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Enhancing multiphoton upconversion emissions through confined energy migration in lanthanide-doped Cs₂NaYF₆ nanoplatelets†

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Lanthanide (Ln³⁺)-doped upconversion (UC) nanocrystals have drawn tremendous attention because of their intriguing optical properties. Currently, it is highly desired but remains challenging to achieve efficient multiphoton UC emissions. Herein, we report the controlled synthesis of a new class of UC nanocrystals based on Cs₂NaYF₆:Yb/Tm nanoplatelets (NPs), which can effectively convert the 980 nm light to five-photon and four-photon UC emissions of Tm³⁺ without the fabrication of a complicated core/multishell structure required in traditional nanocrystals. Particularly, the as-prepared Cs₂NaYF₆:Yb/Tm NPs exhibit a maximal UV-to-NIR emission intensity ratio of 1.2, which is the highest among Tm³⁺-doped core-only UC nanocrystals. We reveal that the enhanced multiphoton UC emissions may benefit from the confined energy migration of Ln³⁺ dopants in the unique two-dimensional-like structure of Cs₂NaYF₆ NPs. As such, intense red and green UC emissions of Eu³⁺ and Tb³⁺ can further be generated *via* the cascade sensitization of Tm³⁺ and Gd³⁺ in Cs₂NaYF₆:Yb/Tm/Gd/Eu and Cs₂NaYF₆:Yb/Tm/Gd/Tb NPs, respectively. These results validate the superiority of Cs₂NaYF₆ for the future design of efficient UC nanocrystals towards versatile applications.

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Introduction

Lanthanide (Ln³+)-doped upconversion (UC) nanocrystals can convert low-energy excitation to high-energy emission, which makes them attractive for applications in photocatalysis, anticounterfeiting and biosensing. Based on the unique ladder-like 4f energy configurations of Ln³+ ions, UC emission from high energy levels is generated through successive absorption of low-energy photons with sensitizer ions (e.g., Yb³+, Nd³+) and transfer of the energy to activator ions (e.g., Er³+, Tm³+, Ho³+). Theoretically, elevating the concentration of Ln³+ dopants may improve the energy transfer efficiency and enhance the UC luminescence (UCL). Is,16 Unfortunately, a high concentration of dopants may cause concentration quenching of UCL due to the deleterious energy migration or

Hitherto, substantial efforts have been made to overcome such obstacles and to enhance the multiphoton UV emission in Ln3+-doped UC nanocrystals.20-22 Typically, a core/multishell structure has to be constructed to suppress the energy migration in traditional nanocrystals. For example, Zhou et al. designed NaYF4:Er@NaYbF4@NaYF4 core/shell/shell nanocrystals to alleviate the energy back-transfer from Er3+ to Yb3+, which promoted the three-photon UC emission of Er³⁺. ²³ Chen et al. synthesized NaYF4@NaYbF4:Tm@NaYF4 core/shell/shell nanocrystals, where efficient five-photon UCL of Tm³⁺ was realized without suffering from concentration quenching of Yb3+.24 To circumvent the complicated synthesis procedures of core/multishell nanocrystals, it is of utmost importance to explore special host lattices to confine energy migration between Ln3+ dopants for producing intense multiphoton UC emissions. 25,26

 Cs_2NaYF_6 , a face-centered cubic crystal with the space-group symmetry of $Fm\bar{3}m$, has been reported as an excellent laser or scintillation host. ^{27,28} In the Cs_2NaYF_6 crystal, Na^+ and Y^{3+} ions are surrounded by six halogen ions that form an

cross-relaxation processes between the neighboring Ln³⁺ ions.^{17,18} Moreover, the long-distance migration of excitation energy *via* highly concentrated Ln³⁺ dopants to lattice/surface defects may severely deteriorate the multiphoton UC emission in the ultraviolet (UV) spectral region.¹⁹

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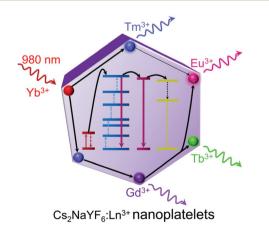
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octahedron. Particularly, the unit cell parameters a = b = c =9.08 Å are much larger than those of widely reported α-NaYF₄ with the same space-group symmetry (unit cell parameters a =b = c = 5.47 Å). As such, the energy migration between Ln³⁺ dopants is expected to be effectively confined.^{29,30} So far, all the previous research studies of Ln3+-doped Cs2NaYF6 have been carried out via hydrothermal and solid-state reaction methods, which resulted in bulk materials.31,32 Nowadays, it remains a great challenge to synthesize monodisperse Ln3+doped Cs2NaYF6 nanocrystals, whose UCL properties and the related UC mechanism deserve to be investigated.

Herein, we propose a facile strategy for the controlled synthesis of Ln³⁺-doped Cs₂NaYF₆ nanoplatelets (NPs). Upon excitation at 980 nm, an integrated UV-to-NIR emission intensity ratio of up to 1.2 can be achieved based on the as-prepared Cs₂NaYF₆:Yb/Tm NPs, which is ~40 times higher than that of α-NaYF₄:Yb/Tm counterparts. By means of structural analysis, the enhanced multiphoton UCL mechanism is attributed to the inhibition of the energy migration between Ln³⁺ dopants in Cs2NaYF6. Furthermore, we demonstrate that intense UC emissions of Eu3+ and Tb3+ can be generated via the sensitization of Tm3+ and Gd3+ in Cs2NaYF6:Yb/Tm/Gd/Eu and Cs₂NaYF₆:Yb/Tm/Gd/Tb NPs, respectively (Scheme 1).

Results and discussion

Cs₂NaYF₆:Yb/Tm NPs were synthesized via a facile high-temperature co-precipitation method, where CsF reacted with metal precursors in the mixed solvents containing oleic acid (OA), oleylamine (OAm) and octadecene (ODE) (Fig. 1a). X-ray diffraction (XRD) patterns show that all the diffraction peaks of the as-prepared NPs match well with the cubic Cs₂NaYF₆ (JCPDS no. 20-1214). Compared with those of the bulk counterparts synthesized via the solid-state reaction method (Fig. S1†), the XRD peaks of these NPs are broadened, indicating the smaller size of the as-prepared NPs (Fig. 1b). The growth rate of the NPs can be controlled with the reaction solvent because the



Scheme 1 Schematic illustration of Cs₂NaYF₆:Ln³⁺ NPs with highly efficient multiphoton UC emission upon 980 nm excitation.

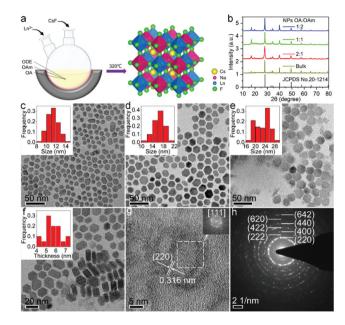


Fig. 1 (a) Schematic illustration of the synthesis of Cs₂NaYF₆:Yb/Tm NPs. (b) XRD patterns of Cs_2NaYF_6 :Yb/Tm NPs and bulk materials. (c-e) Bright-field TEM images of Cs₂NaYF₆:Yb/Tm NPs synthesized with an OA/OAm ratio of 2:1, 1:1, and 1:2, respectively. Insets: a size distribution histogram by randomly calculating 100 particles in the TEM images. (f) Bright-field TEM images of Cs₂NaYF₆:Yb/Tm NPs synthesized with an OA/OAm ratio of 2:1. The inset shows the thickness distribution histogram of the as-prepared NPs. (g) HRTEM and (h) SEAD of Cs2NaYF6:Yb/Tm NPs.

ion diffusion is faster at a lower OA/OAm ratio.33 As a result, the size of NPs can be tuned by adjusting the OA/OAm ratio. When the OA/OAm ratio decreased from 2:1, 1:1 to 1:2, the average size increased from 11.4 ± 1.1 nm, 16.4 ± 1.9 nm to 22.9 \pm 2.9 nm (Fig. 1c-e). The thickness of the Cs₂NaYF₆:Yb/ Tm NPs was determined to be 5.7 \pm 0.8 nm (Fig. 1f). The highresolution transmission electron microscopy (HRTEM) image of Cs₂NaYF₆ NPs shows clear lattice fringes (Fig. 1g). The fast Fourier transform (FFT) image of the NPs from the HRTEM image indicates that there are six nearest scattering points around each white scattering point, and the distance between them is 0.316 nm, verifying that the dominant arrangement of the synthesized Ln³⁺ doped Cs₂NaYF₆ NPs is the [111] orientation.³⁴ The selected-area electron diffraction (SAED) pattern of these NPs displays intense diffraction rings of cubic Cs₂NaYF₆ (Fig. 1h), confirming the pure phase and high crystallinity of the obtained NPs. In addition, the energy-dispersive X-ray (EDX) spectrum confirms the successful doping of Yb³⁺ and Tm³⁺ in Cs₂NaYF₆ NPs (Fig. S2†).

To examine the effect of Ln³⁺ dopants on UC emission, we synthesized a series of Cs2NaYF6:Yb/Tm NPs with different Tm³⁺ and Yb³⁺ concentrations. The optimal Tm³⁺ concentration was 1 mol%, which resulted in the maximal UCL emission upon excitation with a 980 nm laser (Fig. S3†). For Cs₂NaYF₆:x mol% Yb, 1 mol% Tm NPs with different Yb³⁺ concentrations (Fig. S4†), their UCL spectra consist of character**Paper** Nanoscale

istic sharp emission peaks which can be assigned to the fivephoton ${}^{1}I_{6} \rightarrow {}^{3}H_{6}$ and ${}^{3}F_{4}$ (290 and 348 nm), four-photon ${}^{1}D_{2}$ \rightarrow $^{3}H_{6}$ and $^{3}F_{4}$ (362 and 450 nm), three-photon $^{1}G_{4} \rightarrow {}^{3}H_{6}$ and ${}^{3}F_{4}$ (478 and 649 nm) and two-photon ${}^{3}H_{4} \rightarrow {}^{3}H_{6}$ (803 nm) transitions of Tm³⁺ (Fig. 2a). Interestingly, the five-photon and four-photon UCL emissions of Cs2NaYF6:Yb/Tm NPs in the UV region were observed to be strikingly strong. With the Yb³⁺ concentration of 49 mol%, a maximum integrated UV-to-NIR emission intensity ratio can be achieved (Fig. 2b).

We then compared the UCL spectra of Cs2NaYF6:Yb/Tm NPs and bulk materials with that of typical Tm³⁺ doped fluoride nanocrystals like α-NaYF₄ (Fig. 2c). Bright blue UCL can be observed for these samples upon 980 nm excitation at a power density of 150 W cm⁻². The absolute upconversion quantum yields for the visible and NIR regions (400-850 nm) of Cs2NaYF6:Yb/Tm NPs and bulk have been determined to be $0.10 \pm 0.02\%$ and $1.27 \pm 0.10\%$, respectively, which are higher than that of α -NaYF₄:Yb/Tm nanocrystals (0.05 \pm 0.02%). Moreover, the five-photon and four-photon UCL emissions of Cs2NaYF6:Yb/Tm NPs in the UV region were observed to be much stronger than those of Tm³⁺ doped α-NaYF₄ nanocrystals

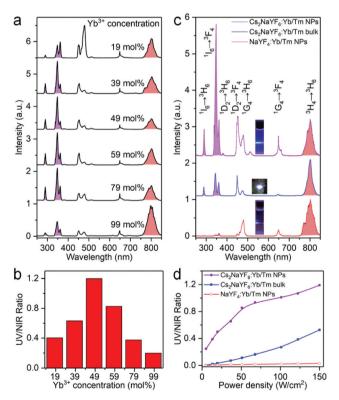


Fig. 2 (a) UC emission spectra and (b) integrated UV-to-NIR emission intensity ratio of Cs2NaYF6:Yb/Tm NPs with different Yb3+ concentrations (λ_{ex} = 980 nm, power density = 150 W cm⁻²). (c) UC emission spectra of Cs₂NaYF₆:49 mol%Yb, 1 mol%Tm NPs, bulk and α-NaYF₄:49 mol%Yb, 1 mol%Tm NPs. These emission spectra were normalized at 803 nm of Tm³⁺ emission. Insets show their corresponding PL photographs. (d) Integrated UV-to-NIR emission intensity ratio in $Cs_2NaYF_6:49$ mol%Yb, 1 mol%Tm NPs, bulk and α -NaYF₄:49 mol%Yb, 1 mol%Tm NPs upon 980 nm excitation with different power densities.

(Fig. S5†). The integrated UV-to-NIR emission intensity ratio of these samples increased with an increase in the excitation power density. With a power density of 150 W cm⁻², the UV-to-NIR ratios for Cs₂NaYF₆:49 mol%Yb, 1 mol%Tm NPs and bulk materials were calculated to be 1.20 and 0.51, respectively, which are ~ 40 and ~ 17 times higher than that of α-NaYF₄:49 mol%Yb, 1 mol%Tm nanocrystals (Fig. 2d). Note that the integrated UV-to-NIR emission intensity ratio of 1,20 is also the highest among Tm3+-activated core-only UC nanocrystals (Table S1†).

As shown in Fig. 3a and b, both α-NaYF₄ and Cs₂NaYF₆ are face-centered cubic crystals with the space-group symmetry of Fm $\bar{3}m$. In α -NaYF₄ and Cs₂NaYF₆, Ln³⁺ dopants like Yb³⁺ and Tm³⁺ ions are doped to substitute for Y³⁺ ions. The nearest distance between Yb^{3+} and Tm^{3+} ions is 3.87 Å in α -NaYF₄ (Fig. 3a), which is much smaller relative to that in Cs₂NaYF₆ (6.42 Å, Fig. 3b). As such, the excitation energy in α -NaYF₄ may be easily depleted owing to the increased probability of energy migration, which does not favor the multiphoton UCL emission.35

We investigated the microscopic models of Cs₂NaYF₆:Yb/ Tm bulk materials and NPs (Fig. 3c). For each Tm³⁺ ion in bulk Cs2NaYF6:Yb/Tm, there are twelve nearest neighboring Ln³⁺ ions, four of which are situated at the top, middle or bottom [001] layer, respectively. The existence of isotropically substituted Ln3+ ions may promote the dissipation of the excitation energy in such a three-dimensional (3D) structured crystal sublattice. 25,36,37 By contrast, the Cs2NaYF6:Yb/Tm nanocrystalline materials experience an anisotropic growth

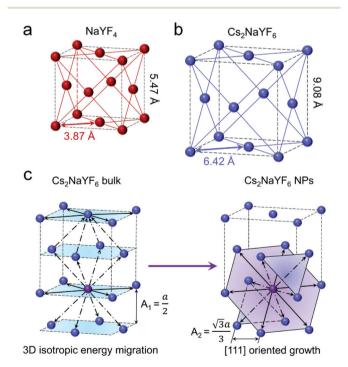


Fig. 3 Schematic illustration of the structure of (a) α -NaYF₄ and (b) Cs₂NaYF₆:Yb/Tm, respectively. (c) Schematic illustration of the topological energy migration pathways in Cs2NaYF6:Yb/Tm bulk and NPs.

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along the [111] orientation (Fig. 1g), resulting in two-dimensional (2D)-like nanoplatelets. For each Tm3+, six nearest neighboring Ln3+ ions are situated at the middle [111] layer and the other six nearest neighboring Ln³⁺ ions are situated at the top and bottom [111] layer, respectively. Moreover, the distance between two [111] layers (A2) is calculated to be 5.24 Å, which is longer than that of two [100] layers (A₁, 4.54 Å).³⁸ Thus, such a 2D-like structure can effectively minimize the migration of excitation energy compared with the 3D structure, 25,39 which resulted in enhanced multiphoton UCL emission in Cs2NaYF6:Yb/Tm NPs relative to that in the bulk counterparts.

Besides Tm³⁺, another Ln³⁺ ion like Gd³⁺ is often doped into inorganic nanocrystals to produce UV emission. 40 In this regard, we synthesized Cs2NaYF6:Yb/Tm/Gd NPs with different Gd³⁺ concentrations. EDX element mapping images indicate that the Ln3+ dopants are homogeneously distributed among the as-prepared NPs (Fig. S6†). Upon 980 nm excitation, a sharp UV emission peak at 311 nm can be observed, which originated from the ${}^{6}P_{7/2} \rightarrow {}^{8}S_{7/2}$ transition of the Gd^{3+} ion (Fig. 4a). The luminescence intensity of such UV emission increased with increasing Gd3+ content from 10 mol% to 30 mol%, and then decreased at higher concentrations. Meanwhile, the five-photon ${}^{1}I_{6} \rightarrow {}^{3}H_{6}$ and ${}^{3}F_{4}$ transitions of Tm3+ peaking at 290 and 348 nm continuously decreased with an increase in the Gd³⁺ concentrations. Moreover, in a control experiment by replacing Cs2NaYF6:Yb/Tm/Gd with Cs2NaYF6: Yb/Gd NPs under otherwise identical conditions, negligible UCL was detected, which indicates that the luminescence of Gd³⁺ was mainly sensitized by the nearby Tm³⁺ ions.

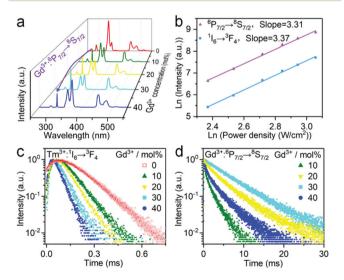


Fig. 4 (a) UC emission spectra of Cs2NaYF6:Yb/Tm/Gd NPs with different Gd3+ contents. These spectra were normalized at 450 nm of Tm³⁺ emission. (b) Ln-ln plots of the UC emission intensity versus excitation power density for the transitions of $^6P_{7/2} \rightarrow \, ^8S_{7/2}$ of Gd $^{3+}$ and 1I_6 \rightarrow 3F_4 of Tm $^{3+}$ in Cs₂NaYF₆:Yb/Tm/Gd NPs, respectively. (c) PL decays of $^{1}\text{I}_{6} \rightarrow ^{3}\text{F}_{4} \text{ of Tm}^{3+} \text{ and (d) } ^{6}\text{P}_{7/2} \rightarrow ^{8}\text{S}_{7/2} \text{ of Gd}^{3+} \text{ in Cs}_{2}\text{NaYF}_{6}:Yb/\text{Tm/Gd}$ NPs by monitoring the emissions at 348 nm and 311 nm, respectively.

To shed more light on the mechanism of the UV emission of Gd³⁺, we obtained the UC spectra of Cs₂NaYF₆:Yb/Tm/Gd NPs excited with a 980 nm laser with different power densities. For a typical UC emission process, the value of pump photons (n) required to populate a certain emission can be determined by the relationship of $I \propto P^n$, where I and P are the UCL intensity and the pump power density, respectively. The n value for ${}^{1}\text{I}_{6} \rightarrow {}^{3}\text{F}_{4}$ (348 nm) of Tm³⁺ was determined to be essentially identical to that of ${}^6P_{7/2} \rightarrow {}^8S_{7/2}$ (311 nm) of Gd³⁺ (Fig. 4b), which indicates that the UCL of Gd³⁺ may occur through the sensitization of the ¹I₆ state of Tm³⁺.

To further verify the process of energy transfer from Tm³⁺ to Gd^{3+} , we measured the UCL decays from $^{1}I_{6}$ of Tm^{3+} and ⁶P_{7/2} of Gd³⁺ in Cs₂NaYF₆:Yb/Tm/Gd NPs. The effective lifetime of the ⁶P_{7/2} level of Gd³⁺ increased from 1.61 ms to 7.03 ms with increasing Gd³⁺ content from 10 mol% to 30 mol%, and then decreased to 2.97 ms at higher concentrations (Fig. 4c and Table S2†). Meanwhile, the effective lifetime of the 1I6 level of the Tm3+ ion was determined to be shortened from 163.96 μs to 50.47 μs with the increase of Gd³⁺ concentration from 0 to 40 mol% (Fig. 4d and Table S2†). All these results verified that the UCL of the ⁶P_{7/2} state of Gd³⁺ is sensitized by the ¹I₆ state of Tm³⁺ ions.

It has been reported that Gd3+ can be used as a bridge ion to sensitize a variety of Ln3+ ions (e.g., Eu3+ or Tb3+) without long-lived intermediate energy states to produce UC emission. 41,42 For Cs₂NaYF₆:Yb/Tm/Gd/Eu and Cs₂NaYF₆:Yb/ Tm/Gd/Tb NPs, a set of new UC emission peaks appeared besides those of Tm3+ and Gd3+ upon excitation at 980 nm (Fig. 5a). These newly appeared UC emission peaks can be assigned to the ${}^5D_0 \rightarrow {}^7F_I$ transitions of Eu³⁺ and ${}^5D_4 \rightarrow {}^7F_I$ transitions of Tb3+, respectively. Correspondingly, the overall UC color output turned from blue to pink or cyan, respectively (insets of Fig. 5a).

The UC mechanism responsible for the intense UCL of Eu³⁺ and Tb³⁺ in Cs₂NaYF₆ is illustrated in Fig. 5b. Upon excitation with a 980 nm laser, sensitizer ions (Yb³⁺) absorb the pumped photons, followed by energy transfer to the neighboring Tm³⁺ to populate the 3F_4 , 3H_4 , 1G_4 , 1D_2 , and 1I_6 states of Tm^{3+} in sequence. Note that the energy of the $^6P_{7/2}$ level of the Gd^{3+} ion matches well with that of the 1I6 level of the Tm3+ ion. Once the ¹I₆ level of the Tm³⁺ ion is populated, its excitation energy will be partially transferred to the Gd³⁺ ion. The excitation energy will then be transferred to the Eu³⁺ or Tb³⁺ ion, because the 6P7/2 level of the Gd3+ ion matches well with the ⁵H_I level of Eu³⁺ or the ⁵D_I level of Tb³⁺. As a result, red UCL of Eu³⁺ or green UCL of Tb³⁺ can be observed. The proposed energy transfer mechanism was further confirmed by the observed UCL decays. It was determined that the photoluminescence lifetime of 6P7/2 of Gd3+ was shortened from 7.03 ms to 2.83 ms, and the photoluminescence lifetime of ¹I₆ of Tm3+ was shortened from 59.89 µs to 40.93 µs after the doping of Eu^{3+} (Fig. S7†).

It is worth emphasizing that two key issues contribute to the generation of efficient UCL of Eu³⁺ and Tb³⁺ in Cs₂NaYF₆: Yb/Tm/Gd/Eu and Cs2NaYF6:Yb/Tm/Gd/Tb NPs, respectively.

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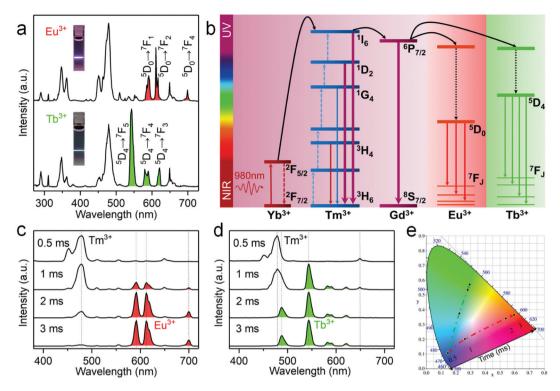


Fig. 5 (a) UCL spectra of $Cs_2NaYF_6:Yb/Tm/Gd/Eu$ and $Cs_2NaYF_6:Yb/Tm/Gd/Tb$ NPs dispersed in hexane upon excitation at 980 nm with a power density of 150 W cm⁻². Insets show their PL photographs. (b) Schematic energy level diagram showing the sensitization mechanism of Eu^{3+} (red) and Tb^{3+} (green) in $Cs_2NaYF_6:Yb/Tm/Gd/Eu$ and $Cs_2NaYF_6:Yb/Tm/Gd/Eu$ and (d) $Cs_2NaYF_6:Yb/Tm/Gd/Eu$ and (d) $Cs_2NaYF_6:Yb/Tm/Gd/Eu$ and (d) $Cs_2NaYF_6:Yb/Tm/Gd/Eu$ upon excitation with a 980 nm pulse laser as the excitation source with the average power density of \sim 40 W cm⁻². (e) Corresponding CIE chromaticity coordinates for $Cs_2NaYF_6:Yb/Tm/Gd/Eu$ (red) and $Cs_2NaYF_6:Yb/Tm/Gd/Tb$ (green) NPs in (c) and (d), respectively.

Firstly, Gd3+ plays an important role as the energy transfer bridge. Without the doping of Gd3+, the UCL of Eu3+ in Cs2NaYF6:Yb/Tm/Eu NPs was observed to be negligibly weak because of the large energy mismatch between the ${}^2F_{5/2} \rightarrow$ $^2\mathrm{F}_{7/2}$ transition of Yb³⁺ and the $^5\mathrm{D}_I \to ^7\mathrm{F}_I$ transition of Eu³⁺. As such, the UCL of Eu³⁺ cannot be efficiently sensitized by the direct energy transfer between Tm3+ and Eu3+. By contrast, additional doping of Gd3+ resulted in much enhanced UCL of Eu^{3+} by ~25 times (Fig. S8†). In addition, the confined energy migration of Ln³⁺ dopants in the Cs₂NaYF₆ lattice is also critical. Note that in the previous reports regarding the generation of UCL from Eu³⁺ and Tb³⁺, the core-shell or core-multishell structure is a prerequisite for space separation of Tm³⁺ and Eu³⁺/Tb³⁺ so as to restrain the deleterious cross-relaxations between them.^{5,41} In this work, the UCL of Eu³⁺ in Cs₂NaYF₆:Yb/Tm/Gd/ Eu NPs can be markedly enhanced by ~38 times that of traditional fluorides like α-NaYF₄:Yb/Tm/Gd/Eu nanocrystals (Fig. S8†). To the best of our knowledge, such an efficient UCL of Eu3+ or Tb3+ in Cs2NaYF6 NPs has not been realized in other Eu³⁺ or Tb³⁺-doped core-only nanocrystals before.

As shown in Fig. 5a, the pure UCL of ${\rm Eu}^{3+}$ or ${\rm Tb}^{3+}$ cannot be obtained directly using the steady-state luminescence mode. The effective lifetimes of the $^5{\rm D}_0$ level of ${\rm Eu}^{3+}$ and the $^5{\rm D}_4$ level of ${\rm Tb}^{3+}$ in ${\rm Cs}_2{\rm NaYF}_6$ NPs have been determined to be 2.60 ms and 2.25 ms, respectively (Fig. S9†), which are about two

orders of magnitude longer than those of Tm³⁺ in these NPs (Fig. S7†). By virtue of the large difference in the UC luminescence lifetime between Eu³⁺/Tb³⁺ and Tm³⁺ ions, it is easy to separate their UCL based on the time-resolved detection technique by setting an appropriate delay time and gate time. Fig. 5c and d show the time-resolved UCL spectra of Cs₂NaYF₆: Yb/Tm/Gd/Eu and Cs2NaYF6:Yb/Tm/Gd/Tb NPs, respectively. Their UCL spectra were dominated by the emission of Tm³⁺ when the delay time was within 1 ms. When the delay time is longer than 3 ms, pure red UCL attributed to the ${}^5D_0 \rightarrow {}^7F_I (J =$ 1, 2, 3, and 4) transition of the Eu³⁺ ion and green UCL attributed to the ${}^5D_4 \rightarrow {}^7F_I$ (J = 3, 4, 5, and 6) transition of Tb³⁺ were observed, respectively. As revealed by their corresponding CIE chromaticity coordinates (Fig. 5e), the UC color changed from blue to red or green for Cs2NaYF6:Yb/Tm/Gd/Eu or Cs2NaYF6: Yb/Tm/Gd/Tb NPs, respectively. Such an intriguing timedependent UCL color output in Ln3+-doped Cs2NaYF6 NPs is favorable for potential applications such as in time-resolved bioimaging and multilevel anti-counterfeiting.

Conclusions

In summary, we have developed a new class of Ln³⁺-doped Cs₂NaYF₆ NPs without a core/shell structure to achieve highly

efficient multiphoton UCL emissions. Upon excitation at 980 nm, intense UV emissions of Tm³⁺ were realized in Cs₂NaYF₆:Yb/Tm NPs by virtue of the large distance between the adjacent Ln³⁺ dopants in the host lattice. The optimal UVto-NIR emission intensity ratio of Cs2NaYF6:Yb/Tm NPs has been determined to be 1.2, which is the highest among Tm³⁺activated core-only UC nanocrystals. Moreover, intense UV emission of Gd3+ has been realized in Cs2NaYF6:Yb/Tm/Gd NPs via the energy transfer from Tm³⁺ to Gd³⁺. Particularly, we have demonstrated that bright red and green UC emissions of Eu³⁺ and Tb³⁺ can be generated *via* the cascade sensitization of Tm³⁺ and Gd³⁺ in Cs₂NaYF₆:Yb/Tm/Gd/Eu and Cs₂NaYF₆: Yb/Tm/Gd/Tb NPs, respectively. These findings reveal the great potential of tuning UCL emissions in Ln3+-doped Cs2NaYF6 NPs, which may open up a promising avenue for the exploitation of Ln3+-doped nanocrystals with excellent optical properties for versatile applications.

Experimental

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Detailed experimental procedures are reported in the ESI.†

Author contributions

C. Z. prepared samples and collected data for the original draft. S.Y. H. and P. Z. assisted in PL measurements. L.P. W., S. H. Y., J. X. and R.F. L. contributed to conceptualization and investigation. C. Z., D.T. T. and X.Y. C. prepared the manuscript.

Conflicts of interest

There are no conflicts to declare.

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