


 Cite this: *RSC Adv.*, 2025, **15**, 19361

## Up-conversion luminescence and temperature sensing based on $\text{Ba}_3\text{Y}(\text{BO}_3)_3:\text{Er}^{3+},\text{Yb}^{3+}$ phosphors†

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Noncontact fluorescence temperature detection systems have become a significant research focus. In this study, a new  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  phosphor co-doped with  $\text{Er}^{3+}/\text{Yb}^{3+}$  was successfully synthesized using a high-temperature solid phase method. The introduction of  $\text{Yb}^{3+}$  as a sensitizer enhanced the luminescence properties of the  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  phosphor. The occupation of  $\text{Er}^{3+}$  and  $\text{Yb}^{3+}$  ions in the crystal lattice was analyzed in detail. The up-conversion luminescence and underlying mechanisms were explained by the double logarithmic relationship between the luminescence intensity and pump power. The temperature sensitivity of the phosphors was explored in the range of 333–513 K using fluorescence intensity ratio technology based on the two green peaks (thermal coupling level  $\text{Er}^{3+}$ ). The temperature sensing  $S_r$  reached  $1.44 \times 10^{-4} \text{ K}^{-1}$  at 333 K, indicating that  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:\text{Er}^{3+},\text{Yb}^{3+}$  phosphors have potential applications as temperature sensors.

Received 21st February 2025

Accepted 21st May 2025

DOI: 10.1039/d5ra01277e

rsc.li/rsc-advances

## 1. Introduction

Highly sensitive temperature detection is crucial for enhancing both production quality and daily life.<sup>1–3</sup> Noncontact temperature sensing using luminescence thermometry offers advantages such as fast response, high sensitivity, and versatility in various environments, including high temperatures, high pressures and biological systems, making it a topic of significant interest.<sup>4–8</sup> Luminescence thermometry measures changes in the luminescence properties of a system with respect to temperature, enabling temperature characterization. These properties include single-emission peak intensity, emission peak position, fluorescence intensity ratio of two emission peaks, fluorescence lifetime, and emission peak half-width.<sup>9–13</sup> Among these techniques, the fluorescence intensity ratio is the most resistant to interference. Therefore, researchers often focus on developing systems based on fluorescence intensity ratios for temperature measurement.<sup>14–16</sup> Inorganic up-conversion luminescent materials, which have low background noise and excitation bands in the infrared range, have garnered widespread attention in temperature sensing and bioimaging.<sup>17–20</sup> Up-conversion temperature-detecting phosphors are usually doped with  $\text{Er}^{3+}/\text{Yb}^{3+}$  ions, utilizing the two thermally

coupled energy levels of  $\text{Er}^{3+}$  as the temperature measurement energy level.<sup>21–24</sup> Although  $\text{Yb}^{3+}$  has a larger absorption cross-section and wider absorption band for near-infrared energies,  $\text{Yb}^{3+}$  ions are often used as sensitizers.<sup>25–28</sup>

Borates, which are known for their diverse crystal structures, good physical stability,<sup>29,30</sup> and low synthesis temperatures,<sup>31,32</sup> are expected to become mainstream phosphors.<sup>33,34</sup> Shangke Pan *et al.* synthesized  $\text{Nd}^{3+}$ -doped  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  phosphors using the lift-off method, achieving a crystalline phase transition temperature of 1148 °C.<sup>35</sup> Zhao *et al.* explored the luminescence mechanism of  $\text{Ce}^{3+}/\text{Nd}^{3+}$  co-doped  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  phosphors and proposed their application as solar spectral converters in Si-based solar cells.<sup>36</sup> Li *et al.* successfully prepared  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  doped with 24 mol%  $\text{Eu}^{3+}$  and 1 mol%  $\text{Bi}^{3+}$  phosphors and demonstrated their potential for application in white LEDs.<sup>37</sup>

To the best of our knowledge,  $\text{Er}^{3+}/\text{Yb}^{3+}$ -doped  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  phosphors have not been extensively studied. In this study, we prepared  $\text{Er}^{3+}/\text{Yb}^{3+}$  co-doped  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  phosphors and thoroughly investigated their structure, morphology, luminescence properties, and energy transfer mechanism between  $\text{Yb}^{3+}$  and  $\text{Er}^{3+}$  ions. The two-photon green emission of  $\text{Er}^{3+}$  was confirmed through the double logarithmic relationship between the power and luminescence intensity. Additionally, we examined the upconversion optical temperature-sensing properties of  $\text{Er}^{3+}/\text{Yb}^{3+}$ -co-doped  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  phosphors using the FIR technique.

## 2. Experimental section

### 2.1 Sample synthesis

$\text{BaCO}_3$ ,  $\text{Y}_2\text{O}_3$ ,  $\text{H}_3\text{BO}_3$ ,  $\text{Er}_2\text{O}_3$  (99.99%),  $\text{Yb}_2\text{O}_3$  (99.99%), deionized water, and anhydrous ethanol were used to prepare the

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† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d5ra01277e>

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phosphors.  $\text{Ba}_3\text{Y}_{1-x}(\text{BO}_3)_3:x\text{Er}^{3+}$  and  $\text{Ba}_3\text{Y}_{0.93-y}(\text{BO}_3)_3:0.07\text{Er}^{3+}, y\text{Yb}^{3+}$  phosphors were synthesized using a high-temperature solid-state method with molar fractions  $x = 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08$ , and  $0.09$ , and  $y = 0.07, 0.14, 0.21, 0.28, 0.35, 0.42, 0.49$ , and  $0.56$ , respectively. The corresponding number of precursors was weighed and ground in an agate mortar and pestle for 10 min. The mixture was then placed in an alumina crucible and pre-annealed in a high-temperature muffle furnace at  $1250^\circ\text{C}$  for 6 h. After cooling to room temperature, the samples were ground into a powder for further analysis.

## 2.2 Sample characterization details

We used a Bruker D8 Advanced Diffractometer to determine the profile of the synthesized materials through X-ray diffraction (XRD) analysis using  $\text{Cu K}\alpha$  radiation ( $1.5406\text{ \AA}$ ) over a range of  $15$ – $80^\circ$ . The emission spectra of the samples were obtained using a Pro-FL spectrometer (F-7000, Hitachi, Japan) under  $980\text{ nm}$  excitation from a semiconductor laser. Temperature-dependent emission spectra were obtained using the same equipment and a TCB1402C temperature controller (China).

## 3. Results and discussion

### 3.1 Structure and morphology of samples

Fig. 1(a) and (b) show the XRD patterns of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:x\text{Er}^{3+}$  ( $x = 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09$ ) and  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+}, y\text{Yb}^{3+}$  ( $y = 0.07, 0.14, 0.21, 0.28, 0.35, 0.42, 0.49, 0.56$ ) samples. The diffraction patterns are consistent with the standard card PDF#51-1849. No significant impurity peaks were observed, indicating that the  $\text{Er}^{3+}$  and  $\text{Yb}^{3+}$  did not change

the lattice structure because  $\text{Er}^{3+}$  and  $\text{Yb}^{3+}$  ions have similar radii to  $\text{Y}^{3+}$  ions.<sup>38</sup> The synthesized material was in a pure hexagonal crystalline phase with space group  $P6_3\text{ cm}$  (185), with cell parameters  $a = b = 9.419\text{ \AA}$ ,  $c = 17.598\text{ \AA}$ , and a cell volume of  $1352.2\text{ \AA}^3$ .<sup>39</sup> As shown in Fig. 1c, every B atom is coordinated with three O atoms to form triangles  $[\text{BO}_3]$ . For the Ba atom, two different coordinate methods are coordinated with nine and six O atoms to form polyhedral  $[\text{Ba}_1\text{O}_9]$  and  $[\text{Ba}_2\text{O}_6]$ . Although all the Y atoms are coordinated with six O atoms, there exist two different kinds of polyhedra owing to the difference in the distortion of  $[\text{Y}_1\text{O}_6]$  and  $[\text{Y}_2\text{O}_6]$ .<sup>40,41</sup>

The SEM patterns of the  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+}, 0.21\text{Yb}^{3+}$  phosphor are presented in Fig. 2a. It can be observed that the sample exhibits better crystallization, with a size of approximately  $3$ – $8\text{ \mu m}$ . Meanwhile, the element mapping in Fig. 2b–f shows that the main elements Ba, Y, O, Er, and Yb are uniformly distributed in the sample. The EDS measure in Table S1† indicates that the Er and Yb ions are doped in the matrix.

### 3.2 Optical properties of samples

The diffuse reflection spectrum of  $0.07\text{Er}^{3+}, 0.21\text{Yb}^{3+}$  phosphor is shown in Fig. S1.† It can be observed that there are some absorption peaks at  $297\text{ nm}$ ,  $379\text{ nm}$ ,  $488\text{ nm}$ ,  $521\text{ nm}$ ,  $651\text{ nm}$ ,  $970\text{ nm}$  and  $1416\text{ nm}$ , respectively. In particular, the strongest band is located at  $870$ – $1040\text{ nm}$ , which indicates that it can well absorb light at  $980\text{ nm}$ . To investigate the up-conversion luminescence performance of the samples, we tested the emission spectra of samples doped with different concentrations of  $\text{Er}^{3+}$  ions under  $980\text{ nm}$  excitation at room temperature. Fig. 3(a) shows the upconverted emission spectra of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:x\text{Er}^{3+}$  ( $x = 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09$ ). The spectra reveal the same emission peaks across the samples, consisting of two groups of peaks in the green domain and one group of peaks in the red domain. Generally, different numbers of peaks are in one group of emissions according to the splitting degree of the ground state and excited state in different crystal fields. The peaks at  $520\text{ nm}$ ,  $525\text{ nm}$  and  $538\text{ nm}$  are attributed to the transition of  $^2\text{H}_{11/2} \rightarrow ^4\text{I}_{15/2}$  while the peaks at  $549\text{ nm}$ ,  $553\text{ nm}$  and  $563\text{ nm}$  are attributed to the transition of  $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ . The group of red emission peaks at  $656\text{ nm}$ ,  $662\text{ nm}$ ,  $670\text{ nm}$ ,  $677\text{ nm}$ , and  $684\text{ nm}$  is caused by the  $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$  transition of  $\text{Er}^{3+}$  ions. All the results confirm the successful incorporation of  $\text{Er}^{3+}$  ions into the  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  lattice.<sup>42,43</sup> The intensities of the green and red emissions increased consistently with increasing  $\text{Er}^{3+}$  concentration from  $0.01$  ( $x = 0.01$ ). The luminescence intensity reaches a maximum at  $x = 0.07$ , after which phosphor concentration quenching occurs, leading to a gradual decrease in luminescence intensity with further  $\text{Er}^{3+}$  doping.

Fig. 3(b) shows the up-conversion emission spectra of phosphor  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:7\text{ mol\% Er}^{3+}, y\text{Yb}^{3+}$  ( $y = 7, 14, 21, 28, 35, 42, 49$ , and  $0.56$ ). When the  $\text{Yb}^{3+}$  doping concentration was less than  $21\text{ mol\%}$ , the red emission intensity significantly increased with increasing  $\text{Yb}^{3+}$  concentration, while the green emission showed no significant relative change; however, the trend in green emission was similar to that of the red emission. At an  $\text{Yb}^{3+}$  doping concentration of  $0.21$ , the luminous

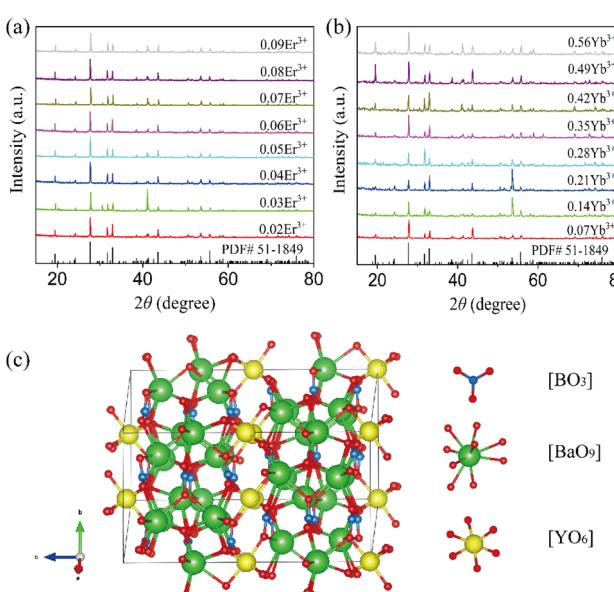


Fig. 1 (a) XRD patterns of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:x\text{Er}^{3+}$  ( $x = 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08$ , and  $0.09$ ) with the standard card of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$ . (b) XRD patterns of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+}, y\text{Yb}^{3+}$  ( $y = 0.07, 0.14, 0.21, 0.28, 0.35, 0.42, 0.49$ , and  $0.56$ ) with the standard card of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$ . (c) Schematic of the crystal structure of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$ .



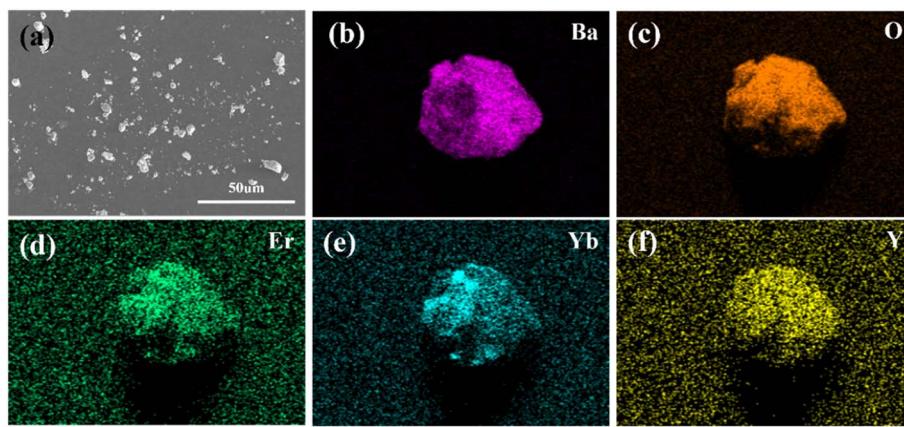


Fig. 2 (a) SEM patterns of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+},0.21\text{Yb}^{3+}$ . (b)–(f) Elemental mapping of Ba, O, Er, Yb, and Y in  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+},0.21\text{Yb}^{3+}$ .

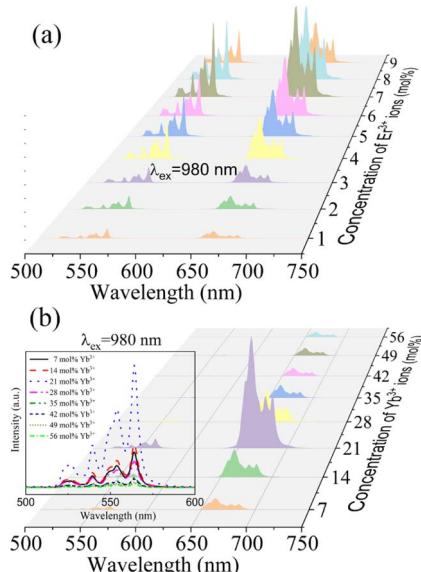


Fig. 3 (a) UCL spectra of (a)  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:x\text{Er}^{3+}$  samples and (b)  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:7\text{mol\% Er}^{3+},\text{Yb}^{3+}$  samples under 980 nm laser excitation.

intensities of both the green and red emission bands reached their maximum values. Beyond this concentration, further Yb<sup>3+</sup> doping resulted in decreased luminescence intensity, indicating the onset of concentration quenching at  $y = 0.21$ . Additionally, with increased Yb<sup>3+</sup> doping, the EBT process from Er<sup>3+</sup> to Yb<sup>3+</sup> was enhanced, as described by the following equation:  $[\text{Er}^{3+}(^4\text{S}_{3/2}) + \text{Yb}^{3+}(^2\text{F}_{7/2}) \rightarrow \text{Er}^{3+}(^4\text{I}_{13/2}) + \text{Yb}^{3+}(^2\text{F}_{5/2})]$ . On the one hand, the defect produced in the synthesis process provides an absorption site that promotes the doping of Yb<sup>3+</sup> ions. On the other hand, energy transfer occurs between the Yb<sup>3+</sup> ions and non-bridging oxygen defects, which limits the amount of Yb<sup>3+</sup> doping. However, the doping content of Yb<sup>3+</sup> and the defect concentration have a nonlinear relationship.<sup>44</sup>

Generally, the luminescence center grows in number, and the distance between the dopant ions decreases with an increase in activator doping concentration, which increases the competition between the radiative transition and the

nonradiative (NR) process and influences PL performance. The critical distance ( $R_c$ ) is an important parameter for expressing the average distance between dopants when the concentration quenching effect occurs and can be expressed as follows:<sup>45</sup>

$$R_c = 2 \left( \frac{3V}{4\pi\chi_c N} \right)^{1/3}, \quad (1)$$

where  $V$  is the volume ( $\text{\AA}^3$ ),  $\chi_c$  is the quenching concentration, and  $N$  is the cation number. In this case, the values of  $V$ ,  $\chi_c$  and  $N$  are  $1352.2 \text{\AA}^3$ , 0.07 and 6, respectively. Substituting these values into eqn (1), the value of  $R_c$  can be calculated as  $18.32 \text{\AA}$ , which is greater than  $5 \text{\AA}$ , and the energy transfer between the dopants is the result of the electric multipolar effect.

To further explain the concentration quenching mechanism of the dopant in the sample, the following equation is used:<sup>46</sup>

$$\log\left(\frac{I}{x}\right) = A - \left(\frac{\theta}{3}\right) \log x, \quad (2)$$

where  $I$  represents the emission intensity under the same excitation conditions,  $x$  is the concentration of doped ions, and  $A$  is the constant related to  $\theta$ . The concentration quenching mechanism is attributed to the electric dipole-dipole (d-d), dipole-quadrupole (d-q) and quadrupole-quadrupole (q-q) interactions, corresponding to 6, 8 and 10, respectively. As illustrated in Fig. S2 and S3,<sup>†</sup> the logarithmic coordinate system is built using  $\log(x)$  and  $\log(I/x)$  as horizontal and vertical coordinates. According to the linear fitting of experimental data, the linear fitting slopes ( $-\theta/3$ ) are calculated to be  $-3.96$ ,  $-4.10$ ,  $-4.04$ ,  $-4.01$ ,  $-3.89$ ,  $-3.73$ ,  $-3.72$ ,  $-4.34$  and  $-3.83$ , which means that all the values of  $\theta$  are close to 10, demonstrating that the concentration quenching mechanism of dopant in  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:\text{Er}^{3+}$  and  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:\text{Er}^{3+},\text{Yb}^{3+}$  phosphor are attributed to electric q-q interaction.

To further investigate the luminescence mechanism of the Er<sup>3+</sup>/Yb<sup>3+</sup> co-doped  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  phosphor, we examined the upconversion emission spectra of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+},0.21\text{Yb}^{3+}$  samples under different excitation powers. As shown in Fig. 4a, as the excitation power of the 980 nm laser increased, the upconversion emission intensity of the samples also increased gradually. When the upconversion emission is in a non-

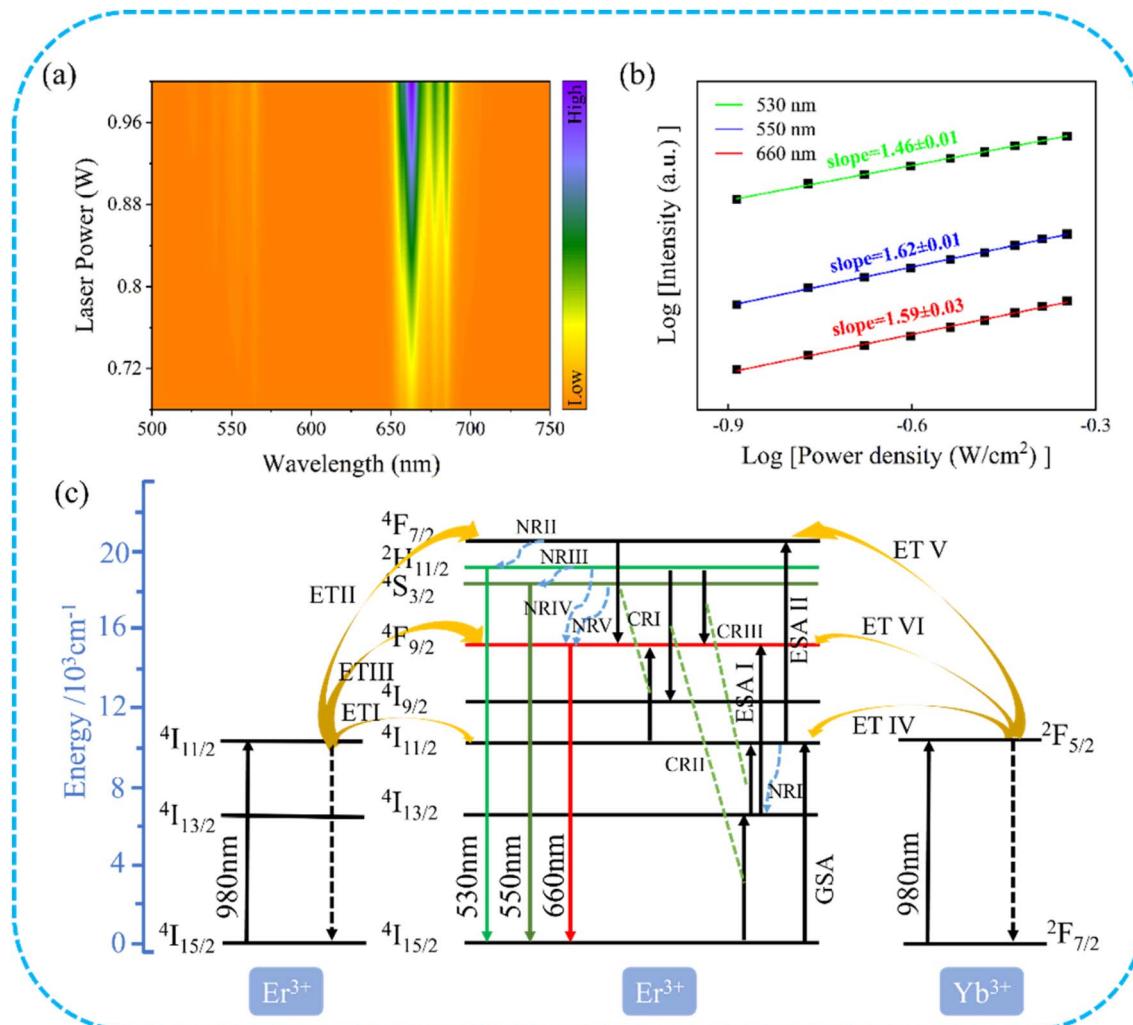


Fig. 4 (a) Pump power-dependent UCL spectra of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+}, 0.21\text{Yb}^{3+}$  under 980 nm laser excitation. (b) Logarithmic plots of pump power versus green and red emission intensities. (c) Energy level diagram and mechanism of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+}, 0.21\text{Yb}^{3+}$ .

saturated excitation state, the luminescence intensity  $I$  is related to the excitation power  $P$  using the following equation:<sup>47</sup>

$$I = P^n, \quad (3)$$

where  $I$  is the luminescence intensity,  $P$  is the excitation power, and  $n$  is the number of photons required for up-conversion emissions. By taking the logarithms of both sides of the above equation, we obtain the following equation:

$$\log I = n \log P + C, \quad (4)$$

where  $C$  is a constant. Therefore the ratio ( $n$ ) of  $\log I / \log P$  indicates that the upconversion process can be attributed to  $n$ -photon absorption. A double logarithmic plot of the upconversion luminescence intensity *versus* excitation power for  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+}$  and  $0.21\text{Yb}^{3+}$  under different excitation powers of 980 nm laser is shown in Fig. 4(b), where we can quantitatively analyze the relationship between light intensity and excitation power. The fitted curves for the three emission

peaks are shown in the figure and closely match the experimental curves with minimal errors. The 530 nm green emission has a fitted slope of 1.46, the 550 nm green emission has a slope of 1.62, and the 660 nm red emission has a slope of 1.59. The values of  $n$  were close to 2, suggesting that the emission of the samples arose from a two-photon process.

To investigate the luminescence mechanism of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+}, 0.21\text{Yb}^{3+}$  phosphor, possible upconversion emission processes are depicted in energy-level leap diagrams, as shown in Fig. 4(c). Under excitation at 980 nm,  $\text{Er}^{3+}$  ions single doped or  $\text{Er}^{3+}$ - $\text{Yb}^{3+}$  ions co-doped  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  have a similar energy-transfer (ET) mechanism.  $\text{Er}^{3+}$  ions absorb a photon (980 nm) through a ground-state absorption (GSA) process, transitioning from  $4\text{I}_{15/2}$  to  $4\text{I}_{11/2}$ , and  $\text{Yb}^{3+}$  ions absorb a photon (980 nm) through a GSA process, moving from  $2\text{F}_{7/2}$  to  $2\text{F}_{5/2}$ . Compared to  $\text{Er}^{3+}$ ,  $\text{Yb}^{3+}$  has a larger absorption cross-section, and its introduction improves energy transfer efficiency. For the  $\text{Er}^{3+}$ ,  $\text{Yb}^{3+}$  co-doped  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  phosphor, energy transfer (ET I) from  $\text{Yb}^{3+}$  to  $\text{Er}^{3+}$  can be expressed as follows:  $2\text{F}_{5/2}(\text{Yb}^{3+}) + 4\text{I}_{15/2}(\text{Er}^{3+}) \rightarrow 2\text{F}_{7/2}(\text{Yb}^{3+}) + 4\text{I}_{11/2}(\text{Er}^{3+})$ .

$^4I_{11/2}$  ( $Er^{3+}$ ). Some ions located at  $^4I_{11/2}$  are transferred to the  $^4I_{13/2}$  energy level by applying a non-radiative transition (NRI) process. Then, the ions at the  $^4I_{13/2}$  energy level can absorb a photon to reach the  $^4F_{9/2}$  energy level by excited-state absorption (ESA I). However, some  $Er^{3+}$  ions at the  $^4I_{11/2}$  excited-state energy level is further excited to  $^4F_{7/2}$  (ESA II) via energy transfer (ET II) from  $Yb^{3+}$  ions. The ions at the  $^4F_{7/2}$  ( $Er^{3+}$ ) energy level can gradually relax to the  $^2H_{11/2}$ ,  $^4S_{3/2}$  and  $^4F_{9/2}$  energy levels by the radiation-less relaxation of NR II, NR III, NR IV, and NR V. The transitions between  $^2H_{11/2} \rightarrow ^4I_{15/2}$  energy levels correspond to green emission at 530 nm, the transitions between the  $^4S_{3/2} \rightarrow ^4I_{15/2}$  energy levels correspond to green emission at 550 nm, and the transitions between the  $^4F_{9/2} \rightarrow ^4I_{15/2}$  energy levels correspond to 660 nm. Furthermore, compared with the green emission, the red emission violently increases with the  $Yb^{3+}$  ion concentration, which is attributed to the decrease in the distance between the ions improving the efficiency of the cross-relaxation (CR):  $[^4F_{7/2} (Er^{3+}) + ^4I_{11/2} (Er^{3+}) \rightarrow ^4F_{9/2} (Er^{3+}) + ^4I_{9/2} (Er^{3+})]$  (CRI);  $[^2H_{11/2} (Er^{3+}) + ^4I_{15/2} (Er^{3+}) \rightarrow ^4I_{9/2} (Er^{3+}) + ^4I_{13/2} (Er^{3+})]$  (CRII); and  $[^2H_{11/2} (Er^{3+}) + ^4I_{13/2} (Er^{3+}) \rightarrow ^4F_{9/2} (Er^{3+}) + ^4I_{11/2} (Er^{3+})]$  (CRIII).

### 3.3 Optical temperature sensing performance of the samples

We investigated the temperature sensing performance of  $Ba_3Y(BO_3)_3:0.07Er^{3+}, 0.21Yb^{3+}$  phosphors. To reduce the heating effect of the laser, we used a low excitation power of 1.0 W. The variable-temperature emission spectra of the samples, measured between 90 K and 279 K, are shown in Fig. S4,<sup>†</sup> in which the PL intensity undergoes irregular changes with

temperature. Under high temperature conditions, the variable-temperature emission spectra of the samples, measured between 333 and 513 K, are shown in Fig. 5(a). As the temperature increased, the intensity of the red emission decreased; however, the 530 nm emission intensity increased and the 550 nm emission initially increased before decreasing with temperature. Fig. 5(a) clearly shows the variations in green emission intensity. The increase in emission intensity with temperature may result from enhanced thermal mobility of ions from the lower to higher energy levels.

$Er^{3+}$  ions have two thermally coupled energy levels,  $^2H_{11/2}$  and  $^4S_{3/2}$ , with the number of ions at these levels following the Boltzmann distribution. Therefore, the intensities of the  $^2H_{11/2} \rightarrow ^4I_{15/2}$  (530 nm) and  $^4S_{3/2} \rightarrow ^4I_{15/2}$  (550 nm) emissions change with temperature. The fluorescence intensity ratio (FIR) of the two green emissions can be expressed as follows:<sup>48</sup>

$$FIR = R = \frac{I_H}{I_S} = \frac{N(^2H_{11/2})}{N(^4S_{3/2})} = C \exp\left(\frac{-\Delta E}{kT}\right) \quad (5)$$

where  $I_H$  denotes the integral intensity of the  $^2H_{11/2} \rightarrow ^4I_{15/2}$  emission;  $I_S$  denotes to the integral intensity of the  $^4S_{3/2} \rightarrow ^4I_{15/2}$  emission;  $\Delta E$  is the forbidden bandwidths of the two thermally coupled energy levels,  $^2H_{11/2}$  and  $^4S_{3/2}$ ; and  $K_B$  is the Boltzmann constant. Taking the logarithm of  $\ln$  for both sides of the above equation, we obtain the following equation:

$$\ln(FIR) = \ln \frac{I_H}{I_S} = \left(\frac{-\Delta E}{kT}\right) + \ln C. \quad (6)$$

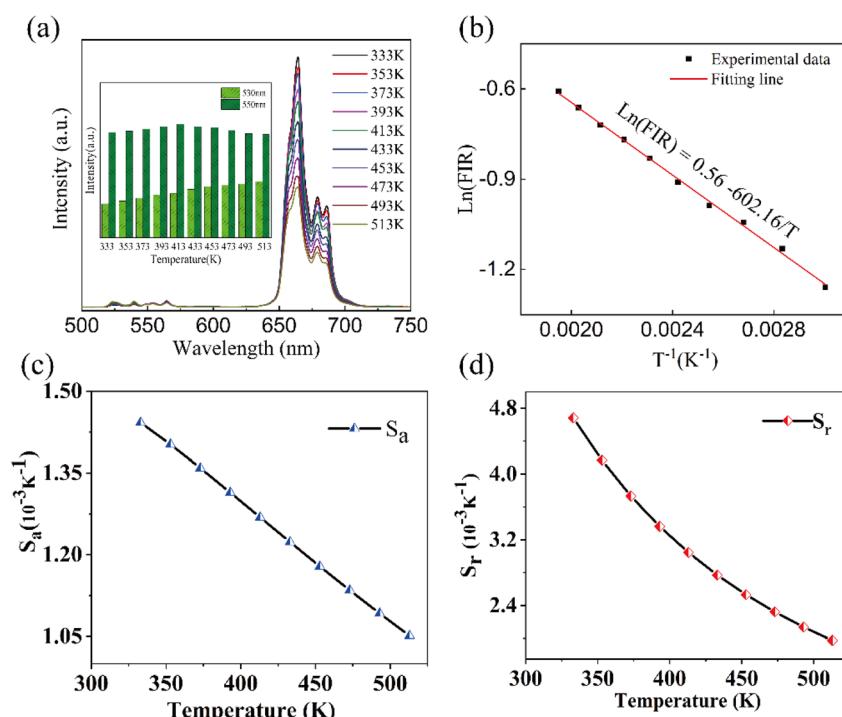


Fig. 5 (a) UCL spectra; (b) the integral intensity ratio of  $^2H_{11/2} \rightarrow ^4I_{15/2}$ ,  $^4S_{3/2} \rightarrow ^4I_{15/2}$ , in  $Er^{3+}$  ions; (c) absolute sensitivity  $S_a$ ; and (d) relative sensitivity  $S_r$  values of the  $Ba_3Y(BO_3)_3:0.07Er^{3+}, 0.21Yb^{3+}$  sample detected in the 303–573 K range under 980 nm laser excitation.



The absolute sensitivity ( $S_a$ ) and relative sensitivity ( $S_r$ ) are crucial parameters for evaluating temperature sensing and can be defined as eqn (7) and (8), respectively:<sup>49</sup>

$$S_a = \frac{dR}{dT} = R \frac{\Delta E}{kT^2} \quad (7)$$

$$S_r = \left| \frac{1}{R} \frac{dR}{dT} \right| = \frac{\Delta E}{kT^2} \quad (8)$$

The fitted curve of the linear relationship between  $\ln(\text{FIR})$  and  $1/T$  is shown in Fig. 5(b), where the linear relationship between  $\ln(\text{FIR})$  and  $1/T$  is consistent with the linear relationship in eqn (4). The slope  $\Delta E/k$  is 602.16, and the intercept  $\ln C$  is 0.56. The calculated  $\Delta E$  for the thermal coupling energy for this phosphor is consistent with previously reported values. The corresponding sensitivities  $S_a$  and  $S_r$  of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:0.07\text{Er}^{3+}$  and  $0.21\text{Yb}^{3+}$  at different temperatures are shown in Fig. 5(c) and (d), respectively. It can be observed that the  $S_a$  and  $S_r$  of the phosphor reach their maximum values of  $1.44 \times 10^{-3} \text{ K}^{-1}$  and  $4.68 \times 10^{-3} \text{ K}^{-1}$  at 333 K, respectively. Table S2† shows some published results and compares them with the results of this study, which indicates that this material can be used as a candidate for temperature sensing.

## 4. Conclusion

In this study, novel up-conversion red phosphors of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  co-doped with  $\text{Er}^{3+}$  and  $\text{Yb}^{3+}$  were successfully synthesized using a high-temperature solid-phase method. Three emission bands at 530, 550, and 660 nm, corresponding to the  $^2\text{H}_{11/2} \rightarrow ^4\text{I}_{15/2}$ ,  $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ , and  $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$  of  $\text{Er}^{3+}$  ions, respectively, were observed under 980 nm excitation. The luminescence of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3$  maintains a high-purity red emission by modulating the doping concentration of  $\text{Yb}^{3+}$ . The introduction of  $\text{Yb}^{3+}$  ions enhanced the emission intensity of the samples. The luminescence mechanism was explained by the double logarithmic relationship between luminescence intensity and pump power. Additionally, the temperature sensitivity from 333 K to 513 K was explored using the FIR technique with two green emissions, achieving a maximum  $S_r$  of  $1.44 \times 10^{-3} \text{ K}^{-1}$  at 333 K. These results demonstrate the potential applications of  $\text{Ba}_3\text{Y}(\text{BO}_3)_3:\text{Er}^{3+}/\text{Yb}^{3+}$  phosphors in luminescence and optical temperature sensing.

## Data availability

The data supporting the findings of this study will be made available from the corresponding author upon request.

## Author contributions

Lei Zhang and You Zhang: writing-original draft and investigation. Cuilin Jin: supervision, software, and investigation. Chunhao Wang: supervision, software, and investigation. Chunhao Wang and Qiongyu Bai: supervision, software, and investigation. Xu Li: writing-review & editing, supervision, and

investigation. Yibo Zheng: writing-review & editing, supervision, software, and funding acquisition.

## Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This work was partly funded by the S&T Program of Hebei, China (No. 22371701D), the Hebei Province Department of Natural Resources (No. 2024043) and the Hebei Province Optoelectronic Information Materials Laboratory Performance Subsidy Fund Project (No. 22567634H). We also appreciate the Excellent Going Abroad Experts' Training Program in Hebei Province.

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