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Eu^{3+/2+} co-doping system induced by adjusting Al/Y ratio in Eu doped CaYAlO₄: preparation, bond energy, site preference and ⁵D₀–⁷F₄ transition intensity†

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CaY_{1-x}Al_{1+x}O₄:2%Eu (x = 0, 0.1, 0.2) phosphors have been synthesized *via* a solid-state reaction process. XRD patterns indicate that they are pure phase. The photoluminescence properties of the CaY_{1-x}Al_{1+x}O₄:2%Eu phosphors exhibit both the blue emission of Eu²⁺ (4f⁶5d¹–4f⁷) and red-orange emission of Eu³⁺ (⁵D₀–⁷F_{1,2,3,4}) under UV light excitation, which showed that the Eu^{3+/2+} co-doping system was obtained by adjusting the Al/Y ratio. Eu³⁺ ions can be reduced to Eu²⁺ ions when the Al/Y ratio was changed. In this work, the bond energy method was used to determine and explain the mechanism of the site occupation of Eu ions entering the host matrix. Also, the emission spectrum showed an unusual comparable intensity ⁵D₀–⁷F₄ transition peak. The relative intensity of ⁵D₀–⁷F₂ and ⁵D₀–⁷F₄ can be stabilized by changing the relative proportions of Al³⁺ and Y³⁺. Furthermore, this was explained by the J–O theory.

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1. Introduction

Rare-earth ions, as widely used activators, have been playing an irreplaceable role in lighting-emitting diodes (LEDs),¹ due to their abundant emission colors based on the 4f–4f or 5d–4f transitions.^{2,3} The luminescence properties of different rare earth ions deliver an explicit comprehension on the internal correlations between them, which is generally determined by electronic configuration of the dopant and dynamic coupling between the dopant and the host lattices.^{4,5} The local structure around the rare earth in the crystal lattice also plays an important role in controlling its luminescence performance especially the 4f–5d transitions.^{6,7}

Eu ions, including Eu³⁺ and Eu²⁺, are the most commonly used activators in phosphor materials among the rare-earth ions.^{8–10} Eu²⁺ ions emit a tunable color ranging from ultraviolet to red due to its 5d–4f transition.^{11,12} The 5d orbit of Eu²⁺ is strongly affected by the environment of the crystal, thus the emission of Eu²⁺ is strongly influenced by the crystal field.¹³ Eu³⁺ is one of the most frequently used red-emitting activators,

which mainly shows characteristic emissions resulting from the transitions of ⁵D₀–⁷F_J (J = 0, 1, 2, 3, 4).^{14,15} However, the partly-forbidden f–f transitions of Eu³⁺ have low oscillator strength, resulting in low absorption efficiency and a low color rendering index (CRI). Therefore, it is a promising method to overcome the limitations of Eu³⁺ activated phosphors *via* the coexistence of Eu³⁺ and Eu²⁺ in single phase phosphors.¹⁶

The Eu^{3+/2+} co-doped phosphors can be prepared through a reduction annealing process in a reducing atmosphere such as H₂, H₂/N₂ mixture or CO.¹⁶ After that, the Eu^{3+/2+} co-doped phosphor can be obtained when Eu³⁺ was reduced to Eu²⁺ partially not completely. However, it is very difficult to obtain the Eu^{3+/2+} co-doped CaYAlO₄ even through conventional high temperature solid-state reaction under a reducing atmosphere. Another extreme example is Eu ion doped CaAl₂O₄, in which an abnormal reduction of Eu³⁺ → Eu²⁺ was observed in monoclinic phase of CaAl₂O₄: Eu that calcined in air atmosphere at high temperature.^{17,18} Comparing the formula of CaYAlO₄ and CaAl₂O₄, the only change is their Al/Y ratio. Herein, we investigated the CaY_{1-x}Al_{1+x}O₄:2%Eu system by adjusting the Al/Y ratio. In our work, the phenomenon of the reduction of Eu³⁺ to Eu²⁺ in CaY_{1-x}Al_{1+x}O₄ systems was observed, and the bond energy method is adopted to theoretically explain the site preferential occupancy of Eu^{2+/3+} in the CaY_{1-x}Al_{1+x}O₄ systems.

The deviation of its bond energy in different lattice can be compared to determine which site the activators will occupy according to the similar property of chemical bonds and the

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similar value of their bond energy.¹⁹ The smaller deviation of the bond energy between the host and activators ions, the more easily the lattice site can be replaced by the ion. Therefore, we use this method to solve the site occupancy problem of doping rare earth ions in the matrix. In the previous research, the site preferential occupancy for Eu in Sr₂V₂O₇, Sr₉Gd(VO₄)₇ and Sr₂V₂O₇/Sr₉Gd(VO₄)₇ phosphors²⁰ as well as the site occupancy preference of Bi²⁺ in β-Ca₂P₂O₇ (ref. 21) crystal have been confirmed though the bond energy method.¹⁹ In addition, the bond energy method can connect the relationship between bond energy and preferential occupancy in Eu³⁺ doped in CaAl₂Si₂O₈ crystal.²² Our calculated results are in good agreement with the experimental data and the photoluminescence spectra.

In addition, Eu³⁺-doped inorganic phosphors can be used as efficient orange to red emitting phosphors due to the ⁵D₀-⁷F_J (*J* = 0, 1, 2, 3 and 4) transitions. Most of the phosphors show the dominant emission either ⁵D₀ → ⁷F₁ (~593 nm) or ⁵D₀ → ⁷F₂ (~610 nm) transition of Eu³⁺ ions. The dominated ⁵D₀ → ⁷F₄ (~703 nm) transition emission is infrequent. Only some numerable phosphors show that they have stronger intensity of ⁵D₀-⁷F₄ than ⁵D₀-⁷F₁, such as Sr_{0.99}[La_(1-x)Eu_x]_{1.01}Zn_{0.99}O_{3.495},²³ LaBO₃:Eu³⁺,²⁴ Na₉[EuW₁₀O₃₆]·14H₂O,²⁵ Na₂CaSiO₄:Eu³⁺,²⁶ Ca₂-Ga₂SiO₇:Eu³⁺,²⁷ YAsO₄:Eu.²⁸ Similarly, this phenomenon has been found in CaYAlO₄ with Eu doped. But, the stronger emission of ⁵D₀-⁷F₄ disappeared when Eu³⁺ and Tb³⁺ were co-doped into CaYAlO₄.²⁹ However, in our work, the relative intensity of ⁵D₀-⁷F₄ and ⁵D₀-⁷F₂ can be modified by changing the Al³⁺ and Y³⁺ ions ratios in CaY_{1-x}Al_{1+x}O₄ and the Judd-Ofelt theory³⁰ was applied to calculate the radiative properties of the prepared materials.

2. Experimental section

2.1 Materials and synthesis

A series of CaY_{1-x}Al_{1+x}O₄:2%Eu (*x* = 0, 0.1, 0.2, 0.3, 0.4) phosphors was prepared by a traditional high temperature solid-state reaction route using stoichiometric amounts of CaCO₃ (A.R.), Y₂O₃ (99.99%), Al₂O₃ (99.99%), Eu₂O₃ (99.99%) as raw materials, after the reactants were mixed and well-ground in an agate mortar, they were preheated at 1400 °C for 4 hours. Then the mixtures were reground and calcined at 1500 °C for 4 hours. All of CaY_{1-x}Al_{1+x}O₄:2%Eu (*x* = 0, 0.1, 0.2, 0.3, 0.4) phosphors prepared under a reducing atmosphere of H₂ (5%) and N₂ (95%). The final power products were obtained after cooling to room temperature and grinding to powder sample.

2.2 Characterization

The phase purity of the products was examined by X-ray diffraction (XRD) using a BRUKER D8 ADVANCE powder diffractometer with Cu K α radiation (0.15405 nm) at room temperature, the diffraction data were collected in 2 θ range from 5 to 90°. The UV-vis diffuse reflectance spectra were collected through a Cary 5000 UV-vis-NIR spectrophotometer equipped with a double out-of-plane Littrow monochromator using BaSO₄ as a standard reference. All excitation, emission,

decay spectra and quantum efficiency were measured on an Edinburgh FLS980 combined fluorescence lifetime, a 450 W xenon lamp was used as the excitation source of emission spectra, while a 60 W μ F flash lamp with a pulse width of 1.5–3.0 μ s was for the measurements of decay curves.

3. Result and discussion

3.1 Phase characterization

For comparison, the CaYAlO₄:2%Eu was prepared firstly under a reducing atmosphere of H₂ (5%) and N₂ (95%). The XRD patterns of the CaYAlO₄:2%Eu together with the Joint Committee on Powder Diffraction Standards (JCPDS) card no. 24-0221 are shown in Fig. 1(a). The XRD patterns of CaYAlO₄:2%Eu shows that the diffraction peaks of all single samples are matched well with the standard card of CaYAlO₄ (JCPDS: 24-0221), which indicates that the samples are purity phase and doping Eu ions do not cause significant changes to the crystal structure.

In order to get further confirmation and knowledge regarding crystal structure information and sites of CaYAlO₄:2%Eu, the XRD Rietveld refinement of CaYAlO₄:2%Eu were performed by the General Structure Analysis System (GASA) program with the single crystallographic data of CaYAlO₄ as the initial model. Fig. 1(b) presents red lines and black lines stand for experimental and calculated patterns, respectively, which matched well with each other. The obtained converged weighted-profiles of *R*_p = 8.4% and *R*_{wp} = 6.1%, which reveals a good quality of fit. As the crystallographic data of CaYAlO₄:2%Eu shown in Table 1. And Fig. S1† shows the XRD refinements of CaY_{0.9}Al_{1.1}O₄:2%Eu and CaY_{0.8}Al_{1.2}O₄:2%Eu. This aluminate compound has a tetragonal crystal system with space group *I4/mmm*, *a* = *b* = 3.664 Å, *c* = 11.889 Å, *V* = 159.61 Å³. However, the lattice constants of CaYAlO₄:2%Eu are *a* = *b* = 3.648 Å, *c* = 11.885 Å, which indicates that its crystal constants increase with increasing the concentration of Eu³⁺.

CaYAlO₄ has a tetragonal K₂NiF₄ structure and belongs to a family of compounds with the general formula ABCO₄, where A is an alkaline earth cation, B is Y, Sc, or a trivalent rare earth element and C is Al, Ga or a transition metal ion. In the unit cell, as shown in Fig. 1(c), the Ca and Y cations are distributed almost statistically in the nine coordinated sites and Al³⁺ ions are coordinated with six oxygen atoms and form the AlO₆ octahedron.

Notably, the (Ca/Y)O₉ polyhedron is closely surrounded by AlO₆ octahedrons to form a cage structure (Fig. S2†). Thus, it can be concluded that the local environment of Ca/Y sites is highly compressed due to the rigid structure of CaYAlO₄, which gives rise to the difficulty of reduction of Eu³⁺ activators. The Lin *et al.* has been reported an effective approach-crystal-site engineering to control Eu³⁺ reduced to Eu²⁺.¹⁶ So, a similar way has been used to change the reduction of Eu³⁺ doped in CaYAlO₄.

Compared with Eu³⁺, the smaller ions will replace the Al³⁺ site (such B³⁺ and Si⁴⁺), therefore, an artificial defect substitution will be used for Al³⁺ doping to CaYAlO₄. Fig. 2 showed the XRD patterns of CaY_{1-x}Al_{1+x}O₄:2%Eu (*x* = 0–0.4). Compared with standard card of CaYAlO₄, When *x* > 0.2, the XRD pattern diffraction peak appeared a weak miscellaneous



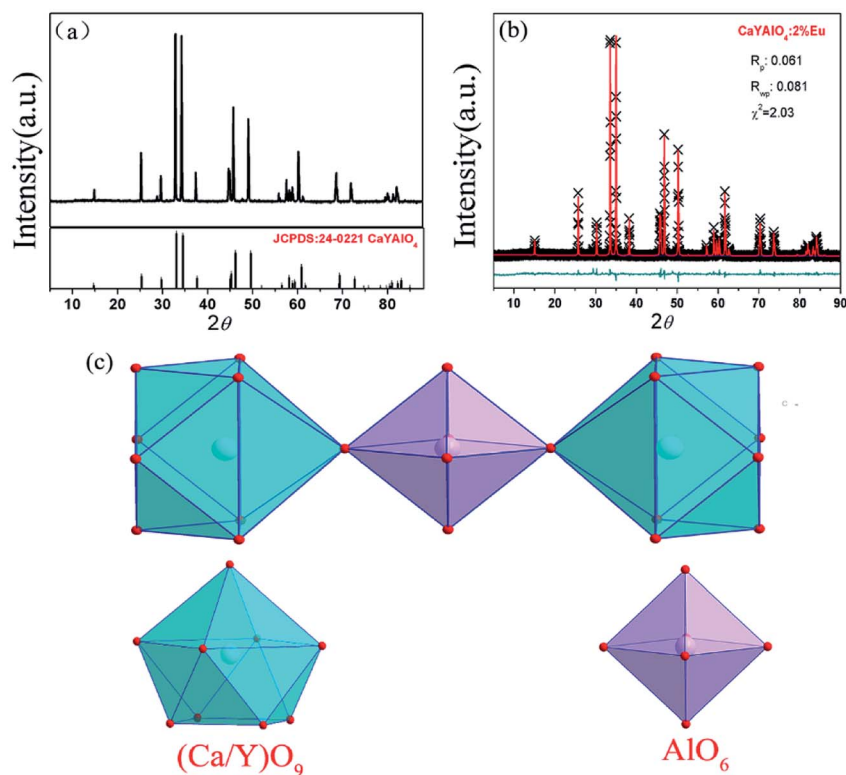


Fig. 1 (a) Powder X-ray diffraction (XRD) patterns of $\text{CaYAlO}_4:2\% \text{Eu}^{3+}$ and the standard cards of CaYAlO_4 (JCPDS: 24-0221); (b) experimental (cross), calculated (solid line) and difference (bottom) results of XRD refinements of $\text{CaYAlO}_4:2\% \text{Eu}^{3+}$. (c) The crystal structure of CaYAlO_4 . Ca^{2+} or Y^{3+} ions are coordinated with nine oxygen atoms to form CaO_9 or YO_9 group and Al^{3+} ions are coordinated with six oxygen atoms and form the AlO_6 octahedron.

Table 1 Crystallographic data of $\text{CaYAlO}_4:0.02\text{Eu}^{3+}$, as determined by the Rietveld refinement of powder XRD data at room temperature

| Atom | Site | x | y | z | Occupancy |
|------|------|--------|--------|--------|-----------|
| Ca1 | 4e | 0.0000 | 0.0000 | 0.3604 | 0.500 |
| Y1 | 4e | 0.0000 | 0.0000 | 0.3603 | 0.490 |
| Eu1 | 4e | 0.0000 | 0.0000 | 0.5000 | 0.010 |
| Al1 | 2a | 0.5000 | 0.5000 | 0.5000 | 1.000 |
| O1 | 4e | 0.5000 | 0.0000 | 0.5000 | 1.000 |
| O2 | 4e | 0.0000 | 0.0000 | 0.1686 | 1.000 |

peak around 31° , which indicates that a new phase appeared at this time, the diffraction peak at about 31° is described to $\text{Ca}_3\text{Y}_2\text{O}_6$, the strongest exact diffraction peak of CaAl_2O_4 is at 30° (see Fig. S3†), so the impurity cannot be ascribed to CaAl_2O_4 . In addition, the properties of luminescence for Eu ions doped in $\text{Ca}_3\text{Y}_2\text{O}_6$ crystals aren't detected in research works at present, which indicates that the Eu^{2+} or Eu^{3+} in $\text{Ca}_3\text{Y}_2\text{O}_6$ has not any emission at room temperature. When $x \leq 0.2$, the diffraction peak of the sample is consistent with the standard card diffraction peak, which means that the Al^{3+} actually occupy the Y^{3+} within a certain range. Thus, we restricted the x value to a maximum of 0.20. Table 2 summarizes the lattice parameters and reliability factors of $\text{CaY}_{1-x}\text{Al}_x\text{O}_4:2\% \text{Eu}$. In addition, because the Al^{3+} ion radius is smaller than that of Y^{3+} , the volume of the unit cell will decrease when Al^{3+} occupies the Y^{3+} site.

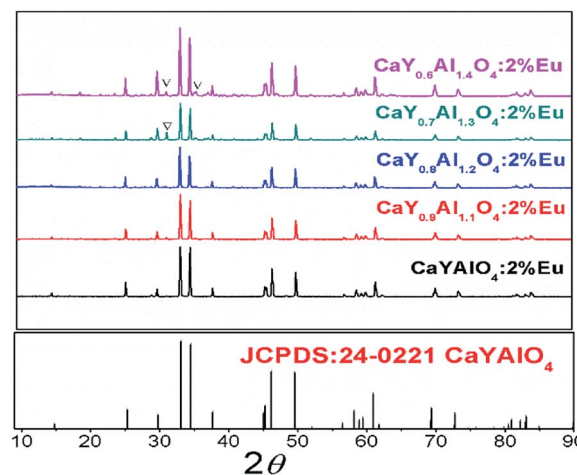


Fig. 2 The powder X-ray diffraction patterns of $\text{CaY}_{1-x}\text{Al}_x\text{O}_4:2\% \text{Eu}$ ($x = 0-0.4$) and the standard cards of CaYAlO_4 (JCPDS: 24-0221).

3.2 Photoluminescence properties

For Eu doped samples, one can clearly distinguish the different emission bands from the photoluminescence (PL) properties of the two valence states of Eu, *i.e.*, the broad ones are attributed to the parity-allowed $4f-5d$ transitions of Eu^{2+} and the sharp ones are ascribed to the parity-forbidden transitions of Eu^{3+} ($^5\text{D}_0 \rightarrow$



Table 2 The lattice parameters and reliability factors of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\% \text{Eu}$ ($x = 0, 0.1, 0.2$)

| Sample | CaAlYO_4 | $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4$ | $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4$ |
|-----------------------|-------------------|---|---|
| R_{wp} | 0.081 | 0.092 | 0.101 |
| R_{p} | 0.061 | 0.071 | 0.082 |
| χ^2 | 2.410 | 2.030 | 3.890 |
| $a = b$ (Å) | 3.664 | 3.642 | 3.610 |
| c (Å) | 11.889 | 11.882 | 11.859 |
| V (Å ³) | 159.61 | 157.60 | 154.55 |

${}^7\text{F}_J$, $J = 0-4$). Fig. 3(a), (c) and (f) illustrate the emission spectra of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\% \text{Eu}$ ($x = 0, 0.1, 0.2$) samples under the NUV excitation of 365 nm. When $x = 0$, as shown in Fig. 3(b), the photoluminescence excitation (PLE) spectrum monitored at 622 nm reveals a broad band with the peak at 277 nm in the range of 200–350 nm due to the charge transfer band (CTB) from O to the Eu ions, along with some sharp peaks in the range of 350–500 nm related to the 4f–4f transitions of Eu^{3+} ions. Under the excitation of 277 or 365 nm, only the sharp f–f

transitions can be found. The sharp emission lines of $\text{CaYAlO}_4:\text{Eu}$ can be assigned to f–f transition of Eu^{3+} , which indicates that Eu^{3+} could not be directly reduced to Eu^{2+} in $\text{CaYAlO}_4:\text{Eu}$ system under a reducing atmosphere. All the emissions spectra are intense. The most intense emission at around 622 nm is attributed to the hypersensitive transition ${}^5\text{D}_0 \rightarrow {}^7\text{F}_2$, indicating that the Eu^{3+} ions mainly occupy the sites without inversion symmetry. The more intense emission at 702 nm is rarely reported. This peak comes from the ${}^5\text{D}_0 \rightarrow {}^7\text{F}_4$ transition of Eu^{3+} . As shown in Fig. S2,† the excitation peaks are similar under the different monitoring wavelength ($\lambda_{\text{em}} = 592, 621, 702$ nm), which indicates that the emission peaks of Eu^{3+} at 592, 621, 702 nm comes from the same site of Eu^{3+} .

Fig. 3(b and f) show the emission spectra of $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4:\text{Eu}$ and $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4:\text{Eu}$ under the excitation of 365 nm, respectively. It is surprising to find an appearance of a broad band with the peak at 445 nm except for some sharp peaks in the range of 350–500 nm related to the 4f–4f transitions of Eu^{3+} ions. Fig. 3(e and h) show the PL spectra of $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4:\text{Eu}$ and $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4:\text{Eu}$ under the monitoring wavelength at 445 and

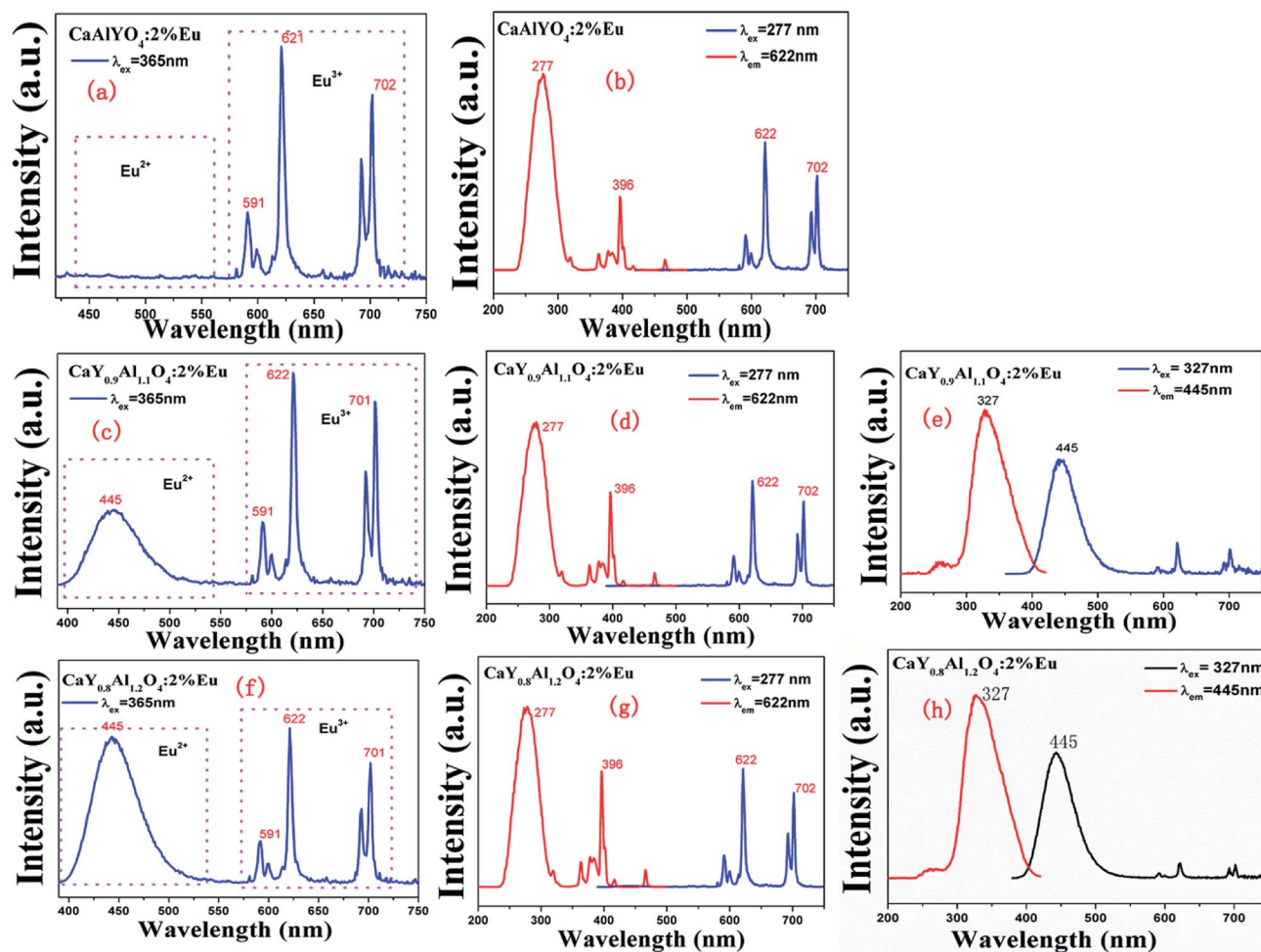


Fig. 3 (a), (c) and (f) are the emission spectra of $\text{CaYAlO}_4:\text{Eu}$, $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4:\text{Eu}$ and $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4:\text{Eu}$ under the excitation wavelength at 365 nm, respectively. (b), (d) and (g) are the excitation spectra under the monitoring wavelength at 622 nm and the emission spectra under the excitation wavelength at 277 nm under excitation wavelength of $\text{CaYAlO}_4:\text{Eu}$, $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4:\text{Eu}$ and $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4:\text{Eu}$, respectively. (e) and (h) are the excitation spectra under the monitoring wavelength at 445 nm and the emission spectra under the excitation wavelength at 327 nm of $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4:\text{Eu}$ and $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4:\text{Eu}$, respectively.



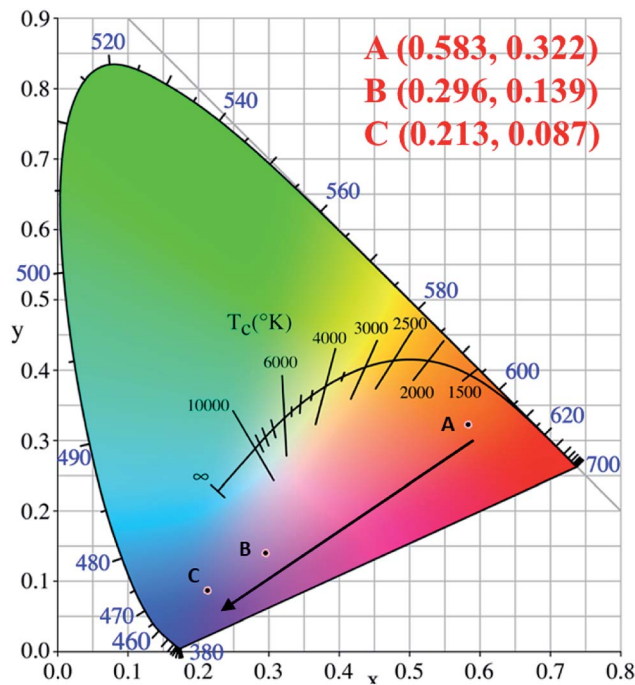


Fig. 4 The corresponding CIE chromaticity diagram for $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$) under the 365 nm excitation. (A) $x = 0$; (B) $x = 0.1$; (C) $x = 0.2$.

the PLE spectra under the excitation wavelength at 327. These correspond to the $4f^65d^1-4f^7$ transition of Eu^{2+} . This indicates that Eu^{3+} had been directly reduced to Eu^{2+} in $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4:\text{Eu}$ and $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4:\text{Eu}$ system under a reducing atmosphere. The luminescence intensity of Eu^{2+} increases with increasing x in $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$) system (Fig. S4[†]), which can be attributed to the increase of x value. These results suggest that Eu^{3+} is partially transformed to Eu^{2+} in $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$).

The corresponding CIE chromaticity diagram for $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$) has been shown in Fig. 4. The points A, B and C stand for the CIE coordinate position when $x = 0, 0.1$ and 0.2 , respectively. With increasing of the Al/Y ratio in $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$, the emission color changed from A (0.583, 0.322) red to C (0.213, 0.083) blue.

The diffuse reflectance in the UV-vis region was used to calculate the experimental band-gap value of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:\text{Eu}^{3+}$ ($x = 0, 0.1, 0.2$). Fig. 5 illustrates the diffuse reflectance of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$). The results show that the samples begin to exhibit low reflectance below 330 nm due to the high radiation absorption. This behavior is assigned to the edge absorption, corresponding to the electronic transition from the valence band to the conduction band of CaYAlO_4 . The matrix of yttrium aluminate and calcium shows optical transparency in the visible region between 330 and 750 nm, making it a candidate for applications in photonic devices.

In Fig. 5b–d, the $(h\nu F(R_\infty))^2$ of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$) was plotted against the $(h\nu)$ using the Kubelka–Munk function.³¹ The following relational expression proposed by Tauc, Davis, and Mott is used:^{32,33}

$$[\alpha h\nu]^n = A(h\nu - E_g) \quad (1)$$

where h is Planck's constant, ν is frequency of vibration, α is absorption coefficient, E_g is band gap, and A is proportional constant. $h\nu$ represents the energy per photon, E_g is the value of the band gap, $n = 1/2$ means a indirect allowed transition, 2 represents a direct allowed transition, $3/2$ stands for a direct forbidden transition, or 3 indicates as indirect forbidden transition. Since the direct allowed transition is used in the experiment, $n = 2$ is used for these samples.

The acquired diffuse reflectance spectra of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$) in Fig. 5 are converted to Kubelka–Munk equation:^{32,34}

$$F(R_\infty) = \frac{(1 - R_\infty)^2}{2R_\infty} \quad (2)$$

where R_∞ is the diffuse reflectance of the layer relative to the standard. Thus, the vertical axis is converted to quantity $F(R_\infty)$, which is proportional to the absorption coefficient α . The α in the Tauc equation is substituted with $F(R_\infty)$. Thus, in the actual experiment, the relational expression (1) becomes:^{23,34}

$$(h\nu F(R_\infty))^2 = C(h\nu - E_g) \quad (3)$$

where C is a proportional constant. Using the Kubelka–Munk function, the was plotted against the $h\nu$. The curves that plots the value of $(h\nu - (h\nu F(R_\infty))^2)$ on the horizontal axis $h\nu$ and vertical axis $(h\nu F(R_\infty))^2$ are drawn in Fig. 5(b–d). Here, the unit for $h\nu$ is eV (electron volts), and its relationship to the wavelength λ (nm) becomes $h\nu = 1239.7/\lambda$. A red lines are drawn tangent to the point of inflection on the black curves. The values associated with the point of intersection of the lines tangent to the plotted curve inflection point with the horizontal axis ($h\nu$ axis) becomes the band gap E_g value. Their band gaps of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$) are 4.10, 4.10 and 4.11 eV. The results show that a significant changing cannot be found in the band-gap edge with increasing value of x . In fact, the R. V. Perrella's³⁴ reported that the difference of energy band-gap between samples doped with 1 and 10 mol% of Eu^{3+} is in the order of magnitude of the phonon energy of the lattice, the Eu^{3+} substitute Y^{3+} cannot change the band gap. Here, when the x increases and cause the band gap also unchanged, so we infer that Al^{3+} also substitute the Y^{3+} site rather than Ca^{2+} site.

The decay curves of Eu^{3+} shown in Fig. 6a–c are accurately fitted using the following single-exponential equation:

$$I(t) = I_0 \exp\left(-\frac{t}{\tau}\right) \quad (4)$$

where I_t and I_0 are the intensity at time t and time zero, respectively, the τ is the lifetime. When under the excitation wavelength of 394 nm, the lifetimes of Eu^{3+} in $\text{CaYAlO}_4:\text{Eu}$, $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4:\text{Eu}$ and $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4:\text{Eu}$ are 1.198 ms, 1.190 ms and 1.201 ms, respectively.

The decay curves of Eu^{2+} in Fig. 6d and e are accurately fitted well to a second-order exponential decay model based on the following formula:



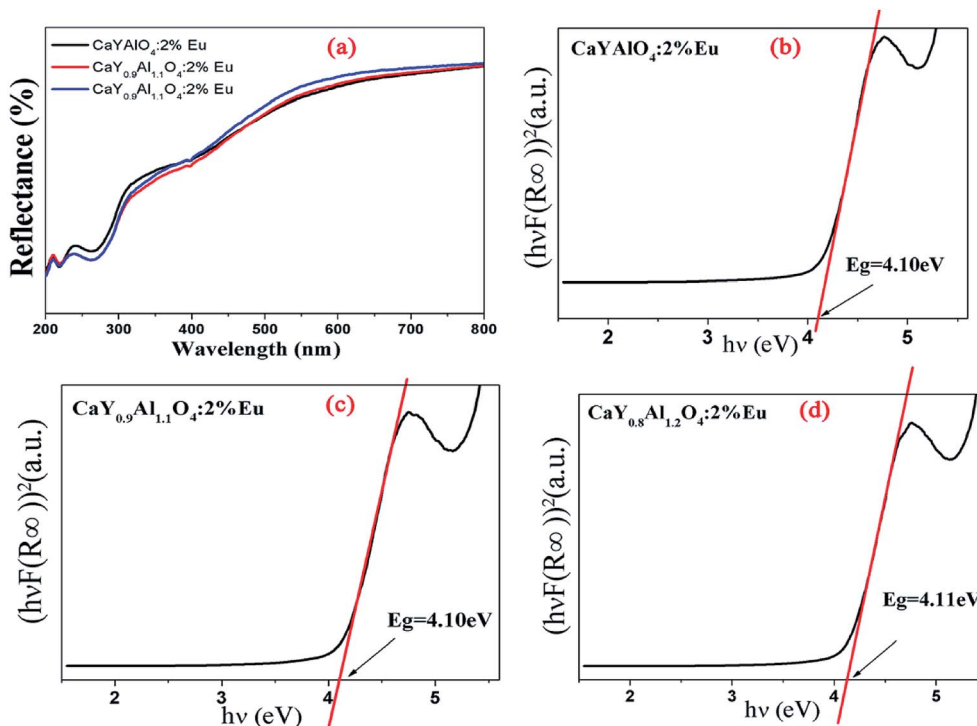


Fig. 5 (a) Diffuse reflectance of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\% \text{Eu}$ ($x = 0, 0.1, 0.2$). (b), (c) and (d): The $(hvF(R_\infty))^2$ was plotted against the (hv) using the Kubelka–Munk function.

$$I(t) = A_1 \exp\left(-\frac{t}{\tau_1}\right) + A_2 \exp\left(-\frac{t}{\tau_2}\right) \quad (5)$$

$$\tau = \frac{(A_1\tau_1^2 + A_2\tau_2^2)}{(A_1\tau_1 + A_2\tau_2)} \quad (6)$$

where $I(t)$ is the luminescence intensity at times t . A_1 and A_2 are fitting constants, τ_1 and τ_2 are exponential component of the decay time and t is the time, respectively. The average decay time can be described by the following formula:

According to the equation, the lifetimes of Eu^{2+} in $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4:\text{Eu}$ and $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4:\text{Eu}$ are calculated to be 1.07 ns and 1.14 ns, respectively.

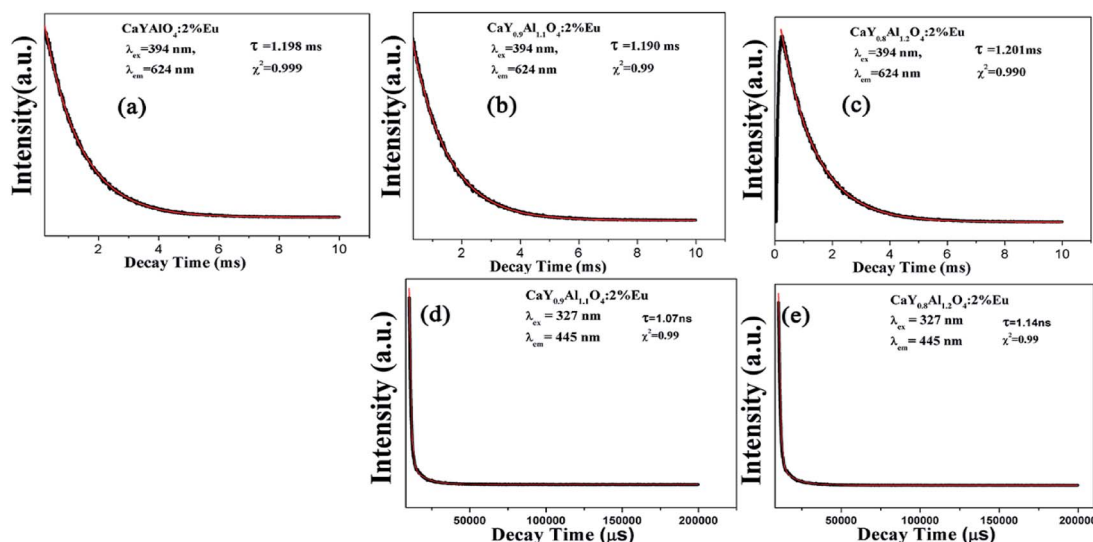


Fig. 6 (a), (b) and (c) are the decay curves of Eu^{3+} ions in $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\% \text{Eu}$ ($x = 0, 0.1, 0.2$) ($\lambda_{\text{ex}} = 394 \text{ nm}$, $\lambda_{\text{em}} = 624 \text{ nm}$). The (d) and (e) are the decay curves of Eu^{2+} ions in the $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\% \text{Eu}$ ($x = 0.1, 0.2$) sample ($\lambda_{\text{ex}} = 327 \text{ nm}$, $\lambda_{\text{em}} = 445 \text{ nm}$).



3.3 Bond energy method and preferential occupancy of Eu ions

The dopant occupancy in the matrix can be determined by comparing the deviation of its bond energy in different lattice location. The similar value of the deviation for its bond energy, the more stable the dopants in matrix are. Thus, to determine which site Eu^{3+} and Eu^{2+} will occupy, the bond-energy method has been used to study to the local structure $\text{Eu}^{3+}/\text{Eu}^{2+}$ in CaYAlO_4 crystals. The bond energy of different dopants in CaYAlO_4 crystallographic frame can be estimated through the following equation:^{19,21,22}

$$E_{\text{Ca/Y/Al-O}} = J \exp\left(\frac{d_0 - d_{\text{Ca/Y/Al-O}}}{0.37}\right) \left(\frac{V_{\text{Ca/Y/Al}}}{V_{\text{Eu}}}\right) \quad (7)$$

V_{Eu} is valence state of Eu (including +2 or +3), both J and d_0 are constant usually they can be found in reference. $E_{\text{Ca/Y/Al-O}}$ is mean the bond energy of Ca-O, Y-O or Al-O. In the case of pure CaYAlO_4 crystals without any dopant, $V_{\text{Ca/Y/Al}}/V_{\text{Eu}}$ is equal to 1. The eqn (7) can be expressed as:^{19,21,22}

$$E_{\text{Ca/Y/Al-O}} = J \exp\left(\frac{d_0 - d_{\text{Ca/Y/Al-O}}}{0.37}\right) \quad (8)$$

and if is not equal to 1, then it means the valence state affects the crystal bond energy effectively.

It is assumed that the $\text{Eu}^{3+}-\text{O}^{2-}$ bonds have the similar bond lengths as Ca/Y/Al-O bonds when the dopant substitutes Ca/Y/Al cations. In this regard, the value of various un-doped and doped CaYAlO_4 crystals can be evaluated. The displacement of dopants leads to a large variation of the crystal composition and bond energy, which may affect not only the crystal properties but also the crystal stability. In such a case, it is convenient to measure the variation of bond energy by the following expression when the Eu locates at Ca/Y/Al sites. Based on chemical viewpoint, the dopants preferentially occupy the sites with smaller alterations of bond energy, the sites with smaller absolute values can be expressed as below,^{19,21,22}

$$\Delta E_{\text{Eu}}^{\text{Ca/Y/Al}} = |E_{\text{Ca/Y/Al-O}} - E_{\text{Eu-O}}| \quad (9)$$

Here $\Delta E_{\text{Eu}}^{\text{Ca/Y/Al}}$ is the variation of bond energy when the Eu locates at Ca/Y/Al sites. Based on chemical viewpoint, the dopants preferentially occupy the sites with smaller deviation of bond energy ($E_{\text{Ca/Y/Al-O}}$), the sites with smaller absolute values of $\Delta E_{\text{Eu}}^{\text{Ca/Y/Al}}$.

According to the bond energy method, the values of bond energy of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\% \text{Eu}$ ($x = 0.1, 0.2$) have been shown in Table 3. The order of variation of bond energy under the assumption that $\text{Ca}^{2+}/\text{Y}^{3+}/\text{Al}^{3+}$ ions are substituted by Eu^{3+} is $\Delta E_{\text{Eu}^{3+}}^{\text{Y}} (3.236 \text{ kcal mol}^{-1}) < \Delta E_{\text{Eu}^{3+}}^{\text{Ca}} (6.533 \text{ kcal mol}^{-1}) \ll \Delta E_{\text{Eu}^{3+}}^{\text{Al}} (118.789 \text{ kcal mol}^{-1})$, which means that Eu^{3+} will preferentially replaces Y^{3+} . The calculation result is consistent with the experiment. In addition, the order of variation of bond energy Eu^{2+} substituted Y^{3+} , Ca^{2+} and Al^{3+} is $\Delta E_{\text{Eu}^{2+}}^{\text{Y}} (12.386 \text{ kcal mol}^{-1}) \approx \Delta E_{\text{Eu}^{2+}}^{\text{Ca}} (12.633 \text{ kcal mol}^{-1}) \ll \Delta E_{\text{Eu}^{2+}}^{\text{Al}} (67.149 \text{ kcal mol}^{-1})$, which means that the site of Ca^{2+} and Y^{3+} could be replaced by Eu^{2+} equally. Considering the valence of Eu^{2+} , we can determine that the Eu^{2+} is preferentially occupied the site of Ca^{2+} .

3.4 The ${}^5\text{D}_0-{}^7\text{F}_4$ emission for $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\% \text{Eu}$ ($x = 0, 0.1, 0.2$)

The emission spectrum showed an unusual comparable intensity ${}^5\text{D}_0-{}^7\text{F}_4$ transition peak. The relative intensity of ${}^5\text{D}_0-{}^7\text{F}_2$ and ${}^5\text{D}_0-{}^7\text{F}_4$ can be stable by changing the relative proportions of Al^{3+} and Y^{3+} . To gain some insight into the nature of the luminescence behavior of Al^{3+} ions in crystal $\text{CaYAlO}_4:2\% \text{Eu}$ powders, the Judd-Ofelt model was applied to the determination of spontaneous emission coefficients. The intensity parameters Ω_2 and Ω_4 were determined from luminescence spectra using the method proposed by Kodaira *et al.*^{28,35}

The emission intensity, $I = \hbar\omega AN$, is expressed in terms of the surface under the emission curve, where $\hbar\omega$ is the transition energy, N is the population of the emitting level (${}^5\text{D}_0$) and the Einstein's coefficient of spontaneous emission can be given by²⁵

$$A_{0-\lambda} = \frac{4e^2\omega^3}{3\hbar c^3} \chi \sum_{\lambda=2,4} \Omega_{\lambda} \langle {}^5\text{D}_0 || U^{(\lambda)} || {}^7\text{F}_J \rangle^2 \quad (10)$$

where $\chi = n_0(n_0^2 + 2)^2/9$ is a Lorentz local field correction. The square reduced matrix elements $\langle {}^5\text{D}_0 || U^{(2)} || {}^7\text{F}_2 \rangle^2 = 0.003289$; $\langle {}^5\text{D}_0 || U^{(2)} || {}^7\text{F}_4 \rangle^2 = 0.002365$ in eqn (10) and an average index of refraction equal to 1.5 was used.³⁶ In this case the $A_{0-\lambda}$ values are obtained by using the relation:^{25,37}

$$A_{0-\lambda} = A_{0-1} \frac{S_{0-\lambda}}{S_{0-1}} \frac{\sigma_{\lambda}}{\sigma_1} \quad (11)$$

where $S_{0-\lambda}$ is the area under the curve related to the ${}^5\text{D}_0-{}^7\text{F}_{\lambda}$ transition obtained from the spectral data, σ_{λ} is the energy barycenter of the $0-\lambda$ transition and A_{0-1} is the Einstein's coefficient for the $0-1$ magnetic dipole transition. The A_{0-1} value is estimated to be around of 50 s^{-1} .

The lifetime (τ), non-radiative (A_{nrad}) and radiative (A_{rad}) rates are related through the following equation:³⁵

$$A_{\text{tot}} = \frac{1}{\tau} = A_{\text{rad}} + A_{\text{nrad}} \quad (12)$$

where the radiative (A_{rad}) rates was obtained by summing over the radiative rates A_{0-J} for each ${}^5\text{D}_0-{}^7\text{F}_J$ transitions. It can be given by:³⁵

$$A_{\text{rad}} = \sum_J A_{0-J} \quad (13)$$

The emission quantum efficiency of the emitting ${}^5\text{D}_0$ level is given by:³⁵

$$\eta = \frac{A_{\text{rad}}}{A_{\text{rad}} + A_{\text{nrad}}} \quad (14)$$

The values of the Ω_2 and Ω_4 parameters as well as other quantities derived from analysis of the luminescence spectra of Al^{3+} replace the Y^{3+} in CaYAlO_4 are given in Table 4.

Table 4 shows intensity parameters Ω_2 and Ω_4 . Ω_{λ} is the emission intensity parameters; Ω_2 is the emission intensity parameter of ${}^5\text{D}_0-{}^7\text{F}_2$. Ω_4 means the emission intensity parameter of ${}^5\text{D}_0-{}^7\text{F}_4$. Here, the Ω_2 intensity parameter values are higher than Ω_4 for $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\% \text{Eu}$ ($x = 0, 0.1, 0.2$). The



Table 3 The bond parameters of the central atom and values of bond energy when Eu^{3+} locates at Ca, Y, and Al sites in CaYAlO_4 . All of the bond energy unit are kcal mol^{-1}

| Central atom | Coordination atom | Count | d (Å) | $E_{\text{M-O}}$ | $E_{\text{Eu}^{3+}}$ | $E_{\text{Eu}^{2+}}$ | $\Delta E_{\text{Eu}^{3+}}^{\text{M}}$ | $\Delta E_{\text{Eu}^{2+}}^{\text{M}}$ |
|--------------|-------------------|-------|---------|------------------|----------------------|----------------------|--|--|
| Ca1 | O2 | 1× | 2.3013 | 51.291 | 39.457 | 28.407 | 6.533 | 12.633 |
| | O1 | 4× | 2.5152 | 28.772 | 22.133 | 15.935 | | |
| | O2 | 4× | 2.6125 | 22.119 | 17.015 | 12.250 | | |
| Al1 | O1 | 4× | 1.8375 | 73.757 | 207.306 | 149.253 | 118.784 | 67.149 |
| | O2 | 2× | 1.9866 | 49.294 | 138.549 | 99.750 | | |
| | O2 | 1× | 2.3013 | 65.045 | 59.186 | 42.611 | | |
| Y1 | O2 | 1× | 2.3013 | 65.045 | 59.186 | 42.611 | 3.236 | 12.385 |
| | O1 | 4× | 2.5152 | 36.488 | 33.200 | 23.903 | | |
| | O2 | 4× | 2.6125 | 28.050 | 25.523 | 18.376 | | |

Table 4 Decay rates of radiative (A_{rad}), nonradiative (A_{nrad}), and total (A_{tot}) processes of ${}^5\text{D}_0\text{--}{}^7\text{F}_J$ transitions, luminescence lifetime (τ), intensity parameters (Ω_2 , Ω_4), quantum efficiencies (η) and actual quantum efficiency (η_a) of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$

| Samples | A_{rad} | A_{nrad} | A_{tot} | τ | Ω_2 | Ω_4 | η | η_a |
|---|------------------|-------------------|------------------|--------|------------|------------|--------|----------|
| CaYAlO_4 | 409 | 427 | 836 | 1.198 | 4.12 | 2.97 | 0.489 | 47.69% |
| $\text{CaY}_{0.9}\text{Al}_{1.1}\text{O}_4$ | 406 | 434 | 840 | 1.190 | 3.99 | 3.09 | 0.483 | 50.42% |
| $\text{CaY}_{0.8}\text{Al}_{1.2}\text{O}_4$ | 403 | 429 | 832 | 1.201 | 3.91 | 3.10 | 0.484 | 55.43% |

Ω_2 parameter depends rather on the lower rank components of crystal field and dynamic coupling interactions, while the Ω_4 parameter depend rather on the corresponding higher components. It suggests that site symmetry occupied by Eu^{3+} ions does not have a character of centrosymmetric chemistry environment considering that the ${}^5\text{D}_0\text{--}{}^7\text{F}_2$ transitions is formally forbidden due to the electric dipole selection rule. Meanwhile, it has been commented in literature that the luminescence spectra of compounds with D_{4d} (see Fig. 1(c)) symmetry are often dominated by the ${}^5\text{D}_0\text{--}{}^7\text{F}_4$ transition of Eu^{3+} because of the absence of central symmetry. An undistorted square anti-prism has D_{4d} symmetry, so a site with symmetry lower than D_{4d} but the coordination polyhedron close to a square anti-prism, is expected to have an intense ${}^5\text{D}_0\text{--}{}^7\text{F}_4$ transition. In $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$, Eu^{3+} is nine-fold coordinated, this coordination polyhedron can be regarded as close to mono-capped square-anti-prism. As a result, in this compound the ${}^5\text{D}_0\text{--}{}^7\text{F}_4$ transition is less intense than the ${}^5\text{D}_0\text{--}{}^7\text{F}_2$ transition but much more intense than ${}^5\text{D}_0\text{--}{}^7\text{F}_1$ magnetic dipole transition. The same remarks have also been for $\text{LaBO}_3:\text{Eu}^{3+}$, $[\text{Eu}(\text{DOTA})(\text{H}_2\text{O})]^-$ and $\text{Sr}_{0.99}\text{La}_{1.01}\text{Zn}_{0.99}\text{O}_{3.495}:\text{Eu}^{3+}$. In addition, the values of Ω_4/Ω_2 is 0.72, 0.77, 0.79 for $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$) respectively, which indicated the ${}^5\text{D}_0\text{--}{}^7\text{F}_4$ emission can be enhanced by properly adjusting the Al/Y ratio, at the same time it does not change the quantum efficiency (η). The quantum efficiency (η_a) measured by the integrating sphere is nearly the result by calculation.

4. Conclusions

A series of $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}^{3+}$ ($x = 0, 0.1, 0.2, 0.3$) phosphors have been identified. The powder XRD patterns and Rietveld

refinement reveal that $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}^{3+}$ have a tetragonal crystal structure with the space group $I4/mmm$ (No. 139). The photoluminescence property of the $\text{CaY}_{1-x}\text{Al}_{1+x}\text{O}_4:2\%\text{Eu}$ ($x = 0, 0.1, 0.2$) phosphors exhibit both blue emission of Eu^{2+} ($4f^65d^1\text{--}4f^7$) and red-orange emission of Eu^{3+} (${}^5\text{D}_0\text{--}{}^7\text{F}_{1,2,3,4}$) under UV light excitation, which showed that $\text{Eu}^{3+/2+}$ co-doping system was obtained by adjusting Al/Y ratio. Eu^{3+} ions can be reduced to Eu^{2+} ions when Al/Y ratio was changed. Calculated by the bond-energy theory found that Eu^{3+} takes priority over the Y^{3+} site, in addition, the site of Ca^{2+} and Y^{3+} all can be occupied by Eu^{2+} . Considering the valence of Eu^{2+} , it can determine that the Eu^{2+} is preferentially occupied the site of Ca^{2+} . The Judd–Ofelt model was applied to the determination of spontaneous emission coefficients. The intensity parameters Ω_2 and Ω_4 were determined from luminescence spectra.

Conflicts of interest

There are no conflicts to declare.

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