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Magnetic And Spintronic Prospects Of Europium-Substituted Neodymium Ferrite Perovskite Nanomaterials: Structure–Property Correlations And Emerging Functionalities

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Abstract

Rare-earth orthoferrites with the general formula $RFeO_3$ (R = rare-earth ion) represent a technologically relevant class of perovskite oxides exhibiting complex magnetic ordering, strong spin–lattice coupling, and ultrafast spin dynamics. Neodymium ferrite ($NdFeO_3$) is distinguished by canted G-type antiferromagnetism, weak ferromagnetism arising from Dzyaloshinskii–Moriya interaction and pronounced magnetocrystalline anisotropy originating from 4f–3d exchange coupling. Partial substitution of Nd^{3+} with Eu^{3+} provides an effective route to modulate lattice distortion, exchange interactions, and spin dynamics while minimizing competing rare-earth magnetic contributions due to the van Vleck nature of Eu^{3+}. This article systematically examines the influence of europium substitution on the crystal structure, magnetic ordering, anisotropy, spin reorientation behaviour, and spintronic potential of $Nd_{1-x}Eu_xFeO_3$. Emphasis is placed on structure–property correlations, microscopic interaction mechanisms, and the emerging relevance of Eu-substituted neodymium ferrite as a tuneable orthoferrite platform for antiferromagnetic spintronics and magnon-based technologies.

Keywords: *Europium, Neodymium Ferrite, Spin, Magnetic Ordering, antiferromagnetic.*

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I. Introduction

Perovskite-type rare-earth orthoferrites ($RFeO_3$) have been extensively investigated due to their high Néel temperatures, rich magnetic phase diagrams, and strong coupling between structural and magnetic degrees of freedom. These materials crystallize in an orthorhombically distorted perovskite structure (space group *Pbnm*), in which Fe^{3+} ions occupy the octahedrally coordinated B-site and rare-earth ions reside at the A-site. The magnetic behaviour of orthoferrites is governed primarily by Fe^{3+}–O–Fe^{3+} superexchange interactions, supplemented by antisymmetric exchange and rare-earth–transition-metal coupling [1,2,3,4].

$NdFeO_3$ is a prototypical orthoferrite exhibiting G-type antiferromagnetic ordering of Fe^{3+} spins with weak ferromagnetism induced by Dzyaloshinskii–Moriya interaction. The presence of Nd^{3+} ions with partially filled 4f orbitals introduces additional anisotropy and temperature-dependent magnetic phenomena, including spin reorientation transitions. These intrinsic features make $NdFeO_3$ an attractive candidate for magneto-functional and spintronic applications [5,6]

Chemical substitution at the rare-earth site has emerged as a powerful approach for tailoring magnetic anisotropy, exchange coupling, and spin dynamics in orthoferrites. Europium substitution is particularly significant because Eu^{3+} possesses a nonmagnetic ground state ($^7F_0$), contributing primarily through van Vleck paramagnetism. Consequently, Eu substitution enables controlled modification of lattice distortions and Fe-based magnetic interactions without introducing strong competing rare-earth magnetic moments [7,8]. This work provides a systematic analysis of the effects of Eu substitution on the structural, magnetic, and spintronic characteristics of neodymium ferrite.

II. Crystal Structure And Structural Evolution

Orthorhombic Perovskite Framework

$NdFeO_3$ adopts an orthorhombically distorted perovskite structure derived from the ideal cubic ABX_3 lattice (where *A* and *B* are cations and *X* is an anion). This structural distortion arises primarily from the ionic size mismatch between the Nd^{3+} ions occupying the A-site and the Fe^{3+} ions at the B-site, which induces cooperative tilting and rotation of the FeO_6 octahedra. Therefore, the Fe–O–Fe bond angles deviate significantly from the ideal 180°, leading to reduced orbital overlap between Fe 3d and O 2p states [9,10]. These octahedral distortions play a crucial role in determining the strength and symmetry of Fe^{3+}–O–Fe^{3+} superexchange interactions, thereby exerting a direct influence on the magnetic ordering and anisotropic behaviour of $NdFeO_3$.

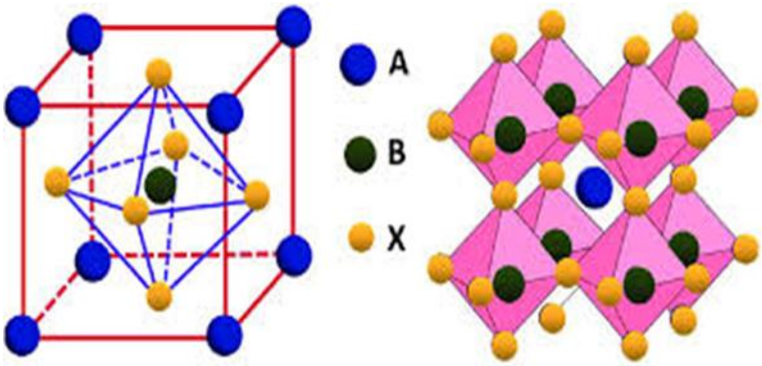

Fig 1 Perovskite Structure

Effect of Europium Substitution

Partial substitution of Nd^{3+} with Eu^{3+} introduces additional lattice distortion in $NdFeO_3$ due to differences in ionic radii and local bonding characteristics at the A-site. With increasing Eu concentration, a systematic reduction in lattice parameters and unit cell volume is typically observed, accompanied by enhanced tilting and distortion of the FeO_6 octahedra [11,12]. These structural modifications result in changes in Fe–O bond lengths and deviations of the Fe–O–Fe bond angles from their ideal values, thereby altering the degree of orbital overlap between Fe 3d and O 2p states. Consequently, the magnetic superexchange interactions are significantly modified. The progressive evolution of lattice distortion with europium content thus establishes a clear structure–property correlation, directly linking A-site substitution to the tuning of magnetic behavior in $Nd_{1-x}Eu_xFeO_3$.

III. Magnetic Ordering And Exchange Interactions

Magnetic Structure of $NdFeO_3$

$NdFeO_3$ exhibits G-type antiferromagnetic ordering of the Fe^{3+} sublattice below a high Néel temperature in the range of approximately 650–700 K. In this magnetic configuration, the Fe^{3+} spins are predominantly aligned antiparallel; however, the presence of antisymmetric Dzyaloshinskii–Moriya interaction, arising from local inversion symmetry breaking at the Fe–O–Fe bonds, leads to a slight canting of the antiferromagnetically ordered spins [13,14]. This canting gives rise to weak ferromagnetism. Furthermore, the exchange coupling between the Nd^{3+} (4f) and Fe^{3+} (3d) sublattices plays a significant role in enhancing magnetocrystalline anisotropy and gives rise to complex, temperature-dependent magnetic behaviour, including possible spin reorientation phenomena at lower temperatures [15]

Influence of Eu^{3+} on Magnetic Interactions

Europium substitution modifies the magnetic properties of $NdFeO_3$ predominantly through indirect mechanisms. Owing to the van Vleck paramagnetic nature of Eu^{3+}, the contribution from the rare-earth magnetic sublattice is substantially reduced, thereby diminishing rare-earth–transition-metal exchange effects. Concurrently, Eu-induced lattice distortions lead to modifications in the Fe^{3+}–O–Fe^{3+} superexchange pathways by altering bond lengths and bond angles. These structural changes can also influence the strength of the antisymmetric Dzyaloshinskii–Moriya interaction, resulting in variations in the spin canting angle and weak ferromagnetic moment. Consequently, changes in macroscopic magnetic parameters such as coercivity, remanent magnetization, and overall magnetocrystalline anisotropy are observed. With increasing Eu concentration, the magnetic response becomes increasingly governed by the Fe^{3+} sublattice, yielding a simplified and more controllable magnetic framework that is particularly advantageous for spin-based and spintronic applications [16,17].

IV. Magnetic Anisotropy And Spin Reorientation Phenomena

Spin reorientation transitions are a characteristic feature of rare-earth orthoferrites and originate from the competition between different magnetocrystalline anisotropy contributions associated with the Fe^{3+} and rare-earth sublattices. In $NdFeO_3$, strong Nd^{3+}–Fe^{3+} exchange interactions play a critical role in governing both the temperature range and the nature of these spin reorientation transitions. Partial substitution of Nd^{3+} with Eu^{3+} weakens the rare-earth–driven anisotropy due to the reduced magnetic contribution of Eu^{3+}, while simultaneously enhancing lattice-mediated anisotropic effects arising from structural distortions [18,19,20]. Therefore, Eu substitution can lead to a suppression or systematic shift of spin reorientation temperatures, stabilization of specific spin configurations, and tunability of anisotropy fields. Such controlled modulation of magnetic anisotropy is particularly significant for spintronic applications that require robust, deterministic spin orientation and long-term magnetic stability [21].

V. Spin Dynamics And Magnonic Properties

Rare-earth orthoferrites have recently attracted considerable attention as promising platforms for antiferromagnetic spintronics owing to their ultrafast spin dynamics, low intrinsic magnetic damping, and the presence of high frequency magnon excitations [22,23]. In the $Nd_{1-x}Eu_xFeO_3$ system, europium-induced structural modulation offers an effective pathway to tailor spin-wave dispersion relations and magnon lifetimes by modifying exchange interactions and magnetic anisotropy. The key advantages of this material system include the presence of antiferromagnetic resonance modes spanning the GHz to THz frequency range, reduced magnetic damping resulting from the suppression of rare-earth magnetic fluctuations, and enhanced controllability of spin-wave propagation through chemical substitution. Collectively, these attributes position europium-substituted neodymium ferrite as a promising candidate for magnonic waveguides, spin-wave–based logic architectures, and other emerging antiferromagnetic spintronic devices [24,25,26]

VI. Spintronic Potential And Device Relevance

From a spintronic perspective, $Nd_{1-x}Eu_xFeO_3$ exhibits a combination of intrinsic properties that make it particularly attractive for next-generation spin-based technologies. The coexistence of weak ferromagnetism with a predominantly antiferromagnetic ground state enables efficient spin manipulation while maintaining robustness against external magnetic perturbations. In addition, strong spin–lattice coupling in this system facilitates strain- or field-mediated control of spin orientation, offering versatile routes for device actuation. The chemical stability of $Nd_{1-x}Eu_xFeO_3$ and its compatibility with complex oxide heterostructures further enhance its suitability for practical applications [27]. Consequently, this material system holds significant promise for implementation in antiferromagnetic spin valves, exchange-bias layers, magnon-based logic elements, and ultrafast spin-switching devices. Moreover, the reduced magnetic complexity introduced by europium substitution improves reproducibility and reliability, which are critical factors for scalable device integration [28].

VII. Synthesis Strategies And Materials Considerations

$Nd_{1-x}Eu_xFeO_3$ has been synthesized using a variety of chemical and solid-state routes, including conventional solid-state reaction, sol–gel processing, co-precipitation, and solution combustion methods. Among these approaches, solution-based synthesis techniques are particularly advantageous due to their ability to achieve improved compositional homogeneity, reduced processing temperatures, and enhanced control over particle size, morphology, and crystallinity. Such precise control over microstructural features is crucial for minimizing extrinsic effects and for reliably probing the intrinsic magnetic and spin-dynamic properties of $Nd_{1-x}Eu_xFeO_3$, which are essential for assessing its suitability in spintronic and magnonic applications [29,30].

VIII. Conclusions

Europium-substituted neodymium ferrite ($Nd_{1-x}Eu_xFeO_3$) emerges as a promising and comparatively underexplored orthoferrite system with substantial relevance for magnetic and spintronic applications. The incorporation of Eu^{3+} at the rare-earth site provides an effective route to decouple rare-earth magnetic contributions from lattice-driven effects, thereby enabling controlled modulation of structural distortion, magnetic exchange interactions, and magnetocrystalline anisotropy. The resulting evolution in magnetic ordering, spin canting, and spin dynamics underscores the strong structure–property correlations inherent to this system. Overall, Eu substitution offers a versatile means to tailor the intrinsic magnetic framework of $NdFeO_3$ while preserving its robust antiferromagnetic character, making $Nd_{1-x}Eu_xFeO_3$ a compelling candidate for antiferromagnetic and magnonic spintronic platforms.

IX. Future Perspectives

Despite the growing understanding of rare-earth orthoferrites, several aspects of Eu-substituted neodymium ferrite remain insufficiently explored. Future research should focus on systematic, doping-dependent investigations combining magnetic, spectroscopic, and dynamic measurements to elucidate the evolution of exchange interactions, anisotropy, and spin excitations across a wide compositional range. First-principles calculations and advanced theoretical modeling will be essential for providing microscopic insight into the electronic structure, magnetic interactions, and spin–orbit coupling effects induced by europium substitution. In addition, the development of high-quality thin films and engineered oxide heterostructures will be critical for assessing interface-driven phenomena and device compatibility. Finally, direct experimental demonstrations of spin transport, magnon propagation, and ultrafast spin manipulation will be crucial for bridging the gap between fundamental materials research and the realization of functional spintronic technologies based on $Nd_{1-x}Eu_xFeO_3$.

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