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# Cooperative and non-cooperative sensitization upconversion in lanthanide-doped LiYbF<sub>4</sub> nanoparticles†

 Qilin Zou,<sup>a,b</sup> Ping Huang,<sup>a</sup> Wei Zheng,<sup>✉ a,b</sup> Wenwu You,<sup>ID a</sup> Renfu Li,<sup>ID a</sup>  
 Datao Tu,<sup>a,b</sup> Jin Xu<sup>ID a</sup> and Xueyuan Chen<sup>ID \*a,b</sup>

Lanthanide (Ln<sup>3+</sup>)-doped upconversion nanoparticles (UCNPs) have attracted tremendous interest owing to their potential bioapplications. However, the intrinsic photophysics responsible for upconversion (UC) especially the cooperative sensitization UC (CSU) in colloidal Ln<sup>3+</sup>-doped UCNPs has remained untouched so far. Herein, we report a unique strategy for the synthesis of high-quality LiYbF<sub>4</sub>:Ln<sup>3+</sup> core-only and core/shell UCNPs with tunable particle sizes and shell thicknesses. Energy transfer UC from Er<sup>3+</sup>, Ho<sup>3+</sup> and Tm<sup>3+</sup> and CSU from Tb<sup>3+</sup> were comprehensively surveyed under 980 nm excitation. Through surface passivation, we achieved efficient non-cooperative sensitization UC with absolute UC quantum yields (QYs) of 3.36%, 0.69% and 0.81% for Er<sup>3+</sup>, Ho<sup>3+</sup> and Tm<sup>3+</sup>, respectively. Particularly, we for the first time quantitatively determined the CSU efficiency for Tb<sup>3+</sup> with an absolute QY of 0.0085% under excitation at a power density of 70 W cm<sup>-2</sup>. By means of temperature-dependent steady-state and transient UC spectroscopy, we unraveled the dominant mechanisms of phonon-assisted cooperative energy transfer ( $T > 100$  K) and sequential dimer ground-state absorption/excited-state absorption ( $T < 100$  K) for the CSU process in LiYbF<sub>4</sub>:Tb<sup>3+</sup> UCNPs.

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## 1. Introduction

Lanthanide-doped upconversion nanoparticles (UCNPs) that are able to convert two or more low-energy pump photons into one high-energy output photon have recently attracted tremendous interest in the fields of biomedicine and nanomedicine because of their superior physicochemical features and unique optical properties.<sup>1–9</sup> Yb<sup>3+</sup>, owing to its large absorption cross-section at ~980 nm, is usually selected as a sensitizer in lanthanide (Ln<sup>3+</sup>)-doped UCNPs, which can effectively absorb near-infrared (NIR) photons and transfer the excitation energy to nearby activators to yield efficient upconversion (UC) luminescence.<sup>10–13</sup> For Ln<sup>3+</sup> activators with stepwise long-lived intermediate energy levels matching those of Yb<sup>3+</sup>, such as Er<sup>3+</sup>, Ho<sup>3+</sup> and Tm<sup>3+</sup>, resonant or phonon-assisted energy

transfer (ET) UC (ETU) occurs easily.<sup>14–17</sup> While for those Ln<sup>3+</sup> ions without metastable levels as the energy storage reservoir, such as Tb<sup>3+</sup> and Eu<sup>3+</sup>, cooperative sensitization UC (CSU) takes place.<sup>18–22</sup> In a typical CSU process, the excitation energy of two adjacent Yb<sup>3+</sup> is simultaneously transferred to Tb<sup>3+</sup> or Eu<sup>3+</sup>.<sup>19</sup> CSU luminescence from activators such as Tb<sup>3+</sup> or Eu<sup>3+</sup> is less influenced by the deleterious surface quenching effect than ETU luminescence from Er<sup>3+</sup> or Tm<sup>3+</sup>, due to the large energy gap between the emitting levels and their next low-lying levels of Tb<sup>3+</sup> or Eu<sup>3+</sup>, thereby demonstrating unique advantages and promises for applications in UC-FRET biodetection and bioimaging.<sup>23–27</sup> Thanks to the pioneering work reported by H. U. Güdel and others in theoretical and experimental studies on CSU,<sup>28–31</sup> much of the spectroscopy and mechanism for the CSU process in bulk materials are well understood. However, in the case of colloidal Ln<sup>3+</sup>-doped UCNPs, their mechanism has remained unexplored so far.

LiYbF<sub>4</sub>, due to its low phonon energy (~460 cm<sup>-1</sup>) and high chemical stability, has been regarded as an efficient host material for UC luminescence (UCL).<sup>32,33</sup> Meanwhile, the sensitizer Yb<sup>3+</sup> ions as a constituent of the host can not only maximize the absorption but also facilitate energy migration among Yb<sup>3+</sup> sub-lattices, which may promote ET processes between Yb<sup>3+</sup> and the activators, thus resulting in distinct UCL characteristics and improved UCL efficiency compared to their

<sup>a</sup>CAS Key Laboratory of Design and Assembly of Functional Nanostructures, and State Key Laboratory of Structural Chemistry, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou, Fujian 350002, China. E-mail: xchen@fjirsm.ac.cn, zhengwei@fjirsm.ac.cn; Fax: +86 591 63179421; Tel: +86 591 63179421

<sup>b</sup>College of Materials Science and Engineering, Fujian Normal University, Fuzhou, Fujian 350007, China

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low-concentration Yb<sup>3+</sup>-doped counterparts.<sup>34–36</sup> However, due to the stringent synthetic conditions and the surface quenching effect, currently it remains difficult for the synthesis of high-quality LiYbF<sub>4</sub>:Ln<sup>3+</sup> UCNP s with controlled particle size and efficient UCL.

Herein, we report a unique strategy for the synthesis of monodisperse LiYbF<sub>4</sub>:Ln<sup>3+</sup> core-only and core/shell UCNP s with controlled particle sizes and shell thicknesses through a modified high-temperature co-precipitation method. Trioctylamine (TOA) instead of 1-octadecene (ODE), that is commonly used in the synthesis of other Ln<sup>3+</sup>-doped UCNP s, is utilized as a solvent to provide an elevated reaction temperature for the crystallization and ripening of the UCNP s,<sup>37,38</sup> in view of its higher boiling temperature (365.8 °C) than ODE (314.2 °C) (Table S1†). The resulting core/shell UCNP s yield remarkably enhanced UCL. ETU from Er<sup>3+</sup>, Ho<sup>3+</sup> and Tm<sup>3+</sup> and CSU from Tb<sup>3+</sup> are systematically surveyed by room-temperature (RT) spectroscopic characterization. Furthermore, by means of low-temperature (10 K) high-resolution steady-state and transient UC spectroscopy, we unravel the excited-state dynamics involved in the CSU process in LiYbF<sub>4</sub>:Tb<sup>3+</sup> UCNP s.

## 2. Experimental

### 2.1. Chemicals and materials

CH<sub>3</sub>COOLi·2H<sub>2</sub>O, NH<sub>4</sub>F, cyclohexane, methanol, and ethanol were purchased from Sinopharm Chemical Reagent Co., China. Oleic acid (OA) and TOA were purchased from Alfa Aesar (China). Yb(CH<sub>3</sub>COO)<sub>3</sub>·4H<sub>2</sub>O (99.999%), Er(CH<sub>3</sub>COO)<sub>3</sub>·4H<sub>2</sub>O (99.99%), Tm(CH<sub>3</sub>COO)<sub>3</sub>·4H<sub>2</sub>O (99.99%), Ho(CH<sub>3</sub>COO)<sub>3</sub>·4H<sub>2</sub>O (99.99%), Tb(CH<sub>3</sub>COO)<sub>3</sub>·4H<sub>2</sub>O (99.99%) and Y(CH<sub>3</sub>COO)<sub>3</sub>·4H<sub>2</sub>O (99.99%) were purchased from Sigma-Aldrich (China). All chemicals were used as received without further purification.

### 2.2. Synthesis of LiYbF<sub>4</sub>:Ln<sup>3+</sup> core-only UCNP s

The LiYbF<sub>4</sub>:Ln<sup>3+</sup> (Ln = Er, Tm, Ho, or Tb) core-only UCNP s were synthesized *via* a high-temperature co-precipitation method. In a typical synthesis of LiYbF<sub>4</sub>:30%Tb UCNP s, 1 mmol of CH<sub>3</sub>COOLi·2H<sub>2</sub>O, 0.7 mmol of Yb(CH<sub>3</sub>COO)<sub>3</sub>·4H<sub>2</sub>O and 0.3 mmol of Tb(CH<sub>3</sub>COO)<sub>3</sub>·4H<sub>2</sub>O were mixed with 8 mL of OA and 12 mL of TOA in a 100 mL three-necked round-bottom flask. The resulting mixture was heated to 160 °C under a N<sub>2</sub> flow with constant stirring for 30 min to form a clear solution, and then cooled down to RT. Thereafter, 10 mL of methanol solution containing 4 mmol of NH<sub>4</sub>F was added and the solution was stirred at 60 °C for 30 min to remove methanol. After methanol was evaporated, the resulting solution was heated to 320 °C under a N<sub>2</sub> flow with vigorous stirring for 60 min, and then cooled down to RT. The obtained UCNP s were precipitated by addition of 30 mL of ethanol, collected by centrifugation, washed with ethanol several times, and finally re-dispersed in cyclohexane. To control the size and morphology of the UCNP s, the mixed solution was allowed to react at

different temperatures (*e.g.*, 300 °C and 310 °C) and for different times (*e.g.*, from 20 min to 120 min).

### 2.3. Synthesis of LiYbF<sub>4</sub>:Ln<sup>3+</sup>@LiYF<sub>4</sub> core/shell UCNP s

Briefly, 0.5 mmol of CH<sub>3</sub>COOLi·2H<sub>2</sub>O and 0.5 mmol of Y(CH<sub>3</sub>COO)<sub>3</sub>·4H<sub>2</sub>O were added to a 100 mL three-necked round-bottom flask containing 8 mL of OA and 12 mL of TOA. The mixed solution was then heated to 160 °C under a N<sub>2</sub> flow with constant stirring for 30 min to form a clear solution. After cooling down to 80 °C, 0.5 mmol of LiYbF<sub>4</sub>:Ln<sup>3+</sup> core-only UCNP s in 10 mL of cyclohexane was added and maintained at 80 °C for 30 min to remove cyclohexane. After the removal of cyclohexane, 10 mL of methanol solution containing 2 mmol of NH<sub>4</sub>F was added and stirred at 60 °C for another 30 min to remove methanol. After methanol was evaporated, the solution was heated to 320 °C under a N<sub>2</sub> flow with vigorous stirring for 60 min, and then cooled down to RT. The resulting core/shell UCNP s were precipitated by addition of 30 mL of ethanol, collected by centrifugation, washed with ethanol several times, and finally re-dispersed in cyclohexane. To control the shell thickness, different amounts of the shell precursors were weighed for the synthesis.

### 2.4. Characterization

Powder X-ray diffraction (XRD) patterns of the samples were collected with an X-ray diffractometer (MiniFlex2, Rigaku) with Cu Kα1 radiation ( $\lambda = 0.154187$  nm). Both the low- and high-resolution transmission electron microscopy (TEM) measurements were performed by using a TECNAI G<sup>2</sup> F20 TEM equipped with the energy dispersive X-ray spectrum (EDS). Downshifting luminescence (DSL) emission and excitation spectra and the corresponding photoluminescence (PL) lifetimes were recorded on a spectrometer (FLS980, Edinburgh) equipped with both continuous xenon (450 W) and pulsed flash lamps. UCL emission spectra were acquired under 980 nm excitation with a continuous-wave semiconductor NIR laser diode (2 W). UCL lifetimes were measured with a customized UV to mid-infrared steady-state and phosphorescence lifetime spectrometer (FSP920-C, Edinburgh) equipped with a digital oscilloscope (TDS3052B, Tektronix) and a tunable mid-band Optical Parametric Oscillator (OPO) pulse laser as the excitation source (410–2400 nm, 10 Hz, pulse width  $\leq 5$  ns, Vibrant 355II, OPOTEK). The absolute UC quantum yield (QY) was measured on a customized UCQY measurement system combined with a fiber optic spectrometer (QE65pro, Ocean Optics), a standard integrating sphere (150 mm in diameter, Edinburgh), a 980 nm diode laser (MDL-III-980-2W, Changchun New Industries Optoelectronics Tech Co., Ltd) as the excitation source, and a neutral density filter to attenuate the excitation light (for details, please see also the Experimental section and Fig. S1 in the ESI†). A tungsten lamp (100 W, Edinburgh) was used as a correction for the spectral response of the system, and the UCL emission peaks in the spectral region of 460–620 nm for Tb<sup>3+</sup>, 410–690 nm for Er<sup>3+</sup>, 330–840 nm for Tm<sup>3+</sup> and 470–630 nm for Ho<sup>3+</sup> were integrated for the QY determination. For low-temperature



measurements, samples were mounted on a closed cycle cryostat (10–300 K, DE202, Advanced Research Systems). To avoid laser burning of the samples in a vacuum environment in the closed cycle cryostat, the as-synthesized UCNPs were washed with acid to yield ligand-free UCNPs. PL photographs of the UCNPs solutions were taken by using a Canon 70D digital camera without using any filter. All the measurements were carried out by using powder samples, and all the spectral data were corrected for the spectral response of both the spectrometer and the integrating sphere.

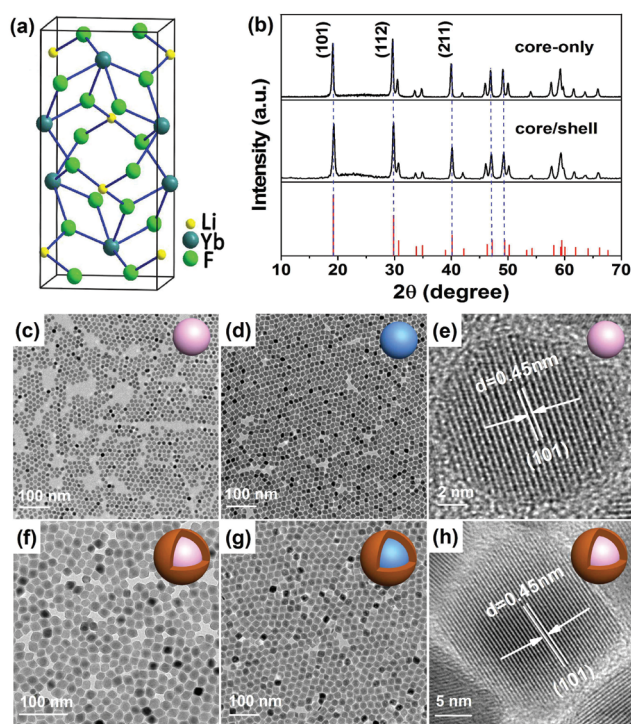
### 3. Results and discussion

#### 3.1. Structure and morphology

The  $\text{LiYbF}_4$  crystal has a tetragonal structure (space group  $I4_1/a$ ) with the  $\text{Yb}^{3+}$  ions surrounded by eight  $\text{F}^-$  ions that form the edges of a slightly distorted dodecahedron (Fig. 1a).<sup>39</sup> All  $\text{Yb}^{3+}$  ions occupy a single site with a symmetry of  $S_4$ . High-quality  $\text{LiYbF}_4\text{:Ln}^{3+}$  ( $\text{Ln} = \text{Er}, \text{Tm}, \text{Ho}, \text{or Tb}$ ) core-only and core/shell UCNPs were synthesized *via* a modified high-temperature co-precipitation method in the presence of OA and TOA as the surfactant and the solvent, respectively. The as-synthesized UCNPs are hydrophobic and can readily disperse

in a variety of nonpolar organic solvents because of the oleic ligands anchored to the surface of the UCNPs. The XRD patterns (Fig. 1b and S2†) show a set of intense and indexed diffraction peaks of tetragonal  $\text{LiYbF}_4$  (JCPDS No. 71-1211) for both  $\text{LiYbF}_4\text{:Ln}^{3+}$  core-only and core/shell UCNPs, indicating the pure phase and the high crystallinity of the UCNPs. Slightly narrower diffraction peaks for core/shell UCNPs than for core-only UCNPs were observed, due to the increase in the particle size of core/shell UCNPs. The TEM images show that the  $\text{LiYbF}_4\text{:30%Tb}$  core-only UCNPs are roughly spherical with a mean size of  $12.2 \pm 0.6$  nm (Fig. 1c and S3†), while the  $\text{LiYbF}_4\text{:2%Er}$  UCNPs synthesized under identical conditions are rhombohedral with a mean size of  $(16.9 \pm 0.8) \times (21.7 \pm 1.3)$  nm (Fig. 1d and S4†). This indicates that the doping concentration of  $\text{Ln}^{3+}$  has a significant impact on the size and morphology of the resulting UCNPs. Meanwhile, it was found that the size and morphology of the UCNPs can be tuned through the control of reaction time and/or temperature. For example, the mean size of the resulting  $\text{LiYbF}_4\text{:2%Er}$  UCNPs can be tuned from  $(12.5 \pm 1.1) \times (15.5 \pm 0.9)$  nm to  $(16.9 \pm 0.8) \times (21.7 \pm 1.3)$  nm by elevating the reaction temperature from 300 °C to 320 °C (Fig. S5†). Similarly, by lengthening the reaction time from 20 min to 2 h at 320 °C, the mean size of the UCNPs can be tuned from  $7.5 \pm 0.8$  nm to  $(17.5 \pm 1.4) \times (22.4 \pm 1.6)$  nm, with their morphology evolving from spherical to rhombohedral (Fig. S6†). Such a morphology evolution of  $\text{LiYbF}_4\text{:Ln}^{3+}$  UCNPs is ascribed to the anisotropic growth of the tetragonal NPs, which agrees well with our previous observations in  $\text{LiLuF}_4\text{:Ln}^{3+}$  and  $\text{LiYF}_4\text{:Ln}^{3+}$ .<sup>40,41</sup>

In addition to core-only UCNPs, core/shell UCNPs with a tunable shell thickness from  $\sim 2$  nm to  $\sim 7$  nm were also synthesized by controlling the ratio of the core/shell precursors through epitaxial growth of an inert  $\text{LiYF}_4$  shell around the core (Fig. S7†). The TEM images (Fig. 1f and g) show that both  $\text{LiYbF}_4\text{:30%Tb@LiYF}_4$  and  $\text{LiYbF}_4\text{:2%Er@LiYF}_4$  core/shell UCNPs synthesized in a core/shell precursor ratio of 1:1 are rhombohedral with their mean sizes of  $(20.0 \pm 0.9) \times (26.2 \pm 1.2)$  nm and  $(25.3 \pm 1.6) \times (30.2 \pm 1.7)$  nm (Fig. S3 and S4†), respectively. The core/shell structure can be verified by the discernible contrasted TEM image and high-angle annular dark-field scanning TEM (HAADF-STEM) analysis of the core/shell UCNPs (Fig. S3 and S4†). The high crystallinity of both core-only and core/shell UCNPs was further confirmed by the intense selected area electron diffraction (SAED) ring patterns (Fig. S3†) and the high-resolution TEM (HRTEM) images (Fig. 1e and h) which exhibit clear lattice fringes with an observed  $d$  spacing of 0.45 nm for the (101) plane of tetragonal  $\text{LiYbF}_4$ . Compositional analysis by EDS revealed the Yb, Y and F elements of the matrix and the Tb and Er elements of the dopant (Fig. S3 and S4†). The absence of Li is because of its small atomic number ( $M = 3$ ) that cannot be detected by EDS. More importantly, the modified high-temperature co-precipitation method can be extended to the synthesis of other  $\text{Ln}^{3+}$ -doped UCNPs, especially those heterovalently doping with  $\text{Ln}^{3+}$  that were difficult to synthesize before, such as cubic  $\text{KMgF}_3\text{:Ln}^{3+}$  and orthorhombic  $\text{BaMgF}_4\text{:Ln}^{3+}$  (Fig. S8†).



**Fig. 1** (a) Crystal structure of tetragonal  $\text{LiYbF}_4$ . (b) XRD patterns of  $\text{LiYbF}_4\text{:30%Tb}$  core-only and  $\text{LiYbF}_4\text{:30%Tb@LiYF}_4$  core/shell UCNPs. The bottom lines show the standard XRD pattern of tetragonal  $\text{LiYbF}_4$  (JCPDS No. 71-1211). TEM images of (c)  $\text{LiYbF}_4\text{:30%Tb}$  and (d)  $\text{LiYbF}_4\text{:2%Er}$  core-only UCNPs synthesized at 320 °C for 1 h, and (f)  $\text{LiYbF}_4\text{:30%Tb@LiYF}_4$  and (g)  $\text{LiYbF}_4\text{:2%Er@LiYF}_4$  core/shell UCNPs synthesized in a core/shell precursor ratio of 1:1. (e, h) The corresponding HRTEM images for (c) and (f).





### 3.2 Non-cooperative sensitization upconversion from $\text{Er}^{3+}$ , $\text{Ho}^{3+}$ , and $\text{Tm}^{3+}$

Under 980 nm NIR laser irradiation, intense yellow, green and blue UCL can be observed in colloidal cyclohexane solution of the UCNPs doped with  $\text{Er}^{3+}$ ,  $\text{Ho}^{3+}$  and  $\text{Tm}^{3+}$ , respectively, which became much brighter after coating by an inert  $\text{LiYF}_4$  shell (Fig. 2). The corresponding UCL spectra show that all the UCNPs exhibit sharp and characteristic emission peaks, which can be exclusively attributed to the intra- $4f^N$  electronic transitions of  $\text{Er}^{3+}$ ,  $\text{Ho}^{3+}$  and  $\text{Tm}^{3+}$ , respectively (Fig. 2b–d). With increasing the particle size, the UCL intensity of the UCNPs was gradually enhanced due to the reduced surface quenching effect, as a result of the decreased surface-to-volume ratio of the UCNPs.<sup>42</sup> For example, the integrated UCL intensity of  $\text{LiYbF}_4\text{:}2\%\text{Er}$  core-only UCNPs was remarkably enhanced by a factor of 14 upon increasing their particle size from  $\sim 7.5$  nm to  $\sim (17.5 \times 22.4)$  nm (Fig. S9†). However, the corresponding UCL lifetimes of  $^4\text{S}_{3/2}$  (0.17 ms) and  $^4\text{F}_{9/2}$  (0.19 ms) of  $\text{Er}^{3+}$  were observed nearly unchanged (Fig. S10†), which contradicts with the common viewpoint that the UCL lifetime of  $\text{Ln}^{3+}$  generally decreases with the decrease in particle size.<sup>43,44</sup> Such a size-independent UCL decay behavior in stoichiometric Yb-containing systems may originate from very fast energy migration among  $\text{Yb}^{3+}$  sub-lattices, as also evidenced by the observation of a nearly unchanged DSL lifetime (0.18 ms) of  $^2\text{F}_{5/2}$  of  $\text{Yb}^{3+}$  (Fig. S10†).<sup>23</sup>

To further improve the UCL, we passivated the surface of the UCNPs by growing an inert  $\text{LiYF}_4$  shell around the core

(Fig. 2a). It was found that the integrated UCL intensity of  $\text{LiYbF}_4\text{:}2\%\text{Er@LiYF}_4$  core/shell UCNPs underwent an initial increase and then decreased with the increase in the shell thickness (Fig. S11†). This can be attributed to a synergic effect of the increased isolation of the core from its environment and the decreased  $\text{Yb}^{3+}$  absorption arising from the increased shell thickness.<sup>41,45</sup> The integrated UCL intensity of the core/shell UCNPs with optimal shell thicknesses was enhanced by a factor of approximately 970, 7 and 6 for  $\text{Er}^{3+}$ ,  $\text{Ho}^{3+}$  and  $\text{Tm}^{3+}$ , respectively, in comparison with their core-only counterparts (Fig. 2b–d). Accordingly, the UCL lifetimes of  $^4\text{F}_{9/2}$  of  $\text{Er}^{3+}$ ,  $^5\text{F}_5$  of  $\text{Ho}^{3+}$  and  $^1\text{D}_2$  of  $\text{Tm}^{3+}$  and the DSL lifetime of  $^2\text{F}_{5/2}$  of  $\text{Yb}^{3+}$  were found to increase from 0.19, 0.21, 0.19 and 0.18 ms to 0.35, 1.00, 0.43 and 1.20 ms, respectively (Fig. S12–S15†). Besides, it was observed that all the UCL decays displayed a rising edge in the initial stage, as a result of the slow population process of the emitting energy levels through ET from  $\text{Yb}^{3+}$ , thus revealing the ETU mechanism for the non-cooperative sensitization UCL of  $\text{Er}^{3+}$ ,  $\text{Ho}^{3+}$  and  $\text{Tm}^{3+}$  in  $\text{LiYbF}_4$  (Fig. S16†).<sup>28,46</sup> Both the enhanced UCL intensity and lengthened lifetime in core/shell UCNPs unequivocally confirm the effective surface passivation that alleviates the deleterious surface quenching effect. The absolute UCQY, defined as the ratio of the number of emitted photons to the number of absorbed photons, was determined to be  $3.36 \pm 0.06\%$ ,  $0.69 \pm 0.01\%$  and  $0.81 \pm 0.06\%$  for  $\text{Er}^{3+}$ ,  $\text{Ho}^{3+}$  and  $\text{Tm}^{3+}$ , respectively, in core/shell UCNPs upon 980 nm NIR laser excitation at a power density of  $70 \text{ W cm}^{-2}$  (Table S2†).

More importantly, we observed that, under 980 nm excitation at a low power density of  $5 \text{ W cm}^{-2}$ , the ratio of the UCL intensity of the UV emission at  $\sim 362$  nm to the NIR emission at  $\sim 800$  nm ( $R_{\text{UV/NIR}}$ ) in  $\text{LiYbF}_4\text{:}1\%\text{Tm}$  was unusually larger (e.g., 0.14 vs. 0.02 in  $\text{NaYbF}_4\text{:Tm}$ ) than that in other  $\text{Tm}^{3+}$ -activated UCNPs, such as  $\text{NaYF}_4\text{:Yb,Tm}$ ,  $\text{NaYbF}_4\text{:Tm}$ , and  $\text{LiYF}_4\text{:Yb,Tm}$  (Fig. S17†).<sup>40,47,48</sup> This can be attributed to the unique crystal structure of  $\text{LiYbF}_4$  and the energy migration process through  $\text{Yb}^{3+}$  sub-lattices to nearby  $\text{Tm}^{3+}$  ions that promotes the high-order multiphoton UCL of  $\text{Tm}^{3+}$ .<sup>36,49</sup> The intense UCL in the UV region is highly desired for triggering the photochemical reactions in several promising biomedical applications, such as the remote control of drug delivery and cell adhesion,<sup>50–52</sup> thus offering the great potential of  $\text{LiYbF}_4\text{:Ln}^{3+}$  UCNPs as effective UCL nano-bioprobes in the field of biomedicine.

### 3.3 Cooperative sensitization upconversion from $\text{Tb}^{3+}$

Apart from ETU from  $\text{Er}^{3+}$ ,  $\text{Ho}^{3+}$  and  $\text{Tm}^{3+}$ , we also investigated the CSU process in  $\text{LiYbF}_4\text{:Tb}^{3+}$  UCNPs. To realize effective CSU in  $\text{LiYbF}_4$ , the doping concentration of  $\text{Tb}^{3+}$  was first optimized to be 30 mol%, by considering the concentration quenching of  $\text{Tb}^{3+}$  and the doping-induced particle size variation (Fig. S18†). Under 980 nm NIR irradiation, green UCL can be explicitly observed in colloidal cyclohexane solution of both  $\text{LiYbF}_4\text{:}30\%\text{Tb}$  core-only and  $\text{LiYbF}_4\text{:}30\%\text{Tb@LiYF}_4$  core/shell UCNPs (Fig. 3b). The UCL spectra show that all the emission peaks can be exclusively assigned to the  $^5\text{D}_4$  (or  $^5\text{D}_3$ )  $\rightarrow$   $^7\text{F}_J$

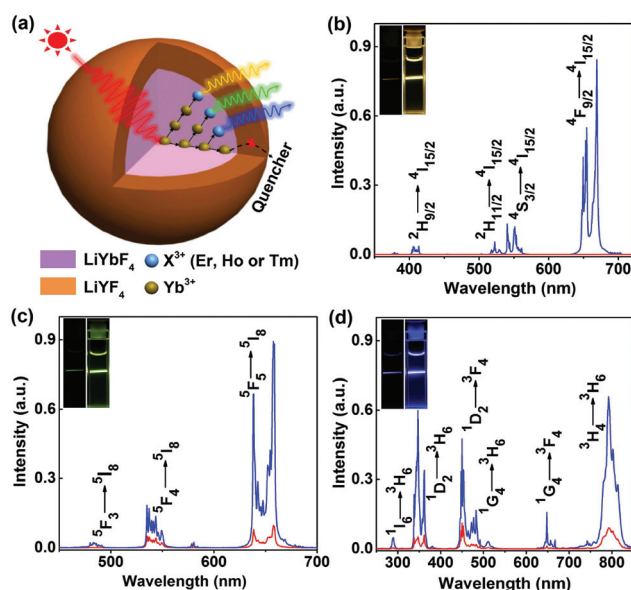
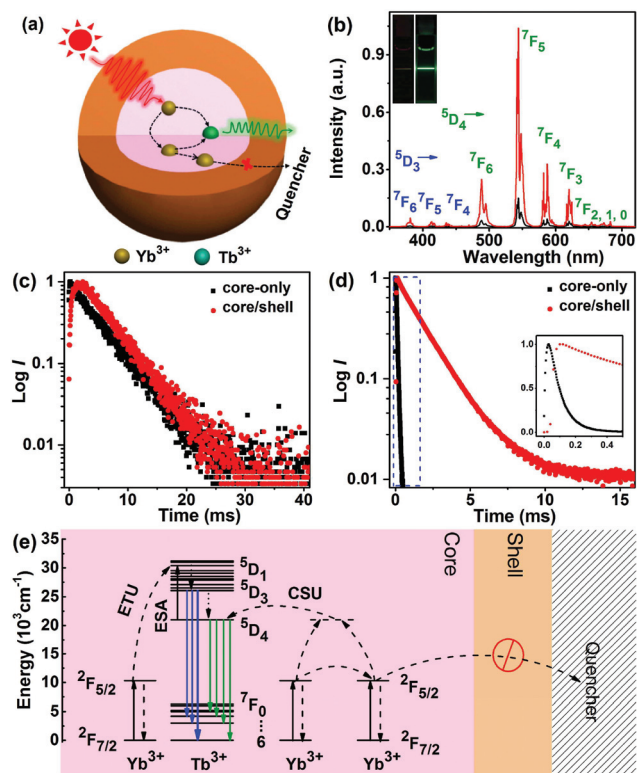


Fig. 2 (a) Schematic illustration of the ET process in  $\text{LiYbF}_4\text{:Ln}^{3+}\text{@LiYF}_4$  core/shell UCNPs. RT UCL spectra of (b)  $\text{LiYbF}_4\text{:}2\%\text{Er}^{3+}$ , (c)  $\text{LiYbF}_4\text{:}2\%\text{Ho}^{3+}$  and (d)  $\text{LiYbF}_4\text{:}1\%\text{Tm}^{3+}$  core-only (red) and core/shell (blue) UCNPs with an optimal shell thickness of  $\text{LiYF}_4$  upon NIR excitation at 980 nm. The insets show the corresponding UCL photographs for the colloidal cyclohexane solution of the UCNPs ( $\sim 5 \text{ mg mL}^{-1}$ ) under 980 nm NIR laser irradiation at a power density of  $10 \text{ W cm}^{-2}$ .





**Fig. 3** (a) Schematic illustration of the ET process in  $\text{LiYbF}_4:\text{Tb}^{3+}@\text{LiYF}_4$  core/shell UCNP. (b) RT UCL spectra of  $\text{LiYbF}_4:30\%\text{Tb}^{3+}$  core-only and core/shell UCNP upon NIR excitation at 980 nm. The insets show the corresponding UCL photographs for the colloidal cyclohexane solution of the UCNP ( $\sim 5 \text{ mg mL}^{-1}$ ) under 980 nm NIR laser irradiation at a power density of  $20 \text{ W cm}^{-2}$ . (c) UCL decays from  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  by monitoring the  $\text{Tb}^{3+}$  emission at 544 nm under 980 nm excitation, and (d) DSL decays from  $^2\text{F}_{5/2}$  of  $\text{Yb}^{3+}$  by monitoring the  $\text{Yb}^{3+}$  emission at 980 nm under 940 nm excitation in  $\text{LiYbF}_4:30\%\text{Tb}^{3+}$  core-only and  $\text{LiYbF}_4:\text{Tb}^{3+}@\text{LiYF}_4$  core/shell UCNP. (e) Schematic energy level diagrams showing the CSU processes for  $\text{Tb}^{3+}$  via the cooperative sensitization of  $\text{Yb}^{3+}$ . The dashed, dotted and full arrows represent the ET, non-radiative relaxation and radiative transition processes, respectively.

( $J = 6, 5, 4$  and  $3$ ) transitions of  $\text{Tb}^{3+}$ , and the integrated UCL intensity of  $\text{Tb}^{3+}$  is  $\sim 7$  times enhanced for core/shell UCNP relative to their core-only counterparts (Fig. 3b), as a result of the reduced surface quenching effect.<sup>42</sup> The UCL decays from  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  display a rising edge in the initial stage followed by a single-exponential decay with a fitted lifetime of  $6.17 \pm 0.01 \text{ ms}$  for both core-only and core/shell UCNP (Fig. 3c). The rising edge in the decay curve reflects the slow population process of  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  through ET from  $\text{Yb}^{3+}$ , which is dictated by the PL decay from  $^2\text{F}_{5/2}$  of  $\text{Yb}^{3+}$ .<sup>28,46</sup> The lengthening in the rising edge of the decay curve for core/shell UCNP is consistent with the PL lifetime lengthening of  $\text{Yb}^{3+}$  (from  $0.12 \text{ ms}$  to  $1.87 \text{ ms}$ , Fig. 3d), thus confirming the ET process from  $\text{Yb}^{3+}$  to  $\text{Tb}^{3+}$ . The exactly same decay time of  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  for core-only and core/shell UCNP is ascribed to the large energy gap ( $14714 \text{ cm}^{-1}$ ) between  $^5\text{D}_4$  and its next low-lying level  $^7\text{F}_0$  of  $\text{Tb}^{3+}$ , which requires more than 30 lattice phonons to bridge and thus prevents  $\text{Tb}^{3+}$  from surface quenching.<sup>53</sup> The

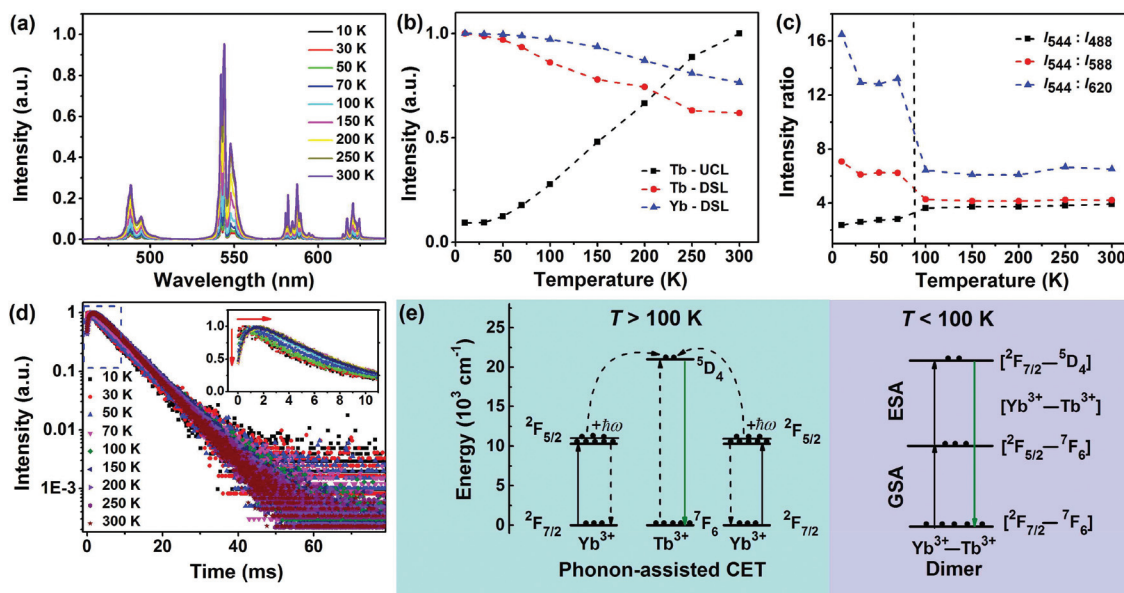
unchanged decay time of  $\text{Tb}^{3+}$  and the significantly lengthened decay time of  $\text{Yb}^{3+}$  confirm that the surface quenching effect in  $\text{LiYbF}_4:\text{Ln}^{3+}$  core-only UCNP originates mainly from energy migration through the  $\text{Yb}^{3+}$  sub-lattice to surface defects or high-energy vibrational groups surrounding the UCNP (Fig. 3a).

Because the energy difference between  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  and  $^2\text{F}_{5/2}$  of  $\text{Yb}^{3+}$  is too large ( $\sim 10304 \text{ cm}^{-1}$ ) to be compensated by lattice phonons of the matrix (e.g.,  $460 \text{ cm}^{-1}$  in  $\text{LiYbF}_4$ ),<sup>54</sup> resonant or phonon-assisted ET from  $\text{Yb}^{3+}$  to  $\text{Tb}^{3+}$  hardly occurs. Therefore, it is generally assumed that the ET from  $\text{Yb}^{3+}$  to  $\text{Tb}^{3+}$  is a second-order cooperative sensitization process, where the energy of a pair of excited  $\text{Yb}^{3+}$  is transferred simultaneously to an adjacent  $\text{Tb}^{3+}$ .<sup>19</sup> Once  $\text{Tb}^{3+}$  is excited to  $^5\text{D}_4$ , it can be further excited to  $^5\text{D}_1$  through absorption of a pump photon (excited-state absorption, ESA) or through ET from a third  $\text{Yb}^{3+}$  (ETU), thus enabling the population of  $^5\text{D}_3$  and thereby its emission through non-radiative relaxation from  $^5\text{D}_1$  (Fig. 3e). The two-photon UCL from  $^5\text{D}_4$  and three-photon UCL from  $^5\text{D}_3$  of  $\text{Tb}^{3+}$  were further corroborated by the number of pump photons ( $n$ ) responsible for the corresponding UC emissions, namely,  $1.75 \pm 0.05$  and  $2.28 \pm 0.05$  for  $^5\text{D}_4 \rightarrow ^7\text{F}_J$  ( $J = 6, 5, 4$  and  $3$ ) and  $^5\text{D}_3 \rightarrow ^7\text{F}_J$  ( $J = 6, 5$  and  $4$ ) transitions, respectively (Fig. S19†). The deviation from the theoretically predicted photon number for the population of  $^5\text{D}_4$  ( $n = 2$ ) and  $^5\text{D}_3$  ( $n = 3$ ) of  $\text{Tb}^{3+}$  is most probably due to the UC saturation caused by the middle-to-high pump power density regime we employed.<sup>55,56</sup> The absolute UCQY for CSU, which had never been reported before, was determined to be  $0.0085 \pm 0.0035\%$  in  $\text{LiYbF}_4:\text{Tb}^{3+}@\text{LiYF}_4$  core/shell UCNP upon 980 nm NIR laser excitation at a power density of  $70 \text{ W cm}^{-2}$ . This QY value for CSU is around 2–3 orders of magnitude lower than that for non-cooperative sensitization ETU in  $\text{LiYbF}_4:\text{Ln}^{3+}$  UCNP (Table S2†), which is in agreement with the theoretical prediction that CSU is 2–3 orders of magnitude less efficient than ETU.<sup>11</sup>

### 3.4 Excited-state dynamics involved in the CSU process

To gain more insights into the CSU process in  $\text{LiYbF}_4:\text{Tb}^{3+}$  UCNP, we recorded the temperature-dependent steady-state and transient UCL spectra of  $\text{Tb}^{3+}$ . It was found that the integrated UCL intensity of  $\text{Tb}^{3+}$  increased significantly with temperature rise (Fig. 4a and b). Typically, the integrated UCL intensity of  $\text{Tb}^{3+}$  at RT is approximately one order of magnitude stronger than that at 10 K. This is in marked contrast with the observation that the integrated DSL intensities of  $\text{Tb}^{3+}$  and  $\text{Yb}^{3+}$  showed a decrease with temperature rise (Fig. 4b, S20 and S21†). The decrease in the DSL intensity is due mainly to the larger non-radiative transition probability at higher temperatures, as well documented in most  $\text{Ln}^{3+}$ -doped phosphors.<sup>57</sup> Because the only difference between the UCL and DSL from  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  lies in their excitation channels, namely, cooperative ET (CET) from  $\text{Yb}^{3+}$  in UCL and non-radiative relaxation from  $^5\text{D}_1$  of  $\text{Tb}^{3+}$  in DSL, the anomalous increase in the integrated UCL intensity with temperature rise can be ascribed to the temperature-dependent CET process from  $\text{Yb}^{3+}$ .<sup>29–31</sup> By means of high-resolution optical spectroscopy at 10 K, the





**Fig. 4** (a) Temperature-dependent UCL spectra of  $\text{LiYbF}_4\text{:}30\%\text{Tb}^{3+}/\text{LiYF}_4$  core/shell UCNP upon NIR excitation at 980 nm. (b) Normalized integrated UCL intensity of  $\text{Tb}^{3+}$  and DSL intensities of  $\text{Tb}^{3+}$  and  $\text{Yb}^{3+}$  as a function of temperature. (c) Ratio of the integrated UCL intensities of  $^5\text{D}_4 \rightarrow ^7\text{F}_5$  (544 nm) to  $^5\text{D}_4 \rightarrow ^7\text{F}_6$  (488 nm),  $^7\text{F}_4 \rightarrow ^7\text{F}_6$  (588 nm), and  $^7\text{F}_3 \rightarrow ^7\text{F}_6$  (620 nm) transitions of  $\text{Tb}^{3+}$  as a function of temperature. (d) Temperature-dependent UCL decays from  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  by monitoring the  $\text{Tb}^{3+}$  emission at 544 nm under 980 nm excitation. The inset shows the rising edges of the decay curves. (e) Schematic illustration showing the simplified energy levels of  $\text{Yb}^{3+}$  and  $\text{Tb}^{3+}$ , and the proposed ET processes for the population of  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  involved in the CSU process in  $\text{LiYbF}_4\text{:Tb}^{3+}$  UCNP.

lowest Stark sub-levels of  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  and  $^2\text{F}_{5/2}$  of  $\text{Yb}^{3+}$  were determined to be  $20\,597\text{ cm}^{-1}$  and  $10\,277\text{ cm}^{-1}$ , respectively, by assuming that all  $\text{Ln}^{3+}$  ions occupy a single site with a symmetry of  $S_4$  in  $\text{LiYbF}_4$  (Fig. S21 and S22†). In fact, we have identified a single occupant site symmetry of  $S_4$  for  $\text{Ln}^{3+}$  ions in similar  $\text{LiLuF}_4$  nanocrystals by using  $\text{Eu}^{3+}$  as the structural probes (unpublished data). As a consequence, there exists an energy mismatch of  $43\text{ cm}^{-1}$  between the lowest  $\text{Tb}^{3+}$   $^5\text{D}_4$  level and twice the lowest  $\text{Yb}^{3+}$   $^2\text{F}_{5/2}$  level, which indicates that the CET from  $\text{Yb}^{3+}$  to  $\text{Tb}^{3+}$  requires the assistance of lattice phonons. This value of energy mismatch is close to the UCL activation energy ( $\sim 128\text{ cm}^{-1}$ ) determined from the Arrhenius plot of the natural logarithm of the normalized integrated UCL intensity of  $\text{Tb}^{3+}$  versus the inverse of temperature (Fig. S23†), thus verifying that the abnormal temperature-dependent UCL of  $\text{Tb}^{3+}$  is caused by the phonon-assisted CET process.<sup>30</sup> At higher temperatures, higher Stark sub-levels of  $^2\text{F}_{5/2}$  of  $\text{Yb}^{3+}$  ions are thermally populated (Fig. S21†), from which CET occurs (Fig. 4e).<sup>29–31</sup>

Meanwhile, it is worth emphasizing that the UCL branching ratios of  $^5\text{D}_4 \rightarrow ^7\text{F}_j$  ( $j = 6, 5, 4$  and  $3$ ) transitions of  $\text{Tb}^{3+}$  exhibited also a dependence on temperature with a typical transition point at  $\sim 100\text{ K}$  (Fig. 4c). For instance, the ratio of the integrated intensity of  $^5\text{D}_4 \rightarrow ^7\text{F}_5/{}^5\text{D}_4 \rightarrow ^7\text{F}_3$  transitions is nearly a constant with a value of  $\sim 6.4$  for  $T > 100\text{ K}$ , whereas it turns out to be  $\sim 13.2$  at  $30\text{--}100\text{ K}$  and  $\sim 16.5$  at  $10\text{ K}$ . This is very different from the DSL of  $\text{Tb}^{3+}$  where the PL branching ratios of  $^5\text{D}_4 \rightarrow ^7\text{F}_j$  ( $j = 6, 5, 4$  and  $3$ ) transitions show only slight changes with temperature rise (Fig. S20†). The change in the UCL branching ratios for  $T < 100\text{ K}$  indicates that the electronic configuration of  $\text{Yb}^{3+}$  could be mixed into the  $^5\text{D}_4$  multi-

plet of  $\text{Tb}^{3+}$  that modifies its transition probability to lower  $^7\text{F}_j$  levels.<sup>30,31,58</sup> This can be further corroborated from the temperature-dependent UCL transients. It was observed that all the UCL decays from  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  exhibited a single exponential decay with fitted decay times ranging from  $6.39\text{ ms}$  to  $6.97\text{ ms}$  at  $10\text{--}300\text{ K}$  (Fig. 4d and Table S3†). The nearly identical decay time at different temperatures is ascribed to the large energy gap ( $14\,714\text{ cm}^{-1}$ ) between  $^5\text{D}_4$  and  $^7\text{F}_0$  of  $\text{Tb}^{3+}$ , which makes  $\text{Tb}^{3+}$  less influenced by non-radiative relaxation. Furthermore, it was observed that the rising edge in the initial stage of the decay curve gradually shortened with the decrease of temperature, and disappeared when the temperature fell below  $30\text{ K}$  (inset of Fig. 4d and Table S3†). The increase of rise time at higher temperatures is due to the increased population on  $^5\text{D}_4$  of  $\text{Tb}^{3+}$  from  $\text{Yb}^{3+}$ ,<sup>59</sup> which agrees well with the improved UCL intensity of  $\text{Tb}^{3+}$ , thus confirming the phonon-assisted CET process. The absence of the rising edge in the decay curves at temperatures below  $30\text{ K}$  suggests that a direct ESA process is involved in the population of  $^5\text{D}_4$  of  $\text{Tb}^{3+}$ .<sup>60</sup> Since  $\text{Tb}^{3+}$  has no intermediate level matching that of  $\text{Yb}^{3+}$ , a reasonable ESA channel within the pair levels of weakly coupled  $\text{Yb}^{3+}\text{--}\text{Tb}^{3+}$  dimers is proposed:  $[\text{Yb}^{3+}({}^2\text{F}_{7/2}\text{--}\text{Tb}^{3+}({}^7\text{F}_6))] \rightarrow [\text{Yb}^{3+}({}^2\text{F}_{5/2}\text{--}\text{Tb}^{3+}({}^7\text{F}_6))] \rightarrow [\text{Yb}^{3+}({}^2\text{F}_{7/2}\text{--}\text{Tb}^{3+}({}^5\text{D}_4))]$  (Fig. 4e), as established by Güdel *et al.* in  $\text{Cs}_3\text{Tb}_2\text{Br}_9\text{:Yb}^{3+}$  single crystals.<sup>59,60</sup> This well interprets the significant change in the UCL branching ratios of  $\text{Tb}^{3+}$  for  $T < 100\text{ K}$ , and also substantiates our assumption that the electronic configuration of  $\text{Yb}^{3+}$  could be mixed into the  $^5\text{D}_4$  multiplet of  $\text{Tb}^{3+}$ . Based on the above analysis, we can now unambiguously unravel the underlying excited-state dynamics involved in the CSU process in  $\text{LiYbF}_4\text{:Tb}^{3+}$  UCNP:





for  $T > 100$  K, phonon-assisted CET is dominant; for  $T < 100$  K, a sequence of two cooperative absorption steps, namely, ground-state absorption (GSA)/ESA within a weakly coupled  $\text{Yb}^{3+}$ - $\text{Tb}^{3+}$  dimer dominates (Fig. 4e). Typically, for  $T = 10$  K, the role of phonon-assisted CET is negligible due to the very small occupation number of the phonon states in the host, as verified by the negligibly weak emission at 960 nm from the second higher Stark sub-level of  $^2\text{F}_{5/2}$  of  $\text{Yb}^{3+}$  (Fig. S21†).

## 4. Conclusions

In summary, we have systematically investigated the cooperative and non-cooperative sensitization UC in  $\text{LiYbF}_4\text{:Ln}^{3+}$  core-only and core/shell UCNPs. Energy migration among  $\text{Yb}^{3+}$  sublattices has been demonstrated to play a key role in the UC processes of  $\text{Ln}^{3+}$  in  $\text{LiYbF}_4$ , which not only resulted in the unusually strong ETU in the UV region from  $\text{Tm}^{3+}$ , but also promoted the CSU from  $\text{Tb}^{3+}$ . Particularly, we have quantified the first CSU efficiency with an absolute UCQY of  $0.0085 \pm 0.0035\%$  and revealed the dominant mechanisms of phonon-assisted CET ( $T > 100$  K) and sequential dimer GSA/ESA ( $T < 100$  K) for the CSU process in  $\text{LiYbF}_4\text{:Tb}^{3+}$  UCNPs. The NIR-triggered CSU luminescence from  $\text{Tb}^{3+}$  that is free of surface quenching might exhibit great potential for applications in a variety of UCL biosensing such as homogeneous UC-FRET bioassays, despite its current limitation with extremely low efficiency. We believe that such a limitation can be circumvented by screening host materials with suitable lattice constants and phonon energies, or by confining the energy migration in a  $\text{Tb}^{3+}$ -doped shell based on smart core/shell nanostructured design, in an effort to markedly promote the three-body CSU process. The modified high-temperature coprecipitation method can be extended to the synthesis of other  $\text{Ln}^{3+}$ -doped UCNPs that were difficult in the synthesis before, which may offer a new avenue for the exploration of  $\text{Ln}^{3+}$ -doped UCNPs towards versatile biomedical applications.

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## References

- G. F. Wang, Q. Peng and Y. D. Li, *Acc. Chem. Res.*, 2011, **44**, 322–332.
- J. C. G. Bünzli and S. V. Eliseeva, *Chem. Sci.*, 2013, **4**, 1939–1949.
- G. Y. Chen, H. L. Qiu, P. N. Prasad and X. Y. Chen, *Chem. Rev.*, 2014, **114**, 5161–5214.
- W. Zheng, P. Huang, D. T. Tu, E. Ma, H. M. Zhu and X. Y. Chen, *Chem. Soc. Rev.*, 2015, **44**, 1379–1415.
- B. Zhou, B. Y. Shi, D. Y. Jin and X. G. Liu, *Nat. Nanotechnol.*, 2015, **10**, 924–936.
- D. M. Yang, P. A. Ma, Z. Y. Hou, Z. Y. Cheng, C. X. Li and J. Lin, *Chem. Soc. Rev.*, 2015, **44**, 1416–1448.
- X. J. Zhu, W. Feng, J. Chang, Y. W. Tan, J. C. Li, M. Chen, Y. Sun and F. Y. Li, *Nat. Commun.*, 2016, **7**, 10437.
- M. K. Tsang, W. W. Ye, G. J. Wang, J. M. Li, M. Yang and J. H. Hao, *ACS Nano*, 2016, **10**, 598–605.
- Y. Li, J. L. Tang, D. X. Pan, L. D. Sun, C. Y. Chen, Y. Liu, Y. F. Wang, S. Shi and C. H. Yan, *ACS Nano*, 2016, **10**, 2766–2773.
- Y. Mita, *J. Appl. Phys.*, 1972, **43**, 1772–1778.
- F. Auzel, *Chem. Rev.*, 2004, **104**, 139–173.
- M. Haase and H. Schafer, *Angew. Chem., Int. Ed.*, 2011, **50**, 5808–5829.
- G. K. Liu, *Chem. Soc. Rev.*, 2015, **44**, 1635–1652.
- J. F. Suyver, J. Grimm, M. K. van Veen, D. Biner, K. W. Krämer and H. U. Güdel, *J. Lumin.*, 2006, **117**, 1–12.
- F. Wang, R. R. Deng, J. Wang, Q. X. Wang, Y. Han, H. M. Zhu, X. Y. Chen and X. G. Liu, *Nat. Mater.*, 2011, **10**, 968–973.
- H. Dong, L.-D. Sun and C.-H. Yan, *Chem. Soc. Rev.*, 2015, **44**, 1608–1634.
- L. Tu, X. Liu, F. Wu and H. Zhang, *Chem. Soc. Rev.*, 2015, **44**, 1331–1345.
- F. W. Ostermayer and L. G. Van Uitert, *Phys. Rev. B: Solid State*, 1970, **1**, 4208–4212.
- F. Auzel, *J. Lumin.*, 1990, **45**, 341–345.
- G. S. Maciel, A. Biswas and P. N. Prasad, *Opt. Commun.*, 2000, **178**, 65–69.
- H. S. Wang, C. K. Duan and P. A. Tanner, *J. Phys. Chem. C*, 2008, **112**, 16651–16654.
- W.-P. Qin, Z.-Y. Liu, C.-N. Sin, C.-F. Wu, G.-S. Qin, Z. Chen and K.-Z. Zheng, *Light: Sci. Appl.*, 2014, **3**, e193.
- Q. Q. Su, S. Y. Han, X. J. Xie, H. M. Zhu, H. Y. Chen, C.-K. Chen, R.-S. Liu, X. Y. Chen, F. Wang and X. G. Liu, *J. Am. Chem. Soc.*, 2012, **134**, 20849–20857.
- R. R. Deng, J. Wang, R. F. Chen, W. Huang and X. G. Liu, *J. Am. Chem. Soc.*, 2016, **138**, 15972–15979.
- M. Xue, X. J. Zhu, X. C. Qiu, Y. Y. Gu, W. Feng and F. Y. Li, *ACS Appl. Mater. Interfaces*, 2016, **8**, 17894–17901.
- H. Dong, L. D. Sun, Y. F. Wang, J. W. Xiao, D. T. Tu, X. Y. Chen and C. H. Yan, *J. Mater. Chem. C*, 2016, **4**, 4186–4192.
- K. Prorok, M. Pawlyta, W. Stręk and A. Bednarkiewicz, *Chem. Mater.*, 2016, **28**, 2295–2300.
- D. R. Gamelin and H. U. Güdel, *Top. Curr. Chem.*, 2001, **214**, 1–56.
- M. V. D. Vermelho, P. V. dos Santos, M. T. D. Araújo, A. S. Gouveia-Neto, F. C. Cassanjes, S. J. L. Ribeiro and Y. Messaddeq, *J. Lumin.*, 2003, **102–103**, 762–767.



- 30 G. M. Salley, R. Valiente and H. U. Güdel, *J. Phys.: Condens. Matter*, 2002, **14**, 5461–5475.
- 31 L. D. Menezes, G. S. Maciel, C. B. de Araujo and Y. Messaddeq, *J. Appl. Phys.*, 2003, **94**, 863–866.
- 32 X. Y. Zhang, M. Q. Wang, J. J. Ding, D. L. Gao, Y. H. Shi and X. H. Song, *CrystEngComm*, 2012, **14**, 8357–8360.
- 33 S. Sarkar, V. Adusumalli, V. Mahalingam and J. A. Capobianco, *Phys. Chem. Chem. Phys.*, 2015, **17**, 17577–17583.
- 34 J. Wang, R. R. Deng, M. A. Macdonald, B. L. Chen, J. K. Yuan, F. Wang, D. Z. Chi, T. S. Hor, P. Zhang, G. K. Liu, Y. Han and X. G. Liu, *Nat. Mater.*, 2014, **13**, 157–162.
- 35 W. Wei, Y. Zhang, R. Chen, J. L. Goggi, N. Ren, L. Huang, K. K. Bhakoo, H. D. Sun and T. T. Y. Tan, *Chem. Mater.*, 2014, **26**, 5183–5186.
- 36 X. Chen, L. M. Jin, W. Kong, T. Y. Sun, W. F. Zhang, X. H. Liu, J. Fan, S. F. Yu and F. Wang, *Nat. Commun.*, 2016, **7**, 10304.
- 37 X. Wang, J. Zhuang, Q. Peng and Y. D. Li, *Nature*, 2005, **437**, 121–124.
- 38 D. M. Liu, X. X. Xu, Y. Du, X. Qin, Y. H. Zhang, C. S. Ma, S. H. Wen, W. Ren, E. M. Goldys, J. A. Piper, S. X. Dou, X. G. Liu and D. Y. Jin, *Nat. Commun.*, 2016, **7**, 10254.
- 39 S. Salaün, M. T. Fornoni, A. Bulou, M. Rousseau, P. Simon and J. Y. Gesland, *J. Phys.: Condens. Matter*, 1997, **9**, 6941–6956.
- 40 M. Wang, Z. Chen, W. Zheng, H. M. Zhu, S. Lu, E. Ma, D. T. Tu, S. Y. Zhou, M. D. Huang and X. Y. Chen, *Nanoscale*, 2014, **6**, 8274–8282.
- 41 P. Huang, W. Zheng, S. Y. Zhou, D. T. Tu, Z. Chen, H. M. Zhu, R. F. Li, E. Ma, M. D. Huang and X. Y. Chen, *Angew. Chem., Int. Ed.*, 2014, **53**, 1252–1257.
- 42 F. Wang, J. Wang and X. G. Liu, *Angew. Chem., Int. Ed.*, 2010, **49**, 7456–7460.
- 43 J. B. Zhao, Z. D. Lu, Y. D. Yin, C. Mcrae, J. A. Piper, J. M. Dawes, D. Y. Jin and E. M. Goldys, *Nanoscale*, 2013, **5**, 944–952.
- 44 W. Zheng, S. Y. Zhou, Z. Chen, P. Hu, Y. S. Liu, D. T. Tu, H. M. Zhu, R. F. Li, M. D. Huang and X. Y. Chen, *Angew. Chem., Int. Ed.*, 2013, **52**, 6671–6676.
- 45 X. M. Li, Z. Z. Guo, T. C. Zhao, Y. Lu, L. Zhou, D. Y. Zhao and F. Zhang, *Angew. Chem., Int. Ed.*, 2016, **55**, 2464–2469.
- 46 W. Q. Luo, C. Y. Fu, R. F. Li, Y. S. Liu, H. M. Zhu and X. Y. Chen, *Small*, 2011, **7**, 3046–3056.
- 47 G. Y. Chen, T. Y. Ohulchanskyy, R. Kumar, H. Ågren and P. N. Prasad, *ACS Nano*, 2010, **4**, 3163–3168.
- 48 H. Y. Xing, W. B. Bu, Q. G. Ren, X. P. Zheng, M. Li, S. J. Zhang, H. Y. Qu, Z. Wang, Y. Q. Hua, K. L. Zhao, L. P. Zhou, W. J. Peng and J. L. Shi, *Biomaterials*, 2012, **33**, 5384–5393.
- 49 H. L. Qiu, C. H. Yang, W. Shao, J. Damasco, X. L. Wang, H. Ågren, P. Prasad and G. Y. Chen, *Nanomaterials*, 2014, **4**, 55–68.
- 50 W. Li, J. S. Wang, J. S. Ren and X. G. Qu, *J. Am. Chem. Soc.*, 2014, **136**, 2248–2251.
- 51 Z. Y. Hou, Y. X. Zhang, K. R. Deng, Y. Y. Chen, X. J. Li, X. R. Deng, Z. Y. Cheng, H. Z. Lian, C. X. Li and J. Lin, *ACS Nano*, 2015, **9**, 2584–2599.
- 52 W. P. Fan, B. Shen, W. B. Bu, X. P. Zheng, Q. J. He, Z. W. Cui, K. L. Zhao, S. J. Zhang and J. L. Shi, *Chem. Sci.*, 2015, **6**, 1747–1753.
- 53 T. Miyakawa and D. L. Dexter, *Phys. Rev. B: Solid State*, 1970, **1**, 2961.
- 54 S. A. Miller, H. E. Rast and H. H. Caspers, *J. Chem. Phys.*, 1970, **52**, 4172–4175.
- 55 M. Pollnau, D. R. Gamelin, S. R. Luthi, H. U. Güdel and M. P. Hehlen, *Phys. Rev. B: Condens. Matter*, 2000, **61**, 3337–3346.
- 56 J. F. Suyver, A. Aebischer, S. Garcia-Revilla, P. Gerner and H. U. Güdel, *Phys. Rev. B: Condens. Matter*, 2005, **71**, 125123.
- 57 G. Blasse and B. C. Grabmaier, *Luminescent Materials*, Springer-Verlag, Berlin, 1994.
- 58 G. Amaranath, S. Buddhudu and F. J. Bryant, *J. Non-Cryst. Solids*, 1990, **122**, 66–73.
- 59 G. M. Salley, R. Valiente and H. U. Güdel, *J. Lumin.*, 2001, **94–95**, 305–309.
- 60 G. M. Salley, R. Valiente and H. U. Güdel, *Phys. Rev. B: Condens. Matter*, 2003, **67**, 134111.

