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Nonlinear spectral and lifetime management in upconversion nanoparticles by controlling energy distribution†

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Optical tuning of lanthanide-doped upconversion nanoparticles has attracted considerable attention over the past decade because this development allows the advance of new frontiers in energy conversion, materials science, and biological imaging. Here we present a rational approach to manipulating the spectral profile and lifetime of lanthanide emission in upconversion nanoparticles by tailoring their nonlinear optical properties. We demonstrate that the incorporation of energy distributors, such as surface defects or an extra amount of dopants, into a rare-earth-based host lattice alters the decay behavior of excited sensitizers, thus markedly improving the emitters' sensitivity to excitation power. This work provides insight into mechanistic understanding of upconversion phenomena in nanoparticles and also enables exciting new opportunities of using these nanomaterials for photonic applications.

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Introduction

Lanthanide-doped photon upconversion materials have been studied for several decades owing to their distinct optical properties such as large anti-Stokes' spectral shift, long luminescence lifetime, and sharp emission band. These attributes make the upconversion materials particularly attractive for use in lighting, lasing, quantum cutting, *etc.*^{1,2} In recent years, the rapid development of nanotechnology has enabled immense interest in upconversion nanoparticles (UCNPs) because of their fascinating optical properties and technological potential in many fields of research.^{3–37} Notably, many strategies, including doping composition/concentration variation, surface ligand coordination and pulse-duration modulation, have been developed to tune the emission profile of the UCNPs.^{38–45} An important and facile route to control upconversion emission, based on the nonlinear power response of

photon upconversion, is to vary the excitation power externally.^{46–48}

In a typical photon upconversion process, the excitation energy is absorbed by sensitizers, such as Yb³⁺ ions doped in a host matrix, and then transferred to neighboring emitters (or activators), such as Er³⁺ or Tm³⁺ featuring ladder-like energy states (Fig. S1 in the ESI†). The sequential photon absorption by the sensitizers permits the emitters to be excited to higher energy levels through energy transfer. It is widely accepted that for multi-step (n) energy transfer, the luminescence intensity I is proportional to n power of the excitation density P .^{49,50} Thus, the number of energy transfer upconversion (ETU) steps can be derived from the slope (I - P slope) of the luminescence intensity curve plotted against pump power density in a double-logarithmic representation (Fig. S2†). However, the upconversion emission intensity I may not be strictly proportional to n power of the excitation density P . The n value is likely to be affected by a multitude of factors related to energy distribution in UCNPs, such as a crystalline structure, particle size, and dopant concentration. Moreover, the variation of the n value is typically accompanied by a concurrent change in luminescence decay lifetime, meaning that n is highly relevant to the spectral properties and the luminescence dynamics of upconversion materials.

In this work, we investigate the spectroscopic properties and decay behaviors of UCNPs under the influence of different types of energy distributors through surface defect engineering or doping (Fig. 1). Our measured n value correlates well with upconversion emission characteristics in that large numbers of energy distributing pathways increase the sensitivity of the

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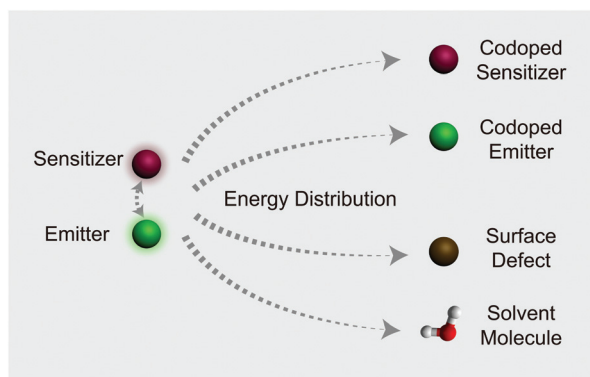


Fig. 1 Illustration of typical energy distribution processes involving Yb^{3+} -sensitized upconversion. Note that for a particular system at the excited state, possible energy distributors include sensitizer ions, codoped emitters, surface defects, and solvent molecules with high energy vibrational groups.

UCNPs to excitation power. Importantly, the decay lifetimes of both sensitizer and emitter ions could be tuned by manipulating the nature of the energy distributors, providing new opportunities for photonic applications in optical switching and security encoding.

Results and discussion

We prepared $\text{NaYF}_4:\text{Yb}/\text{Er}$ (20/2%) UCNPs as a model sample by a well-established co-precipitation method.⁵¹ As seen under a transmission electron microscope (TEM), the as-synthesized nanoparticles are 15.3 ± 1.1 nm in diameter with a narrow size distribution (Fig. 2a and b). A pure hexagonal phase structure of the nanoparticles was confirmed by X-ray diffraction studies (Fig. 2c). Under the excitation of a 975 nm CW laser, we observed visible emission bands at 540 and 654 nm, typically attributable to the $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ and $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$ transitions of Er^{3+} ions (Fig. 2d). We considered the 540 nm emission as an example to study the excitation power response and decay behaviors of the UCNPs. The power dependent luminescence measurement indicates that in the power density range of $29\text{--}70\text{ W cm}^{-2}$, the 540 nm emission is generated *via* a typical 2-photon upconversion process (Fig. 2e). On 975 nm pulsed laser excitation, we observed a distinct rise edge in the temporal luminescence curve of the 540 nm emission due to the time consumed by the multi-step energy transfer process.⁵² We focus on the decay lifetime of the luminescence which is critical to the application of upconversion tuning in the time domain for optical multiplexing.^{9,23} Notably, the emission of Yb^{3+} ($^2\text{F}_{5/2} \rightarrow ^2\text{F}_{7/2}$ transition) at 985 nm has a decay lifetime of

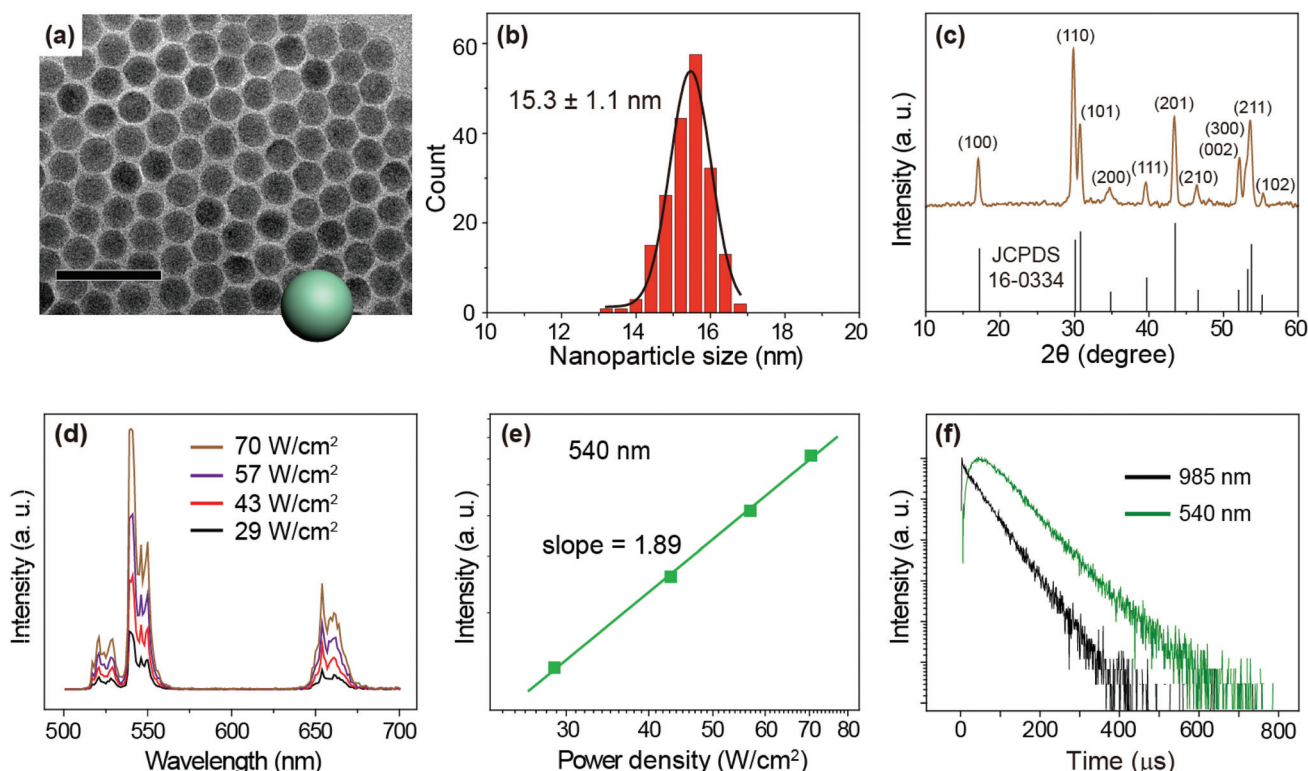


Fig. 2 (a) A typical TEM image of the as-prepared $\text{NaYF}_4:\text{Yb}/\text{Er}$ (20/2%) nanoparticles. Scale bar is 50 nm. (b) Size histogram of the nanoparticles. (c) X-ray diffraction patterns of the nanoparticles, which are in good agreement with the literature reference for hexagonal NaYF_4 crystal (Joint Committee on Powder Diffraction Standards file number 16-0334). (d) Emission spectra of the UCNPs recorded with a 975 nm CW laser excitation at different power densities ($29\text{--}70\text{ W cm}^{-2}$). (e) The 540 nm ($^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ transition of Er^{3+}) emission intensity *versus* pump power density in double-logarithmic representation. (f) Decay curves of 540 nm emissions from Er^{3+} as well as 985 nm from Yb^{3+} obtained upon excitation of the nanoparticles at 975 nm.

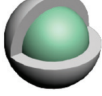
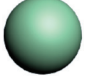
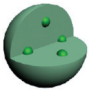


The effect of energy distributors on the measured decay lifetime of Yb^{3+} is investigated using the rate equations derived from a sensitization upconversion model (Fig. 3):

$$\tau = \frac{1}{\sum_i W_i N_i + W_D N_D + R_b} \quad (1)$$

We next carried out theoretical investigations to explore the fundamental principle underlying the spectral and lifetime management of UCNP through the control of energy distribution within the particles. From the analysis of the rate equations of energy levels in a simplified two-photon upconversion process (see the ESI†), the population density at the emitting level N_2 , which is proportional to the emission intensity I , can be expressed by eqn (2):

$$N_2 = \frac{N_b^2}{A \cdot N_b + B} \quad (2)$$

Structure		Core composition	Core diameter (nm)	Shell composition	Shell thickness (nm)	985 nm (μs)	540 nm (μs)	540 nm <i>I-P</i> slope
UCNPs with different inert shells		NaYF ₄ :Yb/Er (20/2%)	15.3	—	—	69	88	1.89
		NaYF ₄ :Yb/Er (20/2%)	15.3	NaYF ₄	1.3	304	187	1.77
		NaYF ₄ :Yb/Er (20/2%)	15.3	NaYF ₄	1.8	403	251	1.73
		NaYF ₄ :Yb/Er (20/2%)	15.3	NaYF ₄	2.8	783	301	1.63
UCNPs with different sizes		NaYF ₄ :Yb/Er (20/2%)	15.3	—	—	69	88	1.89
		NaYF ₄ :Yb/Er (20/2%)	23.8	—	—	327	245	1.76
		NaYF ₄ :Yb/Er (20/2%)	27.2	—	—	506	333	1.65
UCNPs with different active shells		NaYF ₄ :Yb/Er (20/2%)	15.3	NaYF ₄	1.6	379	231	1.74
		NaYF ₄ :Yb/Er (20/2%)	15.3	NaYF ₄ :Yb (10%)	1.9	274	180	1.78
		NaYF ₄ :Yb/Er (20/2%)	15.3	NaYF ₄ :Yb (20%)	1.7	131	128	1.82
UCNPs with different emitter concentrations		NaYF ₄ :Yb/Er (20/0.5%)	15.3	—	—	101	123	1.83
		NaYF ₄ :Yb/Er (20/1%)	15.5	—	—	97	103	1.88
		NaYF ₄ :Yb/Er (20/2%)	15.3	—	—	69	88	1.89
		NaYF ₄ :Yb/Er (20/4%)	15.7	—	—	50	65	1.92
		NaYF ₄ :Yb/Er (20/8%)	15.2	—	—	35	34	1.92
		NaYF ₄ :Yb/Er (20/16%)	15.2	—	—	19	14	1.98
		NaYF ₄ :Yb/Er (20/32%)	15.4	—	—	13	7	2.09

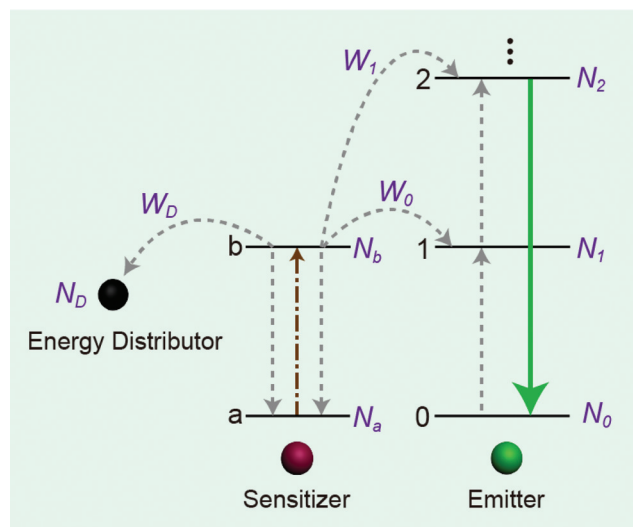


Fig. 3 Simplified scheme of the energy distributor effect on energy transfer processes involving a sensitization upconversion mechanism.

where A and B are constants, N_b denotes the population density of the excited states of the Yb^{3+} sensitizer, which determines the population density of the emitting level. From eqn (2), the N_2 - N_b slope value in double-logarithmic representation is calculated in between 1 and 2.⁵⁰ Upon excitation with a power density of P , N_b can be further derived from eqn (3):

$$N_b = \frac{P}{C + D \cdot P} \quad (3)$$

where C and D are constants. Notably, N_b is not simply proportional to the excitation power density P , as indicated in eqn (3). We conducted numerical simulations on $\text{NaYF}_4\text{:Yb/Er}$ (20/2%) UCNPs to validate the relationship of N_b with the incident photon flux by introducing the rate equations of a two-photon upconversion process, as shown in Fig. 4a. We consider that the population density of Yb^{3+} at the excited state is nonlinear to the excitation photon flux due to the excitation saturation of Yb^{3+} . This phenomenon further affects the relationship of N_2 - P , resulting in the deviation of the I - P slope away from the normal range. Our numerical simulations on both $\text{NaYF}_4\text{:Yb/Er}$ (20/2%) and $\text{NaYF}_4\text{:Yb/Er}$ (20/2%)@ NaYF_4 (~2.8 nm in shell thickness) UCNPs indicated that the slope of N_2 - P diminishes with increasing excitation photons. Compared with the core particles, the shell-coated UCNPs showed a lower value of the I - P slope under identical incident photon flux (Fig. 4b). Remarkably, the simulated value of the I - P slope could be reduced to less than 1 at a high power excitation, which agrees well with our experimental results (Fig. 4c).

From published work, it can be found that in $\text{Yb}^{3+}/\text{Er}^{3+}/\text{Tm}^{3+}$ triply-doped upconversion systems, increasing the excitation power density of UCNPs give rise to a larger rate of increase in the blue emission intensity than that of the green emission intensity.^{46,65–68} This can be attributed to the fact that blue emission from Tm^{3+} ($^1\text{G}_4 \rightarrow ^3\text{H}_6$ and $^1\text{D}_2 \rightarrow ^3\text{F}_4$ transitions) requires more excited photons than green emission from Er^{3+} ($^2\text{H}_{11/2}/^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ transitions) (Fig. S1†). As a result, the blue emission typically features a large I - P slope n , thus its intensity increases rapidly with increasing excitation power density. On the basis of the findings described in

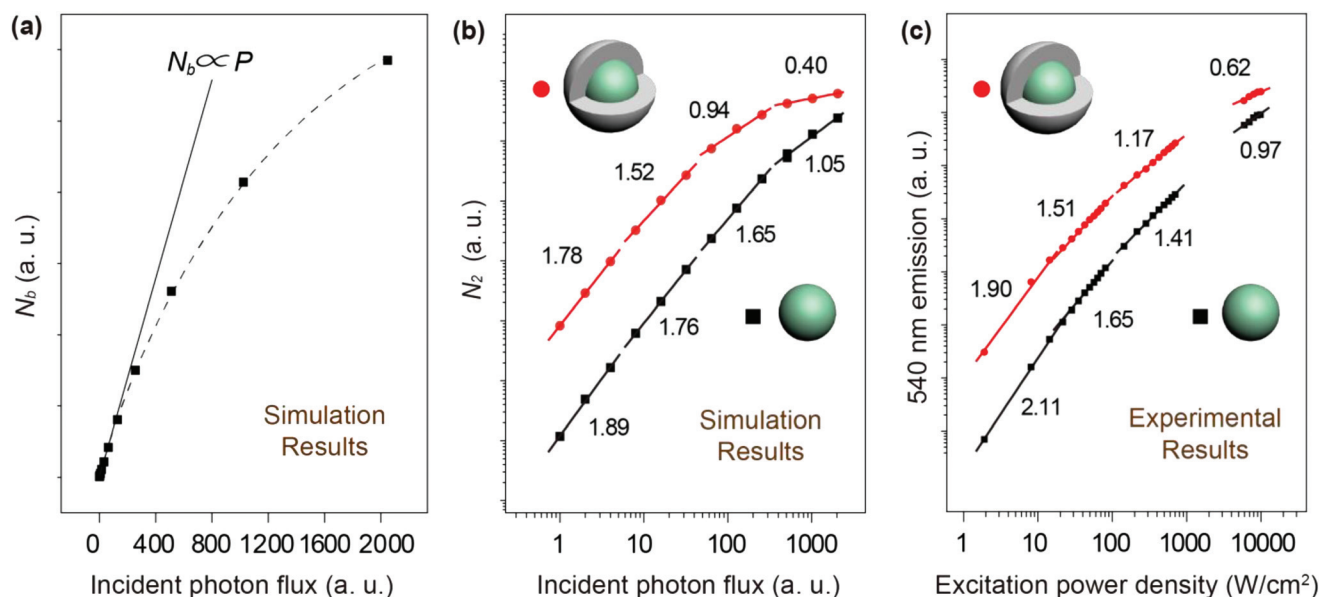


Fig. 4 (a) Numerical simulations on the population density of the excited state of Yb^{3+} ions versus the number of excitation photon flux in linear representation using $\text{NaYF}_4\text{:Yb/Er}$ (20/2%) UCNPs. (b) Numerical simulations on the population density of the 540 nm emission level of Er^{3+} ions versus the number of excitation photon flux in double-logarithmic representation using $\text{NaYF}_4\text{:Yb/Er}$ (20/2%) and $\text{NaYF}_4\text{:Yb/Er}$ (20/2%)@ NaYF_4 (~2.8 nm in shell thickness) core-shell UCNPs. (c) Power-density-dependent emission profiles of $\text{NaYF}_4\text{:Yb/Er}$ (20/2%) and $\text{NaYF}_4\text{:Yb/Er}$ (20/2%)@ NaYF_4 core-shell UCNPs at 540 nm. The excitation power density under study is in the range of 1 – 10^4 W cm^{-2} .



To verify our hypothesis, we prepared two sets of multi-shell structured UCNP s comprising $\text{NaYF}_4\text{:Yb/Tm@NaYF}_4\text{:NaYF}_4\text{:Yb/Er@NaYF}_4\text{:Yb}$ and $\text{NaYF}_4\text{:Yb/Er@NaYF}_4\text{:NaYF}_4\text{:Yb/Tm@NaYF}_4\text{:Yb}$ (Fig. 6a, d and S10†). Note that Tm^{3+} and Er^{3+} ions are doped at different layers for direct comparison of their power-dependent emission profiles. An inert layer of NaYF_4 was inserted between the two emitting layers to minimize cross-relaxation between Er^{3+} and Tm^{3+} (Fig. S12 and S13†).^{69,70} The outermost $\text{NaYF}_4\text{:Yb}$ shell was utilized to enhance the emission of the outer emitting layer to a level comparable to that obtained from the inner emitting layer (Fig. S14†). As expected, from the obtained emission spectra (Fig. 6b and e), it can be seen that the changes in the blue-to-green emission ratio of these two samples are dramatically different as a function of excitation power density (Fig. 6c, f, and S15a and c†). Consequently, the two colloidal samples exhibited different CIE color profiles with varied excitation power densities (Fig. S15b and d†). As control experiments, we synthesized two similar sets of UCNP s except for replacing the outermost layer of $\text{NaYF}_4\text{:Yb}$ with NaYF_4 . Interestingly, we observed that both the samples exhibit a similar trend in the blue-to-green emission intensity ratio as measured in response to different excitation powers (Fig. 7). This observation was largely attributed to the elimination of the surface quenching effect through the use of an optically inert NaYF_4 layer.

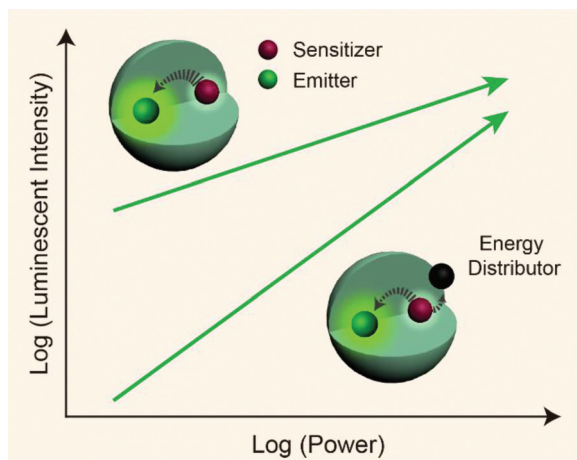


Fig. 5 Schematic representation showing pump-power-dependent luminescence of a sensitizer/emitter codoped nanoparticle in the presence or absence of an energy distributor.

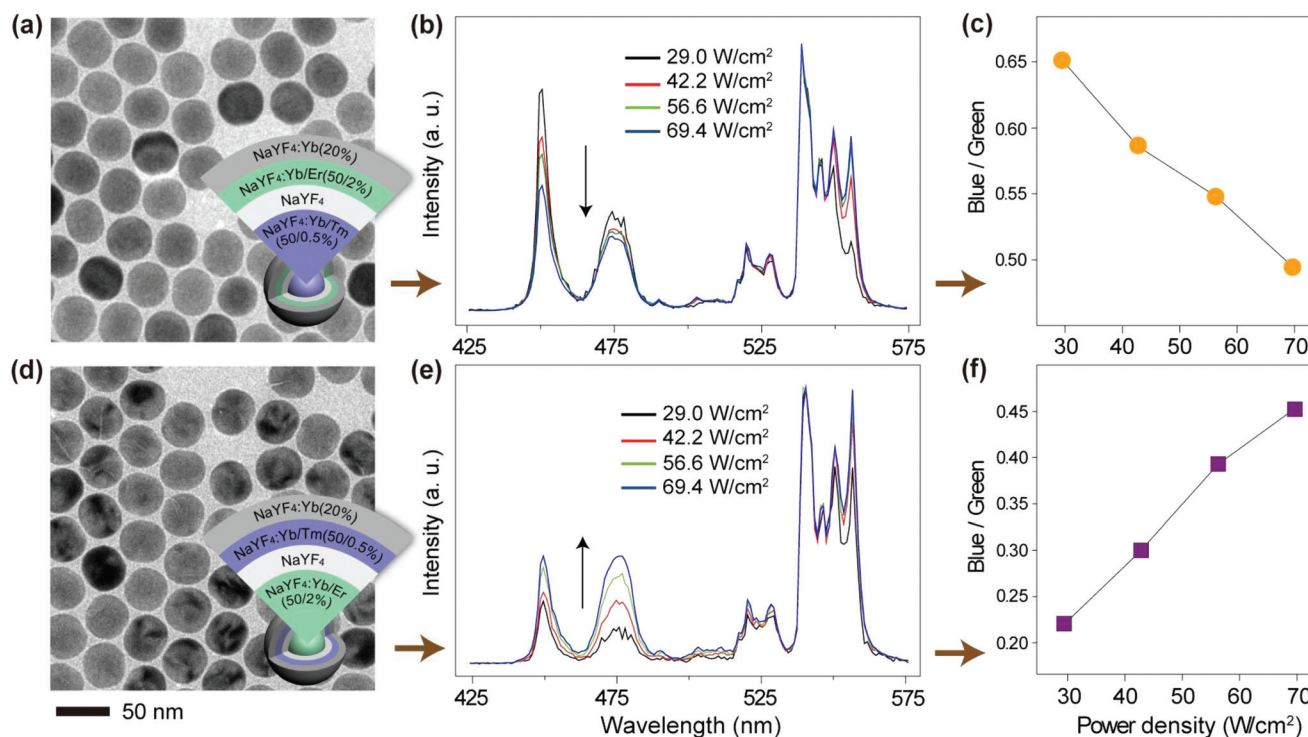


Fig. 6 (a and d) TEM images of $\text{NaYF}_4\text{:Yb/Tm@NaYF}_4\text{:Yb/Er@NaYF}_4\text{:Yb}$ and $\text{NaYF}_4\text{:Yb/Er@NaYF}_4\text{:Yb/Tm@NaYF}_4\text{:Yb}$ nanoparticles, respectively. Insets showing the design layout of the core-shell structures. (b and e) Corresponding power-dependent upconversion emission spectra of the two samples under 975 nm excitation. (c and f) Corresponding pump-power-dependence of the blue/green emission ratio obtained from the two samples.

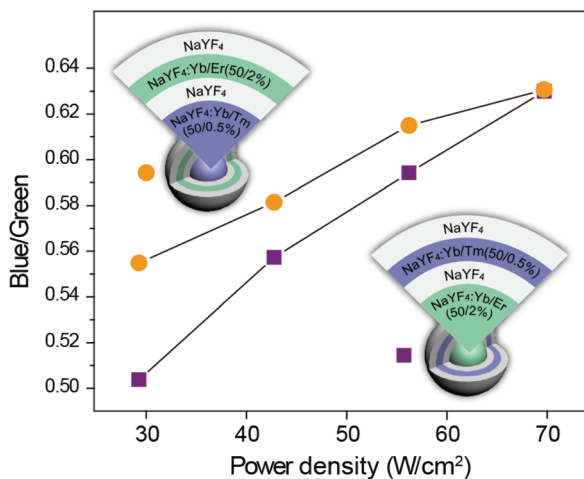


Fig. 7 Power dependent blue-to-green upconversion emission intensity ratio of NaYF₄:Yb/Tm@NaYF₄:Yb/Er@NaYF₄ and NaYF₄:Yb/Er@NaYF₄@NaYF₄:Yb/Tm@NaYF₄ UCNPs upon 975 nm laser irradiation.

Conclusions

We have demonstrated a general approach for the design of upconversion nanocrystals with emitters amenable to non-linear spectral and lifetime management. By controlling the proximity of energy distributors to specific emitters in core-shell structured nanocrystals, power dependent upconversion processes are demonstrated with high temporal tunability. The luminescence lifetime of upconversion nanocrystals can be modified in a wide range, which has potential wide-ranging implications for time-domain optical multiplexing and security applications.

Experimental section

Materials

Yttrium(III) acetate hydrate (99.9%), ytterbium(III) acetate hydrate (99.9%), thulium acetate hydrate (99.9%), erbium(III) acetate hydrate (99.9%), sodium hydroxide (NaOH; >98%), ammonium fluoride (NH₄F; >98%), 1-octadecene (90%), oleic acid (90%), and hydrochloric acid were all purchased from Sigma-Aldrich and used as received without further purification. Analytical grades of ethanol and cyclohexane were purchased from Sigma-Aldrich. Water used in the experiment was purified to have a resistivity of 18.2 MΩ.

Synthesis of NaREF₄ (RE = Y, Yb, Tm, Er) core nanoparticles

In a typical experiment,⁵¹ to a 50 mL flask charged with 3 mL of oleic acid (OA) and 7 mL of 1-octadecene (ODE) was added 2 mL of an aqueous solution containing RE(CH₃CO₂)₃ precursors with a total lanthanide amount of 0.4 mmol. The resulting mixture was heated at 150 °C for 1 h to form a transparent solution and then cooled down to 50 °C. Subsequently, a methanol solution (6 mL) of NH₄F (1.6 mmol) and NaOH (1 mmol) was added and stirred for 30 min. The reaction

temperature was then increased to 110 °C for another 30 min to remove the methanol from the reaction mixture. After that, the solution was heated to 290 °C and maintained at this temperature under an argon atmosphere for 1.5 h. Then the mixture was cooled down to room temperature. The resulting nanoparticles were precipitated out through addition of ethanol, collected by centrifugation (5000 rpm, 10 min), washed with ethanol twice, and finally dispersed in 4 mL of cyclohexane.

Synthesis of NaREF₄@NaREF₄ (RE = Y, Yb, Tm, Er) core-shell nanoparticles

The shell precursor was prepared by mixing RE(CH₃CO₂)₃ (0.2 mmol, RE = Y, Yb, Er, Tm), 3 mL OA and 7 mL ODE in a 50 mL flask, followed by heating at 150 °C for 1 h. After cooling down to 80 °C, 0.2 mmol of NaREF₄ core nanoparticles dispersed in 2 mL of cyclohexane was added. The mixture was slowly cooled down to 50 °C for 30 min, and a methanol solution (3 mL) of NH₄F (0.8 mmol) and NaOH (0.5 mmol) was added. Subsequently, the reaction temperature was increased to 110 °C and kept for 30 min to remove the methanol. After that, the solution was heated to 290 °C and maintained at this temperature under an argon flow for 1.5 h. After cooling to room temperature, the nanoparticles were precipitated out by addition of ethanol, collected by centrifugation, washed with ethanol, and redispersed in 4 mL of cyclohexane. The preparation of multi-shell nanoparticles was carried out by repeating the same procedure except for changing the composition ratio of the lanthanides.

Synthesis of ligand-free nanoparticles

The as-prepared OA-capped nanoparticles were dispersed in the mixture containing 1 mL of ethanol and 1 mL of 0.2 M HCl solution. After removal of the surface ligands by sonication for 1 min, the resulting products were collected by centrifugation (14 000 rpm, 20 min) and were re-dispersed in H₂O after washing with a mixed ethanol-H₂O solution (1 : 1, v/v) 3 times.

Characterization

Transmission Electron Microscopy (TEM) measurements were carried out on a JEOL-1400 transmission electron microscope (JEOL) operating at an acceleration voltage of 100 kV. Powder X-ray Diffraction (XRD) data were obtained on a Siemens D5005 X-ray diffractometer with Cu Kα radiation (λ = 1.5406 Å). The upconversion luminescence spectra under 975 nm excitation were recorded using an Edinburgh FSP920-C spectrometer equipped with a photomultiplier (PMT), in conjunction with a 975 nm diode laser (1 W). The CW laser beam was applied onto UCNPs loaded in a quartz cuvette with a path length of 1 cm. The emission from the samples was collected at an angle of 90° to the excitation beam by using a pair of lenses. The decay curves of upconversion emission were measured by using a customized phosphorescence lifetime spectrometer (FSP920-C, Edinburgh) equipped with a nano-second optical parametric oscillator (OPO) pumped by using a



- 20 C. Liu, Z. Gao, J. Zeng, Y. Hou, F. Fang, Y. Li, R. Qiao, L. Shen, H. Lei, W. Yang and M. Gao, *ACS Nano*, 2013, 7, 7227–7240.
- 21 X. Ai, C. J. Ho, J. Aw, A. B. Attia, J. Mu, Y. Wang, X. Wang, Y. Wang, X. Liu, H. Chen, M. Gao, X. Chen, E. K. Yeow, G. Liu, M. Olivo and B. Xing, *Nat. Commun.*, 2016, 7, 10432.
- 22 Y. F. Wang, G. Y. Liu, L. D. Sun, J. W. Xiao, J. C. Zhou and C. H. Yan, *ACS Nano*, 2013, 7, 7200–7206.
- 23 Y. Q. Lu, J. B. Zhao, R. Zhang, Y. J. Liu, D. M. Liu, E. M. Goldys, X. S. Yang, P. Xi, A. Sunna, J. Lu, Y. Shi, R. C. Leif, Y. J. Huo, J. Shen, J. A. Piper, J. P. Robinson and D. Y. Jin, *Nat. Photonics*, 2014, 8, 33–37.
- 24 Y. Li, J. Tang, L. He, Y. Liu, Y. Liu, C. Chen and Z. Tang, *Adv. Mater.*, 2015, 27, 4075–4080.
- 25 K. Zheng, G. He, W. Song, X. Bi and W. Qin, *J. Mater. Chem. C*, 2015, 3, 11589–11594.
- 26 R. Martín-Rodríguez, S. Fischer, A. Ivaturi, B. Froehlich, K. W. Krämer, J. C. Goldschmidt, B. S. Richards and A. Meijerink, *Chem. Mater.*, 2013, 25, 1912–1921.
- 27 L. Cheng, C. Wang, L. Feng, K. Yang and Z. Liu, *Chem. Rev.*, 2014, 114, 10869–10939.
- 28 S. Gai, C. Li, P. Yang and J. Lin, *Chem. Rev.*, 2014, 114, 2343–2389.
- 29 B. Chen, T. Sun, X. Qiao, X. Fan and F. Wang, *Adv. Opt. Mater.*, 2015, 3, 1577–1581.
- 30 J. Lai, B. P. Shah, Y. Zhang, L. Yang and K. B. Lee, *ACS Nano*, 2015, 9, 5234–5245.
- 31 W. Xu, X. Min, X. Chen, Y. Zhu, P. Zhou, S. Cui, S. Xu, L. Tao and H. Song, *Sci. Rep.*, 2014, 4.
- 32 H. H. Gorris and O. S. Wolfbeis, *Angew. Chem., Int. Ed.*, 2013, 52, 3584–3600.
- 33 J. Wang, R. R. Deng, M. A. MacDonald, B. L. Chen, J. K. Yuan, F. Wang, D. Z. Chi, T. S. A. Hor, P. Zhang, G. K. Liu, Y. Han and X. Liu, *Nat. Mater.*, 2014, 13, 157–162.
- 34 X. Li, X. Liu, D. M. Chevrier, X. Qin, X. Xie, S. Song, H. Zhang, P. Zhang and X. Liu, *Angew. Chem., Int. Ed.*, 2015, 54, 13312–13317.
- 35 Y. Wang, W. Cao, S. Li and W. Wen, *Appl. Phys. Lett.*, 2016, 108, 051902.
- 36 Z. Mi, Y. Zhang, S. K. Vanga, C. B. Chen, H. Q. Tan, F. Watt, X. Liu and A. A. Bettiol, *Nat. Commun.*, 2015, 6, 8832.
- 37 S. Zeng, H. Wang, W. Lu, Z. Yi, L. Rao, H. Liu and J. Hao, *Biomaterials*, 2014, 35, 2934–2941.
- 38 E. M. Chan, G. Han, J. D. Goldberg, D. J. Gargas, A. D. Ostrowski, P. J. Schuck, B. E. Cohen and D. J. Milliron, *Nano Lett.*, 2012, 12, 3839–3845.
- 39 F. Wang and X. Liu, *Acc. Chem. Res.*, 2014, 47, 1378–1385.
- 40 W. Wei, Y. Zhang, R. Chen, J. Goggi, N. Ren, L. Huang, K. K. Bhakoo, H. D. Sun and T. T. Y. Tan, *Chem. Mater.*, 2014, 26, 5183–5186.
- 41 X. Wu, H. Lee, O. Bilsel, Y. Zhang, Z. Li, T. Chen, Y. Liu, C. Duan, J. Shen, A. Punjabi and G. Han, *Nanoscale*, 2015, 7, 18424–18428.
- 42 W. Q. Zou, C. Visser, J. A. Maduro, M. S. Pshenichnikov and J. C. Hummelen, *Nat. Photonics*, 2012, 6, 560–564.

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Notes and references

- 1 F. Auzel, *Chem. Rev.*, 2004, **104**, 139–173.
- 2 S. V. Eliseeva and J.-C. G. Bünzli, *New J. Chem.*, 2011, **35**, 1165.
- 3 M. Haase and H. Schafer, *Angew. Chem., Int. Ed.*, 2011, **50**, 5808–5829.
- 4 H. Schäfer, P. Ptacek, B. Voss, H. Eickmeier, J. Nordmann and M. Haase, *Cryst. Growth Des.*, 2010, **10**, 2202–2208.
- 5 M. Bettinelli, L. Carlos and X. Liu, *Phys. Today*, 2015, **68**, 38–44.
- 6 N. J. Greybush, M. Saboktakin, X. Ye, C. Della Giovampaola, S. J. Oh, N. E. Berry, N. Engheta, C. B. Murray and C. R. Kagan, *ACS Nano*, 2014, **8**, 9482–9491.
- 7 W. Yang, X. Li, D. Chi, H. Zhang and X. Liu, *Nanotechnology*, 2014, **25**, 482001.
- 8 S. Guo, X. Xie, L. Huang and W. Huang, *ACS Appl. Mater. Interfaces*, 2016, **8**, 847–853.
- 9 W. Zheng, P. Huang, D. Tu, E. Ma, H. Zhu and X. Chen, *Chem. Soc. Rev.*, 2015, **44**, 1379–1415.
- 10 D. Liu, X. Xu, Y. Du, X. Qin, Y. Zhang, C. Ma, S. Wen, W. Ren, E. M. Goldys, J. A. Piper, S. Dou, X. Liu and D. Jin, *Nat. Commun.*, 2016, **7**, 10254.
- 11 J. Lai, Y. Zhang, N. Pasquale and K. B. Lee, *Angew. Chem., Int. Ed.*, 2014, **53**, 14419–14423.
- 12 J. Zhou, Q. Liu, W. Feng, Y. Sun and F. Li, *Chem. Rev.*, 2015, **115**, 395–465.
- 13 X. Chen, L. Jin, W. Kong, T. Sun, W. Zhang, X. Liu, J. Fan, S. F. Yu and F. Wang, *Nat. Commun.*, 2016, **7**, 10304.
- 14 B. Zhou, B. Shi, D. Jin and X. Liu, *Nat. Nanotechnol.*, 2015, **10**, 924–936.
- 15 G. Chen, H. Qiu, P. N. Prasad and X. Chen, *Chem. Rev.*, 2014, **114**, 5161–5214.
- 16 Y. I. Park, K. T. Lee, Y. D. Suh and T. Hyeon, *Chem. Soc. Rev.*, 2015, **44**, 1302–1317.
- 17 D. Ni, J. Zhang, W. Bu, H. Xing, F. Han, Q. Xiao, Z. Yao, F. Chen, Q. He, J. Liu, S. Zhang, W. Fan, L. Zhou, W. Peng and J. Shi, *ACS Nano*, 2014, **8**, 1231–1242.
- 18 A. B. Chinen, C. M. Guan, J. R. Ferrer, S. N. Barnaby, T. J. Merkel and C. A. Mirkin, *Chem. Rev.*, 2015, **115**, 10530–10574.
- 19 L. L. Li and Y. Lu, *J. Am. Chem. Soc.*, 2015, **137**, 5272–5275.

- 43 F. Wang and X. Liu, *J. Am. Chem. Soc.*, 2008, **130**, 5642–5643.
- 44 R. Deng, F. Qin, R. Chen, W. Huang, M. Hong and X. Liu, *Nat. Nanotechnol.*, 2015, **10**, 237–242.
- 45 A. Sedlmeier and H. H. Gorris, *Chem. Soc. Rev.*, 2015, **44**, 1526–1560.
- 46 J. C. Boyer, C. J. Carling, B. D. Gates and N. R. Branda, *J. Am. Chem. Soc.*, 2010, **132**, 15766–15772.
- 47 C. Zhang, L. Yang, J. Zhao, B. Liu, M. Y. Han and Z. Zhang, *Angew. Chem., Int. Ed.*, 2015, **54**, 11531–11535.
- 48 G. Chen, T. Y. Ohulchanskyy, A. Kachynski, H. Agren and P. N. Prasad, *ACS Nano*, 2011, **5**, 4981–4986.
- 49 M. Pollnau, D. R. Gamelin, S. R. Lüthi, H. U. Güdel and M. P. Hehlen, *Phys. Rev. B: Condens. Matter*, 2000, **61**, 3337–3346.
- 50 J. F. Suyver, A. Aebischer, S. García-Revilla, P. Gerner and H. U. Güdel, *Phys. Rev. B: Condens. Matter*, 2005, **71**, 125123.
- 51 F. Wang, R. Deng and X. Liu, *Nat. Protoc.*, 2014, **9**, 1634–1644.
- 52 M. T. Berry and P. S. May, *J. Phys. Chem. A*, 2015, **119**, 9805–9811.
- 53 X. Chen, D. Peng, Q. Ju and F. Wang, *Chem. Soc. Rev.*, 2015, **44**, 1318–1330.
- 54 H. Schäfer, P. Ptacek, O. Zerzouf and M. Haase, *Adv. Funct. Mater.*, 2008, **18**, 2913–2918.
- 55 Y. Wang, L. Tu, J. Zhao, Y. Sun, X. Kong and H. Zhang, *J. Phys. Chem. C*, 2009, **113**, 7164–7169.
- 56 A. Kar and A. Patra, *Nanoscale*, 2012, **4**, 3608–3619.
- 57 S. Han, R. Deng, X. Xie and X. Liu, *Angew. Chem., Int. Ed.*, 2014, **53**, 11702–11715.
- 58 F. Zhang, R. Che, X. Li, C. Yao, J. Yang, D. Shen, P. Hu, W. Li and D. Zhao, *Nano Lett.*, 2012, **12**, 2852–2858.
- 59 L. Lei, D. Chen, P. Huang, J. Xu, R. Zhang and Y. Wang, *Nanoscale*, 2013, **5**, 11298–11305.
- 60 Y. Wang, K. Liu, X. M. Liu, K. Dohnalová, T. Gregorkiewicz, X. G. Kong, M. C. G. Aalders, W. J. Buma and H. Zhang, *J. Phys. Chem. Lett.*, 2011, **2**, 2083–2088.
- 61 J. Zhao, Z. Lu, Y. Yin, C. McRae, J. A. Piper, J. M. Dawes, D. Jin and E. M. Goldys, *Nanoscale*, 2013, **5**, 944–952.
- 62 F. Vetrone, R. Naccache, V. Mahalingam, C. G. Morgan and J. A. Capobianco, *Adv. Funct. Mater.*, 2009, **19**, 2924–2929.
- 63 F. Wu, X. Liu, X. Kong, Y. Zhang, L. Tu, K. Liu, S. Song and H. Zhang, *Appl. Phys. Lett.*, 2013, **102**, 243104.
- 64 J.-C. Boyer, M.-P. Manseau, J. I. Murray and F. C. J. M. van Veggel, *Langmuir*, 2009, **26**, 1157–1164.
- 65 Y. P. Li, J. H. Zhang, Y. S. Luo, X. Zhang, Z. D. Hao and X. J. Wang, *J. Mater. Chem.*, 2011, **21**, 2895–2900.
- 66 J. M. Meruga, A. Baride, W. Cross, J. J. Kellar and P. S. May, *J. Mater. Chem. C*, 2014, **2**, 2221–2227.
- 67 G. Y. Chen, Y. Liu, Y. G. Zhang, G. Somesfalean, Z. G. Zhang, Q. Sun and F. P. Wang, *Appl. Phys. Lett.*, 2007, **91**, 133103.
- 68 Y. F. Bai, Y. X. Wang, G. Y. Peng, W. Zhang, Y. K. Wang, K. Yang, X. R. Zhang and Y. L. Song, *Opt. Commun.*, 2009, **282**, 1922–1924.
- 69 M. Quintanilla, F. Q. Ren, D. L. Ma and F. Vetrone, *ACS Photonics*, 2014, **1**, 662–669.
- 70 H. Wen, H. Zhu, X. Chen, T. F. Hung, B. Wang, G. Zhu, S. F. Yu and F. Wang, *Angew. Chem., Int. Ed.*, 2013, **52**, 13419–13423.