K₃LaTe₂O₉:Er: a novel green up-conversion luminescence material†

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A novel green up-conversion luminescence material, K₃LaTe₂O₉:Er, was synthesised via a solid-state reaction method. K₃LaTe₂O₉:Er phosphors were characterised by X-ray diffraction, reflectance spectroscopy, Raman spectroscopy, photoluminescence spectroscopy, up-conversion spectroscopy and temperature sensing performance analysis. The diffraction pattern of the hexagonal K₃LaTe₂O₉·0.02Er microcrystals was indexed with Miller indices and the lattice constants were a = b = 0.60636 ± 0.00018 nm, and c = 1.49543 ± 0.00037 nm. The photoluminescence under 380 nm excitation and the up-conversion luminescence under 980 and 1550 nm pumping were investigated. The influence of Er³⁺ ion concentration and excitation power on the luminescence properties of K₃LaTe₂O₉:Er was also discussed. K₃LaTe₂O₉:Er phosphor presented green down-shifting emission and up-conversion luminescence under 380, and 980 nm excitation and yellow–green up-conversion luminescence under 1550 nm pumping, respectively, and the red emission component was enhanced with the increment in excitation wavelength. The quenching concentration of Er³⁺ ions in K₃LaTe₂O₉:Er was much higher than that in normal phosphors. This result can be attributed to the suppression of energy migration because the shortest (0.606 nm) and average distance (0.9720 nm) between Er³⁺ ions were significantly large in K₃LaTe₂O₉. Therefore, the electric quadrupole–quadrupole interactions between Er³⁺ ions are the dominant energy transfer process in down-shift emission, and the UCL mechanism can be regarded as the excited state absorption in K₃LaTe₂O₉:Er. Furthermore, the doping concentration of Er³⁺ ions influenced the temperature sensitivity of K₃LaTe₂O₉:Er.

1. Introduction

Rare-earth (RE)-doped luminescence materials play an important role in illumination, display, temperature sensor, security and biomedicine. Selecting appropriate materials with excellent luminescence performance based on practical applications is important. In general, the luminescence properties of phosphors are regulated through the selection of matrix materials. Matrix materials can bond doped RE ions, and the symmetry and strength of the crystal field exert significant effects on the optical properties of RE ions. Moreover, the practical applications of matrix materials are largely dependent on their physicochemical properties. Tellurates with rich chemical structures and unique physical properties have attracted considerable attention. RE-doped tellurite glass with relatively low phonon energy, high reflection index, and excellent thermal stability has become a popular research topic. However, tellurate phosphors have seldom been reported. For instance, Sobczyk et al. studied the optical properties of Y₂Te₄O₁₁:Sm³⁺, Zhang et al. investigated the structure and luminescence properties of Li₃Y₃Te₂O₁₂:Eu³⁺.

K₃LaTe₂O₉ is a new quaternary tellurite material with medium phonon energy. In the present work, the diffraction pattern of K₃LaTe₂O₉ microcrystals was indexed with Miller indices. The down-shifting luminescence (DSL, λ_em = 380 nm) and up-conversion luminescence (UCL, λ_em = 980 and 1550 nm) of K₃LaTe₂O₉:Er were reported for the first time. In addition, the thermal quenching and temperature sensor of K₃LaTe₂O₉:Er were investigated.

2. Experimental

2.1 Sample preparation

K₃LaTe₂O₉:Er phosphors were synthesized via the solid-state reaction method. The starting raw materials La₂O₃ (99.99%), Er₂O₃ (99.99%), K₂CO₃ (A. R.), and TeO₂ (A. R.) were weighed according to stoichiometric ratio. Secondly, the above-mentioned materials were thoroughly mixed and ground using an agate ball mill for 20 min. Finally, all samples were sintered at 650 °C for 5 h. K₃LaTe₂O₉:xEr samples with different Er³⁺ concentrations were then obtained (x = 0, 2, 8, 14, 20, 26, 32, 38, 44 mol%).
2.2 Characterisation technique

X-ray powder diffraction was performed at 40 kV and 40 mA from 10° to 70° using a SHIMADZU-6000 X-ray generator with Cu Kα (λ = 0.154184 nm) radiation. The DSL and UCL spectra (400 nm to 900 nm) were recorded on a Hitachi F-4600 fluorescence spectrophotometer equipped with a power-tunable 980 and 1550 nm fibre laser diode (LD). The highest available power for the LD was approximately 800 and 700 mW, respectively. The beam of the LD was focused by the convex lens before measurement. The temperature dependence of the DSL spectra was tested by a self-assembly temperature control system with a XMT-4000 programmable temperature controller. The reaction spectra of the samples were obtained with a UV-3600 SHIMADZU UV-Vis-NIR spectrophotometer. The maximum phonon energy of the K3LaTe2O9 host lattice was obtained by a micro-Raman spectroscope (Jobin Yvon HR800, excited by 633 nm He–Ne laser with a laser spot size of 1 μm², in line mapping mode). The scanning electron microscope (SEM) and Energy Dispersive Spectrometer (EDS) of the sample were obtained by JEO-6360LV field emission gun scanning electron microscopy. The X-ray photoelectron spectroscopy (XPS) spectrum of the sample was obtained by ESCALAB250 surface analysis system.

3. Results and discussion

Fig. 1a shows the XRD pattern of the K3LaTe2O9:0.02Er sample. The diffraction peaks of the present sample are similar to those in ref. 10, indicating that the hexagonal K3LaTe2O9:0.02Er was synthesised. The micrograph and EDS of the K3LaTe2O9 crystal shown in Fig. S1.† The concentration of element in the K3LaTe2O9 crystal shown in Table S1.† The molar ratio of K, La, Te, and O element is 3.0 : 1 : 2.1 : 7.7 (Table S1†). The diffraction peaks in the XPS pattern are assigned to K⁺, O²⁻, Te⁶⁺, and La³⁺ ions (Fig. S2†). The relative concentration values calculated by elemental sensitivity factor method of K, O, Te, and La atoms are 61.88, 18.47, 12.31, and 7.34%, respectively, which are close to the theoretical calculated values in the K3LaTe2O9. However, the standard PDF data of K3LaTe2O9:0.02Er are not available, and ref. 10 did not provide the index data of K3LaTe2O9. The lattice parameters of K3LaTe2O9:0.02Er were calculated by the least square method in accordance with the data in Table S2,† and the crystal lattice parameters of the K3LaTe2O9:0.02Er sample were obtained: a = b = 0.60636 ± 0.00018 nm, c = 1.49543 ± 0.00037 nm, V = 0.47617 nm³. K3LaTe2O9 is a 3D framework structure (Fig. 1b). K atoms are two sites that coordinate with nine and twelve O atoms forming distorted cuboctahedra, respectively. Te atoms are linked to six O atoms to form [TeO₆] octahedral, and two [TeO₆] octahedral are connected to form a face-sharing [Te₂O₉]⁶⁻ anion group. La atoms are surrounded by six O atoms in regular octahedra, and La³⁺ ions have a high-ordered state in the crystal lattice.

Fig. 2 shows the Raman spectrum of the K3LaTe2O9:0.02Er sample. The peaks situated at 285, 415, 667, 718, and 832 cm⁻¹ correspond to the K3LaTe2O9 host shown in ref. 10. Singh11 reported that the range of 500–580 cm⁻¹, 620–680 cm⁻¹, and 780–900 cm⁻¹ are the characteristic peaks of Er³⁺ ion. Therefore, several peaks (remarked as *) are related to Er³⁺ ions. Some weak peaks in Raman spectrum are also observed due to defects.
in the lattice of K₃LaTe₂O₉:Er. Raman peaks shift to the right side, which results from Er³⁺ doping. The maximum phonon energy of the K₃LaTe₂O₉ host lattice is $h\omega = 832$ cm⁻¹. Thus, K₃LaTe₂O₉ with an appropriate phonon energy can be considered as an alternative for the luminescence host material.

Fig. 3 shows the diffuse reflectance spectra of K₃LaTe₂O₉:xEr (x = 2, 26, 44 mol%). As shown in the figure, the absorption peaks become stronger with increasing Er³⁺ ion concentration. The absorption peaks at 380, 409, 486, 525, 550, 653, 798, 973, and 1537 nm can be assigned to transition from an Er³⁺ ground state $^4I_{15/2}$ to excited states $^2K_{15/2}$, $^2H_{9/2}$, $^4S_{3/2}$, $^4F_{9/2}$, $^4I_{15/2}$, $^2I_{11/2}$, and $^4I_{13/2}$ levels. The $^4I_{13/2}$ level of Er³⁺ ions has a strong absorption to 980 nm photons. The absorption efficiency of the $^4I_{13/2}$ level of Er³⁺ ions to 1550 nm photons reached 89% of the 1537 nm. Therefore, Er³⁺ ions can be effectively sensitised by 1550 nm exciting light. The absorption edge of K₃LaTe₂O₉:Er can be obtained in absorption spectra. The reflectance spectra of K₃LaTe₂O₉:Er was converted into the absorption spectra based on the Kubelka-Munk formula (inset in Fig. 3):

$$F(R) = \frac{(1 - R)^2}{2R} = K/S,$$

where $R$ is the reflectance, $K$ is the absorption coefficient, and $S$ is the scattering coefficient. The absorption edges of K₃LaTe₂O₉:xEr are 287, 293 and 301 nm, which correspond to the band gap energies of 4.32, 4.23, and 4.12 eV, respectively (x = 2, 26, 44 mol%). The band gap value decreases with increasing Er³⁺ ion concentration. This phenomenon can be attributed to the fact that the ionic radii of Er³⁺ (0.088 nm) are smaller than that of La³⁺ (0.102 nm), thus resulting in the shrinkage of the lattice matrix and the red shift of the absorption bands after doping Er³⁺ ions.

Fig. 4a shows the excitation and DSL spectra of K₃LaTe₂O₉:Er. The excitation spectrum of K₃LaTe₂O₉:Er presents a strong peak at ~380 nm, which corresponds to the $^4G_{11/2} \rightarrow ^4I_{15/2}$ transition by monitoring the 550 nm emission of Er³⁺ ions. K₃LaTe₂O₉:Er under 380 nm excitation (K₃LaTe₂O₉:Er at 380 nm) exhibits pure green emission ($I_{Er} \quad ^2H_{9/2}/^4S_{3/2} \rightarrow ^4I_{15/2}$), and the red irradiation ($I_{R} \quad ^4F_{9/2} \rightarrow ^4I_{15/2}$) is very weak with the green and red fluorescence intensity ratio ($I_{G}/I_{R}$) $I_{G}/I_{R} = 21.3$. K₃LaTe₂O₉:Er at 380 nm has a relatively strong peak at ~410 nm, which is assigned to the $^4H_{9/2} \rightarrow ^4I_{13/2}$ transition of Er³⁺ ions. In addition, the emission spectra present a weak band located at 450–470 nm, which corresponds to the $^4F_{5/2}/^4F_{7/2} \rightarrow ^4I_{15/2}$ transition. The doping concentration of the optimum Er³⁺ ions is 26 mol% (Fig. 4b). The integrated intensity initially increases with increasing doping concentration, reaches its maximum at around 26 mol%, and then decreases. The quenching concentration is much higher than that of conventional materials. The relationship between the DSL intensity and doping concentration of the luminescence centre can be described by the Van Uitert model:

$$I(C) = C\kappa(1 + \beta C^Q),$$

where $C$ is the concentration of RE³⁺ ions, $\kappa$ and $\beta$ are the constants and $Q$ is the interaction types between RE³⁺ ions. $Q = 3, 6, 8,$ and 10 is related to exchange interaction, electric dipole–dipole (D–D), electric dipole–quadrupole (D–Q), and electric quadrupole–quadrupole (Q–Q) interactions. Eqn [2] was fitted to the data in Fig. 4b, and the $Q$ value of K₃LaTe₂O₉:Er at 380 nm is 10.2 ± 0.3 = 10. Therefore, the Q–Q interaction between Er³⁺ ions is dominant for quenching $^4H_{11/2}/^4S_{3/2}$ levels in K₃LaTe₂O₉:Er. However, ET is usually caused by the D–D interaction in most materials.

The shortest distance between La³⁺–La³⁺ ions is 0.606 nm in the K₃LaTe₂O₉ matrix, which is significantly larger than that of Y³⁺–Y³⁺ ions in Y₂O₃ (0.351 nm). The average distance $\bar{d}$ between doping Er³⁺ ions can be expressed as

$$\bar{d} = \left( \frac{V}{A} \right)^{1/3},$$

where $V$ is the volume of the matrix and $A$ is the area of the matrix.
where \( V \) is the volume of the unit crystal cell, \( x \) is the \( \text{Er}^{3+} \) doping concentration and \( Z \) is the number of molecules in the unit crystal cells. When the \( \text{Er}^{3+} \) ion concentration is 26 mol\%, \( d = 0.9711 \) nm, which is also significantly larger than that in \( \text{Gd}_2 \text{O}_3:10\% \text{Er}^{3+} (0.753 \) nm) and \( \beta-\text{NaYF}_4:25\% \text{Er}^{3+} (0.663 \) nm).\(^{15}\) Therefore, the shortest distance and average distance between \( \text{Er}^{3+} \) ions are large in the \( \text{K}_3\text{LaTe}_2\text{O}_9 \) matrix. The energy migration is affected by matrix.\(^{16}\) The \( \text{K}_3\text{LaTe}_2\text{O}_9 \) host can provide long lattice sites for \( \text{Er}^{3+} \) ions, which is helpful in obtaining heavy dopes and effectively reduces the harmful ET process. Moreover, it is beneficial in improving the absorption of incident light.

Under 980 nm pumping, \( \text{K}_3\text{LaTe}_2\text{O}_9:\text{Er} \) presents the green UCL (\( \text{K}_3\text{LaTe}_2\text{O}_9:\text{Er} \) at 980 nm) (inset of Fig. 5a). The UCL spectra for \( \text{K}_3\text{LaTe}_2\text{O}_9:x\text{Er} \) at 980 nm are shown in Fig. 5a (\( x = 2, 8, 14, 20, 26, 32, 44 \) mol\%). The spectra consist of basically two groups in the visual regions at an interval of 500–800 nm: (1) the strongest green emission at \( \sim 525 \) nm and \( \sim 550 \) nm can be attributed to the joint contributions of the \( \text{Er}^{3+} \) ion \( ^2\text{H}_{11/2} \rightarrow ^4\text{I}_{15/2} \) and \( ^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2} \) transition, and (2) the second strongest red emission at \( \sim 665 \) nm can be attributed to the \( \text{Er}^{3+} \) ion \( ^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2} \) transition. The emission peaks intensity of \( \text{K}_3\text{LaTe}_2\text{O}_9:\text{Er} \) at 980 nm are successively enhanced with increasing concentration of \( \text{Er}^{3+} \) ions. The concentration quenching phenomenon is not observed when the concentration of \( \text{Er}^{3+} \) ion reaches 44 mol\%. Compared with the DSL spectra in Fig. 4a, the red emission is improved significantly, and its \( I_\text{G}/I_\text{R} \) ratio is reduced from 21.3 (DSL) to 2.5–4.7 (UCL, 980 nm). The luminescence colour can be tuned by the doping concentration of \( \text{Er}^{3+} \) ions and the excitation power under 980 nm excitation. As the \( \text{Er}^{3+} \) ion concentration continues to increase from 2 mol\% to 38 mol\%, the red light component is enhanced, and its \( I_\text{G}/I_\text{R} \) ratio is reduced from 3.9 to 2.7. By contrast, the green component can be effectively enhanced and the \( I_\text{G}/I_\text{R} \) ratio is increased from 2.5 to 4.7 with increasing excitation power (Fig. 5e). Under high excitation power pumping, more photons can be absorbed by \( \text{Er}^{3+} \) ions, which results in \( \text{Er}^{3+} \) ions populating high levels easily.

In addition, the dependence of luminescence-integrated intensity on the \( \text{Er}^{3+} \) ion concentration of \( \text{K}_3\text{LaTe}_2\text{O}_9:\text{Er} \) at 980 nm is nearly linear when the concentration is low (2–26 mol\%), which indicates that the UCL mechanism can be
regarded as excited state absorption (ESA). This phenomenon is owed to the long distance between the RE ions in the K₃LaTe₂O₉ structure resulting in the suppression of the ET.²⁵ K₃LaTe₂O₉:Er at 980 nm presents an approximate nonlinear relation when Er³⁺ > 26 mol%, indicating that the ET between Er³⁺ ion pairs also plays an important role in the UC process (Fig. 5b).

K₃LaTe₂O₉:Er exhibits yellow-green emission under 1550 excitation (K₃LaTe₂O₉:Er at 1550 nm) (inset of Fig. 5b). The UCL spectra in the visible region of K₃LaTe₂O₉:Er at 1550 nm have the same peak positions and shape with different relative intensities compared with those at 980 nm excitation. However, the red emission intensity is significantly improved excited by 1550 nm, and its Iₚ/Iₑ ratio is reduced to 0.86-1.17. Whilst a relatively strong NIR emission peak at ~800 nm is observed, the optimum doping concentration of Er³⁺ ions is 32 mol% at 1550 nm pumping (Fig. 5c). When the Er³⁺ ion concentration is increased from 2 mol% to 44 mol%, the Iₚ/Iₑ ratio is reduced from 1.5 to 0.86. On the contrary, the green emission can be significantly enhanced, and the Iₚ/Iₑ ratio is increased from 0.86 to 1.17 with increasing excitation power (Fig. 5f). The UCL mechanism of K₃LaTe₂O₉:Er at 1550 nm is mainly based on the ESA process when the concentration of Er³⁺ ions is less than 16 mol%. Subsequently, the ET process begins to dominate (Er³⁺ > 16 mol%, Fig. 5d). Compared with DSL, the red component of K₃LaTe₂O₉:Er is increased, particularly under 1550 nm pumping. However, the red UCL mechanism is still controversial.²⁶-²¹

The non-radiation multiphonon relaxation rate (αₚ) between the energy levels of RE ions can be expressed using the Miyakawa–Dexter theory:²²-²³

\[
\alpha_p = \alpha_0 \exp \left( -\frac{\Delta E}{\hbar \omega_0} \right),
\]

where α₀ and α₀ are the constants related to the host properties, ΔE is the energy gap (cm⁻¹) and \(\hbar \omega_0\) is the maximum phonon energy of the host lattice.

The energy gaps of \(4S_{3/2} \rightarrow 4F_{9/2}\) and \(4I_{11/2} \rightarrow 4I_{11/2}\) of K₃LaTe₂O₉:Er at 380 nm are observed directly excited at 380 nm, indicating that the non-radiative relaxation \(4S_{3/2} \rightarrow 4F_{9/2}\) is weak (Fig. 4a). However, the non-radiative relaxation probability of \(4I_{11/2} \rightarrow 4I_{11/2}\) is smaller than that of the \(4S_{3/2} \rightarrow 4F_{9/2}\), that is, the \(4S_{3/2} \rightarrow 4F_{9/2}\) non-radiative relaxation process is not the main reason for the red UCL in K₃LaTe₂O₉:Er at 980 nm. Therefore, the mechanism of red intensity enhancement can only be the cross relaxation (CR) between Er³⁺ ions. The red emission intensity is very weak even at high Er³⁺ concentrations for DSL because the CR between Er³⁺ ions is restrained in K₃LaTe₂O₉ owing to the joint contributions of the long distance between the RE ions and the lack of intermediate metastable energy level below the \(4S_{3/2}\) level. However, the long-lifetime spectrum of the intermediate levels is inspired, and the CR processes significantly enhance the red emission in the UCL compared with DSL. The short-lifetime spectrum of the \(4I_{11/2}\) level and the small energy gap of \(4I_{10/2} \rightarrow 4I_{11/2}\) (ΔE ≈ 1950 cm⁻¹, ΔE/\(\hbar \omega_0\) = 2.3) are the major factors influencing the red radiation enhancement of K₃LaTe₂O₉:Er at 1550 nm.²⁴-²⁵

Therefore, the difference in UCL spectra and quenching concentration for DSL and UCL results mainly from the different energy level population of the Er³⁺ ions caused by the different excitation routes.

The different optimum Er³⁺ concentrations of K₃LaTe₂O₉ under various wavelengths pumping is caused by the different excitation paths, level lifetime, and absorption cross section of levels. The transition model of the Er³⁺ ions in the K₃LaTe₂O₉ phosphor excited at 380, 980, and 1550 nm is established to describe the luminescence process in Fig. 6. Red emission \(4F_{9/2} \rightarrow 4I_{13/2}\) of Er³⁺ ions was very weak in the DSL spectrum under 380 nm pumping (Fig. 4a). The green UCL process for K₃LaTe₂O₉:Er at 380 nm is as follows: \(4I_{15/2} + h\nu_{980} \rightarrow 4G_{11/2}\), \(4G_{11/2} \rightarrow 4H_{9/2} + \text{multiphonon relaxation} + h\nu_{410} \text{nm, } 4H_{9/2} \rightarrow 4F_{3/2} + 4I_{13/2} + \text{multiphonon relaxation} + h\nu_{450-470} \text{ nm, } 4F_{3/2} + 4I_{15/2} \rightarrow 2H_{11/2} + 4S_{3/2} + \text{multiphonon relaxation, } 2H_{11/2} + 4S_{3/2} \rightarrow 4I_{15/2} + h\nu_{525-550} \text{ nm}\). The green UCL process for K₃LaTe₂O₉:Er at 980 nm is as follows: \(4I_{15/2} + h\nu_{980} \rightarrow 4I_{13/2}, 4I_{13/2} + h\nu_{450-470} \text{ nm, } 4F_{3/2} + 4I_{15/2} \rightarrow 5I_{11/2} + \text{multiphonon relaxation, } 5I_{11/2} \rightarrow 4I_{15/2} + h\nu_{525-550} \text{ nm}\). Its red UCL mechanism is the \(4F_{7/2} + 4I_{11/2} \rightarrow 4F_{9/2} + 4F_{9/2} \text{ CR process. The red and NIR intensity of K₃LaTe₂O₉:Er at 1550 nm is significantly enhanced. The UCL mechanism is as follows: } 4I_{15/2} + h\nu_{980} \rightarrow 4I_{13/2}, 4I_{13/2} + h\nu_{450-470} \text{ nm, } 4F_{3/2} + 4I_{15/2} \rightarrow 2H_{11/2} + 4S_{3/2} + \text{multiphonon relaxation, } 2H_{11/2} + 4S_{3/2} \rightarrow 4I_{15/2} + h\nu_{525-550} \text{ nm, } 4F_{9/2} \rightarrow 4I_{15/2} + h\nu_{660} \text{ nm, } 4F_{9/2} \rightarrow 4I_{15/2} + h\nu_{525-550} \text{ nm, } 4F_{9/2} \rightarrow 4I_{15/2} + h\nu_{660} \text{ nm}\).

As shown in Fig. 7a, the K₃LaTe₂O₉:0.26Er sample can nearly recover to its original intensity after cooling down to room temperature from 473 K, indicating that K₃LaTe₂O₉:Er phosphors have a high resistance to heating damage by using a 380 nm xenon lamp as the excitation source. Fig. 7b shows the integrated intensities of K₃LaTe₂O₉:Er phosphors as a function of temperature. The integrated emission intensities are normalized at room temperature for K₃LaTe₂O₉:Er (x = 20, 26, 32 mol%). With the successive increase in the heating temperature, the green UCL intensity of different concentration samples gradually decreases. At 473 K, the integrated intensity of the K₃LaTe₂O₉:26Er (x = 20, 26, 32 mol%) samples can retain 32%, 56%, and 58% at room temperature, respectively. Therefore, K₃LaTe₂O₉:Er is a good matrix material to achieve a stable DSL. The higher Er³⁺ ion concentration, the more obvious is the thermal quenching phenomenon of the sample. The thermal quenching mechanism of the luminescent material is usually different, containing ET, CR, and non-radiative transition.²⁶ The integrated intensity curves for various content samples have a similar slope. Thus, the ET rates between Er³⁺ ions causing heating temperature are similar. In addition, the probability of \(4S_{3/2}\) non-radiative relaxation to near-low energy level is small. Therefore, CR is mainly responsible for the luminescent thermal quenching.

According to Boltzmann’s distribution, the intensity ratio \(I_{1550}/I_{980}\) between the thermal equilibrium levels of \(^2\text{H}_{11/2}\) and \(^4\text{S}_{3/2}\) \((I_{1550}/I_{980})\), can be expressed as

\[
R_{1550} = \frac{I_{1550}}{I_{980}} = C \exp(-\Delta E/kT),
\]

where C is the constant relating to the host materials, ΔE is the energy gap between \(^2\text{H}_{11/2}\) and \(^4\text{S}_{3/2}\) levels, k is the Boltzmann
constant and $T$ is the absolute temperature. The DSL spectra are adopted to characterise the temperature sensor properties and to avoid the thermal effect in UCL caused by the LD. Eqn (5) was fit for the experimental data in Fig. 8a, and the curves for the K$_3$LaTe$_2$O$_9$Er samples from 303 K to 473 K ($x = 20, 26, 32$ mol%) were drawn. The fitting data show that the Er$^{3+}$ ion concentrations affect the $C$ and $\Delta \varepsilon$ values. The $R_{H5}$ values of $^2H_{11/2}$ and $^4S_{3/2}$ energy levels continuously enhance with increasing heating temperature, whereas the green DSL intensity decreases with increasing temperature. Sensitivity is an important parameter to evaluate the sensor performance for the temperature sensing. Sensitivity $S$ can be derived according to eqn (6):

$$S = \frac{dR}{dT} = R(-\Delta \varepsilon/kT^2),$$

In the present study, the temperature sensitivity of the K$_3$LaTe$_2$O$_9$:Er samples decreases with increasing Er$^{3+}$ ion concentration (Fig. 7b). This is due to that the change of the concentration of Er$^{3+}$ ions may cause the change of the crystal field surrounding Er$^{3+}$ ions, and the change of crystal field will cause the change of the optical transition rates of Er$^{3+}$ ions. Therefore, the variation of radiation transition rate of $^2H_{11/2}$ and $^4S_{3/2}$ levels arouse the change of fluorescence intensity ratio FIR in different Er$^{3+}$ ion doped samples and affect the sensitivity values. In addition, the thermal effects of samples is remarkable when concentration of doped Er$^{3+}$ ions is higher. The temperature of samples has an effect on crystal field. The sensitivities of 20 and 26 mol% Er$^{3+}$ ions are similar, corresponding to approximately 0.008 and 0.0075 K$^{-1}$ at 473 K, respectively. When the Er$^{3+}$ ion concentration reaches 32 mol%, the sensitivity decreases rapidly, and its value is nearly 0.0057 K$^{-1}$ (Fig. 8b). Therefore, the low Er$^{3+}$ content should be carefully chosen to obtain the optimal sensitivity performance. The previously reports on temperature

![Fig. 6](image-url) Transition model of Er$^{3+}$ ions in the K$_3$LaTe$_2$O$_9$ phosphor excited at 380, 980, and 1550 nm.

![Fig. 7](image-url) DSL spectra of K$_3$LaTe$_2$O$_9$:0.26Er at different temperatures (a) and integrated emission intensities of K$_3$LaTe$_2$O$_9$:xEr phosphors as a function of temperature (b) ($x = 20, 26, 32$ mol%), ($\lambda_m = 380$ nm).
sensitivities data were provided in Table S3.† On the basis of the experimental data in Fig. 8b, the K$_3$LaTe$_2$O$_9$:Er material can be used as the luminescent thermometer for temperature sensing. In addition, the above-mentioned results show that the Er$^{3+}$ ion concentration is important to the thermal quenching and sensitivity of K$_3$LaTe$_2$O$_9$:Er phosphors.

4. Conclusion

A new green up-conversion luminescence material, K$_3$LaTe$_2$O$_9$:Er, was synthesised. The diffraction pattern of the hexagonal K$_3$LaTe$_2$O$_9$ crystal was indexed with Miller indices and the lattice constants $a = b = 0.60636 \pm 0.00018$ nm, $c = 1.49543 \pm 0.00037$ nm, and $V = 0.47617$ nm$^3$. The DSL and UCL properties of K$_3$LaTe$_2$O$_9$:Er were studied under 380, 980 and 1550 nm excitation. The shortest distance and average distance between Er$^{3+}$ ions in the K$_3$LaTe$_2$O$_9$ matrix are significantly larger than that in normal phosphors. Therefore, energy migration is significantly suppressed, which is helpful in obtaining heavy Er$^{3+}$ doping.

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