 4b–d. These forms are quite similar to those observed in FeBO_3 grown from the gas phase by Diehl et al. [58]. These patterns are generally close to either 10 μm or 1 μm in size. It is common for crystals to be intergrown, such as in Figure 4c or the stacked plates shown in Figure 4d. Figure 5 displays the TEM images and electron diffraction patterns of representative crystals synthesized using the flux growth method. The diffraction patterns match with the simulated patterns along the [001] and $[\bar{1}\bar{2}1]$ zone axis, with filled dots denoting allowed reflections and crosses representing forbidden reflections. The close match between demonstrates a high degree of crystallinity in the material.

Figure 6 displays the optical absorption spectrum of the flux-grown FeBO_3 sample, measured in the wavelength range of 200 to 800 nm. A pronounced absorption onset is observed near 445 nm, marking the fundamental absorption edge and corresponding to electronic transitions between the filled valence band and 3d energy levels of the Fe^{3+} ions [11]. There is a broad absorption minimum centered around 529 nm, which gives rise to the characteristic vibrant green color of FeBO_3 [11], along with a second, weaker minimum ~ 730 nm in the far-red region. In contrast, many Fe-O compounds such as spinels, garnets, and orthoferrites display strong absorption in the visible region, resulting in dark red or brown coloration. Similarly, FeBO_3 containing significant impurities typically exhibits brown coloration accompanied by the suppression of the 529 nm absorption minimum [11]. The two distinct absorption features ~ 445 nm and ~ 400 nm are assigned to the

${}^6A_{1g}({}^6S) \rightarrow {}^4A_{1g}({}^4G)$ and ${}^6A_{1g}({}^6S) \rightarrow {}^4E_{1g}({}^4G)$ electronic transitions of Fe^{3+} , respectively [2,59–62]. Additional spectral features, including a step-like increase at ~ 361 nm and a broad peak at 274 nm, are not definitively assigned but may arise from phonon- or magnon-assisted sidebands of ${}^4A_{1g}$ and ${}^4E_{1g}$ excited states. Compared to single-crystal $FeBO_3$ [2,11,13,59–63] where the 445 nm ${}^6A_{1g}({}^6S) \rightarrow {}^4A_{1g}({}^4G)$ transition is well-resolved and well separated below 400 nm, the current flux-grown polycrystalline sample exhibits noticeable peak broadening, resulting in reduced spectral separation of these transitions. Similar broadening effects have been reported previously for polycrystalline $FeBO_3$ [64].

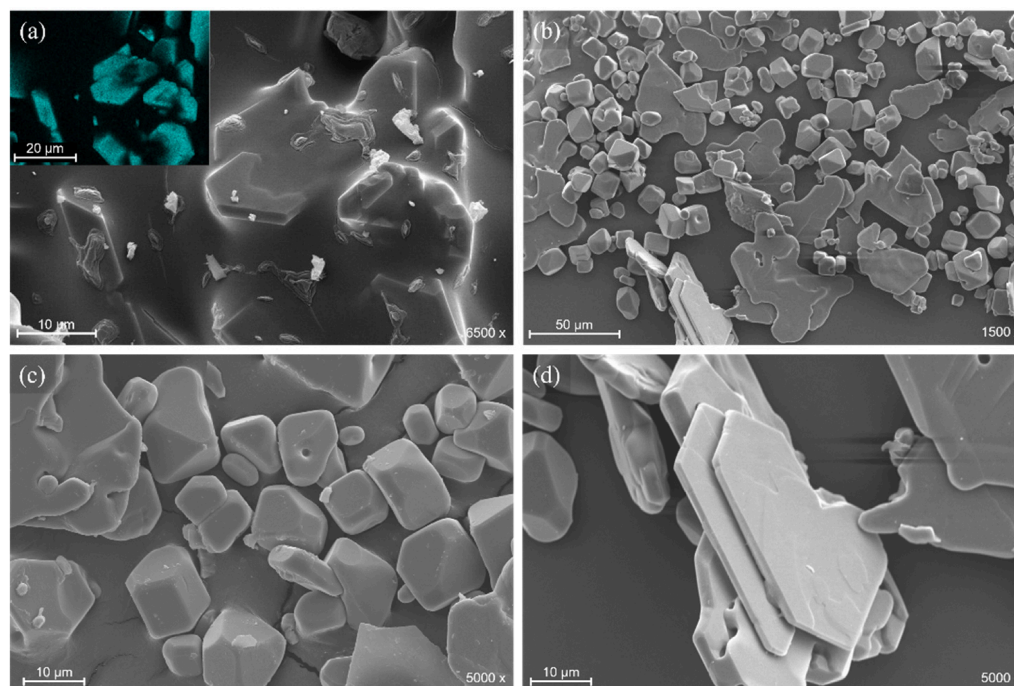


Figure 4. SEM images of $FeBO_3$ synthesized via flux growth. (a) Sample after annealing but before washing with (inset) EDS mapping of iron, showing hexagonal $FeBO_3$ crystals embedded in solid amorphous B_2O_3 flux. (b,c) Representative images of $FeBO_3$ crystallites after washing, which show a range of sizes and crystal habits. (d) Magnified view of crystallites in (b) highlighting plate stacking.

The optical absorption edge can be used to calculate the band energy gap (E_g) via Tauc's equation [65,66]

$$\alpha h\nu = A(h\nu - E_g)^n, \quad (1)$$

where α is the optical absorption coefficient, $h\nu$ is the energy of the incident photon, A is a proportionality constant (taken as 1 in this work), and $n = 1/2$ for direct allowed transitions. Figure 6b shows a plot of $(\alpha h\nu)^2$ as a function of $h\nu$. A linear extrapolation of the dominant absorption edge (red solid line) in Figure 6b yields $E_g = 2.47$ eV, which is much lower than the expected value for single-crystal $FeBO_3$ (2.9 eV). However, this underestimate arises from the overlap with the Fe^{3+} intraionic transitions. The true optical band gap is instead obtained by extrapolating from the baseline at the onset of the 400 nm absorption feature (dashed black horizontal line), which defines the intrinsic absorption edge of $FeBO_3$ [61,67], as illustrated in the inset of Figure 6b by the solid blue line. Using this approach, an optical band gap of $E_g = 2.94$ eV is obtained, which is in excellent agreement with the previously reported values for high-quality $FeBO_3$ single crystals [2,11,13,59–62].

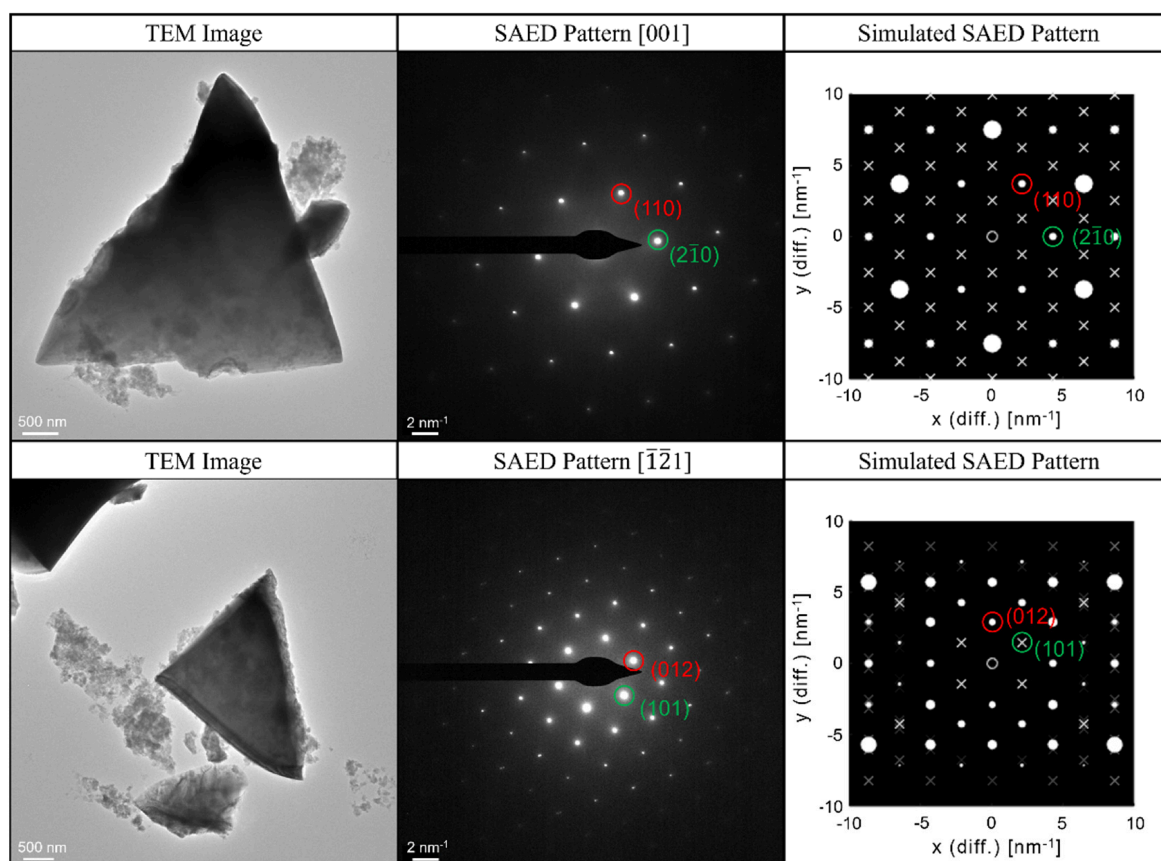


Figure 5. TEM images of two plate-like FeBO_3 crystals obtained via flux growth.

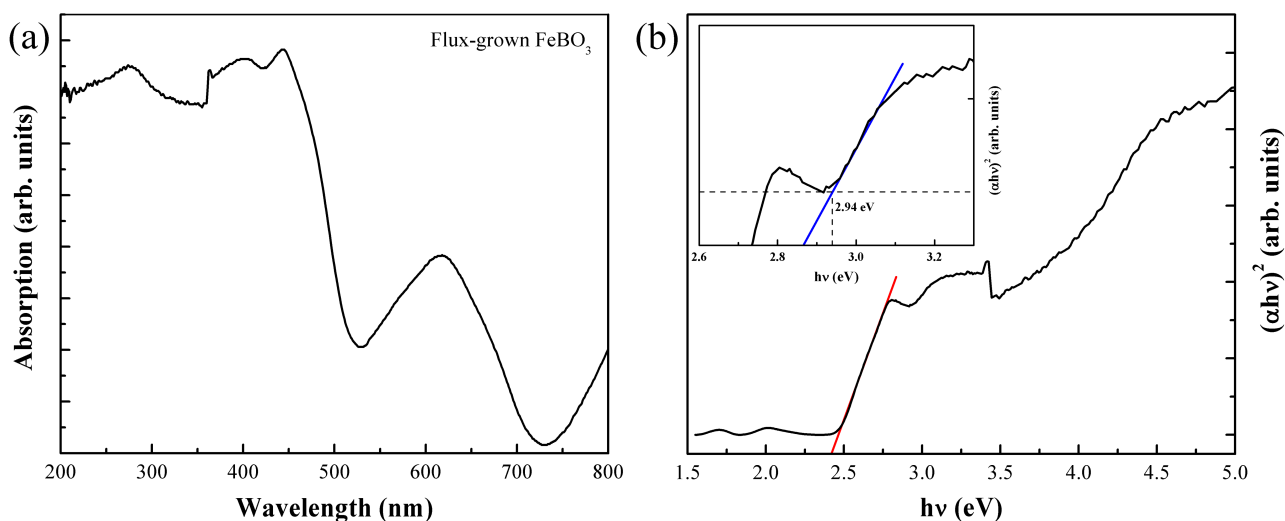


Figure 6. (a) Optical absorption of FeBO_3 synthesized via flux growth. (b) Tauc plot (Equation (2)) with fitting to determine the band gap (E_g) extrapolated from the dominant absorption edge (solid red line), compared to the (inset) intrinsic absorption edge (solid blue line).

One of the most important parameters characterizing magnetic losses in ferromagnetic and ferrimagnetic materials is the ferromagnetic linewidth, ΔH , which is related to the well-known ferromagnetic resonance (FMR) phenomenon. In the present work, FMR measurements were performed on the flux-grown FeBO_3 sample over a frequency range of 5–30 GHz. Since the sample was polycrystalline and multi-orientated, we neglected the field orientation dependence. The field-dependent resonance signals measured at selected frequencies are presented in Figure 7a. The resonance spectra present as Lorentzian deriva-

tives (dP/dH) due to the experimental geometry (as described in the Experimental section). The curves at each frequency were fitted using a Lorentzian line shape [68] with a representative fit shown in Figure 7b. From these fits, the resonance field (H_{Res}) and linewidth (ΔH) values were extracted and are summarized in Figures 7c and 7d, respectively.

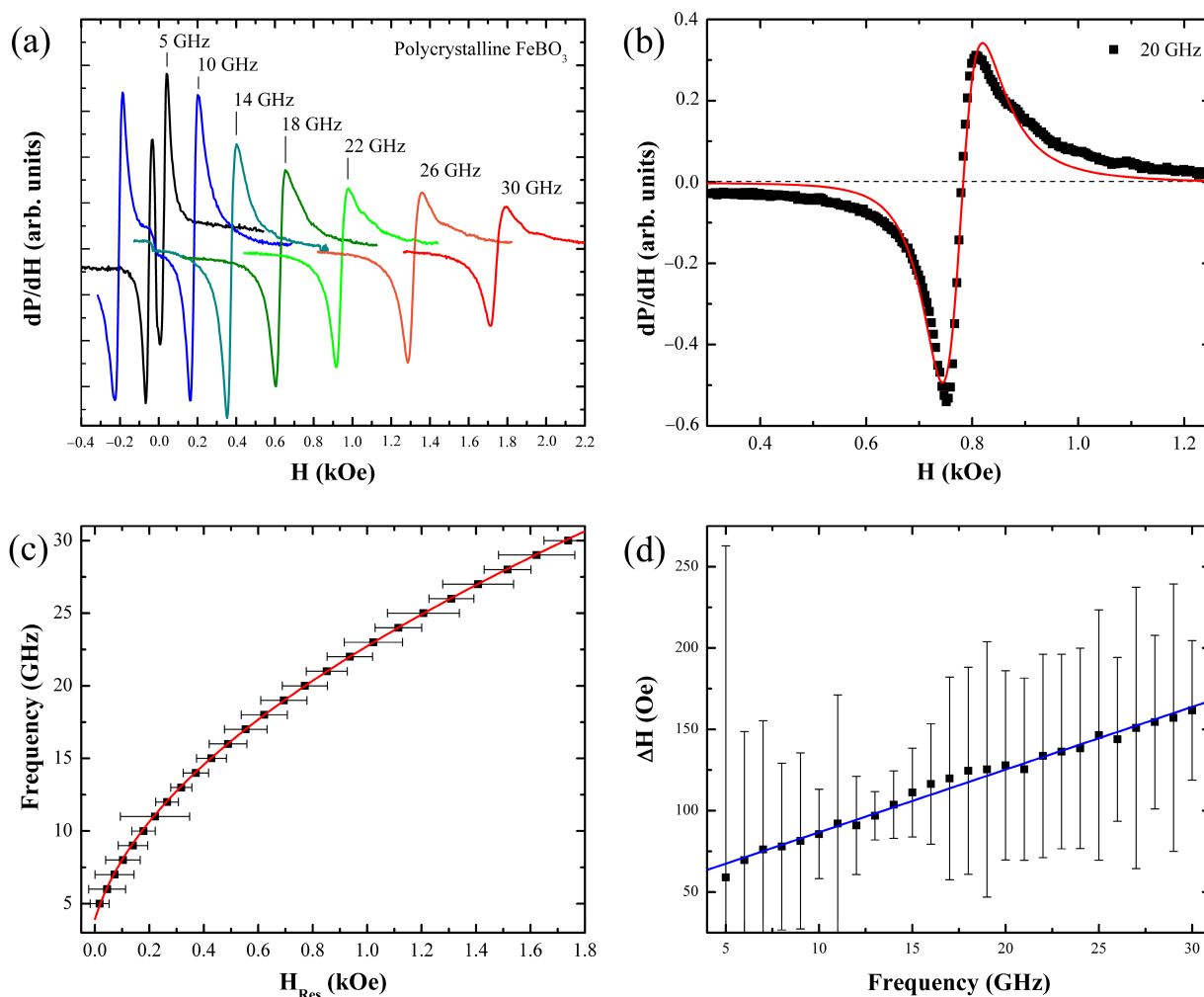


Figure 7. (a) Resonance spectrum derivative (dP/dH) of flux-grown polycrystalline FeBO_3 at various frequencies. (b) Example Lorentzian fit (solid red line) used to determine (c) Resonance frequency as a function of resonance field (H_{Res}); the solid red curve represents a fit to the low-frequency AFMR mode described by Equation (2), incorporating the Dzyaloshinskii–Moriya field, magnetic anisotropy, and susceptibility anisotropy, and (d) Frequency dependence of the FMR linewidth (ΔH) values, along with the solid blue line representing a fit to Gilbert damping equation (Equation (3)).

While we did not perform field angle-dependence measurements, the rhombohedral crystal structure and magnetization of FeBO_3 typically exhibit a low-frequency resonant mode (GHz) when the field is applied along the basal plane ($H \parallel ab$). We therefore assumed that this low-frequency antiferromagnetic resonance (AFMR) mode was the predominant mode present and fitted the mode according to equation:

$$\omega = \gamma \left[H_{Res}(H_{Res} + H_D) \frac{\chi_{\perp}}{\chi_{\parallel}} + H_{\Delta}^2 \right]^{\frac{1}{2}} \quad (2)$$

where γ is the gyromagnetic ratio, H_D is the Dzyaloshinskii–Moriya (DM) field associated with spin-canting, H_{Δ}^2 is the isotropic energy gap, and $\chi_{\perp}/\chi_{\parallel}$ is the ratio of transverse to longitudinal magnetic susceptibilities [69]. Note that this expression ex-

plicitly incorporates anisotropy and therefore differs from the standard Kittel formula, $\omega = \frac{\gamma}{2\pi} \sqrt{(H_{\text{Res}})(H_{\text{Res}} + M_{\text{sat}})}$, which applies to an isotropic ferromagnetic thin film measured in-plane. Using the free-electron gyromagnetic ratio ($\gamma = 2$) [16,69–71], Equation (2) was fitted to the experimentally determined H_{Res} values shown in Figure 7c, yielding $H_D = 32$ kOe, $H_{\Delta}^2 = 0.05$ kOe², and $\chi_{\perp}/\chi_{\parallel} = 0.05$.

The extracted DM field is approximately half of the ~60 kOe reported for single-crystal FeBO₃ [69,72] and films [71,73] at 300 K. This reduction is consistent with the observed decrease in H_D for impure FeBO₃ crystals with brown coloration, which have been attributed to the presence of Fe²⁺ and Fe⁴⁺ ions [69] as well as other defects such as oxygen vacancies common to oxide materials and grain boundaries [74,75]. Although the XRD and Raman measurements (Figures 2 and 3) do not suggest any evidence of a secondary phase in the flux-grown sample, local defects are generally more prevalent in polycrystalline powders than in single crystals, which likely accounts for the reduced DM field. The isotropic energy gap H_{Δ}^2 is reduced by an order of magnitude compared to single crystals [69,72] and by two orders-of-magnitude compared to thin films [71,73]. While significant, order-of-magnitude changes in H_{Δ}^2 have been observed (and can be expected) for FeBO₃ owing to its large magnetoelastic coupling, making the AFMR spectrum highly sensitive to lattice distortions and strain [73,76].

In single-crystal measurements with $H \parallel ab$, the susceptibility ratio $\chi_{\perp}/\chi_{\parallel}$ is often neglected [73] due to extremely small basal plane anisotropy in FeBO₃ (<1 Oe) [11,16], which results in $\chi_{\perp}/\chi_{\parallel} \approx 1$. However, the inclusion of this term is required for polycrystalline powder samples to account for the distribution of all crystallographic orientations. The fitted value of $\chi_{\perp}/\chi_{\parallel} = 0.05$ is much larger than the hard-axis susceptibility calculated by Ovchinnikov et al. [77], but smaller than the value of ~0.5 reported for single-crystal FeBO₃ [5,7] magnetized along the c axis. It is noted that in the present case, $\chi_{\perp}/\chi_{\parallel}$ is an orientation-averaged parameter rather than a comparison between specific crystallographic axes and likely contain contributions from a combination of intrinsic magnetic anisotropy, particle morphology, and packing effects of the plate-like crystallites [11,27].

The linewidth values ΔH shown in Figure 7d are in good agreement with previous reports on single crystal FeBO₃ [16,69,70,72]. As described in [16], even small concentrations of impurities or defects can increase ΔH values by several orders of magnitude, including in crystals that appear visually uniform (in this case completely green in color). The modest increase in ΔH observed here (approximately a factor of three relative to single crystals) is attributed to the polycrystalline nature of the sample and indicates that the material remains relatively defect-free for bulk powder. Furthermore, the absence of any additional features in the dP/dH spectra also supports phase purity [71], consistent with the structural characterization presented in Figures 2–5.

The frequency dependence of the linewidth follows:

$$\Delta H = \Delta H_0 + \frac{4\pi\alpha f}{\gamma}, \quad (3)$$

where ΔH_0 represents extrinsic line broadening and α is the Gilbert damping parameter [72,78–80]. Fitting the experimental data as shown in Figure 7d with this equation yields values of $\alpha = 5.4 \times 10^{-3}$ and $\Delta H_0 = 48$ Oe, which are in good agreement with those reported for single-crystal FeBO₃ results [72], confirming that the intrinsic spin-damping mechanisms are largely preserved despite the polycrystalline nature of the sample. This retention of the damping mechanism indicates that polycrystalline FeBO₃ shares suitability for high-frequency applications with single crystal FeBO₃ [76].

Figure 8a–c displays the temperature-dependent dc magnetic susceptibility for all three synthesized powders, measured in ZFC and FC modes with an applied field of 2 kOe. All three samples show a transition upon heating past $T_N = 347$ K, which is of

ferromagnetic/paramagnetic character. This is typical for FeBO_3 [11,27], as the canted anti-ferromagnetic structure results in a weak ferromagnetism that dominates the temperature behavior of the system. The expected maximum possible mass magnetization of the FeBO_3 material is the spin-only magnetic moment of 4.526 emu g^{-1} , or $0.002263 \text{ emu g}^{-1} \text{ Oe}^{-1}$ at the applied field of 2 kOe in this work. Note that this value is adjusted from the full Fe^{3+} spin-only moment of $5.92 \mu\text{B} = 290 \text{ emu g}^{-1}$ in order to account for the $\sim 0.9^\circ$ canting of Fe^{3+} spins in the magnetic structure of FeBO_3 [81]. As FeBO_3 preferentially grows in flat plates, the particles of any packed powder sample will also exhibit a preferred orientation, which can be corrected for using

$$M_P = \left(\frac{\pi}{4}\right) M_{SC}, \quad (4)$$

where M_P is the magnetization of the powder and M_{SC} is the magnetization of a single crystal sample [11]. This yields a maximum predicted susceptibility of $0.00178 \text{ emu g}^{-1} \text{ Oe}^{-1}$.

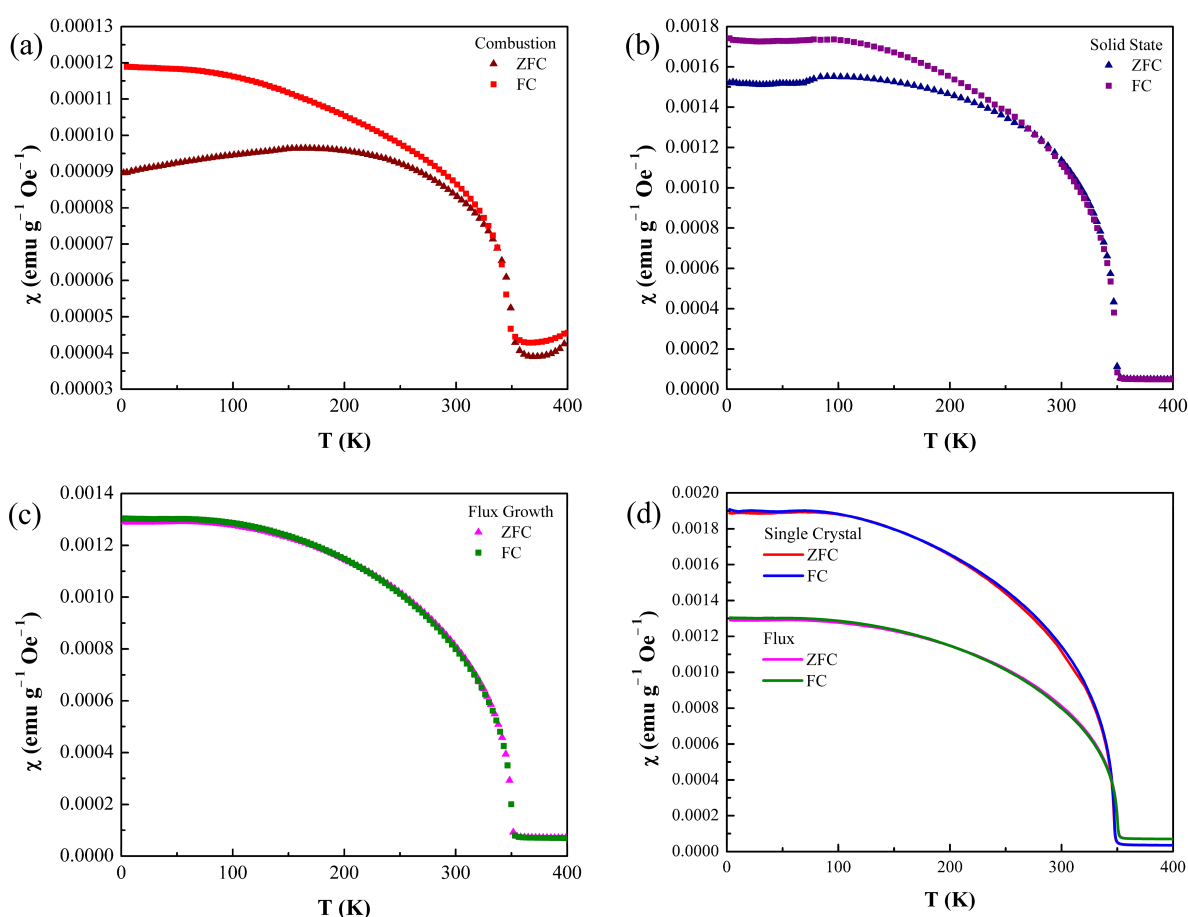


Figure 8. Temperature-dependent susceptibility of (a) combustion, (b) solid-state, (c) flux grown FeBO_3 , all measured in ZFC and FC modes with an applied field of 2 kOe. (d) Comparison of flux-grown FeBO_3 and single crystal FeBO_3 measured in the ab plane.

As seen in Figure 8a, the combustion sample exhibits a much smaller maximum susceptibility of $0.000119 \text{ emu g}^{-1} \text{ Oe}^{-1}$ (for the ZFC mode) at 2 K than the predicted value. While this susceptibility is notably different from what has been reported for polycrystalline Fe_3BO_6 [82,83] at 1 kOe, converting to a mass magnetization of 0.238 emu g^{-1} reveals a very similar value to both reports, which may indicate that the system is near its maximum magnetization by 1 kOe. The relatively temperature-independent value of susceptibility up to approximately 350 K, which is especially visible in the ZFC data, is in agreement with both powder and single-crystal Fe_3BO_6 reports [83–86]. The combustion sample also displays

significant splitting between ZFC and FC susceptibilities for $T < 320$ K. Additionally, above 348 K (T_N for FeBO_3), the susceptibility increases with temperature, which would be highly unusual if the sample was in a purely paramagnetic state. The small susceptibility values at low temperatures, and the increase in susceptibility above 348 K, are both accounted for by the major presence of the Fe_3BO_6 phase in the combustion sample [82]. From the XRD and Raman results discussed above, this sample consists entirely of the Fe_3BO_6 phase, which exhibits a T_N of 508 K as well as a spin reorientation at ~ 415 K [86,87]. Thus, it is believed that the combustion sample is not in a purely paramagnetic state by 400 K (the maximum temperature up to which data were measured in this work).

The solid-state sample exhibits a maximum susceptibility of $0.001738 \text{ emu g}^{-1} \text{ Oe}^{-1}$ at 2 K, as shown in Figure 8b, which is close to the predicted value for pure FeBO_3 . The ZFC data also displays a broad increase from 68 K to 87 K that is not present in the FC data. This could be due to the presence of an $\alpha\text{-Fe}_2\text{O}_3$ impurity, for which the blocking temperature (T_B) is reported to change with the particle size below 50 nm. However, the estimated particle size of the $\alpha\text{-Fe}_2\text{O}_3$ phase in the present solid-state sample is quite large, as shown previously in Table 2. The increased value of the magnetic susceptibility in the solid-state sample could also be due to the presence of $\alpha\text{-Fe}_2\text{O}_3$ impurity [3,4]. While the expected maximum magnetic moment for $\alpha\text{-Fe}_2\text{O}_3$ with 0.065° canting angle [88] is only 0.658 emu g^{-1} , $\alpha\text{-Fe}_2\text{O}_3$ can exhibit a much larger magnetic susceptibility depending on its particle morphology [89–93]. It should be noted that the solid-state sample displays significant ZFC/FC splitting ($\sim 12.5\%$ at 2 K). This splitting reverses at ~ 270 K, which is close to the $\alpha\text{-Fe}_2\text{O}_3$ Morin transition at 260 K [94–96].

The flux-grown sample, consisting of pure FeBO_3 , displays the expected $T_N = 348$ K in Figure 8c, and exhibits a maximum susceptibility of $0.0013 \text{ emu g}^{-1} \text{ Oe}^{-1}$ at 2 K, which is slightly smaller than the predicted FeBO_3 value. The flux-grown FeBO_3 displays negligible ZFC/FC splitting at all temperatures. The lack of ZFC/FC splitting in the susceptibility indicates that the system is highly reversible and should correlate with small magnetic field coercivity (H_C) values at all temperatures, which have been observed for single crystals [7], powder samples of green color [27], and the flux-grown sample in this work. It should be noted that some recent studies do show splitting below 80 K [5,28] which was attributed to sample contamination, and particle size effects of those contaminants [25]. FeBO_3 particle size effects, such as enhanced susceptibility and irreversibility as a result of particle sizes under 200 nm [25], are not observed in the present flux-grown sample. The susceptibility does not reach zero for $T < T_N$, which indicates that the system does contain paramagnetic impurities. For a direct comparison, Figure 8d shows the flux-grown susceptibility alongside that of single-crystal FeBO_3 , measured in the ab plane.

Figure 9 shows the magnetic hysteresis loops of the synthesized FeBO_3 , measured at several temperatures. The corresponding temperature-dependent coercive field (H_C) and remanent magnetization (M_R) values for the synthesized powders are depicted in Figure 10. The combustion sample exhibits wide and non-saturating hysteresis loops with M_R and H_C values of 0.17 emu g^{-1} and 1300 Oe at 2 K, respectively, which are in agreement with typical values for Fe_3BO_6 [35,81,85]. In addition, the loops are shifted vertically by $\sim 0.20 \text{ emu g}^{-1}$, which implies that some moments in the system are pinned and do not rotate when the applied magnetic field is changed. The results in this work are in close agreement with the observations by Kumari et al. [35] that excess B_2O_3 bonded to the Fe_3BO_6 crystallites can significantly affect the surface magnetism and thus the hysteresis properties of the Fe_3BO_6 powder. As combustion reactions often form high-surface-area particles, and the XRD results in Table 2 indicate particle sizes similar to those reported by Kumari et al. [35], we attribute the observed vertical magnetization shift to uncompensated surface spins present in small Fe_3BO_6 particles in the present sample. It should be noted that we do

not attribute the shift to exchange coupling between antiferromagnetic and ferromagnetic materials at their interface [97–99], as is often the case, as there is no evidence of other phases present in the sample. The dramatic change in the hysteresis loop and the increase in H_C and M_R values at 400 K are due to the abrupt spin reorientation in Fe_3BO_6 that occurs at ~ 415 K. This spin reorientation temperature in the present case could have shifted to lower temperature due to the applied field and particle size effects [86,87].

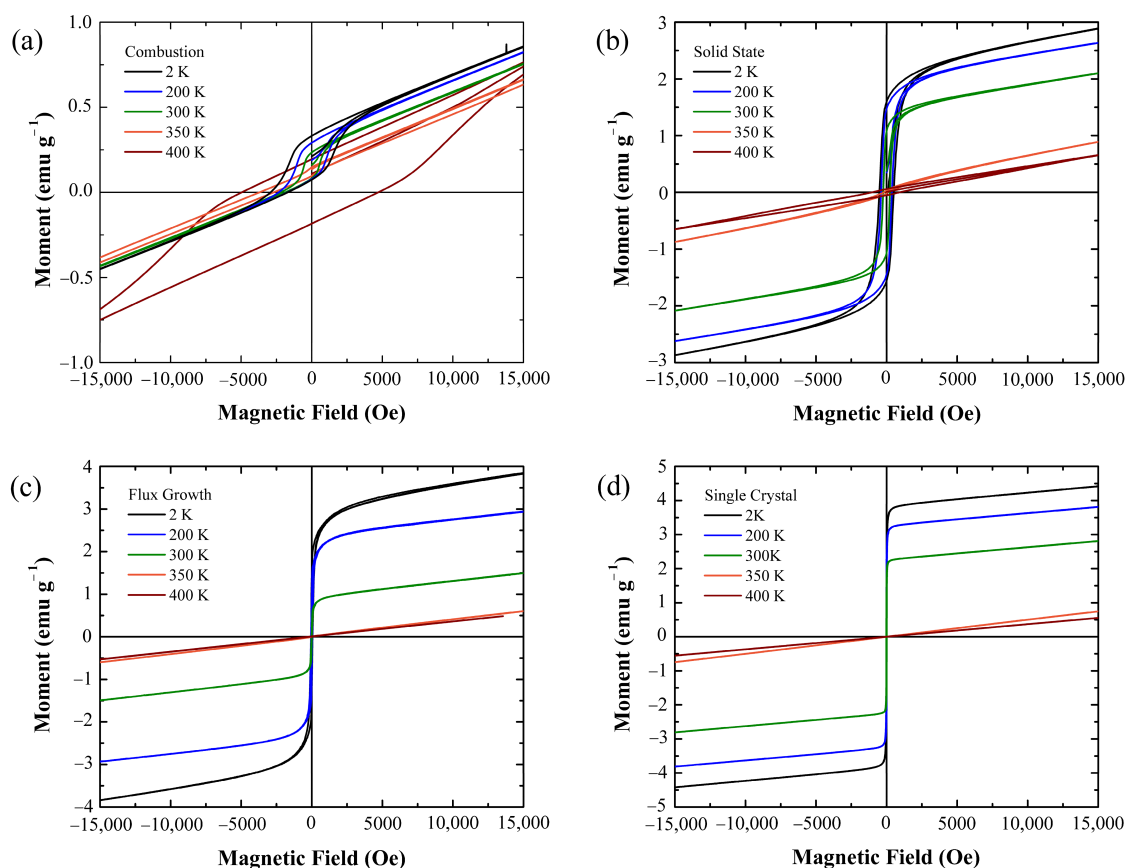


Figure 9. Magnetic hysteresis loops measured at select temperatures of (a) combustion, (b) solid-state, (c) flux grown, and (d) single crystal FeBO_3 .

The magnetic hysteresis loops of the solid-state sample, shown in Figure 9b, exhibit linear behavior typical of an antiferromagnet, in combination with a small ferromagnetic hysteresis component. In the present solid-state sample, the H_C values of ~ 500 Oe shown in Figure 10b are significantly larger than what is typically observed in FeBO_3 [77,100,101] and are therefore attributed to the presence of $\alpha\text{-Fe}_2\text{O}_3$ [101,102] and Fe_3BO_6 [35,81,85]. As discussed earlier for Figure 8c, the FeBO_3 particle size may also play a role in the enhanced H_C values [25], but particle size effects are likely minor as there is no major enhancement of the total susceptibility in Figure 8c. Therefore, the enhanced H_C is attributed to the presence of the $\alpha\text{-Fe}_2\text{O}_3$ and Fe_3BO_6 impurity phases. As with the combustion sample, the solid-state sample exhibits a large jump in H_C between 350 K and 400 K, which is attributed to the spin reorientation in Fe_3BO_6 [76,77] as discussed above. While not visually apparent in Figure 10b, the solid-state sample does also exhibit a corresponding increase in M_R , from 0.034 emu g^{-1} to $0.0583 \text{ emu g}^{-1}$, which is a similar percentage increase to that observed in the combustion sample.

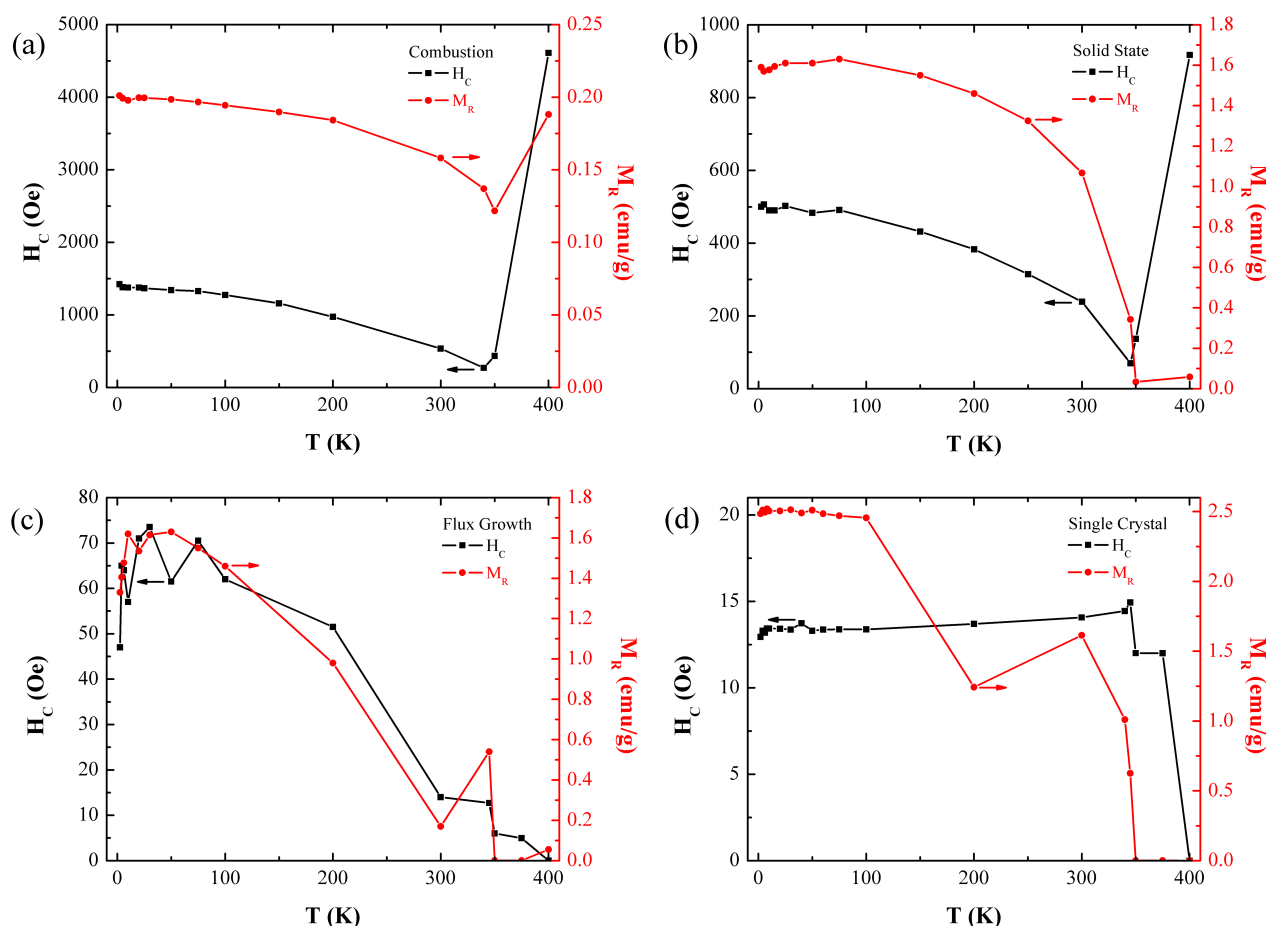


Figure 10. Temperature-dependent values of coercive field (H_C , black) and remnant magnetization (M_R , red) extracted from the magnetic hysteresis data for (a) combustion, (b) solid-state, (c) flux grown, and (d) single crystal FeBO_3 .

Hysteresis loops for the phase-pure FeBO_3 sample synthesized via flux growth are shown in Figure 9c. These exhibit similar behavior to that of the solid-state sample, with linear loops and small ferromagnetic hysteresis at low fields. The H_C values of ~60 Oe exhibited by the sample, as seen in Figure 10c, are larger than what has been observed for FeBO_3 single crystals [7,100] but well within the range for powders [25–28]. It is noted that the values are much larger than the in-plane anisotropy field for FeBO_3 (<1 Oe), and much smaller than the out-of-plane anisotropy field (~11 T at $T = 2$ K) [16,103,104]. M_R values for FeBO_3 are sparse in the literature, but low-temperature values of approximately 1.6 emu g^{-1} are close to those of single-crystal FeBO_3 in Figure 10d, as well as in agreement with FeBO_3 powder [26] and single crystal [77] reports. The lack of exchange bias (horizontal shift) or pinning (vertical shift), the small H_C values, and the lack of ZFC/FC splitting discussed previously, all support the conclusion that magnetic spins and domains within the present flux-grown FeBO_3 powder are highly reversible, with little magnetic energy loss, which will be of advantage for applications such as magneto-optical sensors, optical isolators or modulators, magneto-optical imaging [105,106], and even as an anode material in batteries [107].

From the above discussion, the flux growth synthesis method is shown to be facile, cost-effective, and practical method of producing the phase-pure green FeBO_3 powder required for future efforts towards developing FeBO_3 as a magneto-optical material viable for devices. The magnetic behavior of the flux-grown material is similar to that of single-crystal FeBO_3 , which is a promising indication that the desired magnetic properties of single-crystal FeBO_3 are retained in bulk polycrystalline form. Additionally, clear

differences in maximum susceptibility ZFC/FC splitting, H_C , and M_R provide a comparative analysis tool for identifying the quality of FeBO_3 synthesis products through bulk susceptibility measurements.

3. Experimental Section

In this work, we utilized three solution methods to synthesize bulk polycrystalline FeBO_3 : citrate gel-combustion, solid-state reaction, and flux growth routes. These routes were chosen to offer insights into recently reported growth methods, such as citrate gel-combustion [36,81,107], as well as more established methods such as solid-state and flux growth. Single-crystal FeBO_3 was grown as described elsewhere [5,7].

3.1. Citrate Gel Combustion Method

Iron(III) nitrate hydrate ($\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, Thermo Scientific, Waltham, MA, USA, metal basis 98+% purity), boric acid (H_3BO_3 , Alfa Aesar, Ward Hill, MA, USA, metal basis, 99.99% purity), and citric acid monohydrate ($\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}$, Alfa Aesar, 99.5+% purity) were dissolved in H_2O in a 1:1:1 M ratio to form a 0.4 M solution. The solution was evaporated on a 130 °C hotplate under constant stirring. Once fully dry, the powder was heated to 300 °C for combustion. This powder was then annealed at 700 °C for 2 h in a tube furnace, resulting in an orange powder, as shown in Figure 1a.

3.2. Solid-State Method

Iron (III) oxide ($\alpha\text{-Fe}_2\text{O}_3$, Sigma Aldrich, St. Louis, MO, USA, 96%+ purity) and boric acid were milled together in a 1:2 molar ratio in a mortar and pestle until visually homogeneous. The powder was then annealed in air at 670 °C for up to 100 h in a tube furnace. The resulting powder was orangish-red in color, as seen in Figure 1b and easy to grind using a mortar and pestle.

3.3. Flux Growth Method

Iron nitrate, boric acid, and lithium nitrate hydrate ($\text{Li}(\text{NO}_3) \cdot 3\text{H}_2\text{O}$, Alfa Aesar, metal basis, 99.999% purity), in a molar ratio of 1:5:1/25, were each individually dissolved in an excess of H_2O . Incorporating group 1 or 2 metal ions into the flux is a well-established technique for reducing the flux viscosity, which results in increased reaction speed and crystal growth rates [27,37]. The solutions were then combined, stirred well to homogenize, and dried at 90 °C on a hotplate with regular stirring. The resulting powder was then ground in a mortar and pestle before being suspended in an excess of acetone. The acetone slurry was then dried at 75 °C on a hotplate with regular stirring. Once completely dry, the loose powder was annealed in air at 500 °C for 12 h, followed by 810 °C for (at least) 48 h, with a 2 °C/min temperature ramp rate. Pressing the powder into a pellet before annealing is unnecessary but does not impede the reaction. Immediately after annealing, the powder was air-quenched from 810 °C to room temperature. The resulting powder was primarily green, with a small amount of red-orange discoloration where the powder was in contact with the crucible, which is indicative of Fe_3BO_6 or Fe_2O_3 impurity. This discoloration was most pronounced in small batches of material, as shown in Figure 1c. An entirely green powder, seen in Figure 1d, was achieved by increasing the batch size to at least 15 g of pre-anneal material, which was very well homogenized. This was probably due to the presence of enough flux to conglomerate the entire growth into a single mass, thus promoting ion diffusion and discouraging the decomposition of FeBO_3 into Fe_3BO_6 on exposed areas.

3.4. Material Characterization

Structural analysis of the synthesized powders was performed using X-ray powder diffractometry (XRD) on a D2 Phaser (Bruker, Billerica, MA, USA) with a Cu K α source ($\lambda = 1.54 \text{ \AA}$), and Rietveld refinement was carried out using the FullProf software suite (version 5.20) [108]. Raman spectra were collected at room temperature with a Ramascope System 2000 (Renishaw, Wotton-under-Edge, UK) with a 514 nm laser. Laser exposure time was limited to 30 s at 50% laser power to prevent decomposition of iron oxides [55]. Scanning electron microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) images were collected on a Verios 460L SEM (Thermo Fisher Scientific, Waltham, MA, USA) with an EDAX Octane Elect Plus detector (Gatan Inc., Pleasanton, CA, USA). The transmission electron microscopy (TEM) characterization was performed with a FEI Talos TEM (Thermo Fisher Scientific, Waltham, MA, USA) operated at 200 kV. Electron diffraction simulation was carried out using the CrysTBox software 1.0 [109]. Optical absorbance was measured using a UV-2450 UV-Vis spectrometer (Shimadzu, Kyoto, Japan) attached to a diffuse reflectance integrating sphere. A thin layer of FeBO₃ powder was compressed onto a puck of barium sulfate, which acted as a reflective reference. Ferromagnetic resonance measurements were acquired using a co-planar waveguide in a GMW dipolar electromagnet capable of applying magnetic fields up to 2 Tesla. Powders were placed above the waveguide, with the applied magnetic field aligned perpendicular to the in-plane RF field. The RF signal was supplied via a N5173B signal generator (Keysight Technologies, Santa Rose, CA, USA) and the power output at each frequency was 10 dBm, though we note that the losses from the cables and waveguide are not constant across the measured band. All measurements were performed in a modulated Helmholtz geometry with a modulation frequency of 1 kHz, and demodulated using a lock-in amplifier (SR860). Magnetic measurements were performed on the sample using a vibrating sample magnetometer (VSM) mounted to a DynaCool Physical Property Measurement System (PPMS, from Quantum Design Inc., San Diego, CA, USA). Temperature-dependent dc susceptibility measurements were performed in zero-field-cooled—warming (ZFC) and field-cooled—cooling (FC) modes with a 2000 Oe applied dc magnetic field. Field-dependent hysteresis measurements were performed with increasing temperature. The magnetic field was oscillated back to 0 Oe between each measurement to remove any trapped magnetic flux in the magnet or sample.

4. Conclusions

We have compared three chemical synthesis routes and successfully developed a facile strategy for the synthesis of phase-pure FeBO₃ powder. This reliable and scalable flux-growth method enables precise stoichiometric control in FeBO₃, avoiding Fe₃BO₆ or α -Fe₂O₃ impurities, and offers a significant advantage over combustion or conventional solid-state synthesis methods. We show that flux-grown FeBO₃ is phase-pure and of high structural quality, exhibits the correct optical band gap, and retains magnetic properties comparable to those of single-crystal FeBO₃, including a narrow antiferromagnetic resonance line, a Néel temperature of 348 K, a maximum magnetic susceptibility of $0.0013 \text{ emu g}^{-1} \text{ Oe}^{-1}$, a low-temperature coercive field of 60 Oe, and remanent magnetization of 1.6 emu g^{-1} . These properties highlight that in addition to single-crystal FeBO₃, polycrystalline FeBO₃ has strong potential for use in magneto-optical applications.

Author Contributions: Conceptualization, J.P., M.J.; methodology, J.P., S.J., V.O., N.R.J., S.L.S., M.N., M.J.; software, J.P., M.N.; validation, J.P., M.J.; formal analysis, J.P., S.J., V.O., M.N., M.J.; investigation, J.P., S.J., N.R.J., M.J.; resources, V.O., S.L.S., M.N., M.J.; data curation, J.P., S.J.; writing—original draft preparation, J.P., M.J.; writing—review and editing, J.P., S.J., V.O., N.R.J., S.L.S., M.N., M.J.;

visualization, J.P., S.J., M.J.; supervision, M.J.; project administration, M.J.; funding acquisition, M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Air Force Research Laboratory, Materials and Manufacturing Directorate (AFRL/RXMS), Contract No. FA8650-21-C5711 and the United States Air Force Office of Scientific Research grant number LRIR23RXCOR003, as well as the Asian Office of Aerospace Research and Ministry of Science and Technology (AOARD-MOST) grant number F4GGA21207H002. The research was also partially funded by NSF (ECCS-EAGER-2236879).

Data Availability Statement: The data that supports the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: Authors M.J. and V.O. thank the Air Force Research Laboratory for their support. The authors thank the Air Force Office of Scientific Research and the AOARD-MOST grant. Author M.J. also acknowledges the University of Connecticut's quantum seed funding from OVPR's office and National Science Foundation funding.

Distribution A. Approved for public release: distribution unlimited. (AFRL-202-0480) Date Approved 30 January 2026.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Bernal, I.; Struck, C.W.; White, J.G. New transition metal borates with the calcite structure. *Acta Crystallogr.* **1963**, *16*, 849–850. [\[CrossRef\]](#)
- Kurtzig, A.J.; Wolfe, R.; LeCraw, R.C.; Nielsen, J.W. Magneto-Optical Properties of a Green Room-Temperature Ferromagnet: FeBO₃. *Appl. Phys. Lett.* **1969**, *14*, 350–352. [\[CrossRef\]](#)
- Ovchinnikov, S.G.; Rudenko, V.V.; Kazak, N.V.; Edelman, I.S.; Gavrichkov, V.A. Weak Antiferromagnet Iron Borate FeBO₃. Classical Object for Magnetism and the State of the Art. *J. Exp. Theor. Phys.* **2020**, *131*, 177–188. [\[CrossRef\]](#)
- Thoma, H.; Hutanu, V.; Deng, H.; Dmitrienko, V.E.; Brown, P.J.; Gukasov, A.; Roth, G.; Angst, M. Revealing the Absolute Direction of the Dzyaloshinskii-Moriya Interaction in Prototypical Weak Ferromagnets by Polarized Neutrons. *Phys. Rev. X* **2021**, *11*, 011060. [\[CrossRef\]](#)
- Franklin, J.; Pfund, J.; Bedard, J.; Zhang, W.; Halasyamani, P.S.; Jain, M.; Sochnikov, I. Observation of c-axis magnetization at low temperatures in the weak ferromagnet FeBO₃ reveals a spin-reorientation transition. *Phys. Rev. B* **2023**, *107*, 214433. [\[CrossRef\]](#)
- Pernet, M.; Elmale, D.; Joubert, J.-C. Structure magnetique du metaborate de fer FeBO₃. *Solid State Commun.* **1970**, *8*, 1583–1587. [\[CrossRef\]](#)
- Pfund, J.; Jiang, S.; Zhang, W.; Halasyamani, P.S.; Susner, M.A.; Ortalan, V.; Seehra, M.S.; Jain, M. Magnetic anisotropy and frustration in FeBO₃. *Phys. Rev. B* **2025**, *112*, 014436. [\[CrossRef\]](#)
- Dzyaloshinsky, I. A thermodynamic theory of “weak” ferromagnetism of antiferromagnetics. *J. Phys. Chem. Solids* **1958**, *4*, 241–255. [\[CrossRef\]](#)
- Moriya, T. New Mechanism of Anisotropic Superexchange Interaction. *Phys. Rev. Lett.* **1960**, *4*, 228–230. [\[CrossRef\]](#)
- Moriya, T. Anisotropic Superexchange Interaction and Weak Ferromagnetism. *Phys. Rev.* **1960**, *120*, 91–98. [\[CrossRef\]](#)
- Wolfe, R.; Kurtzig, A.J.; LeCraw, R.C. Room-Temperature Ferromagnetic Materials Transparent in the Visible. *J. Appl. Phys.* **1970**, *41*, 1218–1224. [\[CrossRef\]](#)
- Zubov, V.E.; Kudakov, A.D.; Bulatov, D.A.; Strugatskii, M.B.; Yagupov, S.V. Faraday Effect in FeBO₃ Caused by the Magnetization Component Parallel to the C₃ Axis. *JETP Lett.* **2022**, *116*, 394–397. [\[CrossRef\]](#)
- Troyan, I.A.; Eremets, M.I.; Gavriluk, A.G.; Lyubutin, I.S.; Sarkisyan, V.A. Transport and optical properties of iron borate FeBO₃ under high pressures. *J. Exp. Theor. Phys. Lett.* **2003**, *78*, 13–16. [\[CrossRef\]](#)
- Krinchik, G.S.; Chetkin, M.V. Transparent Ferromagnets. *Sov. Phys. Uspekhi* **1969**, *12*, 307–319. [\[CrossRef\]](#)
- Dillon, J.F. Origin and Uses of the Faraday Rotation in Magnetic Crystals. *J. Appl. Phys.* **1968**, *39*, 922–929. [\[CrossRef\]](#)
- LeCraw, R.C.; Wolfe, R.; Nielsen, J.W. Ferromagnetic Resonance in FeBO₃, a Room-Temperature Ferromagnet. *Appl. Phys. Lett.* **1969**, *14*, 352–354. [\[CrossRef\]](#)
- Yagupov, S.V.; Snegirev, N.I.; Seleznyova, K.A.; Milyukova, E.T.; Mogilenec, Y.A.; Ermolaev, Y.V.; Strugatsky, M.B. Structural Transformations in Iron Borate under High-Temperature Annealing. *Tech. Phys.* **2019**, *64*, 1161–1163. [\[CrossRef\]](#)
- Snegirev, N.; Kulikov, A.; Lyubutin, I.S.; Yagupov, S.; Lyubutina, M.; Strugatsky, M. Magnetic Field Control of Structural Perfection and Diffraction Properties of FeBO₃ Single Crystals. *Cryst. Growth Des.* **2023**, *23*, 5883–5888. [\[CrossRef\]](#)

19. Yagupov, S.; Strugatsky, M.; Seleznyova, K.; Maksimova, E.; Nauhatsky, I.; Yagupov, V.; Milyukova, E.; Kliava, J. $\text{Fe}_x\text{Ga}_{1-x}\text{BO}_3$ single crystals: Synthesis and characterization. *Appl. Phys. A* **2015**, *121*, 179–185. [\[CrossRef\]](#)
20. Yagupov, S.; Strugatsky, M.; Seleznyova, K.; Mogilenec, Y.; Snegirev, N.; Marchenkov, N.V.; Kulikov, A.G.; Eliovich, Y.A.; Frolov, K.V.; Ogarkova, Y.L.; et al. Development of a Synthesis Technique and Characterization of High-Quality Iron Borate FeBO_3 Single Crystals for Applications in Synchrotron Technologies of a New Generation. *Cryst. Growth Des.* **2018**, *18*, 7435–7440. [\[CrossRef\]](#)
21. Ikesue, A.; Kinoshita, T.; Kamata, K.; Yoshida, K. Fabrication and Optical Properties of High-Performance Polycrystalline Nd:YAG Ceramics for Solid-State Lasers. *J. Am. Ceram. Soc.* **1995**, *78*, 1033–1040. [\[CrossRef\]](#)
22. Ikesue, A.; Aung, Y.L. Ceramic laser materials. *Nat. Photonics* **2008**, *2*, 721–727. [\[CrossRef\]](#)
23. Ikesue, A.; Aung, Y.L. Development of optical grade polycrystalline YIG ceramics for faraday rotator. *J. Am. Ceram. Soc.* **2018**, *101*, 5120–5126. [\[CrossRef\]](#)
24. Schober, J. Ferromagnetic resonance in polycrystalline FeBO_3 with crystallite orientation. *J. Magn. Magn. Mater.* **1977**, *6*, 147–150. [\[CrossRef\]](#)
25. Snegirev, N.I.; Lyubutin, I.S.; Yagupov, S.V.; Chuev, M.A.; Chumakov, N.K.; Zhigalina, O.M.; Khmelenin, D.N.; Strugatsky, M.B. Size Effects in Iron Borate FeBO_3 Nanoparticles. *Russ. J. Inorg. Chem.* **2021**, *66*, 1217–1222. [\[CrossRef\]](#)
26. Joubert, J.C.; Shirk, T.; White, W.B.; Roy, R. Stability, infrared spectrum and magnetic properties of FeBO_3 . *Mater. Res. Bull.* **1968**, *3*, 671–676. [\[CrossRef\]](#)
27. Muller, O.; O'Horo, M.P.; O'Neill, J.F. FeBO_3 Solid Solutions: Synthesis, Crystal Chemistry, and Magnetic Properties. *J. Solid State Chem.* **1978**, *23*, 115–128. [\[CrossRef\]](#)
28. Das, S.K.; Nandi, M.; Giri, S.; Bhaumik, A. A new mesoporous FeBO_3 material having dominant surface magnetism. *Microporous Mesoporous Mater.* **2009**, *117*, 362–367. [\[CrossRef\]](#)
29. Gao, S.; Liu, X.; Xu, T.; Ma, X.; Shen, Z.; Wu, A.; Zhu, Y.; Hosmane, N.S. Synthesis and Characterization of $\text{Fe}_{10}\text{BO}_3/\text{Fe}_3\text{O}_4/\text{SiO}_2$ and $\text{GdFeO}_3/\text{Fe}_3\text{O}_4/\text{SiO}_2$: Nanocomposites of Biofunctional Materials. *ChemistryOpen* **2013**, *2*, 88–92. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Biryukov, Y.P.; Filatov, S.K.; Vagizov, F.G.; Zinnatullin, A.L.; Bubnova, R.S. Thermal Expansion of FeBO_3 and Fe_3BO_6 Antiferromagnets Near the Neel Temperature. *J. Struct. Chem.* **2018**, *59*, 1980–1988. [\[CrossRef\]](#)
31. Biryukov, Y.P.; Bubnova, R.S.; Dmitrieva, N.V.; Filatov, S.K. Thermal Behavior of Antiferromagnets FeBO_3 and Fe_3BO_6 at Negative Temperatures. *Glass Phys. Chem.* **2019**, *45*, 147–149. [\[CrossRef\]](#)
32. Rowsell, J.L.C.; Gaubicher, J.; Nazar, L.F. A new class of materials for lithium-ion batteries: Iron(III) borates. *J. Power Sources* **2001**, *97–98*, 254–257. [\[CrossRef\]](#)
33. Ozkendir, O.M.; Yuzer, A. Influence of erbium substitution on the crystal and electronic properties of FeBO_3 oxide. *Vacuum* **2017**, *141*, 222–229. [\[CrossRef\]](#)
34. Pattanayak, N.; Pradhan, M.; Panda, P.; Giri, B.; Pradhan, G.K.; Samal, D. Thermoremanent magnetization and Raman study in weak ferromagnet FeBO_3 . *J. Magn. Magn. Mater.* **2023**, *588*, 171453. [\[CrossRef\]](#)
35. Kumari, K.; Bhargav, K.K.; Kumar, N.; Ram, S.; Kotnala, R.K. Microstructure and frequency sensitive electrical conductivity in $\text{Fe}_3\text{BO}_6/\text{B}_2\text{O}_3$ of a hybrid vitroceramic nanocomposite. *Phys. Status Solidi A* **2011**, *208*, 2130–2139. [\[CrossRef\]](#)
36. Ozer, D.; Icten, O. Solution Combustion Synthesis of Iron Oxyborate (Fe_3BO_6). *J. Turk. Chem. Soc. Sect. Chem.* **2019**, *6*, 97–102. [\[CrossRef\]](#)
37. Makram, H.; Tournon, L.; Lories, J. Phase relations in the system $\text{Fe}_2\text{O}_3\text{--B}_2\text{O}_3$ and its application in single crystal growth of FeBO_3 . *J. Cryst. Growth* **1972**, *13–14*, 585–587. [\[CrossRef\]](#)
38. Jach, J. A Mossbauer Study of the Devitrification of an Iron-Containing Borate Glass. *J. Nonmetals* **1974**, *2*, 89.
39. Seleznyova, K.; Mogilenec, Y.; Yagupov, S.; Strugatsky, M.; Curély, J.; Kliava, J. Iron Borate Based Crystals, Trigonal Weak Ferromagnets with Zero Orbital Moment: Synthesis and Modelling of Intracrystalline Interactions. *IEEE Trans. Magn.* **2022**, *58*, 1300604. [\[CrossRef\]](#)
40. Shang, S.; Wang, Y.; Liu, Z.-K.; Yang, C.-E.; Yin, S. Band structure of FeBO_3 : Implications for tailoring the band gap of nanoparticles. *Appl. Phys. Lett.* **2007**, *91*, 253115. [\[CrossRef\]](#)
41. Snegirev, N.I.; Lyubutin, I.S.; Yagupov, S.V.; Kulikov, A.G.; Artemov, V.V.; Mogilenec, Y.A.; Strugatsky, M.B. Formation of New Crystalline Phases upon High-Temperature Annealing of Iron Borate FeBO_3 in Different Gas Media. *JETP Lett.* **2020**, *112*, 352–356. [\[CrossRef\]](#)
42. ElBaz, N.; El-Damrawi, G.; Abdelghany, A.M. Structural Role of CeO_2 in the Modified Borate Glass-Ceramics. *New J. Glass Ceram.* **2021**, *11*, 34–43.
43. Diehl, R. Crystal structure refinement of ferric borate, FeBO_3 . *Solid State Commun.* **1975**, *17*, 743–745. [\[CrossRef\]](#)
44. Seleznyova, K.; Smirnova, E.; Strugatsky, M.; Snegirev, N.; Yagupov, S.; Mogilenec, Y.; Maksimova, E.; Alekseeva, O.; Lyubutin, I. Effect of magnetoelastic interaction on the thermal expansion of the trigonal crystal FeBO_3 . *J. Magn. Magn. Mater.* **2022**, *560*, 169658. [\[CrossRef\]](#)

45. White, J.G.; Miller, A.; Nielsen, R.E. Fe_3BO_6 , a borate isostructural with the mineral norbergite. *Acta Crystallogr.* **1965**, *19*, 1060–1061. [[CrossRef](#)]
46. Kumari, K.; Ram, S.; Kotnala, R.K. Self-controlled growth of Fe_3BO_6 crystallites in shape of nanorods from iron-borate glass of small templates. *Mater. Chem. Phys.* **2011**, *129*, 1020–1026. [[CrossRef](#)]
47. Kumari, K. Phase analysis, FTIR/Raman, and optical properties of Fe_3BO_6 nanocrystallites prepared by glass route at moderate temperature in ambient air. *J. Mol. Struct.* **2018**, *1173*, 417–421. [[CrossRef](#)]
48. Pauling, L.; Hendricks, S.B. The Crystal Structures of Hematite and Corundum. *J. Am. Chem. Soc.* **1925**, *47*, 781–790. [[CrossRef](#)]
49. González, G.; Sagarzazu, A.; Villalba, R. Study of the mechano-chemical transformation of goethite to hematite by TEM and XRD. *Mater. Res. Bull.* **2000**, *35*, 2295–2308. [[CrossRef](#)]
50. Navarro, H.; Potts, J.E.; Merlin, R. Raman scattering from phonons and magnons in antiferromagnetic Fe_3BO_6 . *Solid State Commun.* **1984**, *50*, 331–333. [[CrossRef](#)]
51. Rousseau, D.L.; Bauman, R.P.; Porto, S.P.S. Normal mode determination in crystals. *J. Raman Spectrosc.* **1981**, *10*, 253–290. [[CrossRef](#)]
52. Shepherd, I.W. Raman Scattering in FeBO_3 . *J. Appl. Phys.* **1971**, *42*, 1482–1483. [[CrossRef](#)]
53. Shepherd, I.W. Temperature Dependence of Phonon Raman Scattering in FeBO_3 , InBO_3 , and VBO_3 : Evidence for a Magnetic Contribution to the Intensities. *Phys. Rev. B* **1972**, *5*, 4524–4529.
54. Chernyshev, V.A.; Avram, C.N. Lattice dynamics of FeBO_3 and GaBO_3 crystals: Ab initio calculation. *AIP Conf. Proc.* **2020**, *2218*, 040005. [[CrossRef](#)]
55. de Faria, D.L.A.; Venâncio Silva, S.; de Oliveira, M.T. Raman Microspectroscopy of Some Iron Oxides and Oxyhydroxides. *J. Raman Spectrosc.* **1997**, *28*, 873. [[CrossRef](#)]
56. Mansour, H.; Letifi, H.; Bargougui, R.; De Almeida-Didry, S.; Negulescu, B.; Autret-Lambert, C.; Gadri, A.; Ammar, S. Structural, optical, magnetic and electrical properties of hematite ($\alpha\text{-Fe}_2\text{O}_3$) nanoparticles synthesized by two methods: Polyol and precipitation. *Appl. Phys. A* **2017**, *123*, 787. [[CrossRef](#)]
57. de Faria, D.L.A.; Lopes, F.N. Heated goethite and natural hematite: Can Raman spectroscopy be used to differentiate them? *Vib. Spectrosc.* **2007**, *45*, 117–121. [[CrossRef](#)]
58. Diehl, R.; Räuber, A.; Friedrich, F. Vapour growth of bulk FeBO_3 single crystals. *J. Cryst. Growth* **1975**, *29*, 225–233. [[CrossRef](#)]
59. Ovchinnikov, S.G.; Zablude, V.N. The energy band structure and optical spectra of FeBO_3 calculated with allowance for strong electron correlations. *J. Exp. Theor. Phys.* **2004**, *98*, 135–143. [[CrossRef](#)]
60. Kazumichi, E.; Toyotaka, M.; Hisao, K. Faraday Rotation in FeBO_3 at 77 °K. *J. Phys. Soc. Jpn.* **1971**, *31*, 602. [[CrossRef](#)]
61. Edel'man, I.S.; Malakhovskii, A.V.; Vasil'eva, T.I.; Seleznev, V.N. Optical Properties of FeBO_3 in the Strong Absorption Region. *Sov. Phys.—Solid State* **1973**, *14*, 2442.
62. Andlauer, B.; Schirmer, O.F.; Schneider, J. Exciton, magnon and phonon structure in the optical spectrum of FeBO_3 . *Solid State Commun.* **1973**, *13*, 1655–1659. [[CrossRef](#)]
63. Postnikov, A.V.; Bartkowski, S.; Neumann, M.; Rupp, R.A.; Kurmaev, E.Z.; Shamin, S.N.; Fedorenko, V.V. Electronic structure and valence-band spectra of FeBO_3 . *Phys. Rev. B* **1994**, *50*, 14849–14854. [[CrossRef](#)] [[PubMed](#)]
64. Hsiao, S.-Y.; Lin, E.-X.; Keng, P.-Y. Facile Synthesis of Carbon- and Nitrogen-Doped Iron Borate as a Highly Efficient Single-Component Heterogeneous Photo-Fenton Catalyst under Simulated Solar Irradiation. *Nanomaterials* **2021**, *11*, 2853. [[CrossRef](#)] [[PubMed](#)]
65. Tauc, J. Optical properties and electronic structure of amorphous Ge and Si. *Mater. Res. Bull.* **1968**, *3*, 37–46. [[CrossRef](#)]
66. Kou, W.W.; Seehra, M.S. Optical absorption in iron pyrite FeS_2 . *Phys. Rev. B* **1978**, *18*, 7062–7068. [[CrossRef](#)]
67. Makuła, P.; Pacia, M.; Macyk, W. How To Correctly Determine the Band Gap Energy of Modified Semiconductor Photocatalysts Based on UV–Vis Spectra. *J. Phys. Chem. Lett.* **2018**, *9*, 6814–6817. [[CrossRef](#)] [[PubMed](#)]
68. Rothschild, A.; Assouline, B.; Shalom, N.A.; Bernstein, N.; Daniel, G.; Cohen, G.; Capua, A. The Ferris ferromagnetic resonance technique: Principles and applications. *AIP Adv.* **2023**, *13*, 065319. [[CrossRef](#)]
69. Velikov, L.V.; Prokhorov, A.S.; Rudashevskii, E.G.; Seleznev, V.N. Antiferromagnetic resonance in FeBO_3 . *Sov. Phys. JETP* **1974**, *39*, 909.
70. Seleznyova, K.; Strugatsky, M.; Yagupov, S.; Mogilenec, Y.; Drovosekov, A.; Kreines, N.; Rosa, P.; Kliava, J. Electron magnetic resonance of iron-gallium borate single crystals. *J. Appl. Phys.* **2019**, *125*, 223905. [[CrossRef](#)]
71. Popov, M.; Liu, Y.; Safonov, V.; Zavislyak, I.; Moiseienko, V.; Zhou, P.; Fu, J.; Zhang, W.; Zhang, J.; Qi, Y.; et al. Strong Converse Magnetoelectric Effect in a Composite of Weakly Ferromagnetic Iron Borate and Ferroelectric Lead Zirconate Titanate. *Phys. Rev. Appl.* **2020**, *14*, 034039. [[CrossRef](#)]
72. Popov, M.A.; Zavislyak, I.V.; Chumak, H.L.; Strugatsky, M.B.; Yagupov, S.V.; Srinivasan, G. Ferromagnetic resonance in a single crystal of iron borate and magnetic field tuning of hybrid oscillations in a composite structure with a dielectric: Experiment and theory. *J. Appl. Phys.* **2015**, *118*, 013903. [[CrossRef](#)]

73. Seleznyova, K.; Mogilenec, Y.; Prilepsky, D.; Strugatsky, M.; Yagupov, S.; Drovosekov, A.; Kreines, N.; Kliava, J. Antiferromagnetic resonance in iron borate films: Dzyaloshinskii–Moriya field and isotropic energy gap. *Appl. Phys. A* **2022**, *128*, 1055. [\[CrossRef\]](#)
74. Michels, A.; Mettus, D.; Titov, I.; Malyeyev, A.; Bersweiler, M.; Bender, P.; Peral, I.; Birringer, R.; Quan, Y.; Hautle, P.; et al. Microstructural-defect-induced Dzyaloshinskii–Moriya interaction. *Phys. Rev. B* **2019**, *99*, 014416. [\[CrossRef\]](#)
75. Michels, A.; Mettus, D.; Honecker, D.; Metlov, K.L. Effect of Dzyaloshinski–Moriya interaction on elastic small-angle neutron scattering. *Phys. Rev. B* **2016**, *94*, 054424. [\[CrossRef\]](#)
76. Petrokovskii, G.A.; Pankrats, A.I. The magnetoelastic coupling in FeBO₃. *Phys. BC* **1977**, *86–88*, 1447. [\[CrossRef\]](#)
77. Ovchinnikov, S.G.; Rudenko, V.V.; Tugarinov, V.I. Weak ferromagnetism along the triad axis of FeBO₃ crystals. *Phys. Solid State* **2016**, *58*, 1995–1998. [\[CrossRef\]](#)
78. Scheck, C.; Cheng, L.; Barsukov, I.; Frait, Z.; Bailey, W.E. Low Relaxation Rate in Epitaxial Vanadium-Doped Ultrathin Iron Films. *Phys. Rev. Lett.* **2007**, *98*, 117601. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Wei, Y.; Liang Chin, S.; Svedlindh, P. On the frequency and field linewidth conversion of ferromagnetic resonance spectra. *J. Phys. Appl. Phys.* **2015**, *48*, 335005. [\[CrossRef\]](#)
80. Petrov, M.P.; Smolensky, G.A.; Paugurt, A.P.; Kizhaev, S.A. Nuclear Magnetic Resonance and Magnetic Properties of FeBO₃-Type Crystals. *AIP Conf. Proc.* **1972**, *5*, 379–391. [\[CrossRef\]](#)
81. Kumari, K. Magnetic and dielectric properties of Fe₃BO₆ nanoplates prepared through self-combustion method. *J. Adv. Dielectr.* **2017**, *07*, 1750043. [\[CrossRef\]](#)
82. Wang, L.; Cai, L.; He, X.; Yang, F.; Chen, J.; Yi, L.; Liu, M.; Xu, Y.; Xia, Z.; Pan, L. Surface weak ferromagnet coupling induced giant room-temperature spontaneous exchange bias in antiferromagnet Fe₃BO₆ polycrystals. *J. Chem. Phys.* **2024**, *161*, 154706. [\[CrossRef\]](#) [\[PubMed\]](#)
83. Voigt, C.; Bonnenberg, D. Temperature dependence of the magnetic susceptibility of Fe₃BO₆. *Phys. B+C* **1975**, *80*, 439–443. [\[CrossRef\]](#)
84. Hirano, M.; Okuda, T.; Tsushima, T.; Umemura, S.; Kohn, K.; Nakamura, S. Spin configurations and spin reorientations in pure and impurity doped Fe₃BO₆. *Solid State Commun.* **1974**, *15*, 1129–1133. [\[CrossRef\]](#)
85. Tsymbal, L.T.; Bazaliy, Y.B.; Bezmaternykh, L.N.; Slawska-Waniewska, A.; Vasiliev, S.V.; Nedelko, N.; Linnik, A.I.; Cherkasov, A.N.; Nepochatykh, Y.I.; Dmitrenko, V.Y.; et al. Orientation phase transition in Fe₃BO₆: Experimental determination of the order of the transition. *Phys. Rev. B* **2006**, *74*, 134429. [\[CrossRef\]](#)
86. Wolfe, R.; Pierce, R.D.; Eibschütz, M.; Nielsen, J.W. Magnetization and Mössbauer effect in single crystal Fe₃BO₆. *Solid State Commun.* **1969**, *7*, 949. [\[CrossRef\]](#)
87. Voigt, C. Field-induced phase transition in Fe₃BO₆. *Phys. Lett. A* **1975**, *53*, 223–224. [\[CrossRef\]](#)
88. Morrish, A.H. *Canted Antiferromagnetism: Hematite*; World Scientific Publishing Co. Pte. Ltd.: Singapore, 1994.
89. Tadic, M.; Panjan, M.; Damjanovic, V.; Milosevic, I. Magnetic properties of hematite (α-Fe₂O₃) nanoparticles prepared by hydrothermal synthesis method. *Appl. Surf. Sci.* **2014**, *320*, 183–187. [\[CrossRef\]](#)
90. Maldonado-Camargo, L.; Unni, M.; Rinaldi, C. Magnetic Characterization of Iron Oxide Nanoparticles for Biomedical Applications. *Methods Mol. Biol.* **2017**, *1570*, 47. [\[CrossRef\]](#) [\[PubMed\]](#)
91. Powell, C.D.; Lounsbury, A.W.; Fishman, Z.S.; Coonrod, C.L.; Gallagher, M.J.; Villagran, D.; Zimmerman, J.B.; Pfefferle, L.D.; Wong, M.S. Nano-structural effects on Hematite (α-Fe₂O₃) nanoparticle radiofrequency heating. *Nano Conver.* **2021**, *8*, 8. [\[CrossRef\]](#) [\[PubMed\]](#)
92. Ghosh, A.; Srinivas, V.; Sundara, R. Comprehensive structural and magnetic properties of iron oxide nanoparticles synthesized through chemical routes. *J. Alloys Compd.* **2020**, *818*, 152931. [\[CrossRef\]](#)
93. Tadic, M.; Čitaković, N.; Panjan, M.; Stojanović, Z.; Marković, D.; Spasojević, V. Synthesis, morphology, microstructure and magnetic properties of hematite submicron particles. *J. Alloys Compd.* **2011**, *509*, 7639–7644. [\[CrossRef\]](#)
94. Morin, F.J. Magnetic Susceptibility of α-Fe₂O₃ and α-Fe₂O₃ with Added Titanium. *Phys. Rev.* **1950**, *78*, 819–820.
95. Morrison, B.R.; Morrish, A.H.; Troup, G.J. High-Field Antiferromagnetic Resonance in α-Fe₂O₃. *Phys. Status Solidi B* **1973**, *56*, 183–195. [\[CrossRef\]](#)
96. Suturin, S.M.; Korovin, A.M.; Gastev, S.V.; Dvortsova, P.A.; Volkov, M.P.; Valvidares, M.; Sokolov, N.S. X-ray magnetic linear dichroism study of field-manipulated canted antiferromagnetism in epitaxial α-Fe₂O₃ films. *Phys. Rev. Mater.* **2021**, *5*, 044408. [\[CrossRef\]](#)
97. Nogués, J.; Leighton, C.; Schuller, I.K. Correlation between antiferromagnetic interface coupling and positive exchange bias. *Phys. Rev. B* **2000**, *61*, 1315–1317. [\[CrossRef\]](#)
98. Gruyters, M. Spin-Glass-Like Behavior in CoO Nanoparticles and the Origin of Exchange Bias in Layered CoO Ferromagnetic Structures. *Phys. Rev. Lett.* **2005**, *95*, 077204. [\[CrossRef\]](#) [\[PubMed\]](#)
99. Fitzsimmons, M.R.; Kirby, B.J.; Roy, S.; Li, Z.-P.; Roshchin, I.V.; Sinha, S.K.; Schuller, I.K. Pinned magnetization in the antiferromagnet and ferromagnet of an exchange bias system. *Phys. Rev. B* **2007**, *75*, 214412. [\[CrossRef\]](#)

100. Sokolov, B.Y. Effect of low-symmetry mechanical stresses on the magnetic properties of iron borate. *Tech. Phys.* **2006**, *51*, 589–594. [[CrossRef](#)]
101. Vallina, B.; Rodriguez-Blanco, J.D.; Brown, A.P.; Benning, L.G.; Blanco, J.A. Enhanced magnetic coercivity of α -Fe₂O₃ obtained from carbonated 2-line ferrihydrite. *J. Nanopart. Res.* **2014**, *16*, 2322. [[CrossRef](#)]
102. Tadic, M.; Citakovic, N.; Panjan, M.; Stanojevic, B.; Markovic, D.; Jovanovic, D.; Spasojevic, V. Synthesis, morphology and microstructure of pomegranate-like hematite (α -Fe₂O₃) superstructure with high coercivity. *J. Alloys Compd.* **2012**, *543*, 118–124. [[CrossRef](#)]
103. Strugatsky, M.; Seleznyova, K.; Yagupov, S.; Drovosekov, A.; Kliava, J. Nature of magnetocrystalline anisotropy in the basal plane of iron borate. *J. Magn. Magn. Mater.* **2017**, *442*, 417–422. [[CrossRef](#)]
104. Scott, G.B. Magnetic domain properties of FeBO₃. *J. Phys. Appl. Phys.* **1974**, *7*, 1574–1587. [[CrossRef](#)]
105. Zhang, L.; Hu, D.; Snetkov, I.L.; Balabanov, S.; Palashov, O.; Li, J. A review on magneto-optical ceramics for Faraday isolators. *J. Adv. Ceram.* **2023**, *12*, 873–915. [[CrossRef](#)]
106. Guerrero, H.; Rosa, G.; Morales, M.P.; del Monte, F.; Moreno, E.M.; Levy, D.; Pérez del Real, R.; Belenguer, T.; Serna, C.J. Faraday rotation in magnetic γ -Fe₂O₃/SiO₂ nanocomposites. *Appl. Phys. Lett.* **1997**, *71*, 2698–2700. [[CrossRef](#)]
107. Wu, B.; Qi, S.; Wu, X.; Wang, H.; Zhuang, Q.; Yi, H.; Xu, P.; Xiong, Z.; Shi, G.; Chen, S.; et al. FeBO₃ as a low cost and high-performance anode material for sodium-ion batteries. *Chin. Chem. Lett.* **2021**, *32*, 3113–3117. [[CrossRef](#)]
108. Rodriguez-Carvajal, J. Recent advances in magnetic structure determination by neutron powder diffraction. *Phys. B* **1993**, *192*, 55–69. [[CrossRef](#)]
109. Klinger, M.; Jäger, A. Crystallographic Tool Box (CrysTBox): Automated tools for transmission electron microscopists and crystallographers. *J. Appl. Crystallogr.* **2015**, *48*, 2012–2018. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.