Sol–Gel Route for the Synthesis of CoFe\textsubscript{2−x}Er\textsubscript{x}O\textsubscript{4} Nanocrystalline Ferrites and the Investigation of Structural and Magnetic Properties for Magnetic Device Applications

Minhajul Islam, M. Khalilur Rahman Khan, Alok Kumar, M. Mozibur Rahman, Md. Abdullah-Al-Mamun, Rimi Rashid, Md. Mahbubul Haque, and Md. Samiul Islam Sarker

ABSTRACT: This study reports the formation of Er-doped nanocrystalline cobalt ferrite with the formula CoFe\textsubscript{2−x}Er\textsubscript{x}O\textsubscript{4} (0.0 ≤ x ≤ 0.10) from nontoxic metal precursors Co(NO\textsubscript{3})\textsubscript{2}·6H\textsubscript{2}O, Fe(NO\textsubscript{3})\textsubscript{3}·9H\textsubscript{2}O, and Er(NO\textsubscript{3})\textsubscript{3}·5H\textsubscript{2}O through an easy and economical sol–gel route in which citric acid is served as the chelating agent. The as-prepared powder was annealed at 700 °C for 3 h in ambient air to get the required spinel structure. The annealed samples were subjected to structural and magnetic characterization. The X-ray diffraction (XRD) data of the samples confirmed the cubic spinel structure formation. The average crystallite size evaluated from XRD data increased from 21 to 34 nm with the substitution of Er due to the larger atomic size of Er\textsuperscript{3+} than Fe\textsuperscript{3+}. Moreover, the crystallite size obtained from XRD data are well matched with the particle size measured from transmission electron microscopy images. The lattice parameters obtained from XRD data agree well with the values estimated from theoretical cation distribution and Rietveld refinement calculation. The hysteresis curve exhibits the particles are soft ferromagnetic and the coercivity increased from 54.7 to 76.6 kA/m with maximum saturation magnetization, \(M_s = 61 \text{ emug}^{-1}\) for 0.10 Er content. The squareness ratios were found to be less than 0.5, which indicates the single-domain nature of our particles. The blocking temperature measured from field cooled-zero field cooled curves is \(T_B > 350 \text{ K}\) for all the samples, which is much higher than the room temperature (300 K). The enhancement of saturation magnetization and coercivity has been explained based on the crystallite size, anisotropy constant, and cation distribution. Thus, the structural and magnetic properties of CoFe\textsubscript{2}O\textsubscript{4} nanoparticles (NPs) can be tuned by Er incorporation and these NPs can be applied in different soft magnetic devices.

1. INTRODUCTION

There is a growing interest in magnetic materials and magnetic oxides owing to their variety of applications. Researchers have given special importance to nanosized soft ferromagnets because of their potential applications in power generation, data storage, magnetic diagnostics, magnetic shielding, and so on.\textsuperscript{1,2} Among different magnetic materials, spinel cobalt (Co) ferrites have drawn continuous attention because of their soft ferromagnetic nature with high electromagnentic performance and exceptional physical properties.\textsuperscript{3,4} The common form of the spinel ferrite structure is \((A^{2+})(B^{3+})\text{O}_4^{2−}\), where the divalent \(A^{2+}\) and trivalent \(B^{3+}\) cations are occupied in the tetrahedral (A) and octahedral (B) sites. The face-centered structure of ferrite arises from the formulation of cations and oxygen anions. When the divalent cations occupy the tetrahedral sites, it forms the normal spinel structure. On the other hand, inverse spinel ferrite is formed when a divalent cation occupies both the tetrahedral and octahedral sites. The physical properties of CoFe\textsubscript{2}O\textsubscript{4} strongly depend on substituting materials, annealing temperature, grain size, and also on the synthesis method. The replacement of trace amounts of rare earth ions on cobalt ferrites can alter their magnetic behaviors, which makes them suitable for hyperthermia applications.\textsuperscript{5} The magnetic and dielectric properties of cobalt ferrite rely on the cation distribution, and the properties can be modified by wavering the location of cations in the interstitial sites. Among the rare earth ions, Er\textsuperscript{3+} is chosen as the doping material as it has a relatively higher magnetic moment (7 \(\mu_B\)) than Fe\textsuperscript{3+} (5.92 \(\mu_B\)). The magnetic properties of CoFe\textsubscript{2}O\textsubscript{4} are strongly affected by the spin coupling of the 3d electrons (Fe\textsuperscript{3+}–Fe\textsuperscript{3+} interactions). For example, the substitution of rare earth ions, such as Er\textsuperscript{3+} (4f electrons) to Fe\textsuperscript{3+} (3d electrons), yields spin coupling of 3d–4f electrons (Re\textsuperscript{3+}–Fe\textsuperscript{3+} interactions).

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actions), which may lead to changes in the magnetic properties of CoFe$_2$O$_4$. The alteration of magnetization and coercivity were reported for Sn-doped cobalt ferrite and Er-doped nickel-zinc ferrite nanoparticles (NPs). Moreover, the improved dielectric properties were reported for Ho-substituted nanocobalt ferrite. Besides, doping of rare earth ions such as Ce$^{3+}$, Dy$^{3+}$, Y$^{3+}$, Ho$^{3+}$, Sm$^{3+}$, Nd$^{3+}$, and Er$^{3+}$ into the ferrite has changed the structural and magnetic parameters.

Different synthesis techniques such as sol–gel, sol–gel-assisted auto combustion, microemulsion, sonochemical, co-precipitation, and hydrothermal have been used to synthesize nanocrystalline Co spinel ferrites. Among them, the sol–gel route is convenient due to its easy preparation, cost effectiveness, and better control of size. During the last 2 decades, a large number of research reports on nanosized CoFe$_2$O$_4$ have been reported using the sol–gel method. However, magnetic studies of Er-doped cobalt ferrites with cation distribution have been rarely reported. Accordingly, in this work, we investigate the effect of Er$^{3+}$ substitution on the microstructural and magnetic properties of nanosized CoFe$_{2-x}$Er$_x$O$_4$ ($x = 0, 0.05$, and $0.10$) powders synthesized through the sol–gel route.

2. MATERIALS AND METHODS

The Er-doped spinel cobalt ferrite with the general formula CoFe$_{2-x}$Er$_x$O$_4$ ($x = 0, 0.05$, and $0.10$) was synthesized through the conventional sol–gel route. The stoichiometric amounts of $2.328$ gm of (0.1 M) Co(NO$_3$)$_2$·6H$_2$O (98%, Loba Chemie), $6.464$ gm of (0.2 M) Fe(NO$_3$)$_3$·9H$_2$O (98%, Merck), and $5.067$ gm of (0.3 M) Er(NO$_3$)$_3$·5H$_2$O (99.9%, Sigma-Aldrich) were mixed with $80$ mL of ethanol. The citric acid was added as the chelating agent. The molar ratios of the raw materials are shown in Table 1.

![Figure 1](https://example.com/image1.png)

Table 1. Characteristics of the Synthesizing Materials

| sample | Er content, x | Co/Fe/citric acid molar ratio |
|--------|---------------|-----------------------------|
| 1      | 0             | 1:2:3                       |
| 2      | 0.05          | 1:1.95:3                    |
| 3      | 0.10          | 1:1.90:3                    |

Then, the mixture was homogenized by stirring magnetically for $2$ h using a laboratory water bath at $80$ °C for gel formation. Then, the sample was dried at $150$ °C for $12$ h in an electric microwave oven to completely swell the xerogel. The reticular substance was found after heating at $250$ °C for $3$ h. The substance was ground to powder in an agate mortar. Then, the powder was annealed at 700 °C for $3$ h in ambient air using a high-temperature furnace to obtain the desired nanopowder sample. Figure 1 shows the different steps of synthesis.

The thermogravimetric analysis (TGA) along with the differential thermal analysis (DTA) was performed using Pyris Series-STA-8000 on the ferrite powder to obtain its phase transition temperature. Structural analysis was performed by using a Philips X’Pert Pro X-ray diffractometer (operating at a
temperature of 25 °C, at a voltage of 40 kV, and a current of 30 mA) with Cu-Kα (λ = 1.5406 Å) radiation. Morphological analysis was performed by using scanning electron microscopy (SEM) (ZEISS EVO-18). The transmission electron microscopy (TEM) (Talos F200X, Thermo Fisher Scientific) images of the samples were taken to measure the size of the particles. The magnetic properties were investigated through a physical property measurement system (PPMS) with an applied magnetic field ±2T.

3. RESULTS AND DISCUSSION

3.1. Thermal Analysis. Figure 2 shows the TGA and DTA curves for the CoFe2O4 sample. The TGA curve shows about 70% weight loss at 530 °C. First, 8% weight loss of the sample was observed for moisture from 30 to 180 °C, and then it dropped about 20% weight at 250 °C. Similar weight loss for CoFe2O4 was reported by Rajput et al.21 The major weight loss from 350 to 530 °C has been attributed to the fragmentation of organic compounds and nitrates. As expected, the decomposition reaction is strongly exothermic and conversions of hydroxides into metal oxides occur in the abovementioned temperature range.22 The stable phase was observed beyond 550 °C in the TGA curve.

In the DTA curve, crystal phase formation peaks were observed at 324 and 370 °C. The exothermic peak at 370 °C indicates the decomposition of organic compounds in the structure due to the crystallization of the spinel ferrite.22 The area enclosed by the dashed line indicates the stable phase.

3.2. Structural Properties. Figure 3 shows the X-ray diffraction (XRD) patterns of undoped and Er-doped CoFe2O4 powder samples (CoFe2−xErxO4, x = 0, 0.05, and 0.10) annealed in ambient air at 700 °C for 3 h. Structural properties, for instance, the lattice constant, crystalline size, and other features, were obtained from XRD data. The major reflection peaks of all the planes for different compositions shown (Figure 3) correspond to the cubic spinel phase having an Fd3̅m space group (JCPDS card no. 22-1086).23,24 An insignificant amount of the orthoferrite (ErFeO3) phase is found for Er-doped ferrite (x = 0.05 and 0.10). The secondary phase formation was also reported for Er3+, Eu3+, and Ho3+-doped ferrites.3,25,26 The heating of iron oxide is prone to forming a hematite phase.27 Therefore, the formation of alpha ferrite is conceivable.

All the XRD patterns were fitted with the Rietveld refinement using the FullProf program, and the corresponding spectra are given in Figure 4. The Rietveld refined values of the lattice parameters are given in Table 2. The crystallite size (D), Rietveld refined (Drefit) crystallite size, cell volume (V), X-ray density (ρx), lattice strain (ε), dislocation density (δ), and packing factor (p) of the samples are given in Table 3.

| Er content, x | D−S method | W−H method | Drefit | V (Å³) | ε | δ (×10⁻⁴) | 1/(Å²) | ρx (gm/cc) | p |
|---------------|-------------|-------------|--------|--------|---|-----------|-------|-------------|---|
| 0.00          | 21          | 18          | 14     | 578.84 | 0.1583 | 13.54 | 5.385 | 108.46     |
| 0.05          | 24          | 22          | 17     | 579.89 | 0.1581 | 11.84 | 5.503 | 120.67     |
| 0.10          | 34          | 31          | 32     | 584.07 | 0.1574 | 8.28  | 5.590 | 167.27     |

Figure 4. Rietveld refinement of XRD patterns for CoFe2−xErxO4, x = 0 (a), 0.05 (b), and 0.10 (c) samples.

Table 2. Chemical Formula, Cation Distribution, Theoretical (aθth), Experimental (aθexpt), and Rietveld Refined (aθriet) Lattice Parameters

| chemical formula | A-site | B-site | aθ (Å) | aθ (Å) | aθ (Å) | aθ (Å) |
|------------------|--------|--------|--------|--------|--------|--------|
| CoFe2O4 (for x = 0) | Co0.3Fe0.7 | [Co0.7Fe1.3]O4 | 0.651 | 0.645 | 8.275 | 8.353 | 8.362 |
| CoFe1.95Er0.05O4 (for x = 0.05) | Co0.33Fe0.67 | [Co0.67Er0.05Fe1.28]O4 | 0.650 | 0.656 | 8.302 | 8.339 | 8.341 |
| CoFe1.90Er0.10O4 (for x = 0.10) | Co0.36Fe0.64 | [Co0.64Er0.1Fe1.26]O4 | 0.649 | 0.661 | 8.314 | 8.358 | 8.369 |

Table 3. Crystallite Size (D), Rietveld Refined (Drefit) Crystallite Size, Cell Volume (V), X-ray Density (ρx), Lattice Strain (ε), Dislocation Density (δ), and Packing Factor (p) of the Samples
constant and crystallite size are also obtained and listed in Tables 2 and 3. The results obtained from refinement are correlated with the values calculated from the XRD analysis as given below.

The crystalline size, \( D \), was estimated from XRD data using the Debye–Scherrer (D–S) formula

\[
D = \frac{0.94\lambda}{\beta \cos \theta}
\]

(1)

where \( \lambda \) is the wavelength of the radiation and \( \beta \) is the full width at half-maximum. The crystalline size, \( D \), was also calculated from the Williamson–Hall (W–H) plot (Figure 5) using the W–H method. The \( D \) values are listed in Table 3. Figure 6 shows the increase in the crystalline size with Er content for both the D–S estimation and the W–H calculation.

Moreover, the value of the lattice constant from XRD data can be calculated as follows:

\[
a_{\text{expt}} = d_{\text{hkl}}\sqrt{h^2 + k^2 + l^2}
\]

(2)

where \( d_{\text{hkl}} \) is the interplanar spacing of the crystal system. The variation of the lattice parameter with Er content is shown in Figure 7. It is seen that the lattice constant first decreases and

Figure 5. W–H plot of CoFe\(_2\)–Er\(_x\)O\(_4\) (\( x = 0.00, 0.05, \) and 0.10) samples’ XRD peaks for crystalline size calculation.

Figure 6. Variation of crystalline size with Er concentration.

Figure 7. Variation of experimental (\( a_{\text{expt}} \)) and theoretical (\( a_{\text{th}} \)) lattice parameters.
then increases with the increase of Er content. Er$^{3+}$ has a tendency to occupy in the octahedral sites due to the larger ionic radius (0.89 Å) than Fe$^{3+}$ ions (0.66 Å). Subsequently, lattice distortion occurs in the grain boundary due to the diffusion of Er$^{3+}$ ions.\textsuperscript{25} The lattice constants can also be estimated theoretically from the following cationic distribution equation given as 

\[
a_{th} = \frac{8}{3\sqrt{3}} [r_A + R_O] + \sqrt{3} [r_B + R_O]
\]

where $R_O$ is the radius of the oxygen ion (1.32 Å) and $r_A$ and $r_B$ are the ionic radius for A- and B-sites' spinel structure.\textsuperscript{30} The values of $r_A$ and $r_B$ will depend critically on the cation distribution of the system. In order to compute $r_A$ and $r_B$, the following cation distribution is proposed for the composition of CoFe$_{2-x}$Er$_x$O$_4$: [Co$^{2+}$Fe$^{3+}$]$_A$[Co$^{2+}$Fe$^{3+}$Er$^{3+}$]$_B$O$_{4-2x}$, where A- and B-sites represent the tetrahedral and octahedral position, respectively. In the present case, CoFe$_2$O$_4$ is an inverse spinel structure in which half of the ferric ions preferentially occupy the tetrahedral (A-sites) and the other half occupy the octahedral sites (B-sites).\textsuperscript{31} On the other hand, paramagnetic Er ions prefer to occupy the octahedral site for their larger ionic radius (0.89 Å) as compared to the ionic radius of Fe$^{3+}$ (0.66 Å). Thus, the values of $r_A$ and $r_B$ can be calculated from the cation distribution of the cubic spinel system by the following equations\textsuperscript{32}

\[
r_A = C_{AFr}(Fe^{3+}) + C_{AFr}(Er^{3+})
\]

\[
r_B = \frac{1}{2}[C_{BFe}(Fe^{3+}) + C_{BFe}(Er^{3+}) + C_{BCo}(Co^{2+})]
\]

The magnetic behavior of ferrites can be explained with the help of cation distribution.\textsuperscript{33} The ionic radius for Co, Fe, and Er are 0.63, 0.66, and 0.89 Å, respectively. The chemical formula, cation distribution of A- and B-sites, and theoretical and experimental lattice parameters attained from XRD data are listed in Table 2.

Figure 7 shows the theoretical lattice constant disagrees with the experimental lattice constant. This can be understood as follows. In theoretical calculation, cationic arrangements are regular and well distributed, but in the experimental case, defects and thermal effects along with synthesis conditions, fairly affect the lattice parameter.

Lattice strain gives information about the ordination of lattice constants, namely the lattice dislocations, which originate from crystal imperfections. To describe the variation in the strain and dislocation density, we calculated the packing factor (Table 3). It is seen from Tables 2 and 3 that the crystallite size, X-ray density, and packing factor increase with Er content but the lattice strain and dislocation density decrease with doping of Er. Similar results were reported by Kumar et al.\textsuperscript{29}

3.3. Morphology. Figure 8 shows the SEM images of Er-doped CoFe$_2$O$_4$ samples annealed at 700 °C for 3 h in ambient air. It is seen from the micrographs of all the samples that the micron-sized crystallites are dispersed and also reveal the polycrystalline nature.\textsuperscript{24}

Figure 9 shows the TEM images, selected area electron diffraction (SAED) patterns and energy-dispersive X-ray spectroscopy (EDS) spectra of CoFe$_{2-x}$Er$_x$O$_4$ ($x = 0, 0.05,$ and 0.10). The average particle sizes are estimated using ImageJ software and found to be 16, 24, and 29 nm, respectively, for $x = 0, 0.05,$ and 0.10. Moreover, the particle sizes are well matched with the crystallite size measured from XRD data.

The corresponding SAED patterns for all the samples are composed of (111), (220), (311), (222), (400), (422), (511), and (440) diffraction rings.\textsuperscript{25} The ring pattern in SAED images shows the crystalline nature of the particles. The calculated values of lattice parameters from the SAED patterns by measuring d-spacing values using ImageJ software are 8.343, 8.337, and 8.351 Å for $x = 0, 0.05,$ and 0.10, respectively, which

![Figure 8. SEM images of the CoFe$_{2-x}$Er$_x$O$_4$ for $x = 0.00, 0.05$, and 0.10 samples annealed at 700 °C.](image-url)
the XRD calculation (Table 2). The EDS spectra of CoFe$_{2−x}$Er$_x$O$_4$ ferrite samples in Figure 9 show the existence of Fe, Co, and O for $x = 0$ and the presence of Fe, Co, O, and Er for $x = 0.05$ and 0.10 samples. No magnetic impurity is detected in the samples, and the C and Cu peaks come from the copper microgrid. The molar ratios obtained from the EDS spectra are tabulated in Table 4. It is seen that there is a close proximity between nominal and experimental composition.

### 3.4. Magnetic Properties

The hysteresis loop of the Er-doped CoFe$_2$O$_4$ NPs measured at room temperature is shown in Figure 10. The saturation magnetization ($M_s$) increases for the increasing of Er content, and the maximum value is found to be 61 emu g$^{-1}$ for the 0.10 content of Er. Moreover, the magnetic coercivity ($H_c$) values increase with the increase of Er substitution, and the values are 54.7, 60.2, and 76.6 kA/m (580, 730, and 1001 Oe) for 0.00, 0.05, and 0.10 compositions, respectively.

The microstructure of the NPs influences their magnetic properties. More explicitly, the magnetic properties of ferrites truly depend on the particle size, cation distributions, A–B interactions, and doping elements.\(^5,34\) The increase of saturation magnetization reported with nonmagnetic Zn doping in the CoFe$_2$O$_4$ matrix is due to the switching of Fe$^{3+}$ ions to the octahedral B-sites from tetrahedral A-sites.\(^35\) Besides, Abdallah et al.\(^36\) reported that the modification of crystallite size and preference of Fe$^{3+}$ ions at octahedral sites is responsible for the

| Table 4. Molar Values of the Elements Present in CoFe$_{2−x}$Er$_x$O$_4$ ($x = 0$, 0.05, and 0.10) Samples |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| element | nominal | experimental | nominal | experimental | nominal | experimental |
|---|---|---|---|---|---|---|
| O | 4.00 | 3.95 | 4.00 | 3.94 | 4.00 | 3.93 |
| Fe | 2.00 | 1.90 | 1.95 | 1.91 | 1.90 | 1.85 |
| Co | 1.00 | 1.13 | 1.00 | 1.10 | 1.00 | 1.07 |
| Er | 0.00 | 0.00 | 0.05 | 0.04 | 0.10 | 0.13 |

correspond to the XRD calculation (Table 2). The EDS spectra of CoFe$_{2−x}$Er$_x$O$_4$ ferrite samples in Figure 9 show the existence of Fe, Co, and O for $x = 0$ and the presence of Fe, Co, O, and Er for $x = 0.05$ and 0.10 samples. No magnetic impurity is detected in the samples, and the C and Cu peaks come from the copper microgrid. The molar ratios obtained from the EDS spectra are tabulated in Table 4. It is seen that there is a close proximity between nominal and experimental composition.

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increase in saturation magnetization. In the present case, as the Er$^{3+}$ ions have preference to hold the octahedral site because of their larger ionic radius as compared to the Fe$^{3+}$; therefore, the Co$^{2+}$ ions may partially transfer to the tetrahedral site by moving the same amount of Fe$^{3+}$ ions from tetrahedral to octahedral sites. Thus, the saturation magnetization, $M_s$, is increased due to the increase of ionic population of Fe$^{3+}$ to the octahedral sites.

Furthermore, the change of coercivity $H_c$ and crystallite size $D$ as a function of Er content are shown in Figure 11a. The increase in coercivity from 54.7 to 76.6 kA/m is observed for an increase in crystallite size from 21 to 34 nm. This increased value of $H_c$, a result of the increased magnetocrystalline anisotropy with the enhancement of crystallite size. Prathapani et al. reported the enhancement of coercivity and found maximum coercivity, $H_c = 65$ kA/m for Er concentration, $x = 0.02$ and thereafter the coercivity decreases. They claimed that the orthoferrite phase pinning the domain wall causes it to suppress the coercivity. However, in the present study, even though the minute orthoferrite phase formation occurs in the doped sample, the increases in crystallite size overcome the domain wall pinning and, subsequently, the coercivity increases.

The magnetocrystalline anisotropy constant, $K$, was calculated by the law of approach method:

$$K = M_s H_c \left( \frac{105}{8} \left(1 - \frac{M}{M_s}\right) \right)$$  

(6)

Here, $M_s$, $H_c$, and $M$ denotes the saturation magnetization, applied magnetic field, and magnetization, respectively. The variation of $K$ for different concentrations of Er is tabulated in Table 5 and the maximum $K$ value was found to be $6.8 \times 10^5$ ergs/cm$^3$ for Er concentration, $x = 0.10$. The magnetocrystalline anisotropy constant, $K$, largely depends on the saturation magnetization value. Also, the anisotropy field $H_k$ for a cubic crystal along with the easy direction [1 0 0] can be obtained using the relation:

$$H_k = \frac{2K}{\mu_0 M_s}$$  

(7)

The calculated $H_k$ values are summarized in Table 5. It is seen that the $H_k$ values increased for doped samples, which resulted in an increase in coercivity.

The net magnetic moment of CoFe$_2$O$_4$ is attributed to the difference in magnetic moments of the cations from the octahedral site and the tetrahedral site. Figure 11b shows the net magnetic moment of CoFe$_2$O$_4$ as a function of Er content. Because Er$^{3+}$ has a higher magnetic moment than Fe$^{3+}$, thus the magnetic moment increases with increasing Er content. The squareness ratio ($M_r/M_s$) gives information about the reorientation of magnetization of the nearest easy axis in the absence of a magnetic field. The values of saturation magnetization, retentivity, squareness ratio, and magnetic anisotropy constant of CoFe$_{2-x}$Er$_x$O$_4$ are tabulated in Table 5. The calculated squareness ratio varies from 0.30 to 0.35, which reveals the anisotropic nature of CoFe$_{2-x}$Er$_x$O$_4$ and also indicates that the CoFe$_{2-x}$Er$_x$O$_4$ ferrites with the increase of Er concentration are more suitable for magnetic memory device applications. The fluctuation of the squareness ratio depends on the crystallite size, domain structure, and the anisotropy of the materials. According to previous investigation, particles show a single-magnetic domain nature for the squareness ratio less than 0.5. On the other hand, the particles become multimagnetic domain in nature. The values of the squareness ratio in the present study are below 0.5. Hence, the particles manifest single-domain behavior.

The field cooled-zero field cooled (FC-ZFC) curves at 100 Oe for CoFe$_{2-x}$Er$_x$O$_4$ ($x = 0, 0.05,$ and 0.10) samples are shown in Figure 12. The blocking temperature, $T_B > 350$ K for all the samples, is much higher than room temperature (300 K). The bifurcation of FC and ZFC magnetization increases with decreasing temperature due to the large anisotropy contribution of CoFe$_{2-x}$Er$_x$O$_4$ ($x = 0, 0.05,$ and 0.10) powder samples.

4. CONCLUSIONS

The structural, morphological, and magnetic properties of the sol–gel-synthesized nanocrystalline CoFe$_{2-x}$Er$_x$O$_4$ ($x = 0, 0.05,$ and 0.10) ferrites were studied. The XRD analysis confirms the
crystalline phase of the cubic spinel structure. The room temperature magnetic measurements show the soft ferromagnetic behavior of the samples. The noticeable change in magnetic properties is influenced by crystallite size and microstructure. The tuning of saturation magnetization, coercivity, squareness ratio, and anisotropy constant is observed due to the increase in crystallite size and the migration of Fe\textsuperscript{3+} ions to the octahedral sides. The FC-ZFC measurements show the blocking temperature is well above 350 K. The obtained NPs may offer potential applications in areas such as magnetic storage devices, magnetic heads and shields, hyperthermia-based therapy, biosensors, and so on.

### Table 5. Magnetic Coercivity ($H_C$), Saturation Magnetization ($M_S$), Magnetic Moment ($n_B$), Retentivity ($M_r$), Squareness Ratio ($M_r/M_S$), Anisotropy Constant ($K$), and Anisotropy Field ($H_K$) Values

| Er content, x | $H_C$ (kA/m) | $M_S$ (emu/g) | $n_B$ (μB/formula unit) | $M_r$ (emu/g) | $M_r/M_S$ | $K \times 10^5$ (ergs/cm\textsuperscript{3}) | $H_K$ (kOe) |
|---------------|--------------|---------------|------------------------|---------------|-----------|--------------------------------|-----------|
| 0.00          | 54.7         | 580           | 41                     | 1.72          | 0.30      | 4.4                        | 21.2      |
| 0.05          | 60.2         | 750           | 60                     | 2.54          | 0.36      | 5.2                        | 21.9      |
| 0.10          | 76.6         | 1001          | 61                     | 2.68          | 0.39      | 6.8                        | 22.5      |

**Figure 12.** FC-ZFC curves for CoFe\textsubscript{2−x}Er\textsubscript{x}O\textsubscript{4} (x = 0, 0.05, and 0.10) samples in a measuring field of 100 Oe.

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## AUTOR INFORMATION

**Corresponding Author**

Md. Samiul Islam Sarker — Department of Physics, University of Rajshahi, Rajshahi 6205, Bangladesh; orcid.org/0000-0002-5399-6150; Email: samiul-phy@ru.ac.bd

**Authors**

Minhajul Islam — Bangladesh Atomic Energy Regulatory Authority (BAERA), Dhaka 1207, Bangladesh; orcid.org/0000-0002-0165-5346

M. Khalilur Rahman Khan — Department of Physics, University of Rajshahi, Rajshahi 6205, Bangladesh

Alok Kumar — Department of Physics, University of Rajshahi, Rajshahi 6205, Bangladesh

M. Mozibur Rahman — Department of Physics, University of Rajshahi, Rajshahi 6205, Bangladesh

Md. Abdullah-Al-Mamun — Department of Physics, Rajshahi University of Engineering & Technology, Rajshahi 6204, Bangladesh

Rimi Rashid — Materials Science Division, Atomic Energy Center, Dhaka 1000, Bangladesh

Md. Mahbubul Haque — Materials Science Division, Atomic Energy Center, Dhaka 1000, Bangladesh

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c00982

**Notes**

The authors declare no competing financial interest.

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