Materials Research Express

PAPER

Study on the influence of ion doping on the crystal structure and magnetic properties of YFeO$_3$

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Keywords: YFeO$_3$, ion doping, magnetic properties, crystal structure, sol-gel

Abstract

A series of pure phase YFeO$_3$ sample powders doped with Eu$^{3+}$ and Nd$^{3+}$ were synthesized by sol-gel method. The influence of different ions doping on the crystal structure and magnetic properties of YFeO$_3$ were investigated. The prepared sample powders were characterized by powder x-ray diffractometer, scanning electron microscope, energy dispersive spectrometer, Fourier transform infrared spectrometer, differential thermal analyzer and vibrating sample magnetometer. The results demonstrate that all sample powders are pure phase orthogonal perovskite structures, the crystal structure and the magnetization have changed. The lattice parameters and the saturation magnetization increase with the increase of ion radius or ion concentration in single doping system. In the case of double doping, the influence of the crystal structure and magnetic properties of YFeO$_3$ is more complicated than that of single doping according to the change of ions concentration.

1. Introduction

In modern industry, high-efficiency storage devices rarely choose materials with a single performance [1]. Multiferroic materials have attracted great attention because of their diverse and important properties, including ferroelectricity, ferromagnetism and ferroelasticity [2]. It is a kind of material affected by external magnetic field and electric field [3]. Up to now multiferroic materials have been confirmed to play an important role in new devices through various experiments [4, 5]. Among them, YFeO$_3$ with rare earth perovskite structure can be used as magneto-optical sensor [6] and magneto-optical memory device because of its excellent properties such as high coercivity [7], high Faraday rotation angle [8], low saturation magnetization, excellent domain wall motion and high Curie temperature. As a classical single-phase multi-ferrous material, YFeO$_3$ has become a research hotspot in recent years [9].

Unfortunately, YFeO$_3$ single-phase crystal, as a classical ABO$_3$ type ferrite material, does not avoid the defect that cannot exhibit large values of ferroelectricity and ferromagnetism at room temperature at the same time due to the problem of d-orbital electron occupation. Its electric polarization value in Shang’s [10] report (0.006 $\mu$C cm$^{-2}$) is very weak and there is no intrinsic magnetoelectric coupling effect at room temperature, lucky it shows excellent magnetic properties. For example, the saturation magnetization of YFeO$_3$ at room temperature is 0.015 emumg$^{-1}$, the coercive field is 1800 Oe, the exchange field H$_{ex}$ is 5.6 $\times$ 10$^6$ Oe, the DM antisymmetric field H$_{as}$ is 9.5 $\times$ 10$^6$ Oe and the anisotropic field H$_{an}$ is 300 Oe. Therefore, we consider it can be an excellent choice of ferromagnetic phase materials for the synthesis of composite multiferroic materials. Our experiment is devoted to improving its magnetic properties and making efforts to make it to be one of the raw material for the synthesis of magnetoelectric composite materials with strong coupling effect in the future.

The application potential of YFeO$_3$ is inseparable from its interesting magnetic properties. The magnetic properties in YFeO$_3$ includes multiple forms [11–17]: isotropic super-exchange interaction which causes magnetic moments to align antiparallel; interaction of magnetic moments in an external magnetic field; Dzialoshinski Moriya (DM) antisymmetric exchange mechanism and the anisotropy energy. YFeO$_3$ crystal has a distorted orthorhombic perovskite structure [18]. The space group of the crystal is Pnma (D$_{2h}$, 16) with cell parameters $a = 5.5946$ Å, $b = 7.6040$ Å, $c = 5.2790$ Å. As show in figure 1 each unit cell has eight molecular
units and each Fe$^{3+}$ ion in the crystal is surrounded by six O$^{2−}$ to form an octahedron [19, 20]. One of the O$^{2−}$ anions forms the common apex of two adjacent octahedra. The Y$^{3+}$ ions with large radius are located in eight octahedral voids. YFeO$_3$ has immeasurable application prospects due to its special crystal structure [21]. Therefore researchers will never stop studying the structure and magnetic performance of YFeO$_3$. In recent years, a number of researchers have focused on changing the magnetic properties of YFeO$_3$ by ions doping. For example, the size of Y$_{1−x}$Ca$_x$FeO$_3$ nanocrystals changes and their magnetization optimizes by doping Ca$^{2+}$ [22]. Magneto-electric and magneto-dielectric effects were observed at different temperatures by substituting Mn for YFe$_{1−x}$Mn$_x$O$_3$. The increase of Er$^{3+}$ content in the Y$_{1−x}$Er$_x$FeO$_3$ can greatly enhance the paramagnetism of YFeO$_3$ powders. It can be seen that most of researchers at this stage focuses on the introduction of a single magnetic or diamagnetic ion into the YFeO$_3$ [23, 24], which leads to effectively improve its magnetic properties and optimize its crystal structure [25, 26]. There is no report about the differences in the structural and magnetic effects of different ion single doping on YFeO$_3$ and the differences on the structural and magnetic effects of single and double doping on YFeO$_3$.

In this work, the radius of the selected doping ions Eu$^{3+}$ and Nd$^{3+}$ are 0.95 Å and 0.98 Å respectively, which are close to 0.95 Å of Y$^{3+}$, meantime they all have the same valence state. We hope that under the premise of successfully incorporating ions into YFeO$_3$ crystal structure, the final sample powders will not be impure due to excessively affecting its distortion. And we know that Y$^{3+}$ at the A position in pure phase YFeO$_3$ is a non-magnetic ion and Eu$^{3+}$ or Nd$^{3+}$ may make extra paramagnetic contribution. We hope that the incorporation of Eu$^{3+}$ or Nd$^{3+}$ can improve the magnetization of YFeO$_3$ or create a new magnetization formation mode by the interaction between A-Fe ions. In our experiment a series of Eu$^{3+}$ and Nd$^{3+}$ doped YFeO$_3$ powders that could be used to study crystal structure and magnetic performance parameters of YFeO$_3$ were prepared by sol–gel combustion method, which are expected to provide reference for the research of magnetic engineering of YFeO$_3$ in the future.

2. Experiment

In this report, all Eu$^{3+}$ and Nd$^{3+}$ doped YFeO$_3$ sample powders were synthesized by sol–gel method using yttrium oxide, europium oxide, neodymium oxide, citric acid, iron nitrate and concentrated nitric acid as raw materials (table 1). All these chemicals and solvents are analytical grade reagent. Firstly, Y$_2$O$_3$, Eu$_2$O$_3$ and Nd$_2$O$_3$ are sequentially added to 25 ml of dilute nitric acid with a concentration of 1 mol l$^{−1}$ according to a certain stoichiometric ratio. The solution was stirred evenly with a magnetic stirrer at a certain heating temperature. Then Fe(NO$_3$)$_3$·9H$_2$O was added to mixed solution and stirred for 5 min. Secondly, the citric acid with a metal ion molar ratio of 1:1.5 was added to the mixed solution and stirring was continued until the solution was evaporated into brown viscous gel to remove the unwanted nitric acid. It was then transferred to a ventilating drying oven and dried (120 °C, 12 h) to obtain fluffy powder (xerogel). The obtained xerogel was pre-sintered in a muffle furnace at 300 °C for 2 h before sufficiently grinding. Finally, it was heated at 850 °C for 2 h for secondary calcination to obtain the final powders.

The crystalline phases of all powders were analyzed by powder x-ray diffraction (XRD) with a Bruker D8, using Cu Kα radiation in 2-theta range from 20° to 80° and the scanning rate is 2° min$^{−1}$. The surface morphology and chemical composition of all powders were observed by scanning electron microscopy (Gemini SEM300, Zeiss, Germany) which equipped with an energy-dispersive X-ray spectroscope. In order to study the
way of decomposition, the dry gel was placed in the DTA crucible and heated to 1050 °C with a slope of 5 °C min⁻¹. All powders were characterized by Fourier Transform Infrared Spectroscopy (FTIR) in the range of 400–800 cm⁻¹ on a Nicolet 380 Fourier Transform Spectrometer. The magnetic properties of all powders were characterized at room temperature by using a vibrating sample magnetometer (VSM) integrated in a physical property measurement system (PPMS-9, Quantum Design).

**3. Result and Discussion**

Figures 2(a)–(c) shows XRD pattern of single-doped Y₁₋ₓEuₓFeO₃ (x = 0.1, 0.3, 0.5), Y₁₋ₓNdₓFeO₃ (x = 0.1, 0.3, 0.5) and double-doped Y₀.₅Eu₀.₅₋ₓNdₓFeO₃ (x = 0.1, 0.2, 0.3, 0.4) powders that sintered at 850 °C. The XRD pattern of the JCPDS card No.86-0171 and the powders data is identical, all peaks correspond to the pure YFeO₃ phase and there is no impurity phase of Y₃Fe₅O₁₂ or Y₂O₃. All powders have strong diffraction peak intensity and sharp shape. This means all powders that sintered at 850 °C belong to Pnma space group and have good crystallinity [27].

This suitable sintering temperature is consistent with the conclusion obtained from DTA curve. The DTA curve can be used to decipher the decomposition steps of the Y₀.₅Eu₀.₅₋ₓNdₓFeO₃ powder that was heated at a rate of 5 °C min⁻¹ below 1050 °C (figure 3), it shows a peak in the temperature range of 150 °C to 250 °C, which may be the removal process of water and organic matter during heat treatment. It is consistent with the phenomenon that the dehydration decomposition process shown in Sanjay Mathur’s report [28].

At the same time, a broad peak appears at 600 °C to 800 °C, which may be due to the growth of crystallization and phase transformation of orthorhombic yttrium ferrite sintered after 850 °C. So we could confirm that YFeO₃ doped with Nd³⁺ and Eu³⁺ still maintain a pure-phase orthogonal perovskite structure in this experiment. Table 2 shows the lattice parameters of all powders calculated by MDI Jade6.0 software. It has been proved that doping ions can randomly occupy the Y³⁺ site in the main structure because of similar ionic radii and valence [29–31] which can also be observed in our experiment. It can be seen in table 2 that when Nd³⁺ or Eu³⁺ replace Y³⁺ in the crystal structure of YFeO₃, the lattice parameters are larger than that of the unsubstituted pure phase YFeO₃. As we know that the lattice parameters of crystal can be influenced by lattice stress. In our experiment, when Y³⁺ position is replaced by Nd³⁺ or Eu³⁺ whose ionic radius is larger than Y³⁺, the interaction between ions of YFeO₃ is affected, which may change the lattice stress and result in the increase of lattice parameters. And when the concentration of Eu³⁺ or Nd³⁺ increases, the lattice parameters will increase accordingly. Table 2 also shows that when Eu³⁺ or Nd³⁺ ions of the same concentration were doped individually, the lattice parameters have differently changes. As we know the atomic weight of Eu³⁺ is larger than that of Nd³⁺ and the radius of rare earth ions decreases with the increases of atomic weight. When Y³⁺ is replaced by a larger radius ion, even if the doping concentration is the same, the lattice distortion is more serious than replaced by a smaller radius ion. This could be the reason why there is a larger increase in lattice parameters of Nd³⁺ doping than that of Eu³⁺ doping. Figure 2(d) illustrates the enlargement patterns of the main peaks of Y₀.₅Eu₀.₅₋ₓNdₓFeO₃ (z = 0, 0.1, 0.2, 0.3, 0.4) powders. It shows that the main diffraction peak shift to a low angle in the range of 32.5 to 33.5 degree with the doping of Nd³⁺ and Eu³⁺. According to Jade6, the main diffraction peak position of pure NdFeO₃ shift toward a lower angle than YFeO₃. When Eu³⁺ and Nd³⁺ ions are double-doped in YFeO₃ at the same time, the lattice parameters decrease with the increase of Eu³⁺ concentration and increase with the increase of Nd³⁺ concentration. As mentioned above, the ionic radius of Nd³⁺ is larger than that of Eu³⁺. Therefore, we speculate that when YFeO₃ is double-doped, the lattice parameters increases with the increase of the concentration of rare earth ion that with larger radius. Similar to the conclusion in single doping system, the lattice distortion is more affected by the doping ions with larger radius. This can be a reference for study of the influence of co-doped on YFeO₃ crystal structure in the future.

| Number | Name               | Molecular formula | Purity       |
|--------|--------------------|-------------------|--------------|
| 1      | Yttrium nitrate    | Y(NO₃)₃ 6H₂O      | 99.9%        |
| 2      | Iron nitrate       | Fe(NO₃)₃ 9H₂O     | 99.9%        |
| 4      | Citric acid        | C₆H₈O₇           | 99.9%        |
| 5      | Europium oxide     | Eu₂O₃            | 99.9%        |
| 6      | Neodymium oxide    | Nd₂O₃            | 99.9%        |
| 7      | Concentrated nitric acid | HNO₃ | 65%–68%        |
Figure 2. XRD patterns of the Y$_{1-x}$Eu$_x$FeO$_3$ ($x = 0.1, 0.3, 0.5$) powders (a), Y$_{1-x}$Nd$_x$FeO$_3$ ($x = 0.1, 0.3, 0.5$) powders (b), Y$_{0.5}$Eu$_{0.5-x}$Nd$_x$FeO$_3$ ($x = 0.1, 0.2, 0.3, 0.4$) powders (c), enlargement patterns of the main peaks of Y$_{0.5}$Eu$_{0.5-x}$Nd$_x$FeO$_3$ ($x = 0.1, 0.2, 0.3, 0.4$) powders (d).

Figure 3. DTA measurements of Y$_{0.5}$Eu$_{0.5}$Nd$_{0.5}$FeO$_3$ powder.
The surface SEM images of YFeO$_3$, Y$_{0.8}$Eu$_{0.2}$FeO$_3$ and Y$_{0.5}$Eu$_{0.2}$Nd$_{0.3}$FeO$_3$ powders are showed in figures 4(a)–(c), respectively. It can be seen that all powders have similar morphology, fluffy structure and a large number of pores, which is due to the combustion of organic citric acid during heat treatment [32]. With the incorporation of rare earth ions, the compactness of the powder becomes better, which may be due to the increase of unit cell volume. There is no significant difference between pure phase YFeO$_3$ and single-doped Eu$^{3+}$ or double-doped Nd$^{3+}$ and Eu$^{3+}$ powders. In addition, energy dispersive spectroscopy measurements were performed on selected areas of Y$_{0.5}$Eu$_{0.5-x}$Nd$_x$FeO$_3$ powder to characterize the composition of the sample. The results show that the powder are mainly composed of five elements Y, Fe, O, Nd and Eu and the proportion of elements is approximately the same as the formula [33]. The above results show that Nd$^{3+}$ and Eu$^{3+}$ have been doped into the crystal structure of YFeO$_3$.

Table 2. The lattice parameters of Y$_{1-x}$Eu$_x$FeO$_3$, Y$_{0.5}$Nd$_{0.3}$FeO$_3$ and Y$_{0.5}$Eu$_{0.5-z}$Nd$_z$FeO$_3$ powders.

| x/y = 0.1, 0.3, 0.5 | x = 0.1 | x = 0.3 | x = 0.5 | y = 0.1 | y = 0.3 | y = 0.5 | z = 0.1 | z = 0.2 | z = 0.3 | z = 0.4 |
|---------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| a(Å)                | 5.5836  | 5.6042  | 5.6058  | 5.5899  | 5.6241  | 5.6757  | 5.3251  | 5.3445  | 5.3483  | 5.3598  |
| b(Å)                | 7.5883  | 7.6106  | 7.6272  | 7.5945  | 7.6415  | 7.6806  | 7.6452  | 7.6518  | 7.6518  | 7.6744  |
| c(Å)                | 5.2796  | 5.2981  | 5.2991  | 5.2828  | 5.2828  | 5.2947  | 5.5956  | 5.5888  | 5.5890  | 5.5919  |

The surface SEM images of YFeO$_3$, Y$_{0.8}$Eu$_{0.2}$FeO$_3$ and Y$_{0.5}$Eu$_{0.2}$Nd$_{0.3}$FeO$_3$ powders are showed in figures 4(a)–(c), respectively. It can be seen that all powders have similar morphology, fluffy structure and a large number of pores, which is due to the combustion of organic citric acid during heat treatment [32]. With the incorporation of rare earth ions, the compactness of the powder becomes better, which may be due to the increase of unit cell volume. There is no significant difference between pure phase YFeO$_3$ and single-doped Eu$^{3+}$ or double-doped Nd$^{3+}$ and Eu$^{3+}$ powders. In addition, energy dispersive spectroscopy measurements were performed on selected areas of Y$_{0.5}$Eu$_{0.5-x}$Nd$_x$FeO$_3$ powder to characterize the composition of the sample. The results show that the powder are mainly composed of five elements Y, Fe, O, Nd and Eu and the proportion of elements is approximately the same as the formula [33]. The above results show that Nd$^{3+}$ and Eu$^{3+}$ have been doped into the crystal structure of YFeO$_3$.

Figure 5(a) is the infrared scanning schematic diagram of Y$_{0.5}$Eu$_{0.5-x}$Nd$_x$FeO$_3$ (x = 0.1, 0.2, 0.3, 0.4) powders in the range of 400 cm$^{-1}$ to 4000 cm$^{-1}$. The result shows that the infrared spectra of all powders are similar. It is believed that the absorption bands of BO$_6$ octahedral belonging to the perovskite structure are observed at around 550 cm$^{-1}$ and 400 cm$^{-1}$, which are derived from the stretching vibration of B–O bond in BO$_6$ octahedral and the bending vibration of B–O–B respectively. The O–H stretching and H–O–H bending vibration of adsorbed water are observed at around 3400 cm$^{-1}$ and 1600 cm$^{-1}$. In our experiment, we observed peaks at 1600 cm$^{-1}$ and 3400 cm$^{-1}$ and 425 cm$^{-1}$ (figure 5(b)). The peak position shifts with the change of doping concentration. It is not monotonous shifted as Wu’s [34] report but is more complicated. This may be due to the different radii of the two ions when double doping, resulting in varying degrees of change in bond length and bond angle.
The perovskite structure YFeO₃ produces two magnetic properties, including antiferromagnetic (AFM), weak ferromagnetic (WFM). Weak ferromagnetic is due to the fact that in Dzyaloshinski-Moriya antisymmetric exchange mechanism, the adjacent Fe³⁺ magnetic moments are not completely anti-parallel but are inclined at a small angle which resulting in a small net magnetization. Antiferromagnetic is due to the fact that the FeO₆ octahedron in YFeO₃ structure is formed by six O²⁻ ions surrounding one Fe³⁺ ion, the adjacent octahedrons are connected by O²⁻ ion and the interaction between two FeO₆ octahedrons forms a Fe–O–Fe bond to produce superexchange interaction.

Figure 6(a) shows the M–H hysteresis loops plot of the Y₁₋ₓEuₓFeO₃ (x = 0.1, 0.3, 0.5, 0.7) powders depending on the variation of magnetic field measured at room temperature. It is known that YFeO₃ exhibits different magnetic performance behaviors in low and high magnetic fields due to anisotropy. Several reports have shown that the magnetization of YFeO₃ decrease with the increase of temperature when the external magnetic field greater than Hₑ, such as Deka’s report [27] which test condition is 300 k–600 k and 70 kOe magnetic field, Mathur’s report [28] which test condition is 0 k–400 k, Rosale’s report [2] which test condition is 773 k–1073 k and 20 kOe magnetic field. The hysteresis loop test condition of our experiment was set to 60 kOe magnetic field and room temperature. We found that each sample has a certain hysteresis. There is a magnetization jump where the curve shape shows a waist shape at zero external magnetic field, which is the weak ferromagnetic behavior of YFeO₃ and the weak ferromagnetic of YFeO₃ and the weak ferromagnetic of YFeO₃ changes the magnetization jump. This phenomenon is related to the change of DM interaction which affecting YFeO₃ ferromagnetic. The saturation magnetization increases with the increase of Eu³⁺ doping concentration from 0.015 emumg⁻¹ to 0.02 emumg⁻¹. The remanent magnetization is almost unchanged when the doping concentration x = 0.1 ~ 0.5 and decrease when the concentration x = 0.7, so the overall tendency of remanent magnetization is decrease. Based on the results, we speculate that the saturation magnetization of YFeO₃ increase and the remanent magnetization of YFeO₃ decrease with the increase of doping concentration when the radius of doped ions is larger than Y³⁺. It can be explained as follows. The doping of Eu³⁺ improves the magnetic moment of YFeO₃ and affects the DM interaction [35]. Meanwhile Y³⁺ is a non-magnetic ion and its spin configuration is stable, while the Eu³⁺ is a magnetic ion. YFeO₃ doped with Eu³⁺ will undergo spin reorientation, which will change the magnetic anisotropy of Re³⁺–O²⁻–Fe³⁺ [36]. The magnetic ion Eu³⁺ will also have an additional paramagnetic contribution at room temperature. It can also be seen in figure 6(a) that the hysteresis loop shape of different samples shrinks or expands, which may be caused by the simultaneous change of ferromagnetic strength and paramagnetic strength. Also as mentioned above, the ion radius of Eu³⁺ and Y³⁺ is different. When Eu³⁺ replaced Y³⁺ in YFeO₃, the deformation of octahedron FeO₆ changed in the perovskite structure [37], which leads to the increase of bond angle of Fe–O–Fe and the enhancement of Fe–O–Fe superexchange effect [16]. Fe–O–Fe superexchange is the main source of YFeO₃ magnetic energy, its enhancement makes YFeO₃ saturation magnetization significantly increased. As the light rare earth compound has a larger saturation magnetic susceptibility than the heavy rare earth compound, so YFeO₃ doped with Eu³⁺ is easier to be magnetized, which may be the reason why the remanent magnetization decrease with the increase of Eu³⁺ concentration. The significant decrease of coercive force may be due to the effect of ions anisotropy. After Eu

![Figure 5. FTIR spectra of YₓEuₓNdₓFeO₃ (x = 0.1, 0.2, 0.3, 0.4) and YFeO₃ powders (a), the main peaks of YₓEuₓNdₓFeO₃ powder (b).](image-url)
being doped, there will be new interaction of \( \text{Eu}^{3+} - \text{Eu}^{3+} \), \( \text{Eu}^{3+} - \text{Fe}^{3+} \), \( \text{Eu}^{3+} - \text{Y}^{3+} \), among which \( \text{Eu}^{3+} - \text{Fe}^{3+} \) interaction is anisotropic [38].

The pure phase \( Y\text{FeO}_3 \) obtained in this experiment has a saturation magnetization value of 0.015 emumg\(^{-1}\), a remanent magnetization value of 0.007 emumg\(^{-1}\) and a coercive force of 25 kOe, which is basically consistent with reported data. Figure 6(b) is a hysteresis loop comparison illustration of \( Y\text{FeO}_3 \), \( Y_{0.5}\text{Eu}_{0.5}\text{FeO}_3 \) and \( Y_{0.5}\text{Nd}_{0.5}\text{FeO}_3 \). It can be seen that when the lattice position of \( \text{Y}^{3+} \) is replaced by these two selected ions with larger radius, the saturation magnetization of both two sample powders increase, the coercive force and remanent magnetization of both two sample powders decrease. What’s more the single-doped \( \text{Nd}^{3+} \) powder has a larger saturation magnetization and a smaller remanent magnetization than that of single-doped \( \text{Eu}^{3+} \) powder at the same concentration. Therefore, we suppose that when ions with same concentration are doped, the larger the ion radius is, the larger the saturation magnetization increase, the larger the remanent magnetization and the coercive force decrease. The reason could be the ion radius of \( \text{Nd}^{3+} \) is larger than of \( \text{Eu}^{3+} \), relatively severely changed the Fe-O bond length and Fe-O-Fe bond angle, that is the distortion of octahedral FeO\(_6\) is more seriously affected by replaced \( \text{Y}^{3+} \) with larger ions, resulting in a significant enhancement of the Fe-O-Fe superexchange effect. So the saturation magnetization increase more. In addition, the difference in the number of unpaired electrons in the 4f orbits of \( \text{Eu}^{3+} \) and \( \text{Y}^{3+} \) results in a different degree of hybridization with the 3d orbital electrons of the \( \text{Fe}^{3+} \) [39], which also has different effect on the magnetic properties of \( \text{YFeO}_3 \).

Figure 6(c) is a hysteresis loop diagram of double-doped \( \text{Nd}^{3+} \) and \( \text{Eu}^{3+} \) ions. Comparing single-doped \( Y_{0.5}\text{Eu}_{0.5}\text{FeO}_3 \) powder, \( Y_{0.5}\text{Eu}_{0.5}\text{FeO}_3 \) powder and double-doped \( Y_{0.5}\text{Eu}_{0.5}\text{Nd}_{0.5}\text{FeO}_3 \) powder, \( Y_{0.5}\text{Eu}_{0.5}\text{Nd}_{0.5}\text{FeO}_3 \) powder. We found that when the concentration of doped \( \text{Eu}^{3+} \) is the same, the saturation magnetization of the powders that co-doped with \( \text{Nd}^{3+} \) is higher. This is consistent with the conclusions that the effect of larger radius ions doping on the magnetic properties is more intense which obtained in the single-doped system. Hysteresis loop diagram of each sample of double-doped system is shown in figure 6(c), as the concentration of \( \text{Nd}^{3+} \) and \( \text{Eu}^{3+} \) ions changes, the saturation magnetization increases first then decreases and increases again. Although the value of
remanent magnetization does not change much, there are complex changes as well. As the coercive force is affected by the anisotropy of the magnetocrystal, the interaction between particles and the microscopic strain, it presents a complex change that decreases first then increases and decreases. It can be observed that the changes of different magnetic parameters are disorderly and irregular. There is no such phenomenon in the single doping system, indicating that the influence of multi-ions doping on the structure and magnetic properties of YFeO$_3$ is more complicated. Although the valence of the two selected ions is the same, it is not certain that if there will be reaction between two ions when they are doped into YFeO$_3$ at the same time. In view of their ion radii and their unpaired electron numbers in $4f$ orbits are different, the influence of double doping on the crystal structure and magnetic properties of YFeO$_3$ will more complicated. After comparison of two doping system, it is found that the law of the magnetic change of the samples in the double-doping system is more difficult to find, mainly because the two doped ions have inconsistent effects on the super-exchange and DM interactions and may react with each other or have new interaction with Y$^{3+}$ and Fe$^{3+}$ ions in the structure of YFeO$_3$. Therefore, more experiments are needed to study the effect of multi ions doping on the structure and magnetism of YFeO$_3$.

4. Conclusion

In summary, the powders of Nd$^{3+}$ and Eu$^{3+}$ doped YFeO$_3$ were successfully fabricated by sol-gel method. All powders were pure phase with Pnma (D$_{2h}^{16}$) space group. When YFeO$_3$ is single-doped by Nd$^{3+}$ or Eu$^{3+}$, its lattice parameters increased, the saturation magnetization was higher than that of pure YFeO$_3$ and the saturation magnetization became larger as the doping concentration increased. When different ions with the same concentration are single-doped, the larger the doped ion radius is, the more severe the crystal distortion is and the more the saturation magnetization increases. When double-doped Nd$^{3+}$ and Eu$^{3+}$ ions, the crystal structure is more affected by the doping ions with larger radius, while the variation of saturation magnetization and remanent magnetization are irregular, which indicates that the effect of double doping on the structure and magnetic properties of YFeO$_3$ is more complicated than we expected.

Acknowledgments

Authors are gratefully thankful to National Natural Science Foundation (51874198), Shanghai Collaborative Innovation Fund (XTCX2017–2), Shanghai Science and Technology Achievement Transformation Association, Shanghai Education Development Foundation and Shanghai Science and Technology Achievement Transformation Foundation (LM201772), Minhang District Science and Technology Project (2015MH172) for support.

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