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## Effect of Er doping on the structural and magnetic properties of cobalt-ferrite

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Nanocrystalline particulates of Er doped cobalt-ferrites  $\text{CoFe}_{(2-x)}\text{Er}_x\text{O}_4$  ( $0 \leq x \leq 0.04$ ), were synthesized, using sol-gel assisted autocombustion method. Co-, Fe-, and Er- nitrates were the oxidizers, and malic acid served as a fuel and chelating agent. Calcination ( $400\text{--}600^\circ\text{C}$  for 4 h) of the precursor powders was followed by sintering ( $1000^\circ\text{C}$  for 4 h) and structural and magnetic characterization. X-ray diffraction confirmed the formation of single phase of spinel for the compositions  $x = 0, 0.01$ , and  $0.02$ ; and for higher compositions an additional orthoferrite phase formed along with the spinel phase. Lattice parameter of the doped cobalt-ferrites was higher than that of pure cobalt-ferrite. The observed red shift in the doped cobalt-ferrites indicates the presence of induced strain in the cobalt-ferrite matrix due to large size of the  $\text{Er}^{+3}$  compared to  $\text{Fe}^{+3}$ . Greater than two-fold increase in coercivity ( $\sim 66\text{ kA/m}$  for  $x = 0.02$ ) was observed in doped cobalt-ferrites compared to  $\text{CoFe}_2\text{O}_4$  ( $\sim 29\text{ kA/m}$ ). © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4854915>]

Ferrimagnetic cobalt-based cubic spinels (cobalt-ferrites) possess exotic electrical and magnetic properties that are of importance in various technological applications viz. information storage systems,<sup>1</sup> ferro-fluid technology,<sup>2</sup> magnetic refrigeration,<sup>3</sup> magnetic diagnostics,<sup>4</sup> and magnetostriction.<sup>5</sup> In cobalt-ferrite the presence of doping elements and the thermal history during the synthesis and processing alter the metal ions distribution and hence influence their structural and magnetic properties.<sup>6</sup> The lanthanide series elements/ions have a net magnetic moment that depends upon the number of *f*-orbital electrons; and among them  $\text{Er}^{+3}$  is relatively small in size (89 pm), and has relatively high magnetic moment ( $7 \mu_B$ ).<sup>7</sup> The presence of Er (octahedral site of the lattice) is expected to influence the magnetic anisotropy of the doped cobalt-ferrites due to strong spin-orbit coupling. For the first time, the synthesis of nanocrystalline particulates of Er doped cobalt ferrites— $\text{CoFe}_{(2-x)}\text{Er}_x\text{O}_4$  ( $0 \leq x \leq 0.04$ ), by a sol-gel assisted autocombustion method is reported. In the present work, various concentrations of  $\text{Er}^{3+}$  are substituted in place of  $\text{Fe}^{3+}$  and their effect on the structural and magnetic properties of cobalt-ferrite was investigated.

Nanocrystalline particulates of Er doped cobalt-ferrites with nominal compositions  $\text{CoFe}_{(2-x)}\text{Er}_x\text{O}_4$  ( $0, 0.01, 0.02, 0.03$ , and  $0.04$ ) were synthesized by sol-gel assisted autocombustion method. The metal precursors used were  $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ ,  $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$  and  $\text{Er}_2\text{O}_3$ .  $\text{Er}_2\text{O}_3$  was brought into solution,  $\text{Er}(\text{NO}_3)_3 \cdot x\text{H}_2\text{O}$ , by mixing with  $\text{HNO}_3$  (68%) and heating (and stirring) at  $100^\circ\text{C}$  for 30 min. The metal nitrate precursors mixed with malic acid (chelating agent and fuel<sup>8</sup>) were subjected to heating (and stirring) at  $100^\circ\text{C}$  followed by addition of ethylene glycol

in 1:4 ratio (with respect to malic acid) at neutral pH, and subsequent drying led to the formation of a viscous gel. The viscous gel was transferred to an oven and maintained at  $200^\circ\text{C}$ , for 3 h and it resulted in the formation of voluminous foamy precursor. The precursor was crushed into fine powders using an agate mortar and pestle and the thermo gravimetric and differential thermal analysis (TG–DTA) was performed (Mettler Toledo TGA/DSC1) at a heating rate of  $10^\circ\text{C}/\text{min}$  in the range–room temperature to  $1000^\circ\text{C}$ . Based on TG–DTA, the calcination temperature was identified and the precursor powders were calcined at  $400\text{--}600^\circ\text{C}$  for 4 h. The calcined powders were pressed into pellets and sintered at  $1000^\circ\text{C}$  for 4 h. The powder x-ray diffraction analysis (BrukerD8 Advanced–Cu  $K_\alpha$  radiation) and the Raman spectral analysis (Lasos 77, argon laser source:  $\lambda = 488\text{ nm}$  and  $10\text{ mW}$  power, and range:  $200\text{--}900\text{ cm}^{-1}$ ) was performed on the sintered samples. The magnetic characterization was performed using vibrating sample magnetometer (Lakeshore Model 7407).

Figure 1 shows the TG–DTA curves of  $\text{CoFe}_{2-x}\text{Er}_x\text{O}_4$  ( $x = 0.00, 0.02$ , and  $0.04$ ) precursors as a representative. The curves for each of the compositions can be divided into three regions based on various processes taking place in each of them—(i)  $40\text{--}150^\circ\text{C}$ , (ii)  $150\text{--}400^\circ\text{C}$ , and (iii)  $400\text{--}1000^\circ\text{C}$ . A similar thermal behavior was reported by Albu *et al.*, using malic acid as chelating agent.<sup>9</sup> In region (i)—the first step of weight loss ( $\sim 10\%$ ) corresponds to the volatilization of the organic solvents and represents exothermic peak (on DTA) around  $115^\circ\text{C}$  curve for  $x = 0$ ; and the less intense endothermic peaks on DTA curve corresponds to the evaporation of the residual moisture around ( $85^\circ\text{C}$ ) in all the compositions. In region (ii)—all the compositions show two exothermic peaks around  $300^\circ\text{C}$  (DTA curve) corresponding to  $\sim 50\%$  weight loss. These peaks are probably due to the decomposition of complex gel network  $[\text{Fe}_{2-x}\text{RE}_x\text{Co}(\text{C}_4\text{H}_4\text{O}_5)(\text{OH})_4] \cdot 6\text{H}_2\text{O}$ .<sup>10</sup> The humongous

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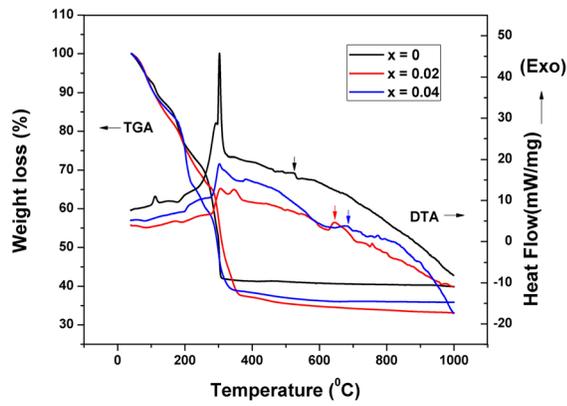


FIG. 1. The TG-DTA curves of  $\text{CoFe}_{2-x}\text{Er}_x\text{O}_4$  ( $x=0.0, 0.02, \text{ and } 0.04$ ) precursors.

weight loss of gel network is due to the combustion reaction resulting in evolution of  $\text{NH}_3$  and  $\text{NO}_2$  corresponds to one of the peaks; and the other peak is likely associated with the burning of residual organic complex or oxidation of residual carbon in the gel network. In region (iii)—the peak at  $535^\circ\text{C}$  for  $\text{CoFe}_2\text{O}_4$  (DTA curve) shows no significant weight loss (TG curve) that can be attributed to crystallization. The crystallization is also evidenced in powder x-ray diffraction (not shown here) of calcined powders of  $400^\circ\text{C}$  and  $600^\circ\text{C}$   $\text{CoFe}_{2-x}\text{Er}_x\text{O}_4$  ( $0 \leq x \leq 0.04$ ). To incorporate larger size  $\text{Er}^{3+}$  into the cobalt-ferrite lattice, higher energy is needed and therefore with increasing dopant concentration, some of the energy is utilized to incorporate  $\text{Er}^{3+}$  into cobalt-ferrite lattice, as a result crystallization takes place at relative higher temperatures in doped cobalt-ferrites.

Figure 2 shows the x-ray diffraction spectra for the sintered ( $1000^\circ\text{C}$  for 4 h) Er doped cobalt-ferrites,  $\text{CoFe}_{2-x}\text{Er}_x\text{O}_4$  ( $x=0, 0.01, 0.02, 0.03, \text{ and } 0.04$ ). The spectra show the presence of desired cubic spinel phase in all the compositions. The emergence of extraneous orthoferrite phase ( $\text{ErFeO}_3$ ) is evident at higher Er content ( $x=0.03$  and  $0.04$ ). The lattice parameter ( $a$ ) of the spinel phase was calculated by Cohen's method<sup>11</sup> (Table I). The  $a$  for  $\text{CoFe}_2\text{O}_4$  ( $8.3810 \pm 0.0008$ ) is similar to  $a$  reported for cobalt-ferrite in literature and minor variation compared to literature is likely due to the variation in impurity level of the initial raw materials and method of synthesis of cobalt-ferrite.<sup>12</sup> Cobalt-ferrite in its inverse-spinel form has half  $\text{Fe}^{3+}$  occupying the tetrahedral site while the other half  $\text{Fe}^{3+}$  and  $\text{Co}^{2+}$  occupy the octahedral sites. Any variation in the site occupation of  $\text{Fe}^{3+}$  and  $\text{Co}^{2+}$  mostly due to synthesis method adopted is known to affect  $a$ .<sup>13</sup>  $\text{Er}^{3+}$  being larger in size than  $\text{Fe}^{3+}$ , its substitution increases  $a$  for  $\text{CoFe}_{2-x}\text{Er}_x\text{O}_4$  ( $x=0.01, 0.02, 0.03, \text{ and } 0.04$ ) as compared to

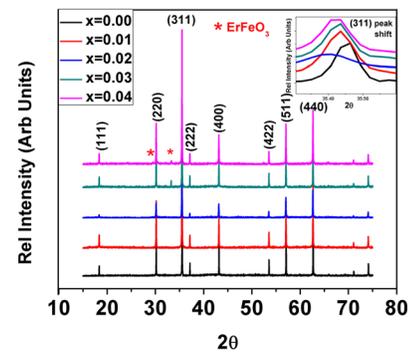


FIG. 2. X-ray diffraction spectra and (inset) (311) peak shift of  $\text{CoFe}_{2-x}\text{Er}_x\text{O}_4$  ( $x=0, 0.01, 0.02, 0.03, \text{ and } 0.04$ ) sintered at  $1000^\circ\text{C}$  for 4 h.

that of  $\text{CoFe}_2\text{O}_4$  (evident from the (311) peak shift—inset Figure 2). The near constant value of  $a$  for Er substituted cobalt-ferrite suggests limited solubility of Er in cubic spinel lattice, which is corroborated by the formation of  $\text{ErFeO}_3$  especially at higher value of  $x$  (0.03 and 0.04). The crystallite size and strain values (using Scherrer's formula<sup>14</sup>) are compiled in Table I. While the crystallite size (130–160 nm) of the Er doped cobalt-ferrites were lower than pure cobalt-ferrite ( $\sim 190$  nm); the lattice strain of Er doped cobalt-ferrites were higher than pure cobalt-ferrite.

The formation of mixed spinel structure with various concentration of Er was confirmed by Raman spectra (Figure 3) with the peaks corresponding to six phonon modes between  $200\text{ cm}^{-1}$  and  $700\text{ cm}^{-1}$ . The spinel structure of ferrites show 39 vibrational modes out of which six phonon modes are Raman active ( $2A_{1g}$ ,  $E_g$ , and  $3T_{2g}$ ). The modes above  $600\text{ cm}^{-1}$  correspond to metal-oxygen (M-O) (symmetrical stretching) bonding at tetrahedral sites and the modes below  $600\text{ cm}^{-1}$  correspond to metal-oxygen bonding (symmetrical, anti-symmetrical bending) in octahedral sites.<sup>15</sup> As the Er concentration increases, the peaks get broadened and the peak position shifts towards higher wavelength. This shift indicates that strain is induced in the lattice due to the presence of large size  $\text{Er}^{3+}$  and the broadening is due to the smaller crystallite size.<sup>16</sup> Relative increase in intensities of modes corresponding to octahedral sites below  $600\text{ cm}^{-1}$  suggests that the  $\text{Er}^{3+}$  has higher preference for octahedral sites. The red shift values are tabulated in Table I.

Figure 4 shows the magnetization ( $M$ - $H$ ) curves for Er doped cobalt-ferrites. The magnetization ( $M$ ), at  $\sim 1200\text{ kA/m}$ , and the coercivity ( $H_c$ ) values are listed in Table I. The  $M$  for  $\text{CoFe}_2\text{O}_4$  is  $\sim 72\text{ Am}^2/\text{kg}$ . With increasing Er substitution  $M$  increases from  $\sim 72\text{ Am}^2/\text{kg}$  ( $x=0$ ) to  $\sim 75\text{ Am}^2/\text{kg}$  ( $x=0.02$ ) followed by a decrease to  $\sim 73\text{ Am}^2/\text{kg}$  ( $x=0.03$  and  $0.04$ ). The Er doped cobalt-ferrites ( $x \leq 0.02$ )

TABLE I. Lattice parameter ( $a$ ), average crystallite size, strain, magnetization ( $M$ ), and coercivity ( $H_c$ ) of  $\text{CoFe}_{(2-x)}\text{Er}_x\text{O}_4$  ( $x=0, 0.01, 0.02, 0.03, \text{ and } 0.04$ ).

Composition	$a$ (Å) ( $\pm 0.0008$ )	Average crystallite size (nm)	Strain ( $10^{-4}$ )	Red shift $W_r$ to $X=0.00$ ( $\text{cm}^{-1}$ ) ( $A_{1g}$ mode)	$M_{at}$ ( $\sim 1200\text{ kA/m}$ ) $\text{Am}^2/\text{kg}$ ( $\pm 1\%$ )	$H_c$ ( $\text{kA/m}$ ) ( $\pm 1\%$ )
$\text{CoFe}_2\text{O}_4$	8.3810	186.74	0.62	...	72.1	29.1
$\text{CoFe}_{1.99}\text{Er}_{0.01}\text{O}_4$	8.3853	135.88	0.85	18.79	72.7	60.2
$\text{CoFe}_{1.98}\text{Er}_{0.02}\text{O}_4$	8.3852	130.75	1.73	27.04	75.3	65.6
$\text{CoFe}_{1.97}\text{Er}_{0.03}\text{O}_4$	8.3847	150.98	2.38	16.73	73.3	56.2
$\text{CoFe}_{1.96}\text{Er}_{0.04}\text{O}_4$	8.3848	132.00	1.90	35.28	73.2	56.5

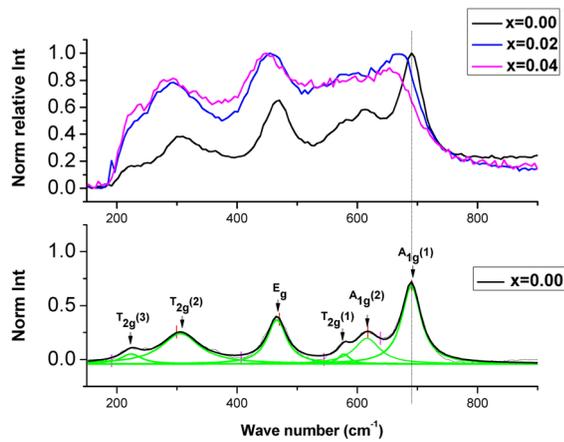


FIG. 3. Raman spectra—(upper) raw data of  $\text{CoFe}_{(2-x)}\text{Er}_x\text{O}_4$  ( $x = 0, 0.02$ , and  $0.04$ ) and (lower) spectral analysis of  $\text{CoFe}_2\text{O}_4$  as a representative, sintered at  $1000^\circ\text{C}$  for 4 h.

have only marginally higher  $M$  values compared to  $\text{CoFe}_2\text{O}_4$ .  $\text{Er}^{+3}$  is expected to have negligible contribution to the room temperature magnetization of Er-doped cobalt-ferrites because of their low magnetic-ordering temperatures ( $<90\text{K}$ )<sup>17,18</sup> and the marginal increase in  $M$  is possibly due to the rearrangement of cations in  $A$  and  $B$  sites. Because of the large ionic radii of  $\text{Er}^{+3}$  they prefer to occupy only the  $B$  site and hence disrupt the original ions distribution. Some of the  $\text{Co}^{+2}$  ions may migrate to the  $A$  site because of their large ionic radii compared to  $\text{Fe}^{+3}$  ions by replacing the equivalent amount of  $\text{Fe}^{+3}$  ions from  $A$  to  $B$  site.<sup>18</sup> So the net magnetization increases marginally up to  $x=0.02$ . However, at higher Er content ( $x=0.03$  and  $0.04$ ) formation of antiferromagnetic  $\text{ErFeO}_3$  phase leads to decrease in  $M$ . The coercivity of pure cobalt-ferrite in the current investigation is  $\sim 29\text{kA/m}$ . Doping of Er ( $x=0.01$ ) leads to doubling ( $\sim 100\%$  increase) of  $H_C$  value ( $\sim 60\text{kA/m}$ ) compared to undoped cobalt-ferrite. Subsequent increase in Er doping ( $x=0.02$ ) increases  $H_C$  value only by  $\sim 10\%$  ( $\sim 66\text{kA/m}$ ), followed by decrease by  $\sim 11\%$  ( $\sim 56\text{kA/m}$ ) for  $x=0.03$  and  $0.04$ ). Increase in  $H_C$  up to  $x=0.02$  may be due to the contribution of  $\text{Er}^{+3}$  to the anisotropy because of its strong spin orbit coupling similar to  $\text{Co}^{+2}$  ions.<sup>18</sup> The inset (Figure 4) shows a strong correlation between  $a$  and  $H_C$  for Er doped cobalt-ferrites. It is evident that  $H_C$  is strongly affected by lattice parameter. At lower  $x$  ( $0.01$  and  $0.02$ ), until solubility limit, steep increase in  $H_C$  confirms sharp increase in anisotropy owing to presence of  $\text{Er}^{3+}$  in octahedral sites of the cubic spinel lattice. Marginal increase ( $\sim 10\%$ ) in  $H_C$  between  $x=0.01$  and  $x=0.02$  suggests only marginal difference in the solubility among the two successive compositions owing to a steep gradient in solvus. This is corroborated with similar  $a$  values for  $\text{CoFe}_{1.99}\text{Er}_{0.01}\text{O}_4$  and  $\text{CoFe}_{1.98}\text{Er}_{0.02}\text{O}_4$ . The presence of antiferromagnetic orthoferrite phase at higher Er compositions ( $x=0.03$  and  $0.04$ ) is expected to initiate the pinning of domain walls of the ferrimagnetic phase along with the existing increased anisotropy in the ferrimagnetic phase to control the coercivity. The domain wall motion of a ferrimagnetic phase through an antiferromagnetic phase is generally complex and in this case the two mechanisms probably work together to decrease  $H_C$ .<sup>6</sup>

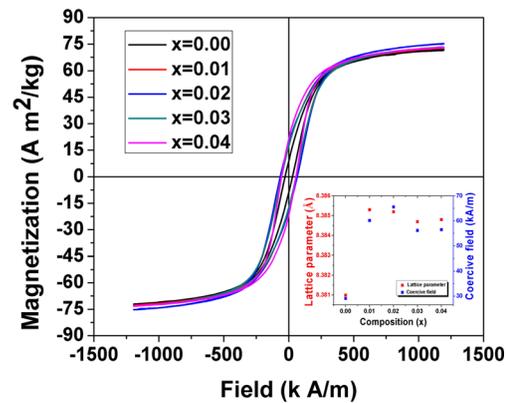


FIG. 4. Magnetization curves and (inset) correlation between lattice parameter ( $a$ ) and coercive field ( $H_C$ ) of  $\text{CoFe}_{2-x}\text{Er}_x\text{O}_4$  ( $x = 0, 0.01, 0.02, 0.03$ , and  $0.04$ ) sintered at  $1000^\circ\text{C}$  for 4 h.

Nanocrystalline particulates of Er doped cobalt-ferrites  $\text{CoFe}_{(2-x)}\text{Er}_x\text{O}_4$  ( $0 \leq x \leq 0.04$ ), were successfully synthesized using sol-gel assisted autocombustion method. Powder x-ray diffraction confirmed the formation of single phase of spinel for the compositions  $x=0, 0.01$ , and  $0.02$  and for higher compositions ( $x=0.03$  and  $0.04$ ) an additional orthoferrite phase formed along with the spinel phase. Lattice parameter of the doped cobalt-ferrites was higher than that of pure cobalt-ferrite. The observed red shift in the doped cobalt-ferrites indicates the presence of induced strain in the cobalt-ferrite matrix due to large size of the  $\text{Er}^{+3}$  compared to  $\text{Fe}^{+3}$ . The magnetization (at  $\sim 1200\text{kA/m}$ ) marginally increased from  $\sim 72\text{Am}^2/\text{kg}$  ( $x=0$ ) to  $\sim 75\text{Am}^2/\text{kg}$  ( $x=0.02$ ), followed by a decrease to  $\sim 73\text{Am}^2/\text{kg}$  ( $x=0.03$  and  $0.04$ ).

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