

Multifield-enhanced multimodal temperature sensing using Er³⁺-rich upconversion nanostructures

Shunan Zhang¹, Hao Wu¹, Jiajun Li¹, Lujun Niu¹, Enhui Wang², Yihao Liu¹, Xiaoming Wan¹, Jiahang Li¹, Langping Tu³, Jian Yang⁴, Donglei Zhou², Tingting Zhou², and Jing Zuo¹

¹ Key Laboratory of Automobile Materials of Ministry of Education, School of Materials Science and Engineering, Jilin University, Changchun 130022, China

² State Key Laboratory of Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, China

³ School of Materials Science and Engineering, Changchun University of Science and Technology, Changchun 130022, China

⁴ School of Physics, Northeast Normal University, Changchun 130024, China

Cite this article: Nano Research, 2026, 19, 94909076. <https://doi.org/10.26599/NR.2026.94909076>

ABSTRACT: Insufficient upconversion luminescence (UCL) intensity under low-irradiance remains a critical bottleneck of lanthanide-doped nanoparticles, which severely limits their further application. Herein, through a multi-field enhanced strategy combining photonic crystal, plasmonic, and low-temperature fields, an UCL enhancement factor of 1290 is achieved in an Er³⁺-rich nanosystem. Based on that, a distinctive multimode fluorescence ratiometric upconversion thermometer is well-achieved. Specifically, leveraging the multi-wavelength excitation capability of the Er³⁺-rich system, six independent operating modes based on infrared-to-green emission intensity ratios are realized in a single composite structure composed of upconversion nanoparticles, gold nanorods, and polymethyl methacrylate (PMMA) opal photonic crystals under 808, 980, and 1530 nm excitation. These modes endow the thermometer with flexible operation selection, high sensitivity, and high precision across the 80–300 K range. The maximum relative sensitivity of all the six modes reaches 7.06%–14.95% K⁻¹, with a high resolution in the range 0.008–0.634 K, which is several to tens of times higher than that of the conventional upconversion systems. This work not only provides an effective strategy for substantially enhancing UCL but also offers new insights into the design of high-performance optical thermometers.

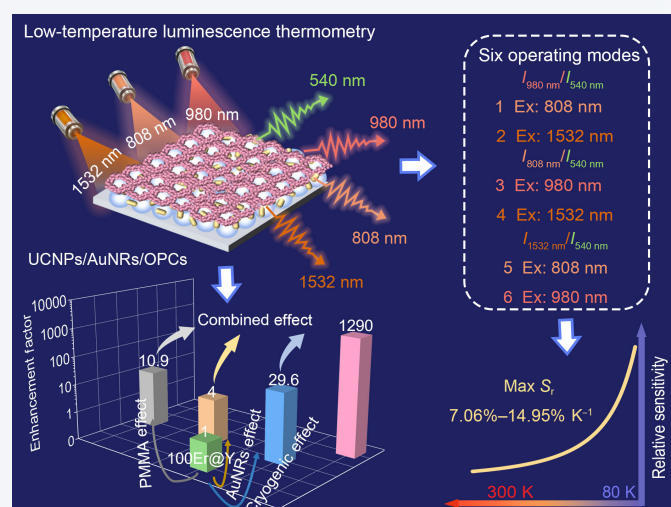
KEYWORDS: upconversion nanoparticles, luminescence thermometers, photonic crystals, luminescence efficiency, gold nanorods

1 Introduction

Upconversion luminescence (UCL), an anti-Stokes process that converts long-wavelength excitation into short-wavelength emission, has attracted considerable attention due to its high

chemical stability [1], multiplexed spectral features [2, 3], and long luminescence lifetime [4], demonstrating broad application potential in photodynamic therapy [5], three-dimensional (3D) displays [6, 7], anti-counterfeiting [8, 9], and biosensing [10]. In recent years, highly doped lanthanide-based nanostructures (HDLNs) have emerged as a research focus due to their relatively high luminescence efficiency and precisely tunable emission properties under external fields [11–13]. Accordingly, the performance optimization and functional expansion of HDLNs have become heated topics in this field.

Among the various modulation aspects (e.g., efficiency, emission color, and lifetime), achieving highly efficient UCL has long been



Received: June 2, 2026; Revised: July 16, 2026

Accepted: August 3, 2026

✉ Address correspondence to Jing Zuo, jzuo@jlu.edu.cn; Tingting Zhou, zhoutt@jlu.edu.cn

recognized as the critical factor for the practical application of upconversion materials [14, 15]. To date, a variety of effective strategies have been reported including particle optimization (e.g., morphology [16, 17], size [18–20], and structure [21–23]), dry synthesis methods [24], and external field modulation (such as plasmonic [25, 26], photonic crystal [27], and temperature fields [28]). Among these, external field modulation offers broad applicability and flexibility, making it one of the most widely employed strategies [29–31]. Specifically, plasmonic field enhancement, which exploits the localized surface plasmon resonance (LSPR) of metallic nanostructures, can markedly increase the local electromagnetic field intensity and photon absorption efficiency, and has therefore become one of the most widely employed strategies for UCL enhancement [32–34]. Similarly, through photonic bandgap modulation, photonic crystal fields can also enhance emission intensity by inducing photon localization [35, 36]. Notably, recent studies have demonstrated that, for specific Er-based highly doped systems, the low-temperature environment can effectively suppress detrimental interionic cross relaxation (CR) processes, reduce energy loss and thereby markedly enhance UCL efficiency [37, 38]. However, it is still a significant challenge to effectively integrate the aforementioned regulation strategies to achieve brighter UCL in terms of magnitude [27, 28].

On the other hand, from the application perspective, upconversion ratiometric fluorescence thermometers have attracted considerable interest owing to their non-contact operation [39–41], high sensitivity [42, 43], and broad temperature response range [44], making them promising for extreme environment monitoring, *in vivo* temperature sensing and other complex scenarios. However, most existing upconversion ratiometric thermometers rely on single-wavelength excitation and their performance in the low-temperature regime (< 100 K) remains limited [45–49]. In general, conventional designs are based on the emission intensity ratio of two thermally coupled energy levels (following Boltzmann's law) [50, 51]. At low temperatures, however, insufficient phonon energy makes the UCL from higher-energy states too weak for reliable temperature sensing [52, 53]. In summary, the limited excitation flexibility and suboptimal performance severely restrict the universal applicability of these thermometers. To date, exploiting the enhanced upconversion system to construct a multi-wavelength ratiometric thermometer with a broad temperature range, high sensitivity, and high resolution remains a huge challenge.

In this work, we present a multi-field enhancement strategy in the facile Er³⁺-rich nanosystem capable of multi-wavelength excitation, combining a polymethyl methacrylate (PMMA) opal photonic crystal field, a gold nanorod-based plasmonic field, and a low-temperature field. Through the combination of multiple physical fields, a robust UCL intensity enhancement is achieved, with a maximum luminescence enhancement factor of 1290, markedly surpassing the reports from single-field manipulation (which typically yield only an enhancement of dozens of times). In addition, leveraging the unique optical properties of Er³⁺-rich nanosystem (Fig. S1 in the Electronic Supplementary Material (ESM)), we construct a novel ratiometric upconversion thermometer, capable of multi-wavelength excitation at 808, 980, and 1532 nm, and, more importantly, unprecedented supporting six distinct ratiometric modes. The thermometer not only allows flexible selection for diverse application scenarios over the broad temperature range (80–300 K), but also exhibits outstanding

sensitivity (7.06%–14.95% K⁻¹) and temperature resolution (0.008–0.634 K) across all six operating modes, surpassing those of conventional upconversion materials (e.g., NaYF₄:20%Yb, 2%Er@NaYF₄) by several- to tens-fold. All these results offer a new avenue for the rational design of high-precision thermometers based on efficient upconversion nanomaterials.

2 Experimental section

2.1 Materials

All chemicals were purchased from commercial suppliers and used as received unless otherwise noted. YCl₃·6H₂O (99.99%), ErCl₃·6H₂O (99.9%), trifluoroacetic acid (CF₃COOH, 98%), oleic acid (OA, 90%), 1-octadecene (ODE, 90%), chloroauric acid (HAuCl₄, 99%), sodium borohydride (NaBH₄, 98%), cetyltrimethylammonium bromide (CTAB, > 98%), silver nitrate (AgNO₃, > 99%), sodium oleate (NaOL, > 97%), and ascorbic acid (C₆H₈O₆, 99%) were purchased from Sigma-Aldrich. Y₂O₃, methyl methacrylate (MMA, C₅H₈O₂, 99%), and sodium hydroxide (NaOH, 99.9%) were obtained from Aladdin. Potassium persulfate (K₂S₂O₈, 99.5%), 2,2'-azobis(2-methylpropionitrile) (AIBN, 98%), ammonium fluoride (NH₄F, 96%), and sodium trifluoroacetate (CF₃COONa, 97%) were purchased from Macklin. Methanol anhydrous (99.5%), hydrochloric acid (HCl, 37%), ethanol absolute (99.7%), and cyclohexane (99.7%) were obtained from Sinopharm Chemical Works.

2.2 Synthesis of β-NaY_{1-x}Er_xF₄@NaYF₄ core@shell upconversion nanoparticles (UCNPs)

1 mmol of rare-earth chlorides (ErCl₃·6H₂O and YCl₃·6H₂O with desired molar ratios) were mixed with OA (6 mL) and ODE (15 mL), heated to 150 °C under argon with stirring to form a clear solution, then cooled to 35 °C. Subsequently, a methanol solution containing NaOH (2.5 mmol) and NH₄F (4 mmol) was added. The mixture was heated to 80–85 °C to evaporate the methanol, then rapidly heated to 300 °C and held for 60 min. After cooling to 60 °C, the obtained core nanoparticles were washed with ethanol and dispersed in cyclohexane.

Synthesis of shell precursors. First, 10 mmol of Y₂O₃ was added to 60 mmol of trifluoroacetic acid and heated to 110 °C until a clear solution formed. After removal of excess acid and water, the CF₃COOH was obtained. Subsequently, the CF₃COOH and CF₃COONa (equimolar ratio), as well as OA and ODE (equal volume ratio), were mixed in a flask, heated to 120 °C to dissolve the solids and remove water, and then cooled to room temperature.

For shell growth, 0.25 mmol of preformed core nanoparticles was dispersed in a 50 mL three-neck flask containing 5 mL OA and 5 mL ODE and heated at 85 °C for 30 min to remove cyclohexane. The solution was then heated to 300 °C under argon, followed by the stepwise injection of 1 mmol shell precursor in four portions at 15 min intervals. After the final addition, the reaction mixture was kept at 300 °C for an additional 45 min to complete shell growth. The resulting product was cooled to room temperature, precipitated with ethanol, washed, and finally redispersed in cyclohexane.

2.3 Synthesis of gold nanorods (AuNRs)

The seed solution was synthesized by mixing 0.25 mL of HAuCl₄ (0.01 M) with 9.75 mL of CTAB (0.1 M), followed by the addition of 0.048 mL of freshly prepared NaBH₄ (0.1 M) under vigorous

stirring for 2 min. To prepare the growth solution, CTAB (0.7 g) and NaOL (1.234 g) were dissolved in water (50 mL). The mixture was stirred at 70 °C for 30 min and then cooled to 30 °C. Subsequently, 0.72 mL of 0.01 mol/L AgNO_3 solution, 2.5 mL of 0.01 mol/L HAuCl_4 solution, 1.8 mL of 1 mol/L HCl, and 0.08 mL of 0.1 mol/L ascorbic acid solution were added sequentially, with gentle stirring after each addition. Finally, 0.04 mL of the seed solution was added and the mixture was left undisturbed at 30 °C for 12 h to obtain AuNRs.

2.4 Synthesis of PMMA opal photonic crystals (OPCs)

Purified MMA (6 mL) was mixed with water (80 mL) and $\text{K}_2\text{S}_2\text{O}_8$ (36 mg) in a three-neck flask, heated to 90 °C under stirring for 90 min, and then cooled to room temperature. To adjust the microsphere size, the resulting PMMA suspension (40 mL) was mixed with water (40 mL), purified MMA (6 mL), and AIBN (36 mg), followed by stirring at 90 °C for 30 min. This seeded growth step was repeated until the desired size was achieved. The obtained PMMA microspheres were then assembled into opal photonic crystals by vertical deposition on glass slides at 32 °C for 26 h.

2.5 Fabrication of UCNPs and UCNPs/ OPCs hybrid films

A square area (0.5 cm $\times$ 0.5 cm) was defined on the glass substrate. UCNPs dispersion (20 μL) was applied to the defined region, and the cyclohexane was allowed to evaporate at room temperature.

A square area (0.5 cm $\times$ 0.5 cm) was defined on the OPCs-coated glass substrate. UCNPs dispersion (20 μL) was applied to the defined region. Upon evaporation of cyclohexane, UCNPs were immobilized onto the OPCs film to form the final hybrid structure.

2.6 Fabrication of UCNPs/AuNRs/OPCs hybrid films

A square area (0.5 cm $\times$ 0.5 cm) of the OPCs on glass was defined. AuNRs solution (20 μL) was applied to this area and dried at room temperature, during which AuNRs self-assembled on the OPC surface. Subsequently, UCNPs dispersion (20 μL) was applied to the same region. Upon evaporation of cyclohexane, UCNPs were immobilized onto the AuNRs/OPCs composite film to form the final hybrid structure.

2.7 Characterization

The X-ray diffraction (XRD) patterns were recorded on a Bruker D8 Advance diffractometer using $\text{Cu K}\alpha$ radiation ($\lambda = 1.542 \text{ \AA}$). Transmission electron microscopy (TEM), scanning transmission electron microscopy (STEM) images, and energy-dispersive X-ray (EDS) mapping were performed using a Tecnai G2 F20 S-TWIN D573 microscope operated at an acceleration voltage of 300 kV. Ultraviolet (UV) absorption spectra were recorded on a UV-1808 spectrophotometer. Steady-state photoluminescence spectra were measured on the FLS 980 spectrometer under 808, 980, and 1532 nm excitation. The visible and 808 nm near-infrared (NIR) emission signals were detected using an R13456 detector, and the 980 and 1532 nm NIR emission signals were collected with an H1033C-75 detector. Temperature-dependent measurements were conducted using an Instec temperature-controlled stage. Luminescence decay dynamics were acquired with a 500 MHz Tektronix digital oscilloscope under 488 and 970 nm nanosecond pulsed excitation generated from an optical parametric oscillator (OPO).

3 Results and discussion

3.1 Structural characterizations of the UCNPs, AuNRs, and PMMA OPCs

Figure 1(a) schematically depicts the fabrication of the UCNPs/AuNRs/OPCs hybrid architecture. PMMA OPCs were assembled on glass substrates via vertical deposition, followed by solvent-evaporation-assisted permeation of AuNRs and $x\text{Er@Y}$ ($\text{NaYF}_4:x\%\text{Er@NaYF}_4$, $x = 25, 50$, and 100) into their pores, enabling the close integration of $x\text{Er@Y}$, AuNRs, and PMMA OPCs. The series of $x\text{Er@Y}$ nanoparticles were prepared via successive epitaxial multi-shell deposition [54], with their TEM and XRD results shown in Figs. 1(b) and 1(c) and Figs. S2 and S3 in the ESM. Taking 100Er@Y as an example, the TEM images (Fig. 1(b) and Fig. S2(e) in the ESM) reveal uniform core and core-shell nanostructures, with average diameters of 18.3 ± 1.1 and 36.7 ± 0.9 nm, respectively. The X-ray diffraction data align with the standard reference card (JCPDS No. 16-0334), indicating the hexagonal phase of UCNPs (Fig. 1(c)). The high-resolution TEM characterization further verifies the lattice periodicity and crystallinity of the sample (Fig. S4 in the ESM). Moreover, elemental mapping confirms the spatial confinement of Er^{3+} ions in the core and Y^{3+} ions in the shell area, demonstrating the successful construction of the core-shell architecture (Fig. 1(d)).

For AuNRs, the SEM image in Fig. 1(e) shows that the AuNRs possess excellent dispersity and uniform dimensions, with an average length of 80.7 nm and diameter of 17.8 nm. The PMMA OPCs used for localized electric field modulation exhibit a well-ordered face-centered cubic (FCC) lattice with a lattice constant of 430 nm (Fig. 1(f)). Subsequently, AuNRs were incorporated onto the surfaces and into the interstitial regions of the well-aligned photonic crystal framework, thereby creating nanoscale gaps between the AuNRs and OPCs in which UCNPs are then embedded (Fig. 1(g) and Fig. S5 in the ESM). Figure 1(h) shows the absorption spectrum of the AuNRs and the transmittance spectrum of the PMMA OPCs, with both peaks centered around 980 nm. In our design, the plasmonic and photonic crystal fields can be simultaneously employed to enhance the UCL of the $x\text{Er@Y}$ nanoparticles.

3.2 UCL enhancement effect using the plasmonic-photonic crystal hybrid structure

Next, we systematically investigated the enhancement effects of PMMA OPCs and AuNRs on the UCL in the Er^{3+} -rich nanosystem at room temperature. To ensure consistent experimental conditions, all optical data were acquired using the same optical configuration (Fig. 2(a)). As shown in Figs. 2(b) and 2(c), for the selected Er^{3+} singly doped system, two characteristic emission bands appear in the visible region, corresponding to the $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$ transition (red emission) and the $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ transition (green emission). With the increase of Er^{3+} doping concentration, the red emission and overall UCL intensities of the UCNPs gradually increase, whereas the green emission intensity progressively declines. This behavior can be attributed to the shortened Er–Er interionic distance, which promotes CR processes and thereby facilitates green-to-red energy transfer, leading to a marked increase in the red-to-green (R/G) emission ratio.

Subsequently, upon the combined modulation of PMMA OPCs and AuNRs, the UCL intensities of 25, 50, and 100Er@Y samples

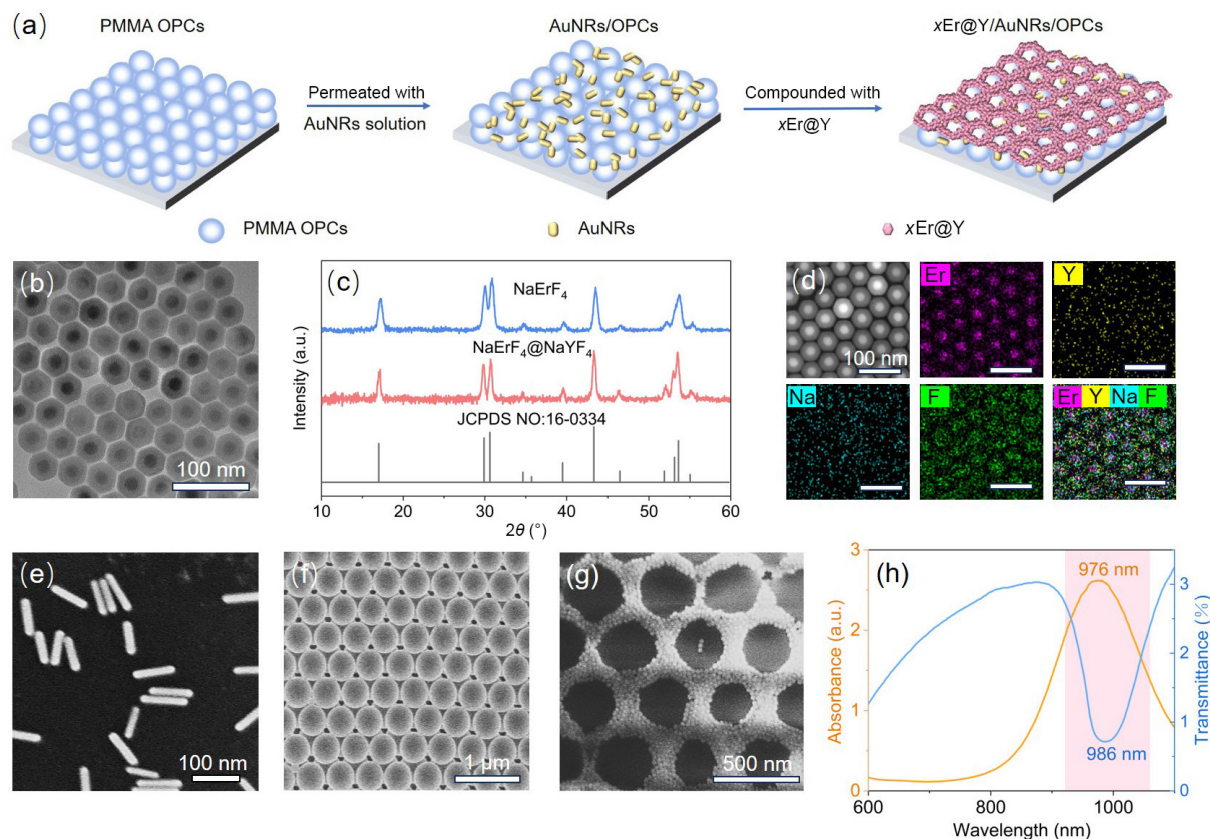


Figure 1 Structural characterizations. (a) Schematic illustration of AuNRs/OPCs and xEr@Y/AuNRs/OPCs hybrids formation process. (b) TEM image of NaErF₄@NaYF₄ nanoparticles. (c) XRD patterns of the core and core-shell samples, together with the standard data of hexagonal-phase NaYF₄ (JCPDS No. 16-0334). (d) HAADF-STEM image and element mapping results. SEM images of (e) AuNRs, (f) PMMA OPCs, and (g) UCNPs/AuNRs/OPCs hybrids. (h) Transmittance spectra of the PMMA OPCs and absorption spectra of the water-dispersed AuNRs.

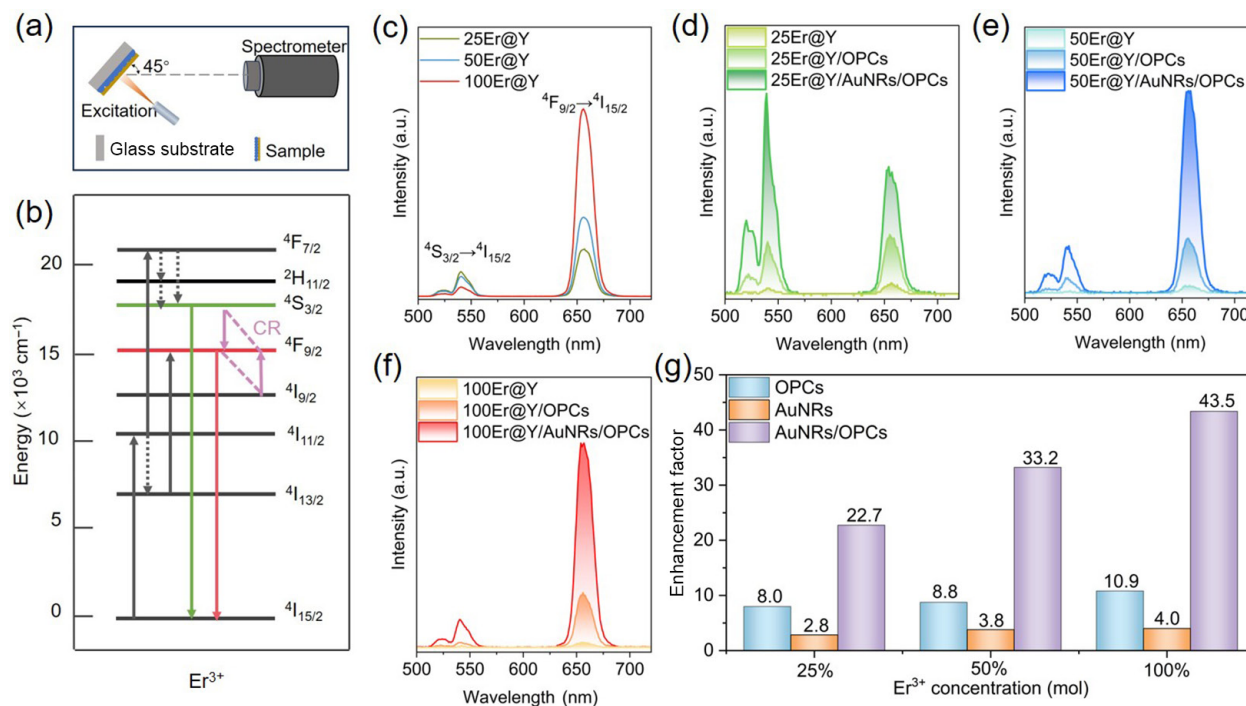


Figure 2 Experimental results of UCL enhancement using the plasmonic-photonic crystal hybrid structure. (a) Schematic of the optical test path employed in all subsequent measurements. (b) Energy level transition diagram of Er³⁺ ions in the Er³⁺-rich system. (c) Emission spectra of xEr@Y ($x = 25, 50$, and 100). Room-temperature UCL spectra of xEr@Y, xEr@Y/OPCs, and xEr@Y/AuNRs/OPCs, with (d)–(f) corresponding to $x = 25, 50$, and 100 , respectively. (g) Enhancement factors of xEr@Y ($x = 25, 50$ and 100) induced by PMMA OPCs, AuNRs, and AuNRs/OPCs hybrids. All the measurements in ((c)–(f)) were performed under the 980 nm excitation, with power density of 0.36 W/cm^2 .

were all markedly enhanced (Figs. 2(d)–2(f)). As shown in Fig. 2(g), PMMA OPCs enhance the UCL intensities of $x\text{Er@Y}$ ($x = 25, 50$, and 100) by factors of $8.0, 8.8$, and 10.9 , respectively. According to previous reports, this enhancement is attributed to the localization effect of PMMA OPCs on 980 nm excitation photons, which effectively increases the absorption efficiency of the UCNP [33, 55]. Upon further hybridization with AuNRs, the plasmonic field provides additional enhancement factors of $2.8-, 3.4-$, and 4.0 -fold, respectively, leading to overall enhancement factors of $22.7-, 33.2-$, and 43.5 -fold with dual-field modulation. To clarify the enhancement mechanism, the time-domain UCL spectra were investigated by using 970 nm pulsed excitation, showing that lifetime of the $\text{Er}^{3+} {}^4\text{I}_{11/2}$ level is nearly unaffected by the incorporation of AuNRs (Fig. S6 in the ESM). Consequently, the observed plasmonic enhancement does not originate from the Purcell effect, which would typically be accompanied by a shortened lifetime [56]. Instead, it arises from excitation-field amplification, which strengthens the local optical field experienced by the UCNP. Notably, among the three series of samples, 100Er@Y exhibits the strongest UCL as well as the largest enhancement factor under the modulation of OPCs and AuNRs (Figs. 2(c) and 2(g)). Therefore, it has been chosen as the representative system for subsequent systematic investigations.

3.3 Effect and mechanism of low temperatures in the Er^{3+} -rich nanosystem

Furthermore, we focused on the modulation of UCL by varying

temperatures in the Er^{3+} -rich nanosystem. The temperature-dependent emission spectra of the $100\text{Er@Y/AuNRs/OPCs}$ hybrids are shown in Fig. 3(a). As expected, both the green and red UCL are markedly enhanced with decreasing temperature, peaking at 80 K . Compared with the room temperature case, the integrated visible emission intensity at 80 K is enhanced by a factor of 29.6 , with green (540 nm) and red (650 nm) emissions increased by 597 - and 16 -fold, respectively (Fig. 3(b)). Combining the measured results from Figs. 2(g) and 3(b), a pronounced synergistic enhancement of UCL (1290 -fold) can be well observed, with photonic-crystal, AuNRs plasmonic field, and low-temperature modulation, contributing 10.9 -, 4 -, and 29.6 -fold enhancement factors, respectively (Fig. 3(c)).

Next, attention is turned to the emission enhancement mechanism induced by low temperatures. For the 100Er@Y system, the excited states on emitting energy levels have three competing depopulation channels: radiative transitions, nonradiative relaxation, and phonon-assisted CR. Due to the ultra-short interionic distances, $\text{Er}^{3+}\text{--}\text{Er}^{3+}$ CR dominates the depopulation process. Especially in the case of relatively high temperatures (e.g., 300 K), abundant phonons accelerate cascaded CR between up-closed Er^{3+} ions, leading high-energy excited states to decay rapidly to the NIR level (Fig. 3(d)), resulting in weak UCL. On the contrary, at low temperatures, the cascaded CR can be suppressed in the absence of essential phonon-assisted processes, resulting in pronounced visible UCL (Fig. 3(d)). To further verify this assumption, we measured the fluorescence lifetimes of the

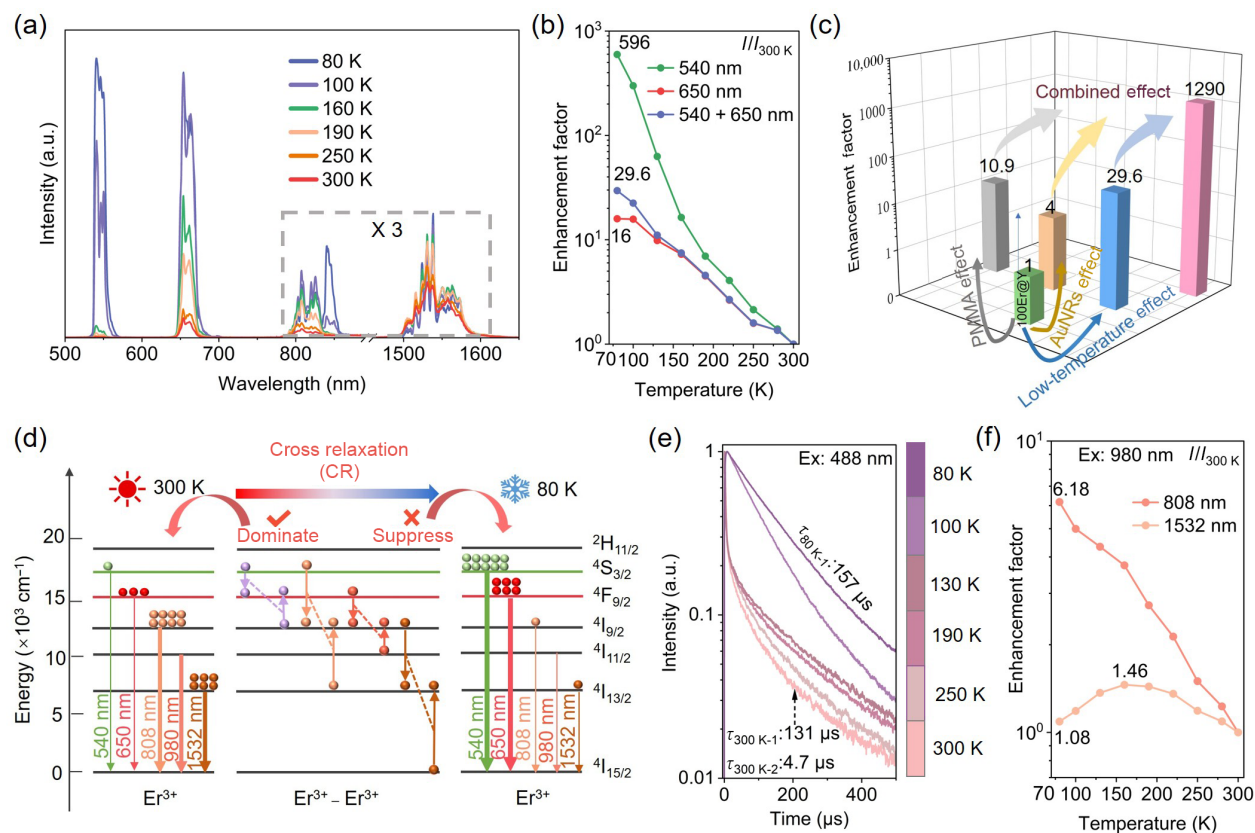


Figure 3 Effect and mechanism of low temperatures in the Er^{3+} -rich nanosystem. (a) UCL spectra of $100\text{Er@Y/AuNRs/OPCs}$ hybrids in the visible and NIR regions (980 nm excitation, $0.36\text{ W}\cdot\text{cm}^{-2}$) at temperatures ranging from 80 to 300 K . (b) Emission enhancement factors of $100\text{Er@Y/AuNRs/OPCs}$ hybrids induced by low temperature (i.e., $I_{80\text{ K}}/I_{300\text{ K}}$). (c) Enhancement of visible UCL in 100Er@Y under individual and combined photonic crystal, plasmonic, and low-temperature fields. (d) Schematic of cascade CR effects in the Er^{3+} -rich nanosystem at 300 and 80 K . (e) The decay curves for ${}^4\text{S}_{3/2} \rightarrow {}^4\text{I}_{15/2}$ transition of 100Er@Y upon 488 nm pulsed excitation. (f) NIR enhancement factor of $100\text{Er@Y/AuNRs/OPCs}$ induced by low temperature.

upconversion nanoparticles. As shown in Fig. 3(e), under 488 nm pulsed excitation (10 ns), the 545 nm emission of the 100Er@Y sample exhibits a relatively long decay lifetime of 157 μ s at 80 K, indicating a strong suppression of Er^{3+} - Er^{3+} CR depopulation. In contrast, at 300 K, an extremely fast decay process (~ 4.2 μ s) can be observed, reflecting the rapid depopulation of the excited state induced by efficient CR.

Notably, the influence of CR on NIR emission channels is considerably weaker. As shown in Figs. 3(a) and 3(f), only minor variation of the 808 nm (6.18-fold) and 1532 nm (1.46-fold) emission intensities can be obtained with the temperature changed from 80 to 300 K, which are in sharp contrast to the green emission (varying 596-fold). These results provide a favorable opportunity for constructing highly sensitive ratiometric luminescence thermometers.

3.4 Temperature-sensing performance of the multimode fluorescence ratiometric upconversion thermometer

As shown in Fig. 4(a), the intensity ratios of 808 or 1532 nm to green emission (540 nm) fit well to the Boltzmann model over the investigated temperature range (80–300 K), indicating reliable thermometric behavior. Based on this, several key parameters: S_a , S_r ,

and δT , were quantitatively calculated using the following expressions

$$\text{LIR} = \frac{I_{\text{NIR}}}{I_{\text{Green}}} = A \exp\left(-\frac{\Delta E}{k_B T}\right) \quad (1)$$

$$S_a = \frac{\partial \text{LIR}}{\partial T} = \text{LIR} \frac{\Delta E}{k_B T^2} \quad (2)$$

$$S_r = \left| \frac{1}{\text{LIR}} \frac{\partial \text{LIR}}{\partial T} \right| = \frac{S_a}{\text{LIR}} = \frac{\Delta E}{k_B T^2} \quad (3)$$

$$\delta T = \frac{1}{S_r} \frac{\delta \text{LIR}}{\text{LIR}} \quad (4)$$

where I_{NIR} and I_{Green} denote the integrated emission intensities; A and ΔE are fitting parameters; k_B and T represent the Boltzmann constant and absolute temperature, respectively. Strikingly, these important parameters maintain excellent performance. Specifically, the maximum S_r reaches 8.10% and 13.47% K^{-1} for the 808 and 1532 nm reference bands, respectively, while the maximum S_a attains 10.18% and 110.89% K^{-1} (Fig. 4(b)). All these numbers

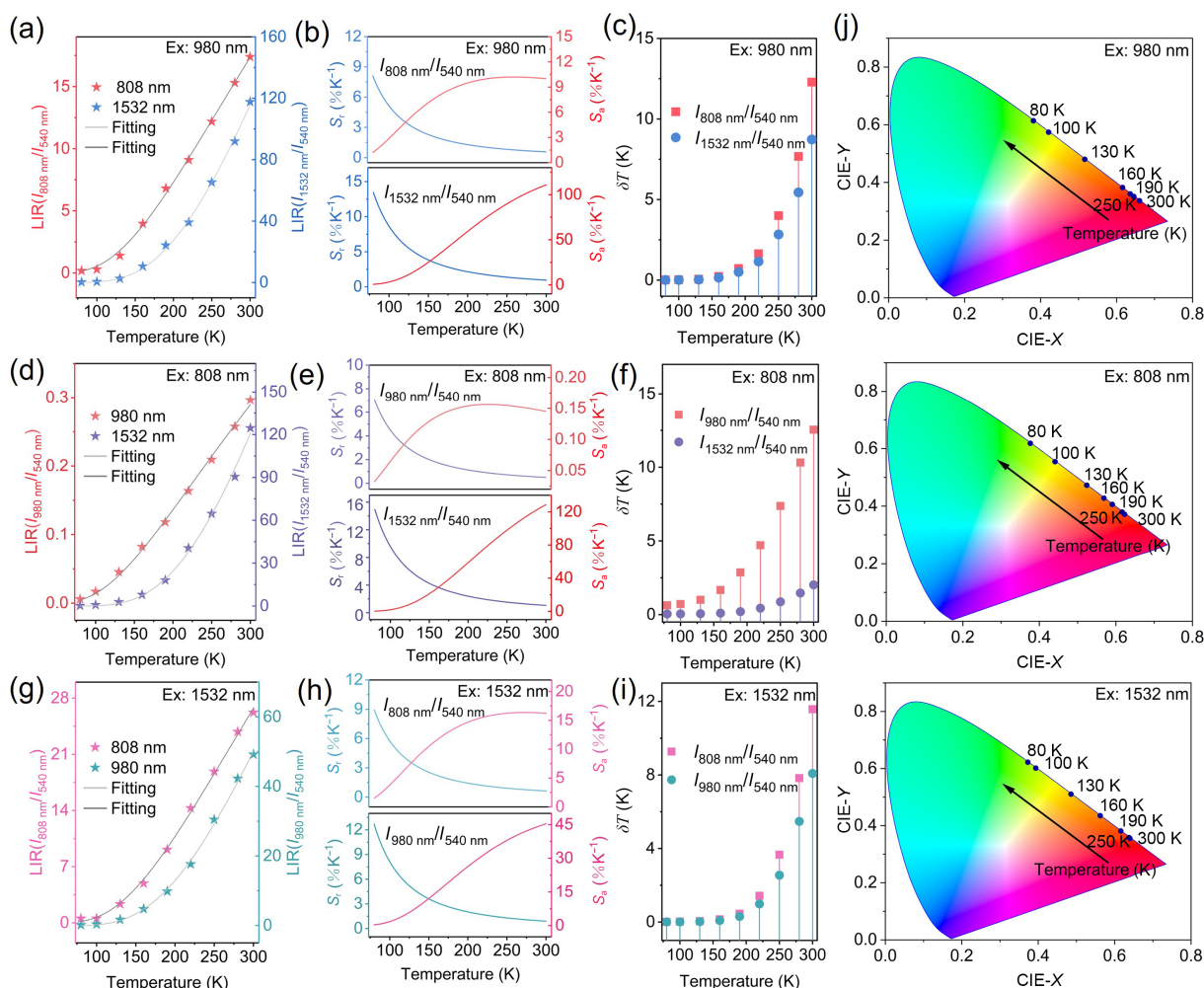


Figure 4 Temperature-sensing performance of the multimode fluorescence ratiometric upconversion thermometer. ((a), (d), and (g)) Luminescence intensity ratio with exponential fitting under 980 (0.36 W/cm^2), 808 (1.33 W/cm^2), and 1532 nm (0.28 W/cm^2) excitation, respectively. ((b), (e), and (h)) The absolute sensitivity (S_a) and relative sensitivity (S_r) of thermometer. ((c), (f), and (i)) The calculated temperature uncertainty (δT) of the thermometer. (j) CIE chromaticity diagrams of emission colors of 100Er@Y/AuNRs/OPCs at various temperatures.

exceed the reported results from the conventional upconversion thermometers by several to tens of times (Table S1 in the ESM). Besides, the largely enhanced UCL maintains a high signal-to-noise ratio even at low excitation power densities, leading to a good performance on the temperature uncertainty, i.e., δT . For example, at 80 K (Fig. 4(c)), the δT values can be reached as low as 0.012 K (808 nm reference) and 0.010 K (1532 nm reference).

Interestingly, the intrinsic multi-wavelength excitation characteristics of the 100Er@Y nanoparticles provide exceptional flexibility for construction of various NIR/green ratiometric thermometers, which is difficult to achieve in most of the conventional systems. Specifically, besides the above 980 nm excitation, 808 and 1532 nm excitation can also be used (Fig. S7 in the ESM), with each excitation wavelength generating two NIR emission bands suitable as reference signals (Figs. 4(d) and 4(g)). As shown in Figs. 4(e), 4(f), 4(h), and 4(i), the thermometric parameters (S , S_0 , and δT) under 808 and 1532 nm excitation are comparable to those under 980 nm excitation, all exhibiting consistently high performance. Notably, the laser power density should not be excessively high to prevent the laser-induced thermal effect from interfering with temperature detection (Figs. S8–S10 in the ESM). In addition, the temperature-induced chromaticity coordinates show a pronounced green-to-red emission transition as the temperature decreases from 80 to 300 K under all modes (due to strong CR modulation of the green-to-red emission ratio). The ambient temperature and its fluctuations can be assessed from the observed output color, showing great potential for non-contact visual temperature sensing (Fig. 4(j) and Fig. S11 in the ESM). These results suggest that our designed hybrids hold considerable promise for low-temperature monitoring in fields such as aerospace engineering, polar exploration, and maintenance of precision instruments.

4 Conclusions

In summary, we have demonstrated a multi-field strategy combining photonic crystal, plasmonic, and low-temperature fields for UCL enhancement in the Er³⁺-rich nanosystem, with a maximum enhancement factor of 1290. Furthermore, leveraging the multi-wavelength excitation capability of the Er³⁺-rich system, a six-mode ratiometric upconversion thermometer is constructed based on 100Er@Y/AuNRs/OPCs composite films, delivering high sensitivity (maximum S : 7.06%–14.95% K^{−1}) and high resolution (minimum δT : 0.008–0.634 K) over 80–300 K. This study not only provides a new strategy for efficient enhancement of UCL but also offers a promising approach for high-precision, multi-mode temperature sensing under extreme conditions.

Electronic Supplementary Material: Supplementary material (TEM images, size histograms, XRD patterns, SEM images, decay curves, enhancement factors, and a summary table of typical temperature sensing materials) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909076>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

Acknowledgements

This work was financed by Jilin Provincial Department of Science and Technology (No. 20240101319JC), the National Natural Science Foundation of China (Nos. 12474416, 62571214, and 12104179), the Fundamental Research Funds for the Central Universities, Jilin University, the Scientific and Technological Innovation Project of Changbaishan Laboratory, Jilin Province (No. CBS2025002-04), the National Key R&D Program of China (No. 2023YFC2811205), and the Laoshan Laboratory (No. LSKJ202203601).

Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

S. N. Z.: Investigation, data curation, formal analysis, writing – original draft, writing – review & editing. H. W.: Methodology, investigation. J. J. L.: Investigation, validation. L. J. N.: Methodology, formal analysis. E. H. W.: Formal analysis, validation. Y. H. L.: Investigation, formal analysis. X. M. W.: Conceptualization, data curation. J. H. L.: Investigation, validation. L. P. T.: Conceptualization, data curation, validation. J. Y.: Investigation, resources. D. L. Z.: Methodology, investigation. T. T. Z.: Conceptualization, data curation, writing – review & editing, validation. J. Z.: Conceptualization, validation, writing – review & editing, project administration, funding acquisition. All the authors have approved the final manuscript.

Use of AI statement

None.

References

- [1] Wang, F.; Wen, S. H.; He, H.; Wang, B. M.; Zhou, Z. G.; Shimoni, O.; Jin, D. Y. Microscopic inspection and tracking of single upconversion nanoparticles in living cells. *Light Sci. Appl.* **2018**, *7*, 18007.
- [2] Liu, S. B.; Yan, L.; Huang, J. S.; Zhang, Q. Y.; Zhou, B. Controlling upconversion in emerging multilayer core-shell nanostructures: From fundamentals to frontier applications. *Chem. Soc. Rev.* **2022**, *51*, 1729–1765.
- [3] Du, K. M.; Feng, J.; Gao, X.; Zhang, H. J. Nanocomposites based on lanthanide-doped upconversion nanoparticles: diverse designs and applications. *Light Sci. Appl.* **2022**, *11*, 222.
- [4] Auzel, F. Upconversion and anti-stokes processes with f and d ions in solids. *Chem. Rev.* **2004**, *104*, 139–174.
- [5] Yi, Z. G.; Luo, Z. C.; Qin, X.; Chen, Q. S.; Liu, X. G. Lanthanide-activated nanoparticles: a toolbox for bioimaging, therapeutics, and neuromodulation. *Acc. Chem. Res.* **2020**, *53*, 2692–2704.
- [6] Mun, K. R.; Kyhm, J.; Lee, J. Y.; Shin, S.; Zhu, Y. Y.; Kang, G. M.; Kim, D.; Deng, R. R.; Jang, H. S. Elemental-migration-assisted full-color-tunable upconversion nanoparticles for video-rate three-dimensional volumetric displays. *Nano Lett.* **2023**, *23*, 3014–3022.
- [7] Na, H.; Woo, K.; Lim, K.; Jang, H. S. Rational morphology control of β -NaYF₄:Yb, Er/Tm upconversion nanophosphors using a ligand, an additive, and lanthanide doping. *Nanoscale* **2013**, *5*, 4242–4251.
- [8] Huang, J. S.; An, Z. C.; Yan, L.; Zhou, B. Engineering orthogonal upconversion through selective excitation in a single nanoparticle. *Adv. Funct. Mater.* **2023**, *33*, 2212037.

- [9] Shen, T.; Zheng, H. Y.; Liao, R. T.; Li, B.; Wu, J. F.; Jiang, Z. Y.; Meng, X. Y.; Cao, C. Invisible to visible: Novel hydrophilic rare earth fluorescent composite inks for security applications. *Nano Res.* **2025**, *18*, 94907380.
- [10] Pei, P.; Chen, Y.; Sun, C. X.; Fan, Y.; Yang, Y. M.; Liu, X.; Lu, L. F.; Zhao, M. Y.; Zhang, H. X.; Zhao, D. Y. et al. X-ray-activated persistent luminescence nanomaterials for NIR-II imaging. *Nat. Nanotechnol.* **2021**, *16*, 1011–1018.
- [11] Chen, Q. S.; Xie, X. J.; Huang, B. L.; Liang, L. L.; Han, S. Y.; Yi, Z. G.; Wang, Y.; Li, Y.; Fan, D. Y.; Huang, L. et al. Confining excitation energy in Er³⁺-sensitized upconversion nanocrystals through Tm³⁺-mediated transient energy trapping. *Angew. Chem.* **2017**, *129*, 7713–7717.
- [12] Zuo, J.; Li, Q. Q.; Xue, B.; Li, C. X.; Chang, Y. L.; Zhang, Y. L.; Liu, X. M.; Tu, L. P.; Zhang, H.; Kong, X. G. Employing shells to eliminate concentration quenching in photonic upconversion nanostructure. *Nanoscale* **2017**, *9*, 7941–7946.
- [13] Wang, E. H.; Wang, W.; Niu, L. J.; Feng, Y. S.; Zhao, H. F.; Luo, Y. S.; Zhang, L. G.; Li, Q. Q.; Chen, H. R.; Chang, Y. L. et al. Significantly boosted upconversion emission in cryogenic Er@Yb@Y core-shell-shell nanostructures. *Adv. Opt. Mater.* **2024**, *12*, 2301827.
- [14] Chen, G. Y.; Qiu, H. L.; Prasad, P. N.; Chen, X. Y. Upconversion nanoparticles: Design, nanochemistry, and applications in theranostics. *Chem. Rev.* **2014**, *114*, 5161–5214.
- [15] Mejia, E.; Zhao, Y. M.; Nie, M. T.; Pittelkau, B.; Garg, A.; Song, J.; Zhu, W. Q.; Lezec, H.; Agrawal, A.; Zhou, W. Multi-pathway upconversion emission in symmetry-broken nanocavities: Broadband multiresonant enhancement and anti-correlated interfacial sensitivity. *Adv. Funct. Mater.* **2025**, *35*, 2424124.
- [16] Yuan, J.; Wu, K. F.; Shao, L.; Li, H. F.; Tu, L. P.; Zuo, J.; Zhang, H. Heavy element approach to realize efficient upconversion luminescence of er-rich nanoparticles. *Laser Photonics Rev.* **2025**, *19*, e00139.
- [17] Huo, Z. Q.; Jia, H.; Guo, S. H.; Feng, X. R.; Zhao, J.; Liu, W. X.; Yang, L.; He, W. Y.; Zhang, Y. L.; Teng, Y. Y. et al. Synthesis of NaYbF₄:Er nanocrystals with controllable size, morphology, and multicolor upconversion luminescence for Anticounterfeiting applications. *J. Lumin.* **2024**, *273*, 120670.
- [18] Li, F.; Tu, L. P.; Zhang, Y. Q.; Huang, D. X.; Liu, X. X.; Zhang, X. R.; Du, J. R.; Fan, R. W.; Yang, C. H.; Krämer, K. W. et al. Size-dependent lanthanide energy transfer amplifies upconversion luminescence quantum yields. *Nat. Photonics* **2024**, *18*, 440–449.
- [19] Liu, X. X.; Tu, L. P.; Li, F.; Huang, D. X.; Ågren, H.; Chen, G. Y. Unravelling size-dependent upconversion luminescence in ytterbium and erbium codoped NaYF₄ nanocrystals. *J. Am. Chem. Soc.* **2025**, *147*, 5955–5961.
- [20] Wang, F.; Han, Y.; Lim, C. S.; Lu, Y. H.; Wang, J.; Xu, J.; Chen, H. Y.; Zhang, C.; Hong, M. H.; Liu, X. G. Simultaneous phase and size control of upconversion nanocrystals through lanthanide doping. *Nature* **2010**, *463*, 1061–1065.
- [21] Zhang, Y. X.; Wen, R. R.; Hu, J. L.; Guan, D. M.; Qiu, X. C.; Zhang, Y. X.; Kohane, D. S.; Liu, Q. Enhancement of single upconversion nanoparticle imaging by topologically segregated core-shell structure with inward energy migration. *Nat. Commun.* **2022**, *13*, 5927.
- [22] Liu, Q.; Zhang, Y. X.; Peng, C. S.; Yang, T. S.; Joubert, L. M.; Chu, S. Single upconversion nanoparticle imaging at sub-10 W·cm⁻² irradiance. *Nat. Photonics* **2018**, *12*, 548–553.
- [23] Chan, E. M.; Levy, E. S.; Cohen, B. E. Rationally designed energy transfer in upconverting nanoparticles. *Adv. Mater.* **2015**, *27*, 5753–5761.
- [24] Homann, C.; Krukewitt, L.; Frenzel, F.; Grauel, B.; Würth, C.; Resch-Genger, U.; Haase, M. NaYF₄:Yb, Er/NaYF₄ core/shell nanocrystals with high upconversion luminescence quantum yield. *Angew. Chem., Int. Ed.* **2018**, *57*, 8765–8769.
- [25] Zhu, S. Q.; Lu, G. H.; Wang, X.; Liu, T. S.; He, Y. T.; Sun, J.; Xie, X. F. Surface plasmon resonance effect enhanced upconversion luminescence in Ag modified NaYF₄:Yb/Er for photovoltaic efficiency improvement under solar irradiation. *Renew. Energy* **2025**, *248*, 123062.
- [26] Ahn, I. H.; Yeo, S. J.; Jung, K.; Kang, G. M.; Shin, D. H.; Jang, H. S.; Kim, B.; Nam, M.; Kwon, S. J.; Ko, D. H. A multi-functional highly efficient upconversion luminescent film with an array of dielectric microbeads decorated with metal nanoparticles. *Adv. Funct. Mater.* **2020**, *30*, 1909445.
- [27] Yin, Z.; Zhu, Y. S.; Xu, W.; Wang, J.; Xu, S.; Dong, B.; Xu, L.; Zhang, S.; Song, H. W. Remarkable enhancement of upconversion fluorescence and confocal imaging of PMMA Opal/NaYF₄:Yb³⁺, Tm³⁺/Er³⁺ nanocrystals. *Chem. Commun.* **2013**, *49*, 3781–3783.
- [28] Li, Q. Q.; Xie, X. Y.; Wu, H.; Chen, H. R.; Wang, W.; Kong, X. G.; Chang, Y. L. Superenhancement photon upconversion nanoparticles for photoactivated nanocryometer. *Nano Lett.* **2023**, *23*, 3444–3450.
- [29] Zhang, F.; Braun, G. B.; Shi, Y. F.; Zhang, Y. C.; Sun, X. H.; Reich, N. O.; Zhao, D. Y.; Stucky, G. Fabrication of Ag@SiO₂@Y₂O₃:Er nanostructures for bioimaging: tuning of the upconversion fluorescence with silver nanoparticles. *J. Am. Chem. Soc.* **2010**, *132*, 2850–2851.
- [30] Das, A.; Bae, K.; Park, W. Enhancement of upconversion luminescence using photonic nanostructures. *Nanophotonics* **2020**, *9*, 1359–1371.
- [31] Tong, X.; Xiang, J.; Lu, X. L.; Karsenti, P. L.; Zhao, Y. Electrically enhancing and modulating the photoluminescence of upconversion nanoparticles using liquid crystals. *J. Mater. Chem. C* **2018**, *6*, 7683–7688.
- [32] Yu, D. C.; Liu, H. S.; Lv, M. T.; Li, B. C.; Zhou, Y. Y.; Han, X. X.; Zhang, D. W. Energy extraction from dark Fe³⁺ in A₂Sc₂B₃O₁₁:Fe³⁺, Yb³⁺ (A = Sr, Ba) toward promoted NIR luminescence and pc-LED light source for multifunctional applications. *Light Sci. Appl.* **2026**, *15*, 229.
- [33] Yin, Z.; Li, H.; Xu, W.; Cui, S. B.; Zhou, D. L.; Chen, X.; Zhu, Y. S.; Qin, G. S.; Song, H. W. Local field modulation induced three-order upconversion enhancement: Combining surface plasmon effect and photonic crystal effect. *Adv. Mater.* **2016**, *28*, 2518–2525.
- [34] Kang, F. W.; He, J. J.; Sun, T. Y.; Bao, Z. Y.; Wang, F.; Lei, D. Y. Plasmonic dual-enhancement and precise color tuning of gold nanorod@SiO₂ coupled core-shell-shell upconversion nanocrystals. *Adv. Funct. Mater.* **2017**, *27*, 1701842.
- [35] Mao, C. C.; Min, K.; Bae, K.; Cho, S.; Xu, T.; Jeon, H.; Park, W. Enhanced upconversion luminescence by two-dimensional photonic crystal structure. *ACS Photonics* **2019**, *6*, 1882–1888.
- [36] Guo, X.; Zou, D. Y.; Guo, X. Y.; Lv, Y.; Wang, T. N.; Wang, Y. J.; Liu, X. Y. Modulated spontaneous and stimulated emission in luminescent films using one-dimensional photonic crystal filters. *J. Mater. Chem. C* **2024**, *12*, 5004–5011.
- [37] Wu, K. F.; Wang, E. H.; Yuan, J.; Zuo, J.; Zhou, D.; Zhao, H. F.; Luo, Y. S.; Zhang, L. G.; Li, B.; Zhang, J. H. et al. Cross relaxation channel tailored temperature response in Er³⁺-rich upconversion nanophosphor. *Angew. Chem., Int. Ed.* **2023**, *62*, e202306585.
- [38] Tu, L. P.; Wu, K. F.; Luo, Y. S.; Wang, E. H.; Yuan, J.; Zuo, J.; Zhou, D.; Li, B.; Zhou, J. J.; Jin, D. Y. et al. Significant enhancement of the upconversion emission in highly Er³⁺-doped nanoparticles at cryogenic temperatures. *Angew. Chem., Int. Ed.* **2023**, *62*, e202217100.
- [39] Li, L.; Zhang, C.; Xu, L.; Ye, C. Q.; Chen, S. R.; Wang, X. M.; Song, Y. L. Luminescence ratiometric nanothermometry regulated by tailoring annihilators of triplet-triplet annihilation upconversion nanomicelles. *Angew. Chem., Int. Ed.* **2021**, *60*, 26725–26733.
- [40] Yu, D. C.; Li, H. Y.; Zhang, D. W.; Zhang, Q. Y.; Meijerink, A.; Suta, M. One ion to catch them all: Targeted high-precision Boltzmann thermometry over a wide temperature range with Gd³⁺. *Light Sci. Appl.* **2021**, *10*, 236.
- [41] Pinto, P. B.; Matrone, P. W.; Ferreira, F. S.; Santos, P. V.; Sigoli, F. A.; Couto Jr, O. D. D. Thermal dynamics induced by surface acoustic

- waves in lanthanide-doped core@multishell nanoparticles. *Adv. Opt. Mater.* **2025**, *13*, 2403497.
- [42] Wei, H. P.; Cai, Z. Y.; Huang, H. Z.; Wei, G. H.; Zhou, B. Ultra-sensitive low-temperature upconversion via interfacial energy transfer toward visual cryogenic nanothermometry. *Adv. Funct. Mater.* **2025**, *35*, e10764.
- [43] Wu, Y. K.; Li, F.; Wu, Y. N.; Wang, H.; Gu, L. T.; Zhang, J. Y.; Qi, Y. K.; Meng, L. K.; Kong, N.; Chai, Y. J. et al. Lanthanide luminescence nanothermometer with working wavelength beyond 1500 nm for cerebrovascular temperature imaging *in vivo*. *Nat. Commun.* **2024**, *15*, 2341.
- [44] Wang, E. H.; Yuan, J.; Niu, L. J.; Xia, L.; Liu, X. Y.; Wu, K. F.; Xiao, H. T.; Sun, Q. R.; Zhu, L. X.; Tu, L. P. et al. Cross relaxation controlled ultralow temperature detection in high-level-doping upconversion thermometer. *Laser Photonics Rev.* **2025**, *19*, 2402222.
- [45] Sun, L. N. NaBiF₄-based hollow upconversion nanoparticles for temperature sensing. *Light Sci. Appl.* **2022**, *11*, 257.
- [46] Brites, C. D. S.; Lima, P. P.; Silva, N. J. O.; Millán, A.; Amaral, V. S.; Palacio, F.; Carlos, L. D. Thermometry at the nanoscale. *Nanoscale* **2012**, *4*, 4799–4829.
- [47] Nexha, A.; Carvajal, J. J.; Pujol, M. C.; Díaz, F.; Aguiló, M. Lanthanide doped luminescence nanothermometers in the biological windows: Strategies and applications. *Nanoscale* **2021**, *13*, 7913–7987.
- [48] Du, P.; Luo, L. H.; Yu, J. S. Upconversion emission and cathodoluminescence of Er³⁺-doped NaYbF₄ nanoparticles for low-temperature thermometry and field emission displays. *Appl. Phys. A* **2017**, *123*, 157.
- [49] Cai, Z. Y.; An, Z. C.; Huang, H. Z.; Zhao, Y.; Zhou, B. High-sensitive nonthermally coupled upconversion for ultralow temperature sensing. *J. Rare Earths* **2024**, *42*, 2027–2032.
- [50] An, R.; Liang, Y.; Deng, R. P.; Lei, P. P.; Zhang, H. J. Hollow nanoparticles synthesized via Ostwald ripening and their upconversion luminescence-mediated Boltzmann thermometry over a wide temperature range. *Light Sci. Appl.* **2022**, *11*, 217.
- [51] Vetrone, F.; Naccache, R.; Zamarrón, A.; Juarranz de la Fuente, A.; Sanz-Rodríguez, F.; Martínez Maestro, L.; Martín Rodríguez, E.; Jaque, D.; García Solé, J.; Capobianco, J. A. Temperature sensing using fluorescent nanothermometers. *ACS Nano* **2010**, *4*, 3254–3258.
- [52] Brites, C. D. S.; Balabhadra, S.; Carlos, L. D. Lanthanide-based thermometers: At the cutting-edge of luminescence thermometry. *Adv. Opt. Mater.* **2019**, *7*, 1801239.
- [53] Zhang, B. B.; Guo, X. J.; Zhang, Z. L.; Fu, Z. K.; Zheng, H. R. Luminescence thermometry with rare earth doped nanoparticles: Status and challenges. *J. Lumin.* **2022**, *250*, 119110.
- [54] Johnson, N. J. J.; Korinek, A.; Dong, C. H.; van Veggel, F. C. J. M. Self-focusing by ostwald ripening: A strategy for layer-by-layer epitaxial growth on upconverting nanocrystals. *J. Am. Chem. Soc.* **2012**, *134*, 11068–11071.
- [55] Noda, S.; Fujita, M.; Asano, T. Spontaneous-emission control by photonic crystals and nanocavities. *Nat. Photonics* **2007**, *1*, 449–458.
- [56] Hoang, T. B.; Akselrod, G. M.; Argyropoulos, C.; Huang, J. N.; Smith, D. R.; Mikkelsen, M. H. Ultrafast spontaneous emission source using plasmonic nanoantennas. *Nat. Commun.* **2015**, *6*, 7788.



This is an open access article under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0, <https://creativecommons.org/licenses/by/4.0/>).

© The Author(s) 2026. Published by Tsinghua University Press.



清华大学出版社
Tsinghua University Press

SciOpen

94909076 (9 of 9)

Nano Research, 2026, 19, 94909076