Luminescence properties and energy transfer of Tb³⁺, Eu³⁺ co-doped YTaO₄ phosphors obtained via sol–gel combustion process

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Abstract

Tantalate is considered as a valuable and efficient luminescence host because of its intense absorption in the ultraviolet area and excellent chemical properties. In this work, a series of pure YTaO₄:Eu³⁺ and/or Tb³⁺ crystals were prepared via a sol–gel combustion method. The morphology, structure, and optical properties of the samples were discussed in detail. The Eu³⁺, Tb³⁺ co-doped YTaO₄ samples are consisted of small spherical particles of around 18 nm. The prepared YTaO₄:Tb³⁺ and/or Eu³⁺ samples exhibit the characteristic wide excitation band around 210–300 nm, the characteristic narrow red emission of Eu³⁺ (⁵D₀ → ⁷F₂) transitions and green emission of the Tb³⁺ (⁵D₄ → ⁷F₅) transitions when excited by UV light. It is focused on the energy transfer processes from the YTaO₄ to Tb³⁺ as well as Eu³⁺ ions and from Tb³⁺ to Eu³⁺ ions of YTaO₄:Eu³⁺/Tb³⁺ phosphors. Color-tunable emissions are realized through adjusting the types of rare earth ion (Eu³⁺ and Tb³⁺) and relative doping concentrations excited by a single wavelength. That is to say, the obtained Tb³⁺ and Eu³⁺ co-doped YTaO₄ phosphors have a promising prospect in lasers, white light diodes (WLED), fluorescent lamp, and field emission display devices, etc.

1 Introduction

At present, owing to the advantages of friendly environment, nice color rendering index and excellent luminescent performance, rare earth active oxide phosphors have been got quite attention in imaging, lighting, display, and other fields. In general, high temperature solid-state method is a common way to synthesize rare earth activated oxide phosphors. Unfortunately, the traditional solid reaction route is not beneficial to control the particle size and separation of components, and may lead to other problems such as long reaction times and stoichiometric losses caused by evaporation at high temperature in general [1]. Therefore, it is still necessary to develop some timesaving and low temperature methods to synthesize the target product such as the hydrothermal method, supersonic microwave co-assistance method, sol–gel method [2–6]. Among these routes, sol–gel combustion method is a good choice because it can obtain

stable precursors and nanometer phosphors with homogeneous composition and high purity. Compared with bulk materials, nanophosphors have a large number of surface atoms. Therefore, the interaction between nanophosphor and the incident UV light is much higher than that of its bulk counterpart. Additionally, nanophosphors have the advantages of better absorption, high conversion efficiency, and high color rendering [7–11]. All of these advantages of reduced dimension phosphors make them easier to use in modern applications [12].

Compared with the common LED used for lighting, the deep UV LED with the wavelength of 240–280 nm has the outstanding advantages of safety, environmental protection, cold light source, pure light quality, high efficiency, rich wavelength type, easy to compound spectral energy, convenient modulation, etc., which is much suitable for civil use. In addition to being a common germicidal lamp, deep UV LED has been widely used in medical and health fields [13, 14]. At the same time, with the outbreak of the coronavirus, the research on UV-C (280–200 nm) LED with bactericidal effect is more and more urgent. Recently, rare earth ions doped tantalate phosphors have received considerable concern for their important applications in lighting fields [15–19]. YTaO₄ is known as an excellent chemical and photoactive host material in virtue of its luminescence

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performance, high density, high irradiation hardness, strong X-ray absorption, and stable physical and chemical properties [20]. YTbO_4 has two crystal phases, one is tetragonal phase (T), namely scheelite structure, with space group $I4_1/a$ [21], the other is monoclinic phase, including the pyrite phase (M) with $I2/a$ space group and the prime phase (M') with $P2_1/a$ space group [22, 23]. The difference of the two structures is essentially on account of the different coordination number of atoms. With M structure, Ta atoms occupy tetrahedral lattice, while in M' structure, Ta atoms exist in twisted octahedral structure [24, 25]. As reported, Rare earth-doped YTbO_4 crystal with M' structure can present the charge transfer process more effectively and provide splendid luminescent emission [26–28].

Eu^{3+} along with Tb^{3+} ions doped phosphors have been extensively studied on account of their ideal luminescent properties [29, 30]. Besides, based on energy transfer mechanism, the phosphors doped with $\text{Eu}^{3+}/\text{Tb}^{3+}$ ions can realize tunable multicolor emission. Particularly, thanks to the $^5\text{D}_0 \rightarrow ^7\text{F}_{1,2}$ transitions, the Eu^{3+} -doped phosphors can emit red light [31–37]. Tb^{3+} can be used as both activator and sensitizer to achieve green light emission due to its $^5\text{D}_4 \rightarrow ^7\text{F}_5$ transitions at approximately 547 nm [38, 39] and improve the emission intensity of activator ions (Eu^{3+}). In addition, Tb^{3+} ions also broaden the UV–visible absorption region when Tb^{3+} along with Eu^{3+} ions co-doping in some hosts owing to the existence of more level transitions [40–43]. It means that owing to the effective energy transfer, the characteristic emission light of Tb^{3+} and Eu^{3+} ions can be adjusted to obtain color-tunable phosphors excited by ultraviolet light. Moreover, the strong excitation band in the ultraviolet region of YTbO_4 host can effectively transfer absorbed energy to the doped activators. Thereby, it allows the energy to be more fully transmitted to rare earth ions to improve the fluorescence efficiency of the phosphors. Hence, we focus on synthesizing color adjustable phosphors by doping Tb^{3+} and Eu^{3+} in YTbO_4 host.

In this work, we prepared the phosphors with the composition of $\text{YTbO}_4:\text{Eu}^{3+}/\text{Tb}^{3+}$ by sol–gel combustion method. Photoluminescence properties, energy transfer, and adjustable color were studied closely. Due to the excellent luminescence properties and colorimetric properties of $\text{YTbO}_4:\text{Ln}^{3+}$ ($\text{Ln}^{3+} = \text{Eu}^{3+}$ and/or Tb^{3+}) samples, there will be potential phosphors used in the fields of display and lighting.

2 Experimental section

2.1 Materials

Yttrium oxide (Y_2O_3) (99.99%), Terbium oxide (Tb_4O_7) (99.99%), Europium oxide (Eu_2O_3) (99.99%), Tantalum oxide (Ta_2O_5) (99.99%), Citric acid (CA) (Analytical

reagent, AR), Nitric acid (HNO_3), Ammonia, Ammonium nitrate (NH_4NO_3) (AR) were used as starting materials. The reagents we used were analytical grade and utilized as purchased without further purification.

2.2 Preparation

The corresponding quantities of Y_2O_3 , Eu_2O_3 , and Tb_4O_7 were put into dilute HNO_3 solution, stirred, and heated in ambient atmosphere, and then after evaporation, crystallization, and cooling, the obtained rare earth nitrate crystals were finally configured into the corresponding aqueous solutions to obtain $0.1 \text{ mol L}^{-1} \text{Y}(\text{NO}_3)_3$, $0.05 \text{ mol L}^{-1} \text{Eu}(\text{NO}_3)_3$ and $0.05 \text{ mol L}^{-1} \text{Tb}(\text{NO}_3)_3$ solutions. Eu^{3+} -, Tb^{3+} -doped YTbO_4 nanocrystals were obtained by sol–gel combustion method. The typical steps for preparing $\text{YTbO}_4:0.07\text{Tb}^{3+}$, 0.02Eu^{3+} are as follows: First, 0.5 mmol of Ta_2O_5 was completely dissolved in HF acid (40%), and then ammonia solution (25%) was added until the pH equals to 9. The obtained precipitate was centrifuged and washed with deionized water to get rid of the redundant F^- , and then dissolved in citric acid aqueous solution at 50°C . Subsequently, $0.97 \text{ mmol Y}(\text{NO}_3)_3$, $0.01 \text{ mmol Eu}(\text{NO}_3)_3$, $0.02 \text{ mmol Tb}(\text{NO}_3)_3$ and 1.20 g of NH_4NO_3 were added into the above solution. Under vigorous stirring at 80°C , a high viscosity gel with pale-yellow was formed. Further, the gel was heated at 180°C for 3 h to get a highly condensed porous network dry gel. After that, it was transferred to the muffle furnace and heated to 500°C for 3 h. Finally, grind the solid taupe mass obtained in the previous process into a fine powder and put it into the alumina crucible then for heat treatment at 1000°C for 5 h. The target phosphors were obtained and used for further characterization. The synthesis steps of other samples are the same as that of $\text{YTbO}_4:0.07\text{Tb}^{3+}$, 0.02Eu^{3+} samples except for doping different concentrations of rare earth ions.

2.3 Characterization

X-ray diffraction (XRD) measurements were carried out on a Rigaku-Dmax-RA diffractometer using $\text{Cu K}\alpha$ radiation ($\lambda = 0.15406 \text{ nm}$), operating at a scanning speed of $10^\circ \text{ min}^{-1}$ in the 2θ range from 10° to 90° . The morphologies of the samples were analyzed using a FEI-30 field emission scanning electron microscope (FE-SEM) equipped with an energy dispersive X-ray spectrometer (EDX). The photoluminescence measurements were carried out on a HITACHI-7000 spectrophotometer equipped with a 150-W Xenon lamp as the excitation source. All the measurements were carried out at room temperature.

3 Results and discussion

3.1 Phase identification, structure, and morphology analysis

The XRD patterns of $\text{YTaO}_4:\text{Eu}^{3+}/\text{Tb}^{3+}$ samples synthesized via sol–gel combustion method are shown in Fig. 1a. We can see that all measured peak positions match with YTaO_4 standard card (PDF# 24-1425) properly. The obtained YTaO_4 powder is a monoclinic structure (M' structure) with P2/a space group and the lattice parameters are $a=5.29$, $b=5.45$, $c=5.11$ Å, and $Z=2$. No any other impure phase is detected, suggesting that the replacement of Y^{3+} ions by Eu^{3+} and Tb^{3+} ions does not affect

the purity of the YTaO_4 . This is because the radii of Y^{3+} ($r=0.908$ Å), Tb^{3+} ($r=0.923$ Å) and Eu^{3+} ($r=0.947$ Å) ions are similar, and all three ions have the same coordination number ($\text{CN}=8$). Figure 1b shows the lattice structure as well as atomic coordination of YTaO_4 . We can see that each tantalum ion and yttrium ion are encircled by six and eight oxygen ions in the YTaO_4 M' -type structure, respectively, to form a distorted octahedron (TaO_6) and a twisted cube (YO_8).

The morphology and elemental component of $\text{YTaO}_4:0.07\text{Tb}^{3+}$, 0.02Eu^{3+} sample are characterized by FE-SEM and EDX, respectively. Figure 2a illuminates that the phosphors are uniform nanoparticles with a small number of agglomerates and the particle size is about 18 nm, seen from the size distribution histogram of the samples

Fig. 1 **a** XRD patterns of the as-prepared $\text{YTaO}_4:\text{Tb}^{3+}$, $\text{YTaO}_4:\text{Eu}^{3+}$ and $\text{YTaO}_4:0.07\text{Tb}^{3+}$, 0.02Eu^{3+} samples, and the corresponding standard data of YTaO_4 (PDF No. 24-1425) are given as reference, **b** the crystal structure of YTaO_4 host

Fig. 2 **a** FE-SEM image and **b** EDX spectrum of $\text{YTaO}_4:0.07\text{Tb}^{3+}$, 0.02Eu^{3+} sample. Inset of **a** is the size distribution histogram

(insert of Fig. 2a). Figure 2b exhibits the EDX spectrum of $\text{YTaO}_4:0.07\text{Tb}^{3+}$, 0.02Eu^{3+} phosphor, and we can see the existence of O, Ta, Y, Tb, Eu, and Si elements. The Si element comes from silicon wafer.

3.2 Luminescence properties

The photoluminescence excitation (PLE) and photoluminescence (PL) spectra of Tb^{3+} singly activated YTaO_4 samples are presented in Fig. 3a. When monitored at 547 nm ($^5\text{D}_4 \rightarrow ^7\text{F}_5$ transition of Tb^{3+}), there is a strong broadband around 210–300 nm with a maximum at 270 nm in PLE spectrum, corresponding to the charge transfer band of $\text{Tb}^{3+}-\text{O}^{2-}$ and $\text{O}^{2-}-\text{Ta}^{5+}$ in TaO_4^{3-} group [13], which lead to better luminescent properties of Tb^{3+} ions in YTaO_4 host for UV excitation [44]. It also indicates that the existence of energy transfer between the host lattice (TaO_4^{3-} group) and the active centers (Tb^{3+} ions) [45]. In addition, the f-f transitions of Tb^{3+} ions from the ground state ($^7\text{F}_6$) to the $^5\text{D}_2$ (354 nm), $^5\text{L}_{10}$ (369 nm) and $^5\text{G}_6$ (378 nm) states result in several sharp PLE peaks ranged from 320 to 380 nm [46, 47]. Upon 270 nm excitation, the representative emission peaks at 492 nm, 547 nm, 585 nm, and 621 nm in the PL spectrum are corresponded to $^5\text{D}_4 \rightarrow ^7\text{F}_{6,5,4,3}$ transitions of Tb^{3+} ions, respectively [48]. The strongest emission peak of $\text{YTaO}_4:0.07\text{Tb}^{3+}$ phosphor situates at 547 nm in the green area. The PL spectra of the $\text{YTaO}_4:x\text{Tb}^{3+}$ phosphors under 270 nm excitation illuminate that the luminescence intensity of Tb^{3+} reaches maximum at $x=0.07$. When Tb^{3+} concentration exceeds 0.07, the emission intensity decreases owing to the concentration quenching effect [49, 50].

The PLE and PL spectra of the Eu^{3+} singly activated YTaO_4 phosphor are illustrated in Fig. 4. When 613 nm

Fig. 3 PL excitation spectrum (left) for $\text{YTaO}_4:0.07\text{Tb}^{3+}$ and emission spectra (right) for $\text{YTaO}_4:x\text{Tb}^{3+}$ ($x=0.01-0.08$) samples. Inset is enlarged excitation spectrum of $\text{YTaO}_4:0.07\text{Tb}^{3+}$ at the range of 320 to 380 nm

Fig. 4 PL excitation spectrum (left) for $\text{YTaO}_4:0.02\text{Eu}^{3+}$ and emission spectra (right) for $\text{YTaO}_4:y\text{Eu}^{3+}$ ($y=0.005-0.04$) samples

($^5\text{D}_0 \rightarrow ^7\text{F}_2$ transition) is used as monitoring wavelength, the PLE spectrum consists of a broad band of 210–300 nm centered at 258 nm and a few of weak sharp peaks ranging from 300 to 450 nm, which are corresponded to the charge transfer band transitions of $\text{Eu}^{3+}-\text{O}^{2-}$ and $\text{O}^{2-}-\text{Ta}^{5+}$ [51–53] and the f-f transitions of Eu^{3+} from the ground state ($^7\text{F}_0$) to the $^5\text{H}_6$ (321 nm), $^5\text{D}_4$ (362 nm), $^5\text{G}_4$ (384 nm), $^5\text{L}_6$ (395 nm), $^5\text{D}_3$ (418 nm), $^5\text{D}_2$ (466 nm) and $^5\text{D}_1$ (537 nm) states [54, 55]. At 258 nm excitation, in PL spectrum, we can see the main peaks at around 578, 593, 613 and 656 nm, which correspond to the $^5\text{D}_0 \rightarrow ^7\text{F}_0$, $^5\text{D}_0 \rightarrow ^7\text{F}_1$, $^5\text{D}_0 \rightarrow ^7\text{F}_2$ and $^5\text{D}_0 \rightarrow ^7\text{F}_3$ transitions of Eu^{3+} [56]. In addition, the symmetry of the doping position of Eu^{3+} directly affects the emission intensity of $^5\text{D}_0 \rightarrow ^7\text{F}_1$ and $^5\text{D}_0 \rightarrow ^7\text{F}_2$. If the Eu^{3+} ion has a site with inversion symmetry, the $^5\text{D}_0 \rightarrow ^7\text{F}_1$ (593 nm) transition dominates, while if the Eu^{3+} ion holds a site with non-inversion symmetry, the $^5\text{D}_0 \rightarrow ^7\text{F}_2$ transition predominates. In our study, the peak at 613 nm ($^5\text{D}_0 \rightarrow ^7\text{F}_2$) is the strongest, which shows that Eu^{3+} ions locate at non-inversion symmetry center in YTaO_4 [57]. It can be concluded that the luminescence intensity reaches maximum at $y=0.02$ from the PL spectra of the $\text{YTaO}_4:y\text{Eu}^{3+}$ ($y=0.005-0.04$) phosphors under 258 nm excitation. When Eu^{3+} concentration exceeds to 0.02, the emission intensity reduces owing to the concentration quenching effect [38].

To obtain the multicolor tunable emission and further prove the possibility of energy transfer process of the $\text{YTaO}_4:\text{Tb}^{3+}$, Eu^{3+} phosphors, a series of $\text{YTaO}_4:x\text{Tb}^{3+}$, 0.02Eu^{3+} ($x=0.01, 0.03, 0.05, 0.07, 0.09$) phosphors were synthesized. The emission spectra of $\text{YTaO}_4:x\text{Tb}^{3+}$, 0.02Eu^{3+} ($x=0.01, 0.03, 0.05, 0.07$ and 0.09) phosphors excited by 270 nm are illustrated in Fig. 5, which shows the variation of luminescence intensity and the intense characteristic emission peaks of Tb^{3+} and Eu^{3+} ions. Because

Fig. 5 Emission spectra of $\text{YTbO}_4:x\text{Tb}^{3+}, 0.02\text{Eu}^{3+}$ ($x=0.01, 0.03, 0.05, 0.07, 0.09$) phosphors under 270 nm excitation, and inset is variation of the normalized intensities at 547 and 613 nm emission corresponding to the Tb^{3+} content (x)

of the concentration quenching, the emission intensity of Tb^{3+} increases first and then decreases with the increase of Tb^{3+} content. Although the concentration of Eu^{3+} is constant, the emission of Eu^{3+} (613 nm) increases gradually in a certain range with the increase of the Tb^{3+} content, which due to the energy transfer from Tb^{3+} to Eu^{3+} ions, but then the emission of Eu^{3+} (613 nm) decreases when Tb^{3+} content is from 0.05 to 0.09, which due to the concentration quenching of Eu^{3+} , the results prove that Tb^{3+} can transfer energy to Eu^{3+} [30].

To further understand the energy transfer process between Tb^{3+} and Eu^{3+} , the emission spectra of $\text{YTbO}_4:0.07\text{Tb}^{3+}, y\text{Eu}^{3+}$ ($y=0.01, 0.02, 0.03, 0.04, 0.05$) samples under 270 nm excitation are shown in Fig. 6. In the emission spectra of $\text{YTbO}_4:0.07\text{Tb}^{3+}, y\text{Eu}^{3+}$ phosphors, we can observe the characteristic sharp peaks of Eu^{3+} and Tb^{3+} ions. As there is increase in doping concentration of Eu^{3+} (y), the emission intensity of Eu^{3+} continues to rise until $y=0.03$, afterward the characteristic emission intensity of Eu^{3+} begins to decrease. In addition, when the doping concentration of Eu^{3+} goes up, the emission intensity of Tb^{3+} declines as a result of the energy transfer from Tb^{3+} to Eu^{3+} in YTbO_4 host [42].

Figure 7 shows the fluorescence lifetime of $\text{YTbO}_4:0.07\text{Tb}^{3+}, y\text{Eu}^{3+}$ ($y=0, 0.01, 0.02, 0.03, 0.04, 0.05$). Test data can be fitted and processed according to the following formula:

$$I = I_0 + Ae^{-t/\tau}$$

Fig. 6 Emission spectra of $\text{YTbO}_4:0.07\text{Tb}^{3+}, y\text{Eu}^{3+}$ ($y=0.01, 0.02, 0.03, 0.04, 0.05$) phosphors under 270 nm excitation, and inset is variation of the normalized intensities at 547 and 613 nm emission corresponding to the Eu^{3+} content (y)

Here I corresponds to the fluorescence intensity at t , I_0 corresponds to the fluorescence intensity of the $t=0$, and τ is on behalf of the fluorescence lifetime. The fluorescence lifetime of Tb^{3+} are 2.42, 1.73, 1.72, 1.54, 1.36 and 1.23 ms for $y=0, 0.01, 0.02, 0.03, 0.04, 0.05$, respectively. With the increase of Eu^{3+} doping concentration, the fluorescence lifetime of Tb^{3+} decreases gradually as we can obviously see, which further proves that Tb^{3+} transfers energy to Eu^{3+} ions.

The energy transfer efficiency could be roughly calculated by the related luminescence intensities as the following equation:

Fig. 7 Decay curves of $\text{YTbO}_4:0.07\text{Tb}^{3+}, y\text{Eu}^{3+}$ ($y=0, 0.01, 0.02, 0.03, 0.04, 0.05$) phosphors under the excitation of 270 nm and monitoring at 547 nm

$$\eta_{ET} = 1 - \frac{I_s}{I_{s0}}$$

Here I_s and I_{s0} correspond to the luminescence intensity of Tb^{3+} ions with and without Eu^{3+} ions, respectively. Figure 8 shows that the energy transfer efficiency increases gradually till about 86% of phosphors with the increase of Eu^{3+} content, indicating that the effective energy transfer between Tb^{3+} and Eu^{3+} is occurred in $YTaO_4$ host.

According to the energy transfer theory of Dexter and Reisfeld, the possible mechanism can be analyzed by the following formula [58]:

$$I_{s0}/I_s \propto C^{n/3}$$

where I_{s0} and I_s are the luminescence intensity of Tb^{3+} with or without Eu^{3+} , respectively. C is the sum concentration of Tb^{3+} and Eu^{3+} , and $n=6, 8$, and 10 are corresponding to the dipole–dipole, dipole–quadrupole, and quadrupole–quadrupole interactions, respectively. Plots of the value of I_{s0}/I_s and $C^{n/3}$ are depicted in Fig. 9. It is found that when $n=8$, the fitting result is the best, indicating that the energy transfer mechanism is dipole–quadrupole interaction.

3.3 Energy transfer mechanism

Figure 10 describes the energy levels and energy transfer mechanism from Tb^{3+} to Eu^{3+} in $YTaO_4$ host which explain the polychromatic luminescence mechanism of $YTaO_4:Tb^{3+}$, Eu^{3+} clearly. For $YTaO_4:Tb^{3+}$, Eu^{3+} phosphors, both $Tb^{3+}/Eu^{3+}-O^{2-}$ charge transfer band and TaO_4^{3-} group make contributions for the emissions of Tb^{3+} and Eu^{3+} [13]. In the whole process of excitation, electrons are transferred

Fig. 8 Energy transfer efficiency (η_{ET}) from Tb^{3+} to Eu^{3+} in $YTaO_4:0.07Tb^{3+}$, yEu^{3+} ($y=0-0.05$) samples under 270 nm excitation

Fig. 9 The dependence I_{s0}/I_s of Tb^{3+} on the $C_{Tb+Eu}^{n/3}$ ($n=6, 8, 10$) in $YTaO_4:0.07Tb^{3+}$, yEu^{3+} ($y=0-0.05$) phosphors

from O^{2-} valence to the Tb^{3+} and Eu^{3+} conduction band upon the excitation of ultraviolet light. Subsequently, the electrons transfer to 5D_3 state of Tb^{3+} ions and 5L_6 of Eu^{3+} ions, respectively. As is known to all, electrons in excited state are unstable. Therefore, the electrons of Tb^{3+} ions relax from 5D_3 to 5D_4 level through non-radiative transition, then transmit to 7F_6 , 7F_5 , 7F_4 and 7F_3 energy level, leading to the emission of 492 nm, 547 nm, 585 nm, and 621 nm, respectively. Similarly, the electrons of Eu^{3+} relax from 5L_6 to 5D_0 state, then go back to 7F_1 and 7F_2 , corresponding to the emission of 593 nm and 613 nm, respectively. In addition, the transitions from ground state 1A_1 of TaO_4^{3-} group to excited levels take place and TaO_4^{3-} group transfers energy to Tb^{3+} and Eu^{3+} ions leading to the characteristic emission of Tb^{3+} and Eu^{3+} ions. Meanwhile, the characteristic emission of

Fig. 10 Schematic energy-level diagram of Tb^{3+} and Eu^{3+} in $YTaO_4$ and the energy transfer process

Fig. 11 CIE chromaticity diagram of $\text{YTaO}_4:0.07\text{Tb}^{3+}$ (1), $\text{YTaO}_4:0.07\text{Tb}^{3+}, y\text{Eu}^{3+}$ ($y=0.01$ (2), 0.02 (3), 0.03 (4), 0.04 (5) and 0.05(6)) and $\text{YTaO}_4:0.02\text{Eu}^{3+}$ (7) samples upon 270 nm excitation

Eu^{3+} ions can be checked, owing to that some electrons of Tb^{3+} ions make a non-radiative transition from $^5\text{D}_4$ to the $^5\text{D}_0$ of Eu^{3+} ions. Due to the manageable energy transfer efficiency, the $\text{YTaO}_4:\text{Tb}^{3+}, \text{Eu}^{3+}$ samples upon excitation of ultraviolet light can show the Tb^{3+} and Eu^{3+} emissions with different intensities at the same time. Consequently, the emission color of phosphors is adjustable.

3.4 Adjustable color

The luminescence properties of $\text{YTaO}_4:0.07\text{Tb}^{3+}$ (1), $\text{YTaO}_4:0.07\text{Tb}^{3+}, y\text{Eu}^{3+}$ ($y=0.01$ (2), 0.02 (3), 0.03 (4), 0.04 (5) and 0.05(6)) and $\text{YTaO}_4:0.02\text{Eu}^{3+}$ (7) samples upon 270 nm excitation have been investigated in detail, and the corresponding CIE chromaticity diagrams are shown in Fig. 11. It is worth mentioning that the CIE chromaticity coordinate of $\text{YTaO}_4:0.07\text{Tb}^{3+}$ locates in the green emission zone with 1 point (0.3119, 0.5294). The emissive color of $\text{YTaO}_4:0.02\text{Eu}^{3+}$ is in the red emission zone and the CIE chromaticity coordinate is calculated to be (0.4165, 0.2909) (7 point). With the change of doping amount of Eu^{3+} ion, the $\text{YTaO}_4:0.07\text{Tb}^{3+}, y\text{Eu}^{3+}$ ($y=0.01$ –0.05) phosphors can achieve color adjustable emission from green to yellow and the corresponding CIE chromaticity coordinates are calculated to be (2, 0.368, 0.5176), (3, 0.3864, 0.5142), (4, 0.3854, 0.4838), (5, 0.2634, 0.5935), (6, 0.3754, 0.4225).

The results show that multi color luminescence can be achieved through adjusting the $\text{Eu}^{3+}/\text{Tb}^{3+}$ ratio.

4 Conclusions

In summary, Eu^{3+} -and/or Tb^{3+} -doped M' - YTaO_4 phosphors were prepared by a sol–gel combustion method, which needs lower temperature than before. Under excitation at 270 nm, due to the typical $^5\text{D}_4$ – $^7\text{F}_5$ transition of Tb^{3+} , the $\text{YTaO}_4:\text{Tb}^{3+}$ phosphors show characteristic green emission. Meanwhile, the PL intensity is strongly dependent on the Tb^{3+} doping concentration and the optimal doping concentration is determined to be 0.07. $\text{YTaO}_4:\text{Eu}^{3+}$ phosphors show excellent red emission on account of the $^5\text{D}_0$ – $^7\text{F}_{1,2}$ transitions. The emission color of the samples is transformed from green to red by adjusting the doping ratio of Tb^{3+} and Eu^{3+} . The energy transfers from YTaO_4 host to Tb^{3+} and Eu^{3+} and Tb^{3+} – Eu^{3+} are systematically discussed. The energy transfer efficiency of Tb^{3+} – Eu^{3+} in the $\text{YTaO}_4:0.07\text{Tb}^{3+}, 0.05\text{Eu}^{3+}$ phosphor can reach up to about 86%. From the above experimental results, it can be concluded that the $\text{YTaO}_4:\text{Tb}^{3+}, \text{Eu}^{3+}$ phosphors have a broad application prospect in phosphor conversion LEDs.

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Compliance with ethical standards

Conflict of interest There are no conflicts of interest to declare.

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