

SYNTHESIS AND MAGNETIC PROPERTIES OF γ -IRON(III) OXIDE/COBALT(II) OXIDE AND COBALT(II) OXIDE/ γ -IRON(III) OXIDE NANOSTRUCTURES FOR SPINTRONIC APPLICATIONS

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Abstract. In this study, γ -Fe₂O₃/CoO and CoO/ γ -Fe₂O₃ two-component nanoparticles were synthesized using a simple, two-step chemical process. Co(acac)₂ and Fe(acac)₃ were thermally decomposed in hot oleylamine, with mixed nucleation and the subsequent growth of the second component on seed nanoparticles forming the basis of the method. The resulting heterostructures were characterized by transmission electron microscopy (TEM), X-ray diffraction (XRD), and complementary techniques to confirm their composition, structure, and morphology. The nanoparticles exhibited high stability in nonpolar organic solvents due to an in situ-formed organic coating. Magnetic measurements revealed that the antiferromagnetic CoO phase induces unidirectional anisotropy, arising from both magnetically compensated and uncompensated interfaces. This work demonstrates a facile approach to produce stable, core-shell cobalt-iron oxide nanoparticles with tunable magnetic interactions, suitable for applications in nanomagnetism and spintronic devices.

Keywords: γ -Fe₂O₃/CoO; CoO/ γ -Fe₂O₃; binary nanoparticles; exchange bias.

1. Introduction

Because of their synergistic qualities that are absent from their individual counterparts, mixed nanostructures made up of two or more nanometer-scale components have drawn a lot of attention in recent years [1–3]. The design of multifunctional materials for cutting-edge technological applications in a variety of fields, including as catalysis, biomedicine, energy storage, spintronics, and magnetic data storage, is made possible by these hybrid nanostructures [4]. Because of their customizable size-dependent characteristics and potential uses in motors, energy conversion, information storage devices, single-electron transistors, magnetic hyperthermia, and targeted drug delivery, magnetic nanoparticles (NPs) are particularly significant among these [5–7].

Unlike bulk magnets, nanoscale magnetic materials display unique behaviors arising from finite-size effects [8], surface/interface effects [9],

and interparticle interactions [10]. Sheu et al. investigated white-light emission from near-UV InGaN/GaN LED chips precoated with blue, green, and red phosphors [11]. The combination of three phosphors produced white light with good color rendering, demonstrating the potential of phosphor-converted LEDs for white-light applications. Shih et al. studied phosphor-in-glass structures for high-performance WLEDs by reducing phosphor interactions and applying an antireflection coating [12]. The results showed improved luminous efficiency and high color rendering performance. Tsai investigated the thermal aging performance of glass-based phosphor converted WLEDs [13]. The results demonstrated good thermal stability and maintained color-rendering performance at elevated temperatures. Nogués et al. reviewed exchange bias in magnetic nanostructures, focusing on the interaction between ferromagnetic and antiferromagnetic materials [14]. The study discussed the mechanisms and applications of exchange bias at the nanoscale. Yan et al. investigated the luminescence properties of Tm^{3+} - and Eu^{3+} -co-doped LaPO_4 phosphors for white-light emission [15]. The results showed that the Eu^{3+} concentration affected the emission intensity and enabled white-light generation. Yang et al. studied the enhancement of $\text{ZnAl}_2\text{O}_4:\text{Eu}^{3+}$ phosphor luminescence by adding carbon dots [16]. The addition of carbon dots improved the luminescence performance through interactions with Eu^{3+} ions. Yuen et al. investigated various phosphor packaging configurations for chip-on-board warm-white LEDs [17]. The results showed that packaging configuration significantly affected the optical performance and emission characteristics.

Because of their excellent chemical stability, adjustable interfacial magnetism, and compatibility with solution-processed fabrication methods, iron-cobalt oxide heterostructures are very appealing for spintronic technologies. While CoO is an antiferromagnet with an T_N temperature near ambient temperature (~ 291 K), $\gamma\text{-Fe}_2\text{O}_3$ (maghemite) is a soft ferromagnet with substantial saturation magnetization and outstanding oxidation resistance. By combining these two stages into a single nanoscale design, a model platform for controlling interface

area, crystallinity, and spin compensation at the FM/AFM border may be used to create exchange anisotropy.

Most previous studies have focused on $\gamma\text{-Fe}_2\text{O}_3@\text{CoO}$ systems prepared by post-oxidation of metallic cobalt cores, a route that frequently leads to poorly controlled shell thicknesses and the presence of intermediate oxide phases. In contrast, chemically driven seeded-growth strategies allow the direct formation of oxide-oxide interfaces in solution, avoiding additional oxidation steps and enabling access to both normal and inverted FM/AFM configurations. The approach adopted in the present work therefore offers a unique opportunity to compare, within the same material system, how structural inversion and particle-size asymmetry influence exchange bias and coercivity, thereby deepening the understanding of nanoscale magnetic coupling mechanisms.

The main novelties and contributions of this work are summarized as follows:

- A simple two-step seeded-growth synthesis route was developed for the fabrication of $\gamma\text{-Fe}_2\text{O}_3/\text{CoO}$ and $\text{CoO}/\gamma\text{-Fe}_2\text{O}_3$ hetero-nanostructures.
- Both conventional FM/AFM and inverted AFM/FM architectures were successfully realized within the same material system, allowing direct comparison of their magnetic behaviors.
- The influence of structural inversion on exchange bias, coercivity enhancement, and interfacial magnetic coupling was systematically investigated.
- The relationship between nanoparticle morphology, crystallinity, and interfacial spin interactions was clarified through structural and magnetic characterization.
- The synthesized heterostructures demonstrate potential multifunctional applications in spintronic devices and phosphor-converted white LED systems.

Besides investigating the magnetic behavior of $\gamma\text{-Fe}_2\text{O}_3/\text{CoO}$ heterostructures for spintronic

applications, this work also explores their optical scattering capability in phosphor-converted white LEDs, highlighting the multifunctional nature of these oxide nanomaterials.

2. Theoretical Background

2.1. Exchange Bias Effect

Exchange bias is a magnetic phenomenon that occurs at the interface between ferromagnetic (FM) and antiferromagnetic (AFM) materials. After field cooling through the Néel temperature of the AFM phase, interfacial exchange coupling generates a unidirectional anisotropy that shifts the magnetic hysteresis loop along the magnetic field axis. The exchange bias field (H_{ex}) and coercive field (H_c) are calculated from the hysteresis loop according to:

$$H_{\text{ex}} = \frac{H_L + H_R}{2} \quad (1)$$

$$H_c = \frac{-H_L + H_R}{2} \quad (2)$$

where H_L and H_R are the left and right coercive fields, respectively.

2.2. Magnetic Coupling in $\gamma\text{-Fe}_2\text{O}_3/\text{CoO}$ Heterostructures

In $\gamma\text{-Fe}_2\text{O}_3/\text{CoO}$ heterostructures, $\gamma\text{-Fe}_2\text{O}_3$ acts as a ferrimagnetic component, while CoO behaves as an antiferromagnetic phase. The magnetic properties are strongly governed by the interfacial exchange interaction between the two phases. The density of uncompensated spins and the interfacial contact area determine the magnitude of exchange bias and coercivity enhancement.

For the conventional $\gamma\text{-Fe}_2\text{O}_3/\text{CoO}$ configuration, the CoO domains provide pinning centers for the ferrimagnetic moments. In contrast, the inverted $\text{CoO}/\gamma\text{-Fe}_2\text{O}_3$ structure increases the interfacial contact area and modifies the balance between pinned and reversible spins. Therefore, structural inversion can significantly influence magnetic anisotropy and hysteresis behavior.

3. Experimental Procedure

Iron(III) acetylacetonate ($\text{Fe}(\text{acac})_3$, $\geq 99\%$, Sigma-Aldrich), cobalt(II) acetylacetonate ($\text{Co}(\text{acac})_2$, $\geq 99\%$, Sigma-Aldrich), oleylamine ($\text{C}_{18}\text{H}_{37}\text{NH}_2$, 70%, Sigma-Aldrich), trioctylphosphine oxide (TOPO, $\geq 99\%$, Sigma-Aldrich), and ethanol ($\geq 99.5\%$, Sigma-Aldrich) were used. All chemicals were used as received without further purification. 20 mL of oleylamine was heated to 80 °C under magnetic stirring (400 rpm) in a 50 mL three-neck flask. $\text{Fe}(\text{acac})_3$ (0.5 mmol) and TOPO (0.4 mmol) were added, and the mixture was stirred until a clear solution formed. The solution was then heated to 280 °C at 5 °C/min and maintained for 30 min under nitrogen atmosphere [18]. After cooling to room temperature, nanoparticles were precipitated with ethanol, separated by centrifugation (8000 rpm, 10 min), redispersed, and washed twice to remove residual oleylamine. $\text{Co}(\text{acac})_2$ (0.5 mmol) dissolved in 10 mL oleylamine was added to the as-prepared $\gamma\text{-Fe}_2\text{O}_3$ nanoparticle dispersion under vigorous stirring. The mixture was heated to 280 °C at 5 °C/min for 30 min under nitrogen to form CoO shells on the $\gamma\text{-Fe}_2\text{O}_3$ seeds. The product was cooled, precipitated with ethanol, centrifuged (8000 rpm, 10 min), and washed three times to remove unreacted reagents. The reverse $\text{CoO}/\gamma\text{-Fe}_2\text{O}_3$ nanoparticles were synthesized similarly, starting with CoO seeds.

The same protocol was applied in reverse, starting from CoO nanoparticles to obtain the inverted AFM/FM configuration.

Powder X-ray diffraction was performed using a Bruker D8 Advance XRD with $\text{Cu K}\alpha$ radiation ($\lambda = 1.5418 \text{ \AA}$) at 40 kV and 40 mA. Scans were recorded from 10–80° 2θ with a step size of 0.02° and a scan rate of 0.5°/min to determine crystal structure and phase purity. Temperature-dependent Mössbauer spectra were recorded using a Wissenschaftliche Elektronik GmbH Mössbauer spectrometer with a $^{57}\text{Co}(\text{Rh})$ source. Measurements were performed between 4.2 K and room temperature using an Oxford Variox cryostat. Isomer shifts were referenced to metallic Fe at room tempera-

ture, and spectra were fitted to extract magnetic and electronic information. Energy-dispersive X-ray spectroscopy (EDS) was performed using a FEI Quanta SEM with Oxford EDS system to determine elemental composition and verify Fe:Co ratios. TEM and HR-TEM were conducted using a JEOL JEM-2100 microscope operating at 200 kV. Samples were prepared by dropping a diluted nanoparticle solution onto carbon-coated copper grids and drying at room temperature. Particle size distributions were measured from at least 200 particles using ImageJ software. FT-IR spectra were recorded using a Bruker Vertex 70 FT-IR in the range 400–4000 cm^{-1} to confirm the presence of oleylamine on the nanoparticle surfaces. Magnetic properties were measured with a Quantum Design MPMS SQUID magnetometer. Hysteresis loops and zero-field-cooled/field-cooled curves were obtained at 5 K, 50 K, and 300 K under magnetic fields up to 5 T [19].

A Monte-Carlo ray-tracing method was used in optical simulations to assess the scattering behavior of CoO particles placed in phosphor-converted white LED (WLED) devices. A blue InGaN chip measuring $1 \times 1 \text{ mm}^2$ and emitting at 450 nm was encased in a silicone dome (refractive index $n = 1.52$) to form the LED package geometry. The chip was covered with a 0.5 mm-thick remote phosphor layer that contained YAG:Ce³⁺ particles and scattering additives. Particle size distributions from 1 to 19 μm were incorporated into the model, and the refractive indices of the scattering materials were taken from studies in the literature. Mie-theory-based scattering cross sections integrated into the ray-tracing technique were used to calculate light propagation, absorption, and scattering events. To guarantee statistical convergence, at least ten rays were launched for every configuration. In accordance with CIE guidelines, colorimetric data such as correlated color temperature (CCT), color rendering index (CRI), color quality scale (CQS), luminous flux, and ΔCCT were retrieved from the simulated emission spectra.

Samples were cooled from 300 K to 5 K with a 50 kOe applied magnetic field using the SQUID magnetometer prior to magnetic hysteresis experiments. Hysteresis loops were recorded with-

out altering the direction of the cooling field once the desired temperature was reached. The samples were cooled in a zero applied field prior to data collection in order to perform zero-field-cooled measurements.

4. Results and Discussion

The two-component nanoparticles are formed through a heterogeneous nucleation–growth pathway governed by surface chemistry, precursor decomposition kinetics, and interfacial energetics. During the first reaction step, monodisperse $\gamma\text{-Fe}_2\text{O}_3$ or CoO nanocrystals are generated in oleylamine and capped by amine and phosphine-oxide ligands, which stabilize the particles and simultaneously provide preferential adsorption sites for incoming metal precursors.

When $\text{Co}(\text{acac})_2$ is injected into a dispersion of $\gamma\text{-Fe}_2\text{O}_3$ seeds and heated to 280 °C, cobalt-containing species preferentially decompose at the oxide surface rather than homogeneously in solution because of the reduced interfacial nucleation barrier. This process results in partial or complete decoration of the maghemite surface by CoO domains, yielding a conventional FM/AFM configuration [20].

On the other hand, the higher surface energy and bigger average size of the CoO cores encourage more conformal overgrowth of the ferrimagnetic phase when $\gamma\text{-Fe}_2\text{O}_3$ is grown atop CoO seeds, which maximizes the FM/AFM interfacial contact area. The unique hysteresis behavior that follows is a direct result of this inverted architecture, which drastically alters the balance between magnetically compensated and uncompensated interfacial spins.

In both configurations, the phase deposited during the second reaction step exhibits enhanced crystallinity, as evidenced by sharper XRD reflections, indicating that crystal growth on a solid substrate is energetically favored over homogeneous nucleation in solution. Such behavior is consistent with surface-mediated growth and oriented-attachment models commonly reported for seeded colloidal nanocrystal synthesis.

The X-ray diffraction patterns show a distinct asymmetry in crystallite sizes between the two oxide components: in the usual arrangement, γ -Fe₂O₃ areas of around 5 nm coexist with CoO domains of about 18 nm. The trivalent form of iron is further confirmed by Mössbauer spectroscopy, which also shows thermally induced relaxation events connected to superparamagnetic maghemite nanocrystals [21].

A larger disruption of Fe³⁺ spins at the interface is indicated by the somewhat lower hyperfine fields derived from low-temperature spectra in the inverted arrangement. This perturbation is likely due to improved exchange coupling with the surrounding CoO matrix. HR-TEM findings demonstrating smaller particle sizes and a greater relative interfacial area between the two phases lend credence to this theory.

Together, these results demonstrate that not only the chemical composition but also the order of phase formation critically governs crystallinity, morphology, and ultimately magnetic behavior in γ -Fe₂O₃/CoO heteronanostructures.

When CoO particles are employed as seeds to develop γ -Fe₂O₃, the XRD structure primarily reveals γ -Fe₂O₃ stage. The XRD peak positions and relative intensities agree well with the standard JCPDS card (39-1346) for maghemite. CoO stage's existence was verified by EDAX investigation. The Co/Fe atomic proportion is 2.12, which matches the forerunner's molecular proportion in the production process.

The synthesized heterostructures possess average particle sizes in the range of 7–8 nm. TEM observations reveal that CoO nanoparticles are generally larger than the γ -Fe₂O₃ particles. High-resolution TEM images clearly show the growth of CoO domains on the surface of γ -Fe₂O₃ nanoparticles, confirming the formation of binary heterostructures. In several particles, a second heterointerface can also be identified, indicating the coexistence of multiple growth modes during the seeded-growth process [22]. The HR-TEM images display well-defined lattice fringes, demonstrating the high crystallinity of both oxide phases. For the inverted CoO/ γ -Fe₂O₃ configuration, the particle size distribution is more uniform than that observed in the conventional structure. Owing to the re-

duced dimensions of both phases, the effective FM/AFM interfacial area becomes larger, which is expected to strengthen interfacial exchange interactions and significantly influence the magnetic properties discussed below [22, 23].

Both types of heterostructures exhibit excellent dispersibility in nonpolar solvents such as toluene, hexane, and chloroform, forming stable colloidal suspensions without noticeable precipitation for several months. This behavior is attributed to the adsorption of oleylamine molecules on the nanoparticle surfaces. FT-IR spectra confirm the presence of oleylamine through characteristic symmetric and asymmetric CH₂ stretching vibrations, CH₂ deformation bands, and NH₂-related absorption peaks. The preservation of these vibrational features suggests that oleylamine is primarily attached to the nanoparticle surface through weak physical adsorption rather than strong covalent bonding. The organic surface layer plays a critical role in maintaining colloidal stability and preventing nanoparticle aggregation.

Both the typical and reversing forms exhibit the expected properties of moderate FM behavior and interfacial magnetic coupling. The field-cooled cycles are moved horizontally and vertically. Nevertheless, changes in blocking heat and interfacial magnetic coupling processes may be identified, as described following [23].

Field-cooled (FC) loops are contrasted to zero-cooled (ZFC) loops. The usual arrangement has a loop shape, but the inverted configuration exhibits two parabolic-like branches in the hysteresis loop [24]. The differences align with the TEM results. The FM duration shifts with the impact of the AF exchange field because, according to the normal setup, the AF NPs are large enough to remain constant in their FC conditions throughout the reversed procedure. This results in a more conventional cycle similar to an FM stage with interfacial magnetic coupling. The inversion form states that both stages have small dimensions and are therefore more successfully connected due to the relatively large contacting region. During the magnetization reversal process, it is difficult to distinguish between the magnetic contributions of the FM and AFM phases.

The exchange bias field (H_{ex}) and coercive field (H_c) were calculated from the horizontal displacement and half-width of the hysteresis loop using in Equations (1) and (2) [25].

Field-cooled hysteresis loops exhibit both horizontal displacements (exchange bias field, H_{ex}) and, in some cases, vertical shifts associated with frozen uncompensated spins at the AFM interface. Exchange bias in FM/AFM nanostructures originates from exchange coupling between reversible ferromagnetic spins and pinned or partially pinned antiferromagnetic spins at the interface. In nanoscale systems, structural roughness, lattice mismatch, oxygen vacancies, and surface disorder often generate uncompensated AFM moments that remain fixed during magnetization reversal. In $\gamma\text{-Fe}_2\text{O}_3/\text{CoO}$ nanoparticles, the relatively large CoO domains behave as magnetically rigid components at low temperature, thus imposing a unidirectional anisotropy on the softer $\gamma\text{-Fe}_2\text{O}_3$ phase during field-cooling. This results in a horizontal shift of the hysteresis loop and a moderate increase in coercivity.

For the inverted $\text{CoO}/\gamma\text{-Fe}_2\text{O}_3$ configuration, both phases approach the superparamagnetic size regime, and partial rotation of AFM spins during field cycling cannot be excluded. Such dynamic AFM behavior reduces the effective pinning strength and leads to more complex loop shapes without well-defined saturation plateaus. The observation of vertical loop shifts further indicates the presence of frozen uncompensated interfacial spins, which contribute an additional magnetization offset. These two phenomena, horizontal and vertical shifts, therefore reflect distinct microscopic origins: unidirectional exchange anisotropy and pinned interfacial magnetic moments, respectively.

When the $\gamma\text{-Fe}_2\text{O}_3$ phase reverses in the traditional configuration, the relatively large CoO domains maintain their magnetic stability, resulting in a classic exchange-biased loop structure. Partial reversal of the antiferromagnetic component during field cycling cannot be ruled out in the inverted architecture, where both FM and AFM regions are nanometric. This situation explains the more intricate hysteresis forms seen in experiments and would naturally obscure

the difference between fixed and reversible interfacial spins.

The development of interfacial exchange anisotropy, a feature that is technologically relevant for pinning layers in spin-valves and magnetoresistive memory devices, is further supported by the 5–16% increase in coercivity under field-cooled conditions compared to zero-field-cooled measurements.

The coexistence of horizontal and vertical loop shifts confirms the simultaneous contribution of exchange anisotropy and frozen uncompensated interfacial spins. Although the individual contributions cannot be completely separated from the present hysteresis measurements, the observed loop displacements and coercivity enhancement provide strong evidence of interfacial exchange coupling in both heterostructures. Field-cooled hysteresis loops exhibit coercivity increases of approximately 5–16% compared with the corresponding zero-field-cooled loops, further supporting the development of exchange anisotropy.

Measurements of temperature-dependent magnetization offer further information about the stability of interfacial exchange coupling. Thermal variations gradually disrupt AFM spin order as the temperature gets closer to the CoO Néel temperature, which lowers the exchange bias field and coercivity. Enhanced anisotropy in the CoO domains maximizes the pinning effect on the $\gamma\text{-Fe}_2\text{O}_3$ phase at low temperature by suppressing spin rotation. On the other hand, at room temperature, thermal activation and decreased AFM anisotropy encourage partial interfacial spin reversal, which reduces the amount of loop displacement. These findings emphasize how crucial operating temperature is for creating oxide-based pinning layers for magnetic tunnel junctions or spin-valves, particularly for systems meant to operate close to ambient conditions.

The growth of exchange anisotropy has been linked to an elevation of H_c levels in exchange-biased structures, which is easy to comprehend. In an exchange-biased structure, looping displacement occurs when the relationship of power among ferromagnetic and antiferromagnetic stages is weaker than the anisotropic power

of the AF sheet, allowing it remaining stationary throughout FM reversion.

In addition to their magnetic characteristics, CoO-containing heterostructures may serve as optical scattering media in phosphor-converted white LEDs. To explore this multifunctional potential, optical simulations were performed to evaluate the influence of CoO particle size on light scattering, color stability, luminous flux, and color-rendering performance. The following results provide insight into the applicability of CoO particles in photonic systems beyond their magnetic functionality.

In Figures 3–8, the label “GEP particle size” refers to the size of CoO scattering particles used in the optical simulation. For consistency, all discussions in this work refer to this parameter as the CoO particle size. Figures 1 and 2 show the relationship between light dispersion and CoO particle sizes (1–19 μm). Figure 1a illustrates the scattering distribution for CoO particles with sizes ranging from 1 to 9 μm . The scattering pattern is relatively broad, indicating increased angular dispersion and stronger light diffusion. Figure 1b presents a magnified view of the forward-scattering region for small particle sizes. It can be observed that increasing particle size gradually enhances forward light propagation. Figure 2a shows the scattering behavior of larger CoO particles (11–19 μm). Compared with smaller particles, the scattering pattern becomes more concentrated in the forward direction. Figure 2b provides an enlarged view of the forward-scattering region for larger particles. The results indicate that larger CoO particles improve forward scattering efficiency and reduce backward scattering, thereby contributing to enhanced luminous performance and color uniformity in WLED structures. It improves CoO performance through improved wavelength conversion efficiency and light transmission. Blue light brightness can be increased by reducing forward scattering and reabsorption while increasing forward emission dispersion. This is accomplished by increasing the particle size of CoO while lowering the quantity of yellow phosphorus. Similarly, determining the optimal color temperature (CCT) is challenging. Figure 3 indicates that the YAG:Ce yellow phosphor dosage increases proportionally to the CoO dose. Figure 3 shows

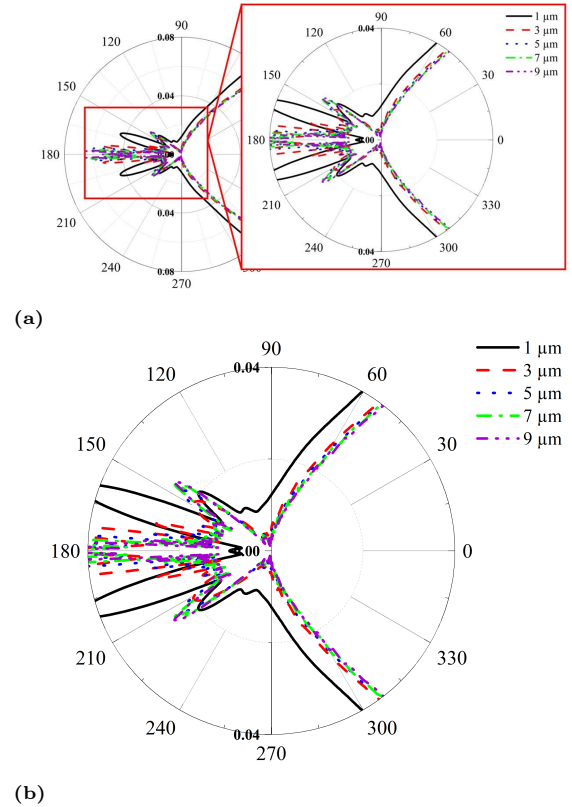


Figure 1: (a) Scattering pattern of 1–9 μm CoO particles; (b) Magnified view of forward scattering.

that increasing CoO particle sizes (1–19 μm) decreases the YAG:Ce phosphor ratio from over 25.5% to about 27%. Figures 4 and 5 show that the CCT value is not concentration dependent. Figure 4 shows how increased doping lowers a phosphor’s CCT variance. CCT data indicate a peak at about 3050 K for CoO particles of 9 μm and a minimum at about 2970 K for CoO particles of 1 μm . Figure 5 shows the D-CCT reaching its lowest value of ~ 25 K at 13 μm of CoO, about 309 K lower than the maximum value of ~ 334 K at 5 μm of CoO.

CoO does not always make white light emissions brighter, as Figure 6 illustrates. A CoO particle size of 9 μm produced the highest result (~ 73.75 lm), whereas a particle size of 1 μm produced the lowest result (~ 67.34 lm). Reduced blue emission and an uneven color distribution result from increased backscattering and reabsorption. Larger CoO particles allow the phos-

Table 1: Result comparison of scattering coefficients influenced by particle sizes of scattering materials.

Scattering Materials	Scattering coefficients (mm ⁻¹)	Reduced scattering coefficients (mm ⁻¹)	References
CoO	8,49	1,55	This work
ZnO	133,99	11,36	(Le et al., 2024)
KBr	42,5	13,5	(N. D. Q. Anh et al., 2025)
TiO ₂	129,4	39,3	(Anh and Lee, 2024)

Table 2: Comparative tables of this research results with reported research.

Scattering Materials	YAG:Ce ³⁺ (%)	CCT (K)	D-CCT (K)	CRI	CQS	Lumen (lm)	References
CoO	27,5	3000	25,36	56,16	42,67	73,75	This work
ZnO	12,5	4000	28,85	57,75	64,13	125,7	(Le et al., 2024)
KBr	27,4	3000	35,4	56,2	42,4	73,7	(N. D. Q. Anh et al., 2025)
TiO ₂	10,6	4000	49,6	54,5	63,3	118,81	(Anh and Lee, 2024)

phor to turn yellow or orange-red when exposed to more backscattered blue light. Only a particular size of CoO particles can be covered by the phosphor coating. A shorter emission spectrum would arise from the multiple reflections caused by the shifting light from different objects. To put it another way, a high phosphor dose may raise the percentage of converted light that is reflected back, increasing CCT while lowering luminous intensity. Figure 6 shows how brightness and color uniformity are improved when 9 μm of CoO is added to a simulated WLED with a lumen output power of about 73 lm. The effects of varying CoO particle sizes on white LED brightness and color rendering are depicted in Figures 7 and 8. Use the color rendering indicator (CRI) and color quality scale (CQS) to test color rendition proportions between 1 and 19 μm . CoO particle sizes increased significantly from 55.3% to 56.13% with the CRI value and from around 34.03% to roughly 42.31% with the CQS value. The erratic nature of blue, green, and yellow-orange could be the cause of CRI and CQS reductions. Increased dispersion, a tilt toward the yellow-orange spectrum, and irregular light emission are the outcomes of large CoO particle sizes. We will modify this phosphor's

CRI and CQS while considering other factors like particle size as we assess the outcomes.

Table 1 compares the scattering coefficients and reduced scattering coefficients of different materials influenced by particle size. In this work, CoO shows moderate scattering performance, with a scattering coefficient of 8.49 mm⁻¹ and a reduced scattering coefficient of 1.55 mm⁻¹. Compared with CoO, ZnO (Le et al., 2024) and TiO₂ (Anh and Lee, 2024) exhibit much stronger scattering abilities, with values as high as 133.99/11.36 mm⁻¹ for ZnO and 129.4/39.3 mm⁻¹ for TiO₂. KBr (N. D. Q. Anh, 2025) also demonstrates strong scattering, with coefficients of 42.5 mm⁻¹ and 13.5 mm⁻¹. These results indicate that while CoO has weaker scattering compared to ZnO, TiO₂, and KBr, its moderate values may still contribute to controlled scattering effects where excessive light diffusion is undesirable.

Table 2 evaluates the optical performance of scattering materials in YAG:Ce³⁺-based white LEDs. In this work, CoO achieves a YAG:Ce³⁺ conversion of 27.5%, a stable CCT of 3000 K, and a low ΔCCT of 25.36 K, indicating strong color stability. Its CRI (56.16) and CQS (42.67) are comparable to those of KBr (56.2 and 42.4),

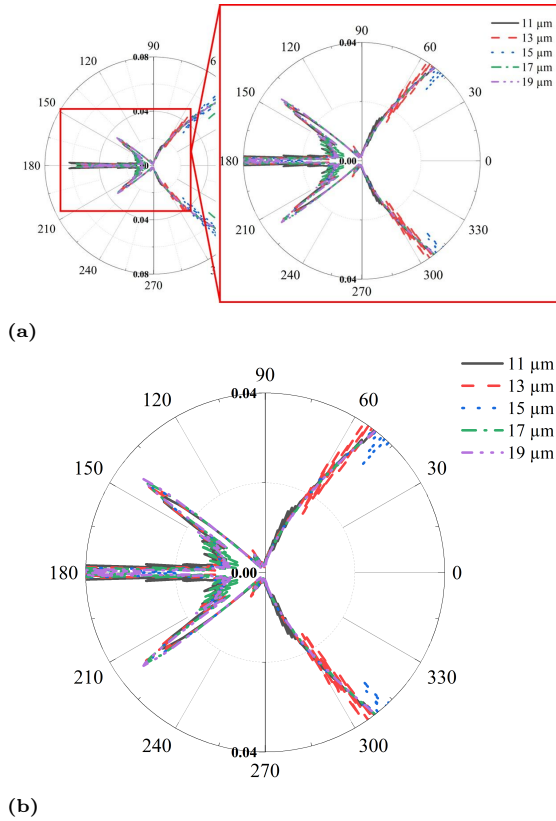


Figure 2: (a) Scattering pattern of 11–19 μm CoO particles; (b) Magnified view of forward scattering.

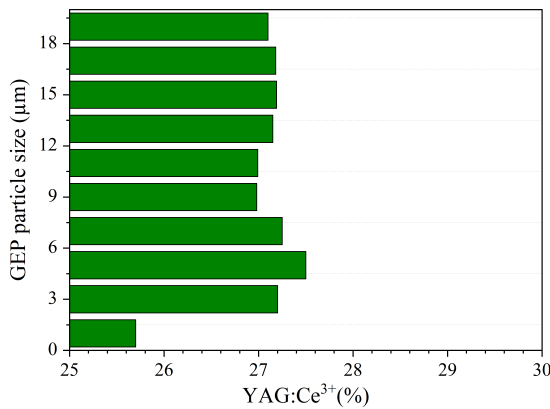


Figure 3: YAG:Ce phosphor proportion values for different CoO particle sizes.

while its luminous flux of 73.75 lm is nearly identical to KBr's 73.7 lm. ZnO (Le et al., 2024) provides significantly higher luminous flux (125.7 lm) and CQS (64.13), but at the cost

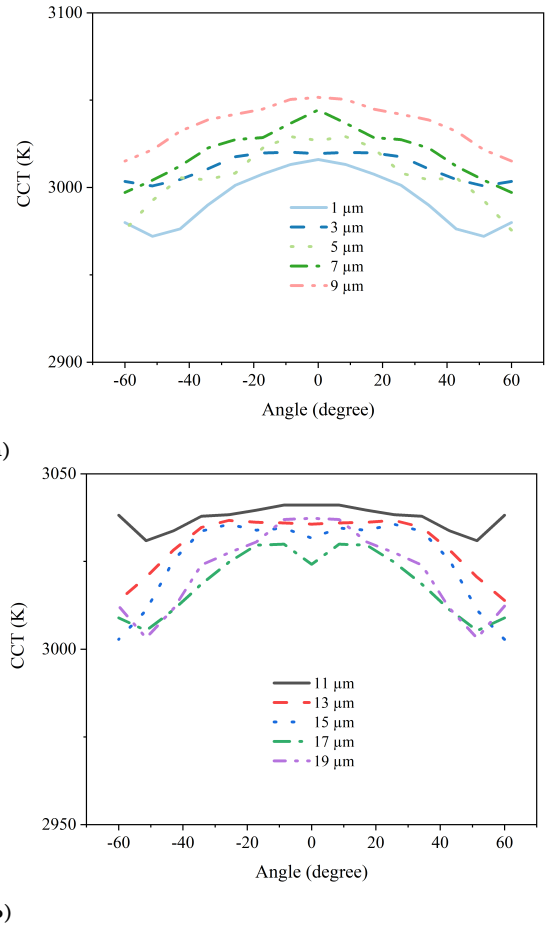


Figure 4: Angle-dependent CCT distributions for different CoO particle sizes.

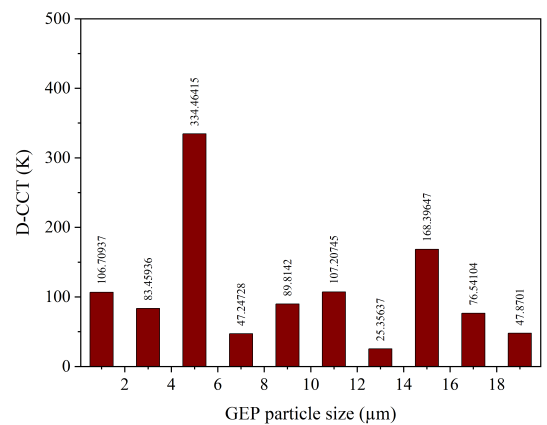


Figure 5: Color difference values for different CoO particle sizes.

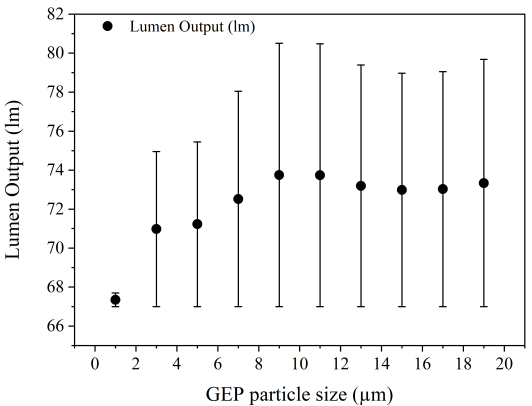


Figure 6: Luminous flux for different CoO particle sizes.

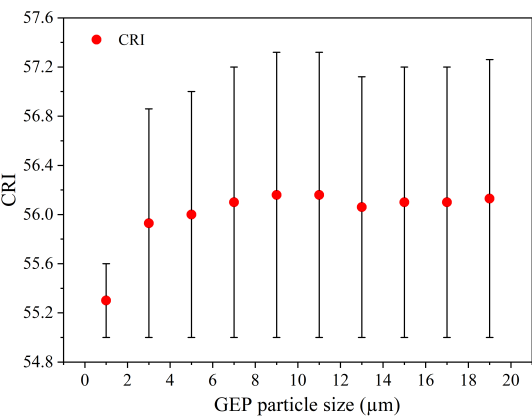


Figure 7: CRI values for different CoO particle sizes.

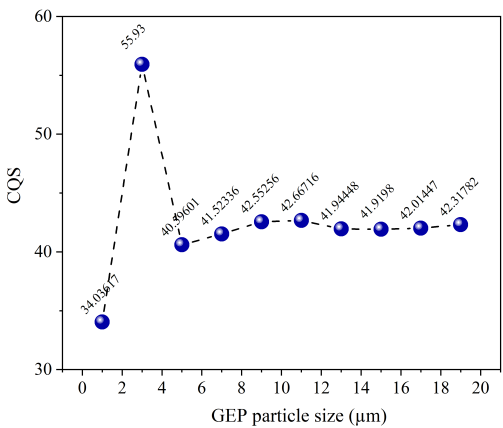


Figure 8: CQS values for different CoO particle sizes.

of lower YAG:Ce³⁺ conversion (12.5%). Similarly, TiO₂ (Anh and Lee, 2024) produces higher brightness (118.81 lm) and strong CQS (63.3), but with reduced conversion efficiency (10.6%) and greater deviation in color stability (Δ CCT = 49.6 K).

Taken together, these two tables highlight the distinct advantages of the investigated scattering materials. CoO exhibits moderate scattering coefficients compared with the stronger scattering behavior of ZnO, TiO₂, and KBr; however, it provides a balanced optical performance characterized by excellent color stability, low Δ CCT values, and consistent luminous output. Although ZnO and TiO₂ achieve higher luminous flux and color quality metrics, CoO demonstrates superior stability and maintains satisfactory optical performance over a wide range of operating conditions. These characteristics make CoO a promising scattering material for phosphor-converted white LEDs, particularly in applications where color consistency and optical reliability are more important than maximum luminous efficacy.

Although the primary focus of this work lies in magnetic nanostructures for spintronic applications, optical simulations reveal that CoO particles can simultaneously function as scattering centers in phosphor-converted white LEDs. The moderate scattering coefficients obtained for CoO relative to ZnO or TiO₂ indicate that this material provides controlled forward scattering rather than excessive diffusion, thereby improving color uniformity while preserving luminous efficiency.

The dependence of Δ CCT and luminous flux on particle size suggests the existence of an optimum regime around 9–13 μ m, where forward scattering dominates over back-reflection. This behavior is consistent with Mie-type scattering models for dielectric particles whose dimensions are comparable to the wavelength of visible light.

The solution-processed γ -Fe₂O₃/CoO and CoO/ γ -Fe₂O₃ nanoparticles described here are especially well suited for lithographically patterned structures, thin films, and polymer matrices. In theory, seed particle size, secondary phase thickness, annealing and field-cooling conditions, and interfacial crystallinity can all be

adjusted to modify the exchange bias's amplitude. For the development of low-power spin-logic devices, magnetic sensors, and nanoscale pinning layers, all of which require stable and controllable anisotropy fields, such tunability is crucial.

5. Conclusion

γ -Fe₂O₃/CoO and CoO/ γ -Fe₂O₃ heterostructures were successfully synthesized using a two-step seeded growth method that allows precise control over phase sequence and interfacial architecture. Structural analysis revealed that the phase deposited in the second step consistently exhibits higher crystallinity, while inverted configurations maximize the FM/AFM contact area. Magnetic measurements demonstrate pronounced exchange bias and coercivity enhancement under field-cooled conditions, originating from the competition between pinned antiferromagnetic spins and reversible ferrimagnetic moments. Structural inversion was shown to play a decisive role in determining interfacial spin stability and hysteresis loop morphology. Optical simulations further indicate that CoO can function as a moderate scattering medium in phosphor-converted white LEDs, suggesting potential multifunctional applications of these oxide heterostructures in hybrid photonic-magnetic devices. Future work will focus on systematic control of shell thickness, interface roughness, and thermal treatments, as well as in-depth temperature-dependent magnetic studies near the Néel point of CoO to optimize these materials for next-generation spintronic and magneto-optical platforms. Beyond their magnetic properties, the investigated heterostructures also exhibit promising optical scattering characteristics, suggesting potential applications in multifunctional magneto-phonic systems.

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