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Editor's Choice collection: photon upconversion

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Associate Editor, Professor Xiaogang Liu (National University of Singapore), introduces this Editor's Choice collection in *Nanoscale* on photon upconversion.

Multiphoton upconversion with lanthanide ions enables the conversion of low-energy quanta to higher-energy quantum states and has attracted tremendous interest in materials chemistry and physics since its discovery in bulk crystals in the 1960s.[1] Initially hindered by challenges in nanocrystal synthesis, recent advances now enable precise control of upconversion nanocrystals, from doping concentration to spectral profile and surface chemistry. Lanthanide-doped upconversion nanomaterials have found applications in various fields, including biosensing, super-resolution imaging, deep-brain stimulation, light-guided nanomedicine, optical encryption, solid-state lasing, full-color displays, solar energy harvesting, and photocatalysis.[2,3]

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Professor Xiaogang Liu earned his PhD (2004) in inorganic chemistry from Northwestern University, Evanston, USA and worked as a postdoctoral researcher at Massachusetts Institute of Technology for two years. Currently, he works at the National University of Singapore and holds a joint appointment at the Institute of Materials Research and Engineering. He is an associate editor of Nanoscale and BMEMat and serves on the editorial boards of several scientific journals. Among his research interests are the study of energy transfer in lanthanide-doped nanomaterials, the application of optical nanomaterials for neuromodulation, the development of advanced X-ray imaging scintillators, and the prototyping of electronic tools for assistive technologies.

In this Editor's Choice collection, we highlight the latest publications in photon upconversion, focusing on fundamental principles, spectral engineering, multifunctional integration, synthetic protocols, materials characterization, versatile applications, and future directions.

Precise modulation of upconversion luminescence is crucial for the translation of upconversion nanocrystals into specific applications. Grzyb *et al.* (DOI: **https://doi.org/10.1039/D0NR07136F**) develop a robust method for tunable upconversion emission across the visible to near-infrared range under different laser excitations. Coupling upconversion nanoparticles with organic molecules has become a popular strategy for improving upconversion efficiency for various applications. Liu *et al.* (DOI: **https://doi.org/10.1039/D1NR07329J**) report dye-sensitized core–multishell upconversion nanoparticles for enhanced ultraviolet and near-infrared emission. Meanwhile, Mavridi-Printezi *et al.* (DOI: **https://doi.org/10.1039/D1NR01401C**) discuss molecular engineering strategies for extending the spectral activity of semiconductor photocatalysts by functionalizing them with molecularly sensitized upconversion nanocrystals.

Spatial confinement of the excitation energy in nanocrystals has proven effective in enhancing the emission intensity. In their contribution, Zhou *et al.* (DOI: **https://doi.org/10.1039/D1NR01745D**) report the controlled synthesis of a new class of Cs_2NaYF_6:Yb/Tm nanoplatelets. Energy migration within these nanoplatelets leads to enhanced multiphoton upconversion emission. Quintanilla *et al.* (DOI: **https://doi.org/10.1039/D1NR06319G**) present a thorough assessment of how phase, size and morphology affect the photoluminescence quantum yield of $NaGdF_4$:Er^{3+}/Yb^{3+} nanocrystals. Understanding lattice defects is essential for developing efficient upconversion systems. Using a first-principles calculation method, Qin and Liu (DOI: **https://doi.org/10.1039/D1NR06904G**) critically analyze the effect of elastic strain on lattice defect formation in upconversion nanocrystals.

To elucidate the relationship between crystal structure and upconversion behavior, various instrumentation techniques have been utilized. Ferrera-González *et al.* (DOI: **https://doi.org/10.1039/D1NR00389E**) present optical investigations for photophysical characterization of upconversion nanocrystals using near-infrared laser scanning microscopy. This technique allows visualization of resonance energy transfer processes and colocalization of fluorophores and nanocrystals. In another contribution, Kumar *et al.* (DOI: **https://doi.org/10.1039/D1NR02103F**) explore the utility of upconversion nanocrystals as single nanoscopic sources for single-molecule absorption spectroscopy and offer insights into possible energy transfer mechanisms between nanocrystals and molecules.

Upconversion nanoparticles, known for their high photostability and minimal background autofluorescence, serve as ideal luminescent probes for high-resolution *in vivo* bioimaging. Goh *et al.* (DOI: **https://doi.org/10.1039/D2NR01999J**) discuss the use of upconversion nanocrystal-based bioprobes for real-time, long-term tracking of intercellular cargo transfer. In parallel, Qiao *et al.* (DOI: **https://doi.org/10.1039/D0NR07399G**) develop super-bright red-emitting bipyramidal upconversion nanoparticles for plant tissue imaging. Upconversion-stimulated emission depletion provides a powerful sub-diffraction imaging modality for biological studies. In their contribution, Camillis *et al.* (DOI: **https://doi.org/10.1039/D0NR04809G**) report exquisite control of nonlinear emissions from Tm^{3+}/Yb^{3+} co-doped nanoparticles to enhance super-resolution performance in super-linear excitation–emission microscopy and stimulated excitation-depletion microscopy.

The demand for upconversion nanomaterials that emit in the second biological near-infrared window (NIR-II) has increased in emerging biological applications. Tsang *et al.* (DOI: **https://doi.org/10.1039/D2NR01680J**) describe the design and synthesis of Pr^{3+}/Yb^{3+} co-doped nanocrystals capable of ultraviolet upconversion and NIR-II downconversion, highlighting their potential applications in deep-tissue bioimaging and light-triggered germicidal applications. Liu *et al.* (DOI: **https://doi.org/10.1039/D0NR06790C**) focus on producing hybrid upconversion nanocomposites for multimodal imaging-guided synergistic biotherapy.

The finely controlled light emission and lack of autofluorescence background of upconversion nanoparticles make them promising for volumetric displays and anti-counterfeiting applications. Gao *et al.* (DOI: **https://doi.org/10.1039/D0NR03076G**) devise a series of upconversion nanoparticles with excitation-power-dependent emission and enhanced brightness for video-rate upconversion display systems. By taking advantage of interfacial energy transfer in a coupled Ho^{3+}/Yb^{3+} upconversion system, Huang *et al.* (DOI: **https://doi.org/10.1039/D0NR09068A**) achieve excitation power-dependent tunable upconversion emission for anti-counterfeiting. Upconversion nanomaterials have also been integrated into semiconductor materials to develop near-infrared light-responsive devices. In their contribution, Yu *et al.* (DOI: **https://doi.org/10.1039/D0NR06719A**) review the latest achievements in optoelectronic devices integrated with lanthanide-based materials to construct next-generation optical and optoelectronic data-storage systems.

Lanthanide-doped luminescent nanomaterials have shown promise for non-contact and fast nanoscale temperature measurements. Martínez *et al.* (DOI: **https://doi.org/10.1039/D1NR03223B**) report irreversible patterns in the upconversion intensity of Yb^{3+}/Er^{3+} co-doped nanoparticles during thermal cycling. The shape and trajectory of the thermal hysteresis loop highly depend on the hydrophilicity of the nanoparticle surface, which can be modified by using different capping molecules. Moreover, Bastos *et al.* (DOI: **https://doi.org/10.1039/d0nr06989b**) design a nanohybrid, featuring a lipid-bilayer-tethered upconversion nanoparticle, to explore the transient regime of temperature profiles and determine the specific heat capacity of both the lipid bilayer and the nanoparticle.

Stopikowska *et al.* (DOI: **https://doi.org/10.1039/D1NR01395E**) establish a link between the pumping power and luminescence properties of nanocrystals, providing guidelines for improving the sensitivity of optical nanothermometers. Nexha *et al.* (DOI: **https://doi.org/10.1039/D0NR09150B**) provide a comprehensive overview of the fundamental mechanisms underlying luminescent nanothermometers and guidelines for improving thermal sensitivity, temperature resolution, and emission regulation in biological windows for biomedical applications. Moreover, Wang *et al.* (DOI: **https://doi.org/10.1039/D0NR08603G**) investigate the phenomenon of thermal quenching in upconversion systems to unravel the role of energy transfer in thermal quenching.

The assembly of different functional elements into core–shell upconversion systems opens doors to nanostructures with multifaceted capabilities. In their contribution, Xiang *et al.* (DOI: **https://doi.org/10.1039/D0NR09115D**) highlight the design and characterization of Cu_2S-modified upconversion nanomaterials, enabling both photothermal therapy and high-resolution real-time temperature sensing. In parallel, Ferreira *et al.* (DOI: **https://doi.org/10.1039/D1NR03796J**) focus on the controlled synthesis of lanthanide-based opto-magnetic core–shell nanoparticles for temperature and magnetic-field sensing.

Another avenue to achieve anti-Stokes emission relies on triplet–triplet annihilation (TTA) systems, which are known for their high absorption coefficients and near-unit upconversion efficiencies.[4] Perovskite nanocrystals have recently emerged as effective inorganic triplet sensitizers for TTA upconversion, as demonstrated by Koharagi *et al.* (DOI: **https://doi.org/10.1039/D1NR06588B**), where green light is converted to ultraviolet light. Moreover, Mitsui *et al.* (DOI: **https://doi.org/10.1039/D2NR00813K**) employ Au_{25}-rod clusters as TTA sensitizers and show direct singlet–triplet transitions in the near-infrared region (730–900 nm).

We hope that this Editor's Choice collection will provide insights into recent advances in the field of photon upconversion, bridging the gap between fundamental research and practical applications. We extend our heartfelt appreciation to the dedicated authors, reviewers, and editorial staff for their invaluable contributions to this themed collection.

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