



# A luminescent view of the clickable assembly of $\text{LnF}_3$ nanoclusters

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Nanoclusters (NCs) bridge the gap between atoms and nanomaterials in not only dimension but also physicochemical properties. Precise chemical and structural control, as well as clear understanding of formation mechanisms, have been important to fabricate NCs with high performance in optoelectronics, catalysis, nanoalloys, and energy conversion and harvesting. Herein, taking advantage of the close chemical properties of  $\text{Ln}^{3+}$  ( $\text{Ln} = \text{Eu}, \text{Nd}, \text{Sm}, \text{Gd}, \text{etc.}$ ) and  $\text{Gd}^{3+}$ - $\text{Eu}^{3+}$  energy transfer ion-pair, we report a clickable  $\text{LnF}_3$  nanoparticle assembly strategy allowing reliable fabrication of diversely structured NCs, including single-component, dimeric, core-shelled/core-shell-shelled, and reversely core-shelled/core-shell-shelled, particularly with synergized optical functionalities. Moreover, the purposely-embedded dual luminescent probes offer great superiority for in situ and precise tracking of tiny structural variations and energy transfer pathways within complex nanoarchitectures.

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Organic ligands have played an irreplaceable role in myriads of nanomaterials synthesis towards control of size<sup>1,2</sup>, morphology<sup>3,4</sup>, crystal structure<sup>5</sup>, and functionality<sup>6,7</sup>. Meanwhile, rational selection of the chemical groups on ligand molecules is also critical for post-modulations such as assembly, hybridization, and fabrication of micro or macroscaled architectures from individual nanoparticles (NPs) aiming at unprecedented chemical and physical properties<sup>8,9</sup>, particularly when other technologies such as Langmuir–Blodgett<sup>10,11</sup>, layer-by-layer<sup>12</sup>, and optical or electron-beam lithography are combined<sup>13,14</sup>.

Moreover, development of a library of ligand exchange methods through nanoscale chemical reactions has facilitated easy conversion of nanomaterials from hydrophobic to hydrophilic or vice versa<sup>15–17</sup>, which generates additional functionalities to realize various purposes such as QLED display<sup>18</sup>, trace analysis<sup>19</sup>, disease diagnosis<sup>20</sup>, bioimaging<sup>21</sup>, as well as photodynamic therapy<sup>22</sup>, and so on. As a typical example, replacement of citrate ligand on gold NPs with thiol-ended single chain DNA has enabled successful assembly of gold NPs possessing complementary DNA sequences, which leads to precise fabrication of supercrystals with varied lattice structures<sup>23</sup> and remarkable features that neither individual component possesses<sup>24,25</sup>.

However, ligand molecules may also affect or even prevent functionality expression. For example, insulating molecules are unwanted for semiconducting quantum dots when used for nanodevice fabrication<sup>26</sup>, chemical molecules surrounding perovskite nanocrystals usually exacerbate the optoelectronic performance in therein fabricated solar cells<sup>27</sup>, and catalytic noble metal NPs get poisoned by organic molecules used as protecting ligands and so do for the photo- and/or electrochemical catalysis<sup>28</sup>. On the other side, aggregation of nanomaterials occurs once ligands are removed, accompanied with irreversible functionality loss. Thus, it remains an urgent challenge to find an optimal balance between this dilemma, that is, how to fully exploit the functionalities of nanomaterials that are prone to aggregation once without ligand and meanwhile avoid the influence of ligand molecules, particularly for tiny NPs (<5 nm) that are very active due to the high surface energy<sup>29</sup>.

Herein, we have developed a clickable assembly strategy that facilitates reliable fabrication of variously structured lanthanide nanoclusters (NCs) with synergized multi-functionalities. The formation of LnF<sub>3</sub> NCs starts with conversion of LnOF NPs to LnF<sub>3</sub> NPs after organic ligand removal, followed by the assembly process. This HCl-triggered click-reaction allows arbitrary fabrication of the compositions and structures of target NCs such as single-component, dimeric, core-shelled/core-shell-shelled, and reversely core-shelled/core-shell-shelled. The embedded dual luminescent probes via either dynamic energy transfer (Gd<sup>3+</sup>–Eu<sup>3+</sup>) or direct excitation (of Eu<sup>3+</sup>) enables sensitive track of tiny variations in structure and energy transfer pathways.

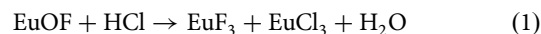
## Results

**Assembly of EuOF NPs into EuF<sub>3</sub> NCs.** Specifically, addition of certain amount of diluted HCl into the stock solution of EuOF NPs (Fig. 1a and Supplementary Fig. 1) strips off majority of the oleic acid anion (OA<sup>−</sup>) ligands and almost simultaneously triggers the conversion to small EuF<sub>3</sub> NPs (Fig. 1b). The coordination between surface Eu<sup>3+</sup> on EuF<sub>3</sub> NPs and solvent molecules (H<sub>2</sub>O or C<sub>2</sub>H<sub>5</sub>OH)<sup>30</sup> improves the solubility. Although these consequent nanoscaled-rare earth chemical reactions complete within 5 mins, they describe exactly why the solution changes from opaque to transparent after HCl addition (Supplementary Fig. 2a, b). However, EuF<sub>3</sub> NPs are metastable due to high surface energy and finally assemble into stable NCs through a random attachment mechanism (Fig. 1c, d, Supplementary Fig. 3 and

Supplementary Fig. 4). The reason we speculate that the final solution turned back from transparent to opaque (Supplementary Fig. 2c) is that, the trace amount of OA<sup>−</sup> left on each EuF<sub>3</sub> NP gradually accumulated on NCs surface when assembly progresses, which leads to increased hydrophobicity and thus decreased solubility in ethanol (Fig. 1c).

Based on systematic analysis of TEM (Fig. 2a–h) and FT-IR (Fig. 2i) results of the samples collected at different assembly times, the growth process of EuF<sub>3</sub> NCs can be divided into the following three stages:

**Stage 1: Conversion of EuOF NPs to EuF<sub>3</sub> NPs.** This is the most critical step, which forms the foundation for subsequent assembly and growth of EuF<sub>3</sub> NCs. TEM images (Fig. 2a–c and Supplementary Fig. 5) suggest that EuOF NPs at diameter of 3.2 nm turned into semi-dissociated morphologies after 1 min of H<sup>+</sup> addition, which is caused by the ligands (OA<sup>−</sup>) removal induced by the post-added H<sup>+</sup><sup>30,31</sup>. Then, chemical conversion of EuOF NPs to EuF<sub>3</sub> NPs occurred, which can be explained by the theory of hard and soft acids and bases (HSAB)<sup>32</sup>. The so called “hard” acids and “hard” bases prefer to bond with each other, and so do the “soft” acids and “soft” bases. In our reaction system, F<sup>−</sup> ion as a base is harder than O<sup>2−</sup> and similarly H<sup>+</sup> as an acid is harder than Eu<sup>3+</sup>. Therefore, the Eu–O bond was broken under the attack of H<sup>+</sup>, which results in the semi-dissociation of EuOF NPs and release of non-bonded Eu<sup>3+</sup> and F<sup>−</sup> ions. Then Eu<sup>3+</sup> preferentially bonds with F<sup>−</sup> rather than O<sup>2−</sup> by forming tiny EuF<sub>3</sub> NPs<sup>33</sup>. The chemical equation can be expressed as:

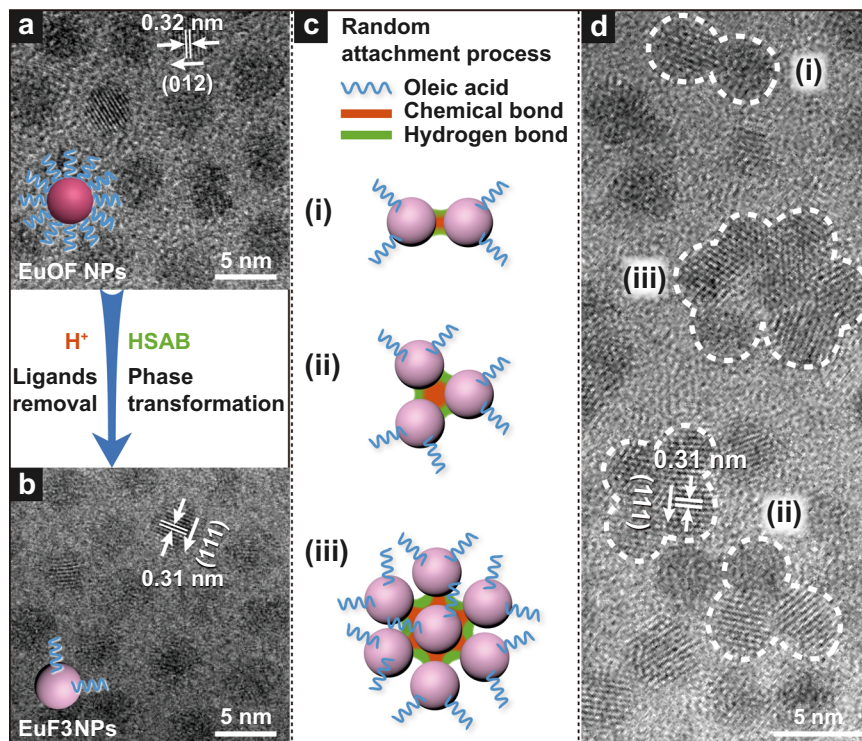


Moreover, disappearance of FT-IR peaks at ~2923, 2852, 1560 and 1466 cm<sup>−1</sup> clearly indicates debond of OA<sup>−</sup> ligands from surface Eu<sup>3+</sup>. The conversion of EuOF NPs to EuF<sub>3</sub> NPs completes at reaction time of 5 min (Supplementary Fig. 5). This is also consistent with the change of solution from opaque to transparent at 5 min (Supplementary Fig. 2), which is due to the improved solubility of EuF<sub>3</sub> NPs through solvent molecule (H<sub>2</sub>O or C<sub>2</sub>H<sub>5</sub>OH) coordination, as proved by the broad hydroxyl peak at ~3400 cm<sup>−1</sup> (ref. <sup>34</sup>) (Fig. 2i).

**Stage 2: Initiation of the assembly.** Presence of OA<sup>−</sup> improves solubility and mitigates collision probability of NPs in solution, which allows long-term storage of LnOF NPs precursors without worrying about aggregation (Supplementary Fig. 1). However, surface ions become exposed once OA<sup>−</sup> is removed, causing sharply risen surface energy of EuF<sub>3</sub> NPs<sup>29</sup> and initiates the assembly (Fig. 2c).

**Stage 3: Growth of EuF<sub>3</sub> NCs.** The size of EuF<sub>3</sub> NCs grew from 3.1 to 21.8, 29.2, 35.7, 38.4, and 40.1 nm at the assembly time of 15, 30, 60, 120, 240, and 360 min, respectively (Fig. 2c–h, j and Supplementary Fig. 6). Parallely, the FT-IR peaks at 2852 and 2923 cm<sup>−1</sup> corresponding to –CH<sub>3</sub> stretching vibration intensified from almost nil at 5 min to that of 30 min and further at 360 min (Fig. 2i). This is reasonable because trace amount of OA<sup>−</sup> on the surface of individual EuF<sub>3</sub> NP can't produce sufficient FT-IR signal at stages 1 and 2. More and more ligands are accumulated (Fig. 1c, d) when NCs grow larger as assembly progresses, resulting in stronger signals. This also well agrees with the solubility change in ethanol solution from transparent to opaque (Supplementary Fig. 2b, c). Thus, the intensity variation of FT-IR peaks at 2852 and 2923 cm<sup>−1</sup> (Fig. 2i) could qualitatively unveil the structural details of NCs formed at different assembly stages.

**Driving force for EuF<sub>3</sub> NCs assembly.** As previously reported<sup>35</sup>, multiple interactions usually work together to make for the final structure of assemblies. In our case, removal of surface ligands from NPs not only exposes a large number of uncoordinated Eu<sup>3+</sup>, but



**Fig. 1 Self-assembly mechanism of NCs.** High-resolution transmission electron microscope (HRTEM) images of **a** EuOF NPs and **b** EuF<sub>3</sub> NPs. **c** Schematic diagram illustrating the structural details, random attachment process, and interaction forces responsible for NCs formation. **d** HRTEM image taken at assembly time of 15 min. The insets in **a** and **b** enlighten the difference of the number of ligand molecules after H<sup>+</sup> introduction. TEM structures of (i), (ii), and (iii) in **d** correspond exactly to those in **c**.

also leads to increased surface energy. In this situation, unstable EuF<sub>3</sub> NPs tend to contact and attach with each other to decrease the total energy through interparticle interactions, and eventually assemble into NCs. The FT-IR peak at 3400 cm<sup>-1</sup> implies the existence of hydrogen bond among solvent molecules, while the partially fused crystal lattices (Fig. 1d) suggest the formation of Eu-F chemical bond among EuF<sub>3</sub> NPs, both of which are the main interactions responsible for the assembly of EuF<sub>3</sub> NCs through a random attachment process (Fig. 1c, d). Moreover, as widely reported<sup>36,37</sup>, dipole-induced interaction is a strong force at the nanoscale to drive self-assembly, which usually occurs in NPs with asymmetric crystal lattice. Considering the trigonal crystal structure of EuF<sub>3</sub> NPs with relatively low symmetry among the seven crystal systems and the big difference in electronegativity between F<sup>-</sup> and Eu<sup>3+</sup>, there might exist electric dipole moment originated from the polarity of crystal lattice of EuF<sub>3</sub> NPs, which may generate dipole-dipole interactions between EuF<sub>3</sub> NPs and act as a driving force for the self-assembly process.

More intriguingly, although the as-assembled EuF<sub>3</sub> NCs are polycrystalline, they are readily to be converted into single crystals when annealed at temperatures as low as 50 °C (Supplementary Fig. 7). This principle might be instructive to the synthesis of nanocrystals or nanoalloys that are not possible at nearly room temperature. Moreover, NCs of NdF<sub>3</sub>, SmF<sub>3</sub>, and GdF<sub>3</sub> were also successfully constructed by following the same strategy (Supplementary Figs. 8 and 9).

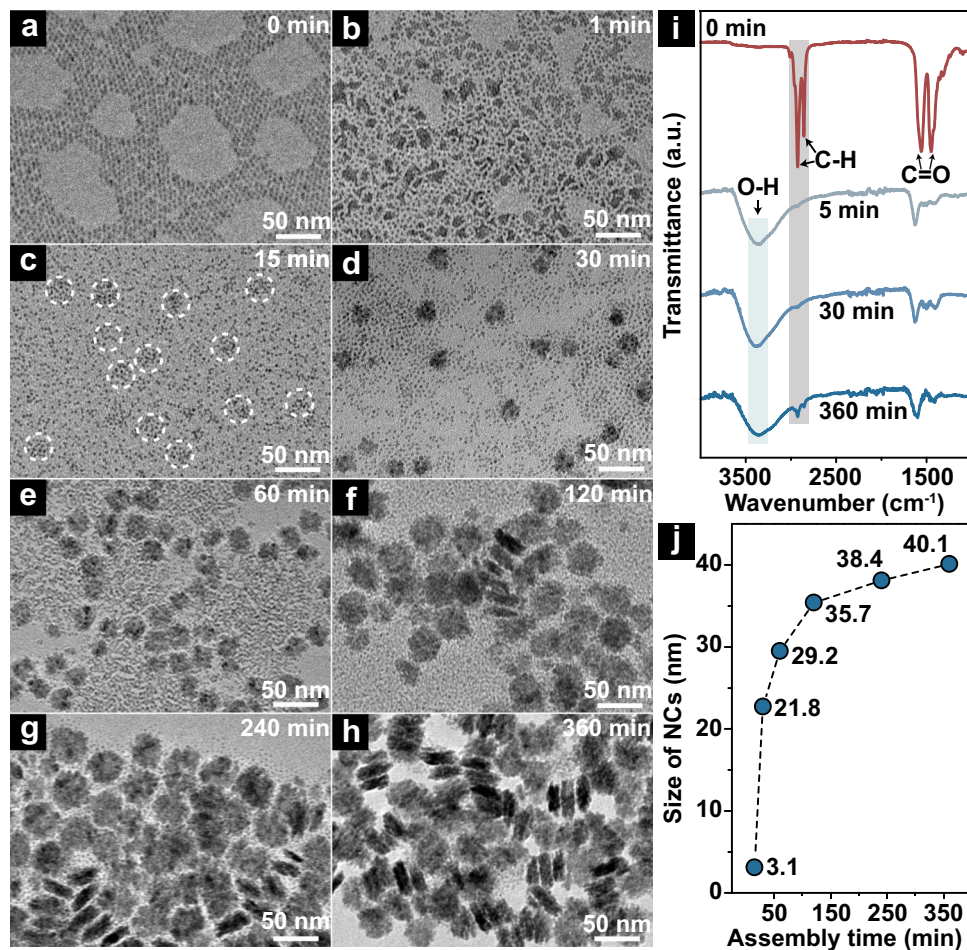
**Working principle of Eu<sup>3+</sup> as luminescent probe.** As two major photoluminescence (PL) emissions in Eu<sup>3+</sup>, the intensity at 612 nm corresponding to the <sup>5</sup>D<sub>0</sub>→<sup>7</sup>F<sub>2</sub> electric dipole transition (I<sub>E</sub>) is highly sensitive to the local site symmetry while that of the <sup>5</sup>D<sub>0</sub>→<sup>7</sup>F<sub>1</sub> magnetic dipole transition (I<sub>M</sub>) at 591 nm is not<sup>38</sup> (Fig. 3a). Considering that local site symmetry of luminescent

ions, here means Eu<sup>3+</sup>, usually links with surface coordination environment, evolution of the value of I<sub>E</sub>/I<sub>M</sub> may be used as a luminescent probe to track the changes of the proportion of surface Eu<sup>3+</sup> in different assemblies (Fig. 3a, b and Supplementary Table 1). Indeed, when excited at the characteristic working wavelength of Eu<sup>3+</sup> (395 nm), the calculated I<sub>E</sub>/I<sub>M</sub> decreases gradually from 3.80 in EuF<sub>3</sub> NPs to 1.14 in EuF<sub>3</sub> NCs, indicating that the amount of surface Eu<sup>3+</sup> keeps reducing with the size increase of NCs (Fig. 3b, c)<sup>39</sup>. This well-agrees with the mergence of NPs when forming NCs, which causes reduced surface area (Figs. 1d and 3a).

It is worth pointing out that the gradually decrescent full-width at half maximum (FWHM) at 591 nm is due to the increased site symmetry of Eu<sup>3+</sup> during NCs growth<sup>38</sup>. Generally, the crystallographic site symmetry significantly affects the spectral line-width of Eu<sup>3+</sup>, and a minor structural distortion may alter the crystal field symmetry of Eu<sup>3+</sup>, which will be reflected by the gradual change of FWHM from 12.1 to 7.2 nm as the NCs grow from 3.1 to 40.1 nm<sup>40,41</sup>.

**Construction of arbitrarily designed NCs.** Clear understanding of the NC formation mechanisms, particularly the information extracted from luminescent probe has inspired us to further fabricate more complicated NCs and explore their structural relationships with the evolution of I<sub>E</sub>/I<sub>M</sub>. Instead of the above uninterrupted NC assembly (Fig. 2), the conversion of LnOF NPs to and the following assembly of LnF<sub>3</sub> NPs were purposely separated, which offers more freedom to grow NCs with widely varied structures and pre-designed chemical compositions. For example, dimeric NCs of EuF<sub>3</sub>&GdF<sub>3</sub> and EuF<sub>3</sub>&2GdF<sub>3</sub> could be reliably constructed by simply mixing NPs of EuF<sub>3</sub> and GdF<sub>3</sub> that were pre-converted from EuOF and GdOF NPs via a H<sup>+</sup>-induced clickable reaction, at molar ratios of 1:1 and 1:2, respectively





**Fig. 2** Different assembly stages of NCs. TEM images of the products obtained at assembly time of **a** 0, **b** 1, **c** 15, **d** 30, **e** 60, **f** 120, **g** 240, and **h** 360 min, respectively. **i** FT-IR spectra of the products obtained at the assembly time of 0, 5, 30, and 360 min, respectively. **j** Time-dependent size evolution of NCs. White dotted-circles in **c** show the NCs formed at very early stage.

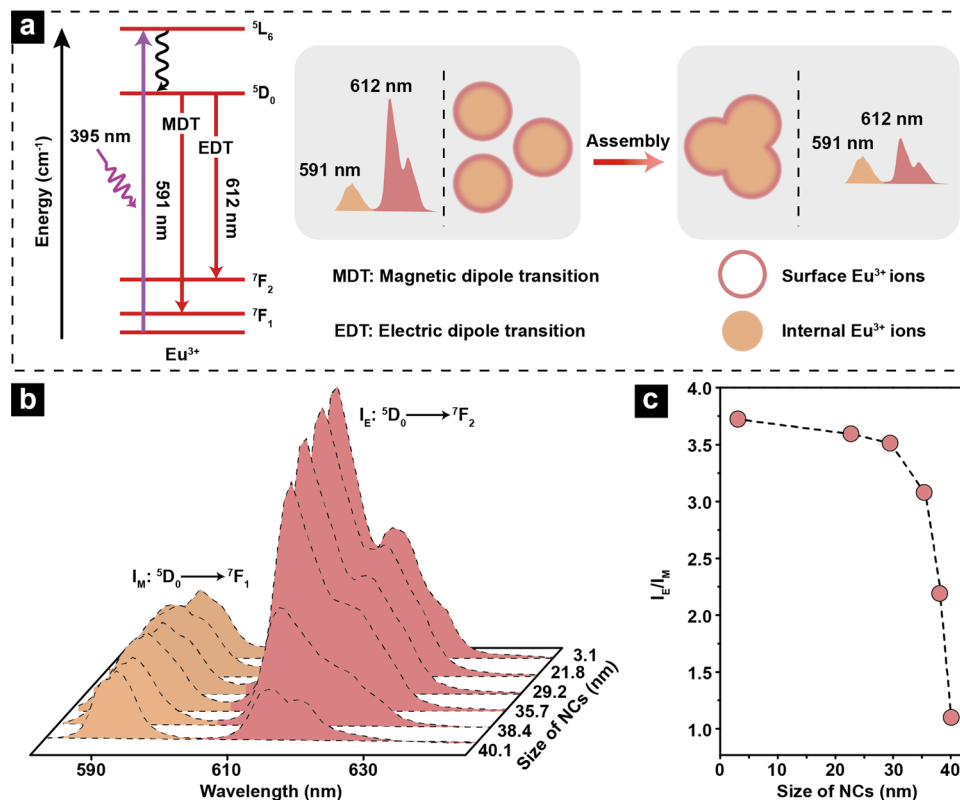
(Fig. 4a–c). Similarly, core-shelled NCs of  $\text{EuF}_3@GdF_3$  and  $\text{EuF}_3@GdF_3@GdF_3$  could also be fabricated by controlling the number of  $GdF_3$  shells grown on pre-formed core of  $\text{EuF}_3$  NCs (Fig. 4d–f) and alternatively, the reversely core-shelled NCs of  $GdF_3@EuF_3$  and  $GdF_3@EuF_3@EuF_3$  were further grown by reversing the assembly sequence of respective components (Fig. 4g–i).

**Luminescent probes for tracking of structural variations and energy transfer pathways.** Compared with previous assembly mechanism studies where HRTEM, XRD, and synchrotron characterizations were heavily relied<sup>42,43</sup>, information provided by luminescent probes can be in situ, dynamic, precise, and particularly sensitive to its surrounding environment. Indeed, as depicted in Fig. 4, different  $Gd^{3+}$ – $Eu^{3+}$  energy transfer modes were clearly distinguished in their respective PL spectral evolution, which could be utilized to track the distribution variation of surface  $Eu^{3+}$  on NCs with different structures.

For pure  $\text{EuF}_3$  NCs, there is only very weak PL because  $Eu^{3+}$  has almost no absorption at 273 nm (Supplementary Fig. 10a, b). However, a 70-fold emission enhancement (Fig. 5a) was seen in  $\text{EuF}_3@GdF_3$  NCs, which is rational because 273 nm is the characteristic working wavelength of  $Gd^{3+}$  and more energy is transferred to  $Eu^{3+}$  in the co-assembled NCs (Fig. 4b and Supplementary Fig. 11). Subsequently, a 103-fold PL enhancement was obtained in  $\text{EuF}_3@2GdF_3$  NCs due to further increased energy transfer from  $Gd^{3+}$  to  $Eu^{3+}$  (Fig. 4c). Consistently, the characteristic

absorption peak of  $Gd^{3+}$  at 273 nm appeared in  $\text{EuF}_3@GdF_3$  and became stronger in  $\text{EuF}_3@2GdF_3$ , proving the successful assembly of  $GdF_3$  NPs at increased amount (Supplementary Fig. 10a). More excitingly, such PL evolution also agrees with the gradually intensified optical images of respective samples (Supplementary Fig. 12a) under 273 nm light excitation where  $\text{EuF}_3@2GdF_3$  is the brightest. Correspondingly, the lifetime of  $Eu^{3+}$  (Fig. 5a and Supplementary Fig. 13a) shows similar trend of increase from  $\text{EuF}_3$  NPs (0.59 ms) to  $\text{EuF}_3@GdF_3$  (1.46 ms) as that from  $\text{EuF}_3@GdF_3$  (1.46 ms) to  $\text{EuF}_3@2GdF_3$  (2.12 ms). As a stark contrast, neither emission intensity nor lifetime change was observed in  $Eu^{3+}$  under 273 nm light excitation (Supplementary Fig. 14) when solutions containing pre-formed NCs of  $GdF_3$  and  $\text{EuF}_3$  were physically mixed at the atomic ratios of 2:1, 1:1, and 0:1, respectively. This proves straightforwardly that  $Gd^{3+}$ – $Eu^{3+}$  energy transfer can hardly occur if without uniform co-assembly between  $\text{EuF}_3$  and  $GdF_3$  NPs (Fig. 4a–c).

Similarly,  $Gd^{3+}$  in  $GdF_3$  shell keeps transferring energy to internal  $Eu^{3+}$ , resulting in enhanced PL in  $\text{EuF}_3@GdF_3$  NCs (Fig. 5b and Supplementary Fig. 10c, d). However, it is reasonable to see only 2.5-fold enhancement because there exists partial energy loss from surface  $Gd^{3+}$  on  $GdF_3$  shell (Fig. 4e). Indeed, an enhancement of 6.5 folds is seen in  $\text{EuF}_3@GdF_3@GdF_3$  NCs, which is due to: 1) increased amount of  $Gd^{3+}$  that transfers more energy to  $Eu^{3+}$  and meanwhile, 2) decreased amount of  $Gd^{3+}$  energy loss due to the growth of the second  $GdF_3$  shell (Fig. 4f). Accordingly, there is a larger  $Eu^{3+}$  lifetime increase (Fig. 5b and



**Fig. 3** Working principle of Eu<sup>3+</sup> used as luminescent probe. **a** Illustration of different electron transition pathways in Eu<sup>3+</sup> and intensity evolutions of electric-dipole (612 nm) and magnetic-dipole (591 nm) transitions during NCs growth. **b** Evolution of PL spectra and **c**  $I_E/I_M$  value of Eu<sup>3+</sup> in NCs with different sizes. 395 nm light was used as excitation source.

Supplementary Fig. 13b) after growth of the second GdF<sub>3</sub> shell (from 1.07 to 2.43 ms) compared with that of the first GdF<sub>3</sub> shell (from 0.59 to 1.07 ms).

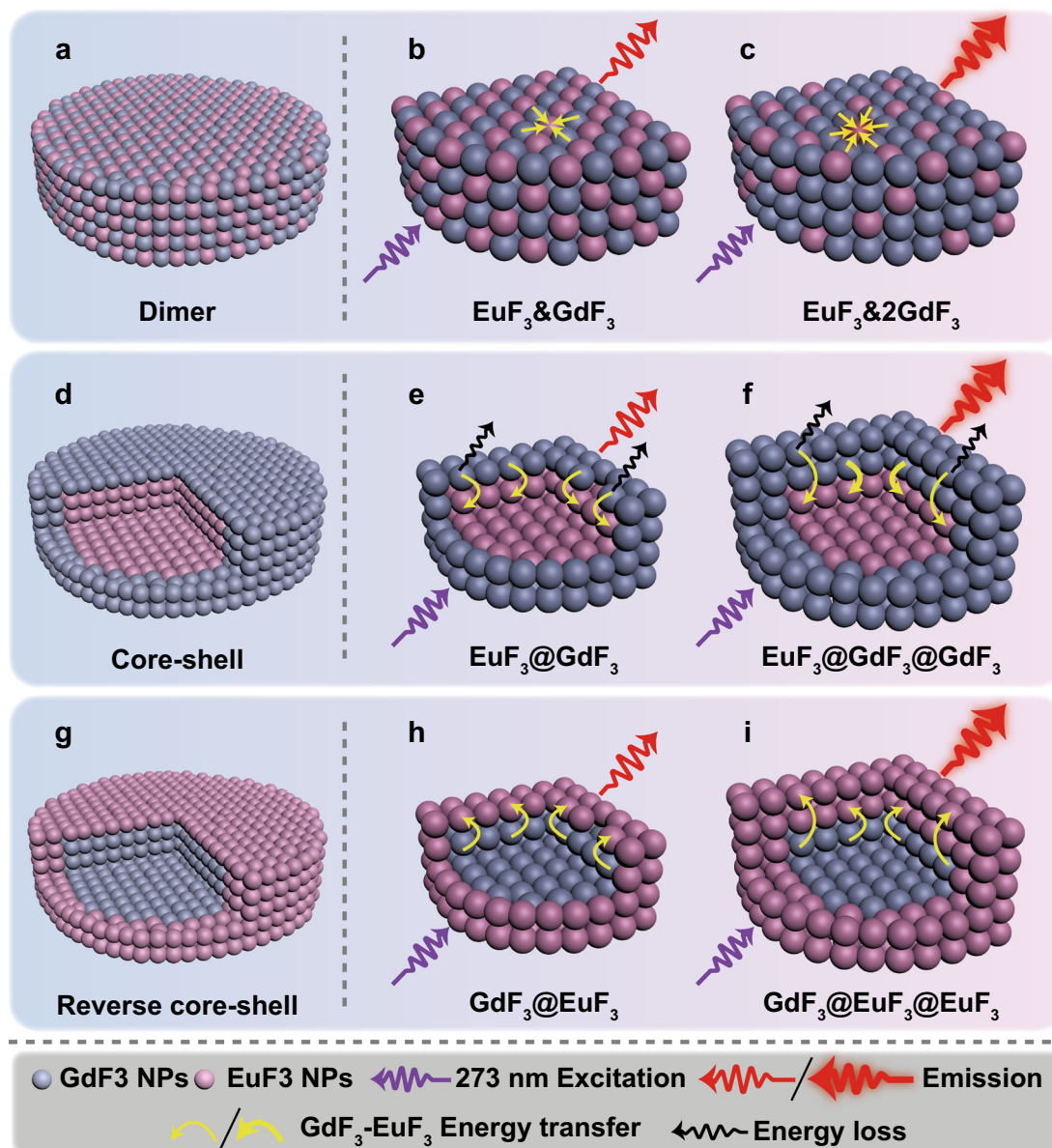
Interestingly, more enhanced (7.3-fold) PL is seen in GdF<sub>3</sub>@EuF<sub>3</sub> NCs than that of 2.5-fold in EuF<sub>3</sub>@GdF<sub>3</sub> NCs (Fig. 5b, c and Supplementary Fig. 10e, f). This is due to more efficient energy transfer from internal Gd<sup>3+</sup> to exterior Eu<sup>3+</sup> where energy loss in Fig. 4e was largely impressed in Fig. 4h. However, the reason that only 8.1-fold PL enhancement is gained after growth of a second EuF<sub>3</sub> shell is because the amount of energy transferred from Gd<sup>3+</sup> is fixed so that the second layer of Eu<sup>3+</sup> can only absorb the extra energy that passes through the first Eu<sup>3+</sup> shell (Fig. 4i). Rationally, the lifetime increase of Eu<sup>3+</sup> (Fig. 5c and Supplementary Fig. 13c) is not as much after growth of the second EuF<sub>3</sub> shell (from 1.33 to 1.61 ms) compared with that of the first (from 0.59 to 1.33 ms). It is worth emphasizing that the calculated quantum yields<sup>39,44</sup> of EuF<sub>3</sub> (Supplementary Equation (1) and Supplementary Table 2) are consistent with above-discussed PL intensity evolution, and variation of the calculated GdF<sub>3</sub>-EuF<sub>3</sub> energy transfer rate<sup>45–48</sup> in different NCs based on simplified models (Supplementary Fig. 15) provides further support to our schematic illustrations in Fig. 4.

To dig out more structural information from another point of view, the PL evolution in different NCs was investigated by directly exciting Eu<sup>3+</sup> at 395 nm (Supplementary Fig. 16). For easy comparison, the PL intensity in pure EuF<sub>3</sub> NCs was set at 1.0 and the calculated enhancement factors in different NCs were shown in Fig. 5d–f. It is reasonable to see enhanced PL in EuF<sub>3</sub>@GdF<sub>3</sub> and EuF<sub>3</sub>@2GdF<sub>3</sub> because there exists a Eu<sup>3+</sup>-Eu<sup>3+</sup> energy migration loop (Supplementary Fig. 16a and Supplementary Fig. 17a–c) in pure EuF<sub>3</sub> NCs<sup>49</sup> that deteriorates the emission while insertion of co-assembled GdF<sub>3</sub> NPs breaks the loop and

leads to enhanced PL in EuF<sub>3</sub>@GdF<sub>3</sub>. It is also reasonable to see a 2.6- and 2.0-fold enhancement because the unit number of Eu<sup>3+</sup> is diluted 2 and 3 times in EuF<sub>3</sub>@GdF<sub>3</sub> and EuF<sub>3</sub>@2GdF<sub>3</sub> (Fig. 5d), respectively. In another word, there shall be a 5.2- and 6-fold absolute PL enhancement in EuF<sub>3</sub>@GdF<sub>3</sub> and EuF<sub>3</sub>@2GdF<sub>3</sub>, respectively. This phenomenon is quite instructive for materials design towards maximized PL intensity while minimizing the amount of activators used. Parallely, the lifetime of Eu<sup>3+</sup> also increases from 0.62 to 1.49, and 2.08 ms (Supplementary Fig. 16b).

Growth of a GdF<sub>3</sub> shell suppresses the energy loss of surface Eu<sup>3+</sup> similar to that of Gd<sup>3+</sup> in Fig. 4e and results in 3.6-fold PL enhancement in EuF<sub>3</sub>@GdF<sub>3</sub>, while the 6.0-fold PL enhancement in EuF<sub>3</sub>@GdF<sub>3</sub>@GdF<sub>3</sub> suggests that the second shell has even better energy loss suppression (Supplementary Fig. 16c). This is also consistent with the lifetime increase of Eu<sup>3+</sup> from 0.62 to 1.05, and 2.40 ms (Supplementary Fig. 16d). Alternatively, growth of a EuF<sub>3</sub> shell around pre-formed core of GdF<sub>3</sub> NCs results in larger inter-particle distance, which generates similar (3.8-fold) effect as that in EuF<sub>3</sub>@GdF<sub>3</sub> (Supplementary Fig. 17a–c), that is, the broken energy migration loop and enhanced PL (Supplementary Fig. 17a, d and e). Growth of the second EuF<sub>3</sub> shell not only suppresses the energy loss of Eu<sup>3+</sup> in the first EuF<sub>3</sub> shell, the increased amount of Eu<sup>3+</sup> generates extra PL so that a total enhancement of 6.7-fold is obtained in GdF<sub>3</sub>@EuF<sub>3</sub>@EuF<sub>3</sub> NCs (Supplementary Fig. 16e). Accordingly, the lifetime of Eu<sup>3+</sup> increases from 0.62 to 1.35 and 1.65 ms (Fig. 5f and Supplementary Fig. 16f).

Moreover, based on the principle discussed in Fig. 3a, evolution of  $I_E/I_M$  value directly links with the variation of surface Eu<sup>3+</sup> proportion in different NCs where tiny structural difference may be precisely probed. Indeed, for EuF<sub>3</sub>@GdF<sub>3</sub> NCs with different EuF<sub>3</sub>/GdF<sub>3</sub> molar ratios, the  $I_E/I_M$  remains almost constant



**Fig. 4 Schematic illustration of the structures and energy transfer pathways of different NCs.** The structures of **a** dimeric, **b**  $\text{EuF}_3$ & $\text{GdF}_3$ , and **c**  $\text{EuF}_3$ & $2\text{GdF}_3$  NCs. **d** Core-shelled, **e**  $\text{EuF}_3$ @ $\text{GdF}_3$ , and **f**  $\text{EuF}_3$ @ $\text{GdF}_3$ @ $\text{GdF}_3$  NCs. **g** Reversely core-shelled, **h**  $\text{GdF}_3$ @ $\text{EuF}_3$ , and **i**  $\text{GdF}_3$ @ $\text{EuF}_3$ @ $\text{EuF}_3$  NCs, as well as their respective energy transfer pathways. **b**, **c**, **e**, **f** and **h**, **i** illustrate the energy transfer details in differently structured NCs using 273 nm light to excite  $\text{Gd}^{3+}$ , which transfers energy to  $\text{Eu}^{3+}$  (Supplementary Fig. 11). Note: for simplicity, energy migrations between  $\text{Gd}^{3+}$ - $\text{Gd}^{3+}$  and  $\text{Eu}^{3+}$ - $\text{Eu}^{3+}$  were not shown.

(Fig. 5g), which is reasonable because  $\text{EuF}_3$  and  $\text{GdF}_3$  NPs are mixed uniformly during co-assembly process. So, no matter what the  $\text{EuF}_3/\text{GdF}_3$  molar ratio is, the proportion of surface  $\text{Eu}^{3+}$  compared to internal  $\text{Eu}^{3+}$  remains unchanged, which agrees exactly with the proposed structure in Fig. 4a.

Similarly, compared with pure  $\text{EuF}_3$  NCs, growth of external  $\text{GdF}_3$  shell sharply reduces the proportion of surface  $\text{Eu}^{3+}$ , so  $I_E/I_M$  value declined rapidly from 1.10 in  $\text{EuF}_3$  NCs to 0.87 in  $\text{EuF}_3$ @ $\text{GdF}_3$  and further to 0.78 in  $\text{EuF}_3$ @ $\text{GdF}_3$ @ $\text{GdF}_3$  (Fig. 5h). The  $I_E/I_M$  value of  $\text{Eu}^{3+}$  also declined (Fig. 5i) from 1.10 in  $\text{EuF}_3$  NCs to 1.00 in  $\text{GdF}_3$ @ $\text{EuF}_3$  NCs and 0.92 in  $\text{GdF}_3$ @ $\text{EuF}_3$ @ $\text{EuF}_3$  NCs because enlarged NCs shows lower proportion of surface  $\text{Eu}^{3+}$ .

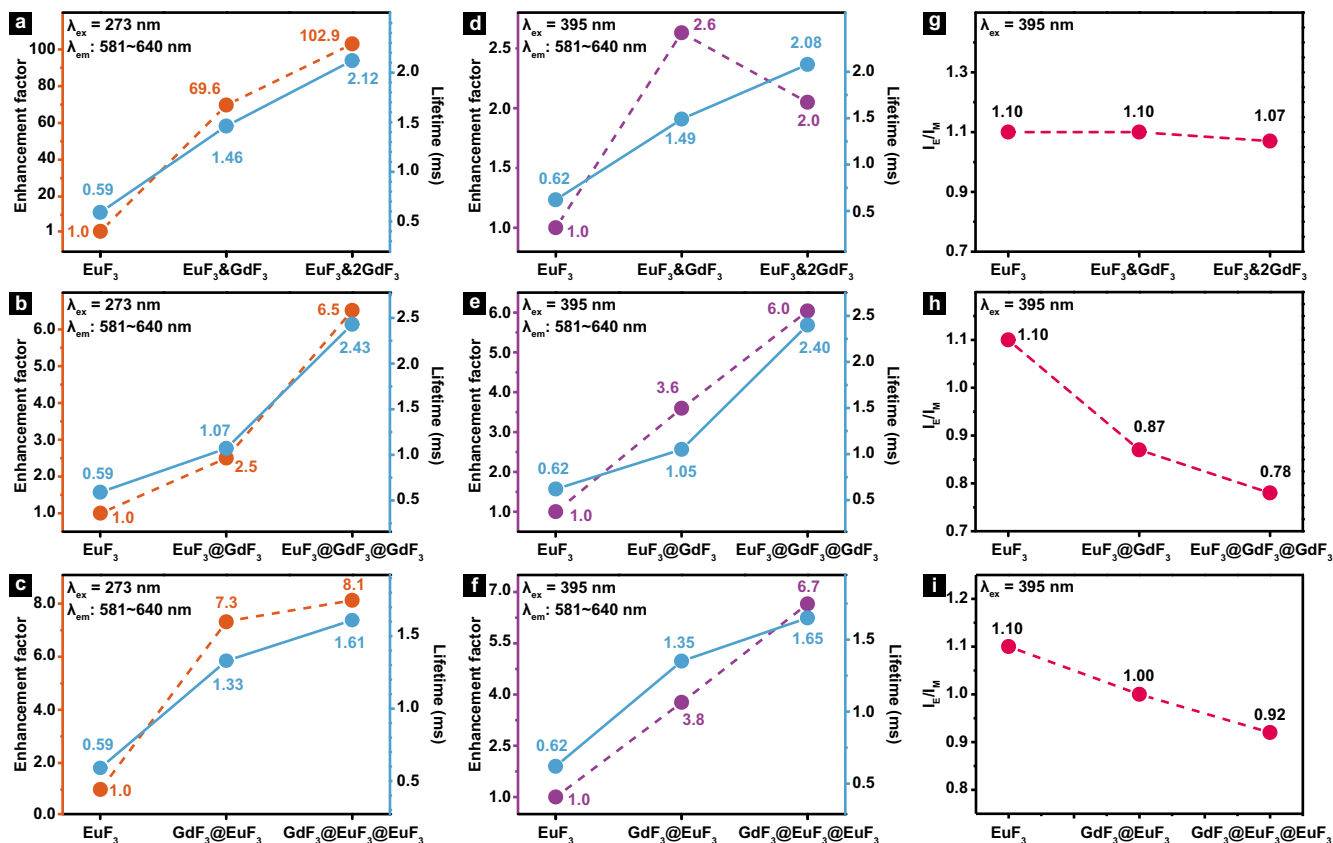
Although TEM images only show morphological and dimensional differences of the above NCs (Supplementary Figs. 18, 19 and 20), the elemental mapping results provide unambiguous

evidence for the structural differences of the purposely fabricated NCs illustrated in Fig. 4. For example, uniform distribution of Eu and Gd signals in the structure of  $\text{EuF}_3$ & $2\text{GdF}_3$  (Fig. 6a) suggests the complete co-assembly of  $\text{EuF}_3$  and  $\text{GdF}_3$  NPs, as depicted in Fig. 4c. Similarly, the opposite Eu and Gd signal distribution in Fig. 6b and c perfectly matches the core-shelled structure of  $\text{EuF}_3$ @ $\text{GdF}_3$ @ $\text{GdF}_3$  (Fig. 4d) and reversely core-shelled structure of  $\text{GdF}_3$ @ $\text{EuF}_3$ @ $\text{EuF}_3$  (Fig. 4g), respectively. These results are also highly consistent with both our principle designs and the structural details extracted from PL signals generated by the embedded dual luminescent probes of  $\text{Gd}^{3+}$  and  $\text{Eu}^{3+}$ .

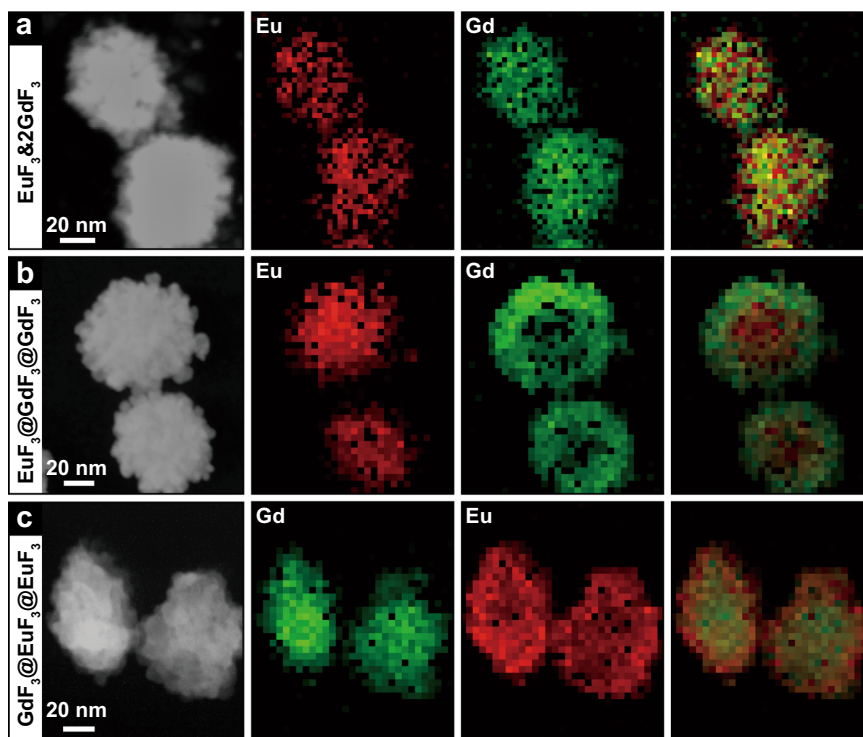
## Discussion

We have developed a clickable assembly strategy that allows facile construction of arbitrary NCs from individual  $\text{LnF}_3$  NPs. As a





**Fig. 5** The PL evolution in different-structured NCs. **a-c** Variation of luminescence enhancement factor (orange lines) and lifetime (baby blue lines) of  $\text{Eu}^{3+}$  in different NCs under 273 nm light excitation, through  $\text{Gd}^{3+}$ - $\text{Eu}^{3+}$  energy transfer. **d-f** Luminescence enhancement factor (purple lines) and lifetime (baby blue lines) of  $\text{Eu}^{3+}$  in different NCs under 395 nm light excitation. **g-i** Normalized  $I_E/I_M$  value of  $\text{Eu}^{3+}$  in different NCs.



**Fig. 6** Structural details of different NCs. High-angle annular dark-field scanning TEM images and corresponding energy-dispersive X-ray elemental mapping results of **a**  $\text{EuF}_3\&2\text{GdF}_3$  dimeric, **b**  $\text{EuF}_3\&\text{GdF}_3\&\text{GdF}_3$  core-shelled, and **c**  $\text{GdF}_3\&\text{EuF}_3\&\text{EuF}_3$  reversely core-shelled NCs.

complement to widely used one-step assembly, this two-step method enables fabrication of more versatile nanoarchitectures such as clusters, dimers, core-shells, and more importantly with multiple components and tunable functionalities without worrying about aggregation of precursors. It is worth emphasizing that the in-situ, sensitive, and dynamic PL signal generated by the embedded luminescent probes offers unparalleled superiority in precisely tracking not only tiny structural variations of but also energy transfer pathways in complex nanoarchitectures. Considering the large family of OA-stabilized NPs and principally other systems, this work has paved a potential avenue to the fabrication of widely diversified NCs with promising functionalities in the areas of catalysis, optoelectronics, energy conversion/harvesting, nanoalloys, bioimaging, as well as theranostics.

## Methods

**Materials.** Oxides of  $\text{Ln}_2\text{O}_3$  (99.99%, Ln = Eu, Gd, Sm, and Nd) were purchased from Beijing HWRK Chem. Co. LTD. Oleic acid (OA, 90%) and oleylamine (OM, 70%) were purchased from Sigma-Aldrich. Trifluoroacetic acid (TFA) and hydrochloric acid (HCl) was purchased from Shanghai Lingfeng Chemical Company, China. All the chemicals were used as received without further purification.

**Preparation of  $\text{Ln}(\text{CF}_3\text{COO})_3$ .** In a typical synthesis, lanthanide oxide was added into the aqueous solution containing slightly excessive trichloroacetic acid with continuous stirring, which was then kept refluxing so as to form an optically transparent solution. The resulting solution was filtered to remove the insoluble materials (if any), and the following solution was dried in an oven at 85 °C for 24 h to obtain  $\text{Ln}(\text{CF}_3\text{COO})_3$ .

**Synthesis of LnOF NPs.** Typical procedure: a given amount of  $\text{Ln}(\text{CF}_3\text{COO})_3$  (2 mmol) was added into the mixture of OA (20 mmol) and OM (20 mmol) in a three-necked flask (100 mL) at room temperature. The slurry was heated to 100 °C with vigorous magnetic stirring under vacuum for 10 min in a temperature-controlled electromantle to remove water and oxygen, thereby forming an optically transparent solution, which was then ramped to 310 °C at a heating rate of 10 °C/min and maintained for 2 h under  $\text{N}_2$  atmosphere. When cooling down to room temperature, the NPs were precipitated by adding excessive absolute ethanol into the reaction solution, followed by washing with ethanol for three times. Then the as-prepared NPs were dispersed into cyclohexane for further use.

**Self-assembly of LnOF NPs into  $\text{LnF}_3$  NCs.** The NCs assembled from LnOF NPs were obtained through an acid treatment process. Typically, a certain amount of LnOF NPs and GdOF NPs were transferred into 4 mL ethanol solution, which was then poured into a 20 mL beaker and stirred for 5 min. 200  $\mu\text{L}$  diluted hydrochloric acid solution (1 M) was added into the above solution and stirred at around 1000 r/min. After 6 h, the assembled NCs were generated in the solution, which was centrifuged at a speed of 8000 r/min for 4 min to obtain the NC samples, and then washed twice with ethanol under this condition to obtain the final NC samples.

**Self-assembly of  $\text{EuF}_3$ & $\text{GdF}_3$  dimeric NC.** Take the  $\text{EuF}_3$ & $\text{GdF}_3$  dimeric NC (molar ratio of  $\text{EuF}_3$ : $\text{GdF}_3$  = 1:1) as an example: typically, a certain amount of EuOF NPs and GdOF NPs were transferred into 4 mL ethanol solution, respectively, which was poured into 20 mL beaker, and stirred for 5 min for complete dispersion. Then, 200  $\mu\text{L}$  diluted hydrochloric acid solution (1 M) was added respectively into the above EuOF and GdOF solutions and kept stirring at around 500 r/min. After 10 min, the EuOF NPs and GdOF NPs totally converted into  $\text{EuF}_3$  NPs and  $\text{GdF}_3$  NPs, respectively. Then, solutions of  $\text{EuF}_3$  NPs and  $\text{GdF}_3$  NPs were mixed together into 20 mL beaker, and stirred at 1000 r/min. After 6 h, the above solution was centrifuged at a speed of 8000 r/min for 4 min to obtain the  $\text{EuF}_3$ & $\text{GdF}_3$  dimeric NCs, which were then washed with ethanol twice under this condition to obtain the final products.

**Self-assembly of core-shelled NCs.** Take the  $\text{EuF}_3$ @ $\text{GdF}_3$  core-shelled NCs (molar ratio of  $\text{EuF}_3$ : $\text{GdF}_3$  = 1:1) as an example: typically, a certain amount of EuOF NPs was transferred into 4 mL ethanol solution, poured into 20 mL beaker, and stirred for 5 min. 200  $\mu\text{L}$  diluted hydrochloric acid solution (1 M) was then added into the above solution and kept stirring for 6 h, until the assembled  $\text{EuF}_3$  NCs were formed. The such-obtained  $\text{EuF}_3$  NCs were further used as core for  $\text{EuF}_3$ @ $\text{GdF}_3$  core-shell structured NCs growth. Meanwhile, a certain amount of GdOF NPs was transferred into 4 mL ethanol solution, poured into 20 mL beaker, and stirred for 5 min. Subsequently, 200  $\mu\text{L}$  diluted hydrochloric acid solution (1 M) was added into the above GdOF solution and kept stirring for 10 min, until GdOF NPs totally converted into  $\text{GdF}_3$  NPs. Then, solutions containing  $\text{GdF}_3$  NPs and  $\text{EuF}_3$  NCs were mixed together at certain ratio, and stirred for 6 h. The

solution was centrifuged at 8000 r/min for 4 min to obtain the  $\text{EuF}_3$ @ $\text{GdF}_3$  core-shelled NCs, which were then washed twice with ethanol for future analysis.

**Characterization.** Powder X-ray diffraction (XRD) analysis was carried out on a Rigaku Smartlab (3 kW) X-ray diffractometer (Rigaku Corporation, Japan) using Cu K $\alpha$  radiation ( $\lambda$  = 1.5406 Å) and the measurement was performed at ambient temperature in the range of  $2\theta$  = 10–60 degree with 0.02 degree/step. Transmission electron microscope (TEM) images were recorded on a JEOL-1400 Plus (JEOL Ltd, Japan) at an acceleration voltage of 120 kV. High-resolution TEM (HRTEM) images and Energy-dispersive X-ray (EDX) spectra were obtained on a Tecnai G2 F20 TEM (FEI, America) at an acceleration voltage of 200 kV.

Fourier transform infrared (FT-IR) spectra were collected on a Nicolet 380 FT-IR spectrometer (Nicolet, America). Photoluminescence (PL) emission spectra were recorded on an Edinburgh FLS1000 Photoemission Spectrometer (Edinburgh Instruments, UK). All luminescent characterizations including PL emission spectra, excitation spectra, and luminescence decay curves were collected at 25 °C. Excitation and emission spectra were measured by using a 450 W continuous xenon arc lamp for sample excitation, and detailed parameters are shown in Supplementary Table 1. Luminescence decay curves were measured by using a compact 60 W xenon flash lamp ( $\mu\text{F}2$ ) as excitation source with the frequency of 40 Hz.

## Data availability

All data supporting the findings of this study are available within the paper and its supplementary information files.

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## Author contributions

L.H. initiated and led this research. J.Z. and Y.We. contributed equally to this work. The manuscript was written through the contributions of all authors. All authors gave approval to the final version of the manuscript. L.H., J.Z. and Y.We. designed the experimental approaches. J.Z., Y.We., Y.Wa. and F.Z. performed the experiments. L.H., J.Z., Y.We., Y.P., Z.Y., H.So., J.Y., H.Su. and X.X. analyzed the data. L.H., J.Z. and Y.We. wrote the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

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